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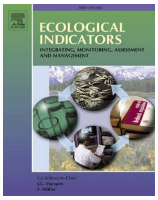

A conceptual modelling framework for assessment multiple soil degradation: A case study in the region of Šumadija and Western Serbia

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ABSTRACT

Soil degradation is a global problem and researchers are facing the challenge of assessing the scale, trends, and consequences of contributing processes. With this in mind, this study implemented the new concept of multiple soil degradation indices (MSDI) for the first time in the region of Šumadija and Western Serbia (SWS). This concept enables the simultaneous integration of several environmental components that can act separately or synergistically and offers concrete answers and information on the state and distribution of physical (PSDI), chemical (CSDI) and biological (BSDI) soil degradation. Using several different geospatial-modelled approaches, results indicated that physical degradation was the greatest contributor to soil degradation in the SWS region with an impact of 55%, followed by chemical degradation at 16%, while biological degradation only had a 6% impact. The dominant indicator of physical degradation was the vegetation cover management factor with an impact of approximately 58%, while for chemical degradation it was soil organic matter, with a relative impact of almost 49%. Total microflora and total number of fungi were the most significant biological indicators with an average impact of approximately 43%. In addition, this study indicated that about 59% of the region is currently degraded, with about 44% of it classified as moderately degraded. The results of this study offer new insights into the geospatial dynamics of interactive degradation processes in Serbia and can form the basis for strengthening scientific, expert, and political support when implementing international and national policies concerned with protecting soil from degradation.

1. Introduction

Soil degradation is the result of the action of a large number of factors (physical, chemical, biological, and anthropogenic) and can cause a loss in soil's ability to provide services and ecosystem functions at different levels of interaction between climate, vegetation, topography, and also socioeconomic factors (Kadović, 1999; Ferreira et al., 2021; Wang et al., 2022). Although there are no reliable global estimates of the scale of soil degradation, some studies suggest that over 20% of the world's soil resources are affected by some form of degradation, with a degradation rate of 5–10 million ha per year (Barbier and Hochard, 2016; Zou et al., 2021). Productivity of the global land area is also estimated to have decreased by 23% (IPBES, 2019), with 1.3 to 3.2 billion people living in these areas (Olsson et al., 2019). However,

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Abbreviations: SWS, Šumadija and Western Serbia; USLE, Universal Soil Loss Equation; PTEs, Potentially toxic elements; SOM, Soil organic matter; MMEC, Modification Multi-Element Contamination; TM, Total microflora; ACT, Actinomycetes, TNF, Total number of fungi; AZO, Azotobacter spp.; DA, Dehydrogenase activity; DI, Distance to industry; PD, Population density; DR, Distance to road; AHP, Analytic Hierarchy Process; GDM, Geodetector modelling; WN, Weakened, nonlinear; WU, Weakened, unilinear; EB, Enhanced, bilinear; I, Independent; EN, Enhanced, nonlinear; BRT, Boosted Regression Trees; RI, Relative importance; PSDI, Physical Soil Degradation Index; CSDI, Chemical Soil Degradation Index; BSDI, Biological Soil Degradation Index; MSDI, Multiple Soil Degradation Index.

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degradation is not evenly distributed around the world as approximately 40% of these processes occur in poorer countries, which are also least able to mitigate them (UNCCD, 2019). This fact is particularly worrying given that demand for food, energy and water is expected to rise by 2030 (by between 30% and 50%), forcing around 700 million people to migrate (IPBES, 2018), with economic consequences that are already estimated at between USD 18 and 20 trillion annually (UNCCD, 2019). In an effort to deal with these major environmental and economic problems, the European Commission adopted the Thematic Strategy for Soil Protection in 2006, which aimed to provide a comprehensive common framework for soil protection across the EU. Later, in 2015, the United Nations General Assembly adopted Sustainable Development Goals (SDGs) with the aim of reducing soil degradation by 2030, while the goal to make Europe climate neutral by 2050 was set out in the recent European Green Deal (Montanarella and Panagos, 2021).

Although there is strong consensus that the context of soil degradation is an extremely important issue, there are different points of view when it comes to the methodology for assessing these phenomena and processes. In scientific literature, there are several approaches and methodologies for assessing soil degradation, although four basic types can be identified: expert concepts, the application of remote detection methods, biophysical models, and inventories of land use/condition (Gibbs and Salmon, 2015), primarily using qualitative, semi-quantitative, and quantitative methods (Sun et al., 2022). In recent decades, several assessments of the scale of soil/land degradation have been carried out based on methodologies such as GLASOD (Oldeman et al., 1991), ASSOD (van Lynden and Oldeman, 1997), FAO TerraSTAT (Bot et al., 2000), GLADA (Bai et al., 2008), and LDSF (Vågen et al., 2013). Additionally, studies and reports such as the recent IPBES Assessment Report on Land Degradation and Restoration (IPBES, 2018) have indicated that an assessment of multiple degradation processes is necessary to assess soil degradation accurately (Prăvălie et al., 2021), where simple solutions such as multi-criteria decision analysis (MCDA) can ensure better results (Bardgett et al., 2021). However, some of these studies also had various limitations. Firstly, these included limitations when interpreting data related to national or regional climate and environmental frameworks, deficiencies in assessing the complexity and importance of degradation indicators (Vogt et al., 2011), assessing differences in the potential of ecosystem services, but not in the degradation of this potential (Vågen et al., 2005), and the impossibility of applying a universal approach or method (Qi et al., 2009). Secondly, to date, various forms of this environmental issue have been analysed mainly in a traditional way, often based on approaches that include the analysis and assessment of a relatively small number of degradation indicators (Prăvălie et al., 2021; Petrosillo et al., 2021). These cannot explicitly and accurately indicate the general status of soil degradation in a given area (Romshoo et al., 2020) and are therefore not useful as a degradation early-warning system (Higginbottom et al., 2014; Olsson et al., 2019). For these reasons, contemporary research requires soil degradation metrics that can provide an assessment of several different degradation indicators, the specific actions of which have an impact on the environment in a particular area (Prăvălie et al., 2021; Nickayin et al., 2021; Salvati and Zitti, 2007), using specialised degradation multi-metric indices and using predominantly conceptual and combined models and methods (Bünemann et al., 2018). Therefore, this study presents a new methodological approach that includes at least one physical (Physical Soil Degradation Index - PSDI), chemical (Chemical Soil Degradation Index - CSDI) and biological (Biological Soil Degradation Index - BSDI) indicator of soil degradation in assessing the multiple degradation of soil (Multiple Soil Degradation Index - MSDI) in the Šumadija and Western Serbia region (SWS), starting from the assumption that these indicators, with their different forms of action, have a harmful impact on the environment of this area. Hence, this study answers the following questions: 1) What is the current state of soil degradation in the SWS region? 2) What are the dominant indicators of physical, chemical, and biological soil degradation in the SWS region? 3) What is the geospatial distribution of different forms of soil degradation in the SWS region? 4) What, according to the assessment, is the dominant form of soil degradation in the SWS region?

2. Material and methods

2.1. Study area

The SWS region, located in central and western Serbia (Fig. 1), is one of the five statistical regions of Serbia and the largest in terms of population (1,890,449), area (26,493 km^2), and number of settlements (2,111), (SORS, 2021). It borders Montenegro and Bosnia and Herzegovina and is characterised by hilly/mountainous relief intersected by rivers and valleys, while lowlands in the north-eastern part of the area create good conditions for agricultural production. The region is divided into eight administrative districts (Zlatibor, Kolubara, Mačva, Moravica, Pomoravlje, Rasina, Raška and Šumadija) and 52 local government units (10 towns and 42 municipalities). The most significant rivers in the region are the Sava, Western Morava, Kolubara, and Ibar, including the upper course of the Drina and Lim. The SWS region is dominated by mountain ranges broken up by deep valleys and canyons. The most important mountains over 1000 m are: Maljen (1,103 m), Povlen, Tara, Zlatibor (1,496 m), Javor, Radan (1,408 m), Rogozna (1,479 m), Čemerno, Radočelo (1,643 m), Zlatar, Jadovnik, Golija (1,833 m) and Kopaonik (2,017 m), (Pavlović et al., 2017).

2.2. Modelling architecture

For the purposes of this study, three databases with a total of 1024 surface soil samples were used, as well as 321 pedological profiles (databases: Department of Ecology – the Institute for Biological Research 'Siniša Stanković', the Institute of Soil Science, and the Faculty of Forestry (Belgrade University), Fig. 1). The processes for analysing the soil are provided in detail in the Supplementary Materials (Supplement 1). Based on a detailed review of literature related to the study area (Mrvić et al., 2009; Pavlović et al., 2017; Čakmak et al., 2018; Antić-Mladenović et al., 2019; Perović et al., 2021), 19 indicators (16 natural and 3 anthropogenic) that impact the degradation of soil in this region were selected with their evaluation criteria set to vary gradually from very low to very high (Table 1). Thus, the 16 natural indicators presented are soil erosion, soil organic matter (SOM), potentially toxic elements (PTEs) - As, Cd, Cr, Cu, Hg, Ni, Pb and Zn, pH (KCl), Total microflora (TM), Actinomycetes (ACT), Total number of fungi (TNF), Azotobacter spp. (AZO), and Dehydrogenase activity (DA), while the three anthropogenic indicators presented are distance to industry (DI), population density (PD), and distance to road (DR). For the purposes of this research, several different methodological approaches were used. Specifically, the Analytic Hierarchy Process (AHP), Geodetector modelling (GDM), and Boosted Regression Trees (BRT) integrated with GIS technologies served as a basis for a better understanding of the complex interactions affecting soil degradation. For this reason, the architecture of the applied model was developed to help understand the relationships between the presented methods and the model more easily (Fig. 2). The development of the applied methodology involved four steps. The first step was to build a modelling and data collection structure, while the second step was to select the required soil degradation indicators and to determine their geospatial distribution. The third phase of the model involved a complex analysis in order to obtain a hierarchical distribution of PSDI, CSDI and BSDI variations, as well as the generation of MSDI in the SWS region. Finally, quantification of the explanatory power of the individual degradation indices (PSDI, CSDI and BSDI) in the SWS region as well as in the eight administrative districts was performed (Fig. 2).

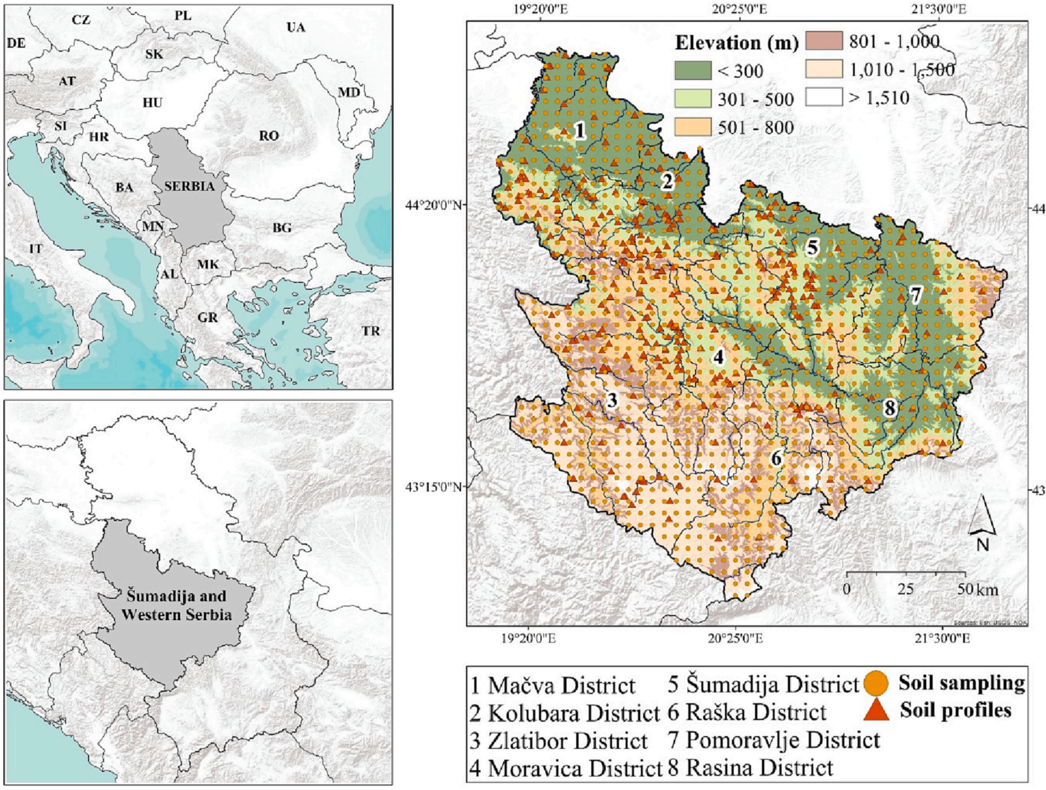

Fig. 1. Location of the study area.

Table 1
Evaluation criteria of various soil degradation indicators in the SWS region.

Indicators	Assessment degradation level					References
	Very low	Low	Moderate	High	Very high	
Soil erosion	>2	2–5	5–10	10–20	<20	(Djorović, 1975)
SOM	<10	5–10	3–5	3–1	>1	(Škorić and Sertić, 1966)
*MMEC	>0.5	0.5–1	1–2	2–3	<3	(Hakanson, 1980)
pH (KCl)	>4.5	4.5–5.5	5.5–6.5	6.5–7.2	<7.2	(Živković, 1966)
TM (x 10^6)	<2434	1403–2434	620–1403	143–620	>143	(Jenks, 1967)
TNF (x 10^4)	<36.41	25.54–36.41	17.91–25.54	11.45–17.91	>11.45	(Jenks, 1967)
ACT (x 10^5)	<28.72	20.50–28.72	13.42–20.50	7.26–13.42	>7.26	(Jenks, 1967)
AZO	<131.35	85.04–131.35	44.62–85.04	15.15–44.62	>15.15	(Jenks, 1967)
DA (μg TPF g^1 24 h)	<538.91	318.34–538.91	161.80–318.34	55.07–161.80	>55.07	(Jenks, 1967)
DI	> 2.5	2.5–5	5–10	10–20	<20	(Saljnikov et al., 2019)
PD	>50	50–100	100–300	300–500	<500	(Perović et al., 2021)
DR	>500	500–1000	1000–2500	2500–5000	<5000	(Saljnikov et al., 2019)

*MMEC – modified multi-element contamination, which included the following PTEs in the calculation: As, Cd, Cr, Cu, Hg, Ni, Pb and Zn; TPF – triphenylformazan.

2.3. Physical degradation of soil

In this study, water erosion of soil was analysed as the most dominant type of physical degradation in the SWS region (Djorović, 1975; Kadović, 1999; Kostadinov et al., 2006). Its occurrence leads to the removal of the most fertile surface layer of soil, where SOM and nutrients are stored, thus posing the greatest threat to food safety and environmental health, and resulting in ecological and economic damage (Pimentel, 2006). In order to formulate effective strategies aimed at mitigating soil erosion and implementing protection measures against it, the objective identification and quantification of risk areas is essential (Gobin et al., 2004). The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) was used to define PSDI as it is a method particularly applicable to regional assessments (Barbosa et al., 2015). USLE is an empirical soil erosion method based on five parameters, namely the rainfall erosivity (R factor), soil erodibility (K factor), topographic (LS factor), cover management (C factor), and conservation practice (P factor) factors. (For a more detailed description, see the Supplementary material - Supplement 2). Mean annual soil loss was estimated according to the following formula (Wischmeier and Smith, 1978):

$$A = R \times K \times LS \times C \times P \tag{1}$$

2.4. Chemical degradation of soil

In this study, CSDI was defined on the basis of SOM, MMEC and pH (KCl). SOM is the most significant individual factor of soil quality and its fertility, i.e., its quality and quantity affects soil's resistance to degradation by regulating the chemical, physical and biological functions of the soil (Krull et al., 2004). PTE content has a great impact on processes in soil, i.e., on the interaction and movement between elements, as well as on their balance in the soil, and an effective assessment of the impact of those PTEs present in soil is based on the use of different pollution

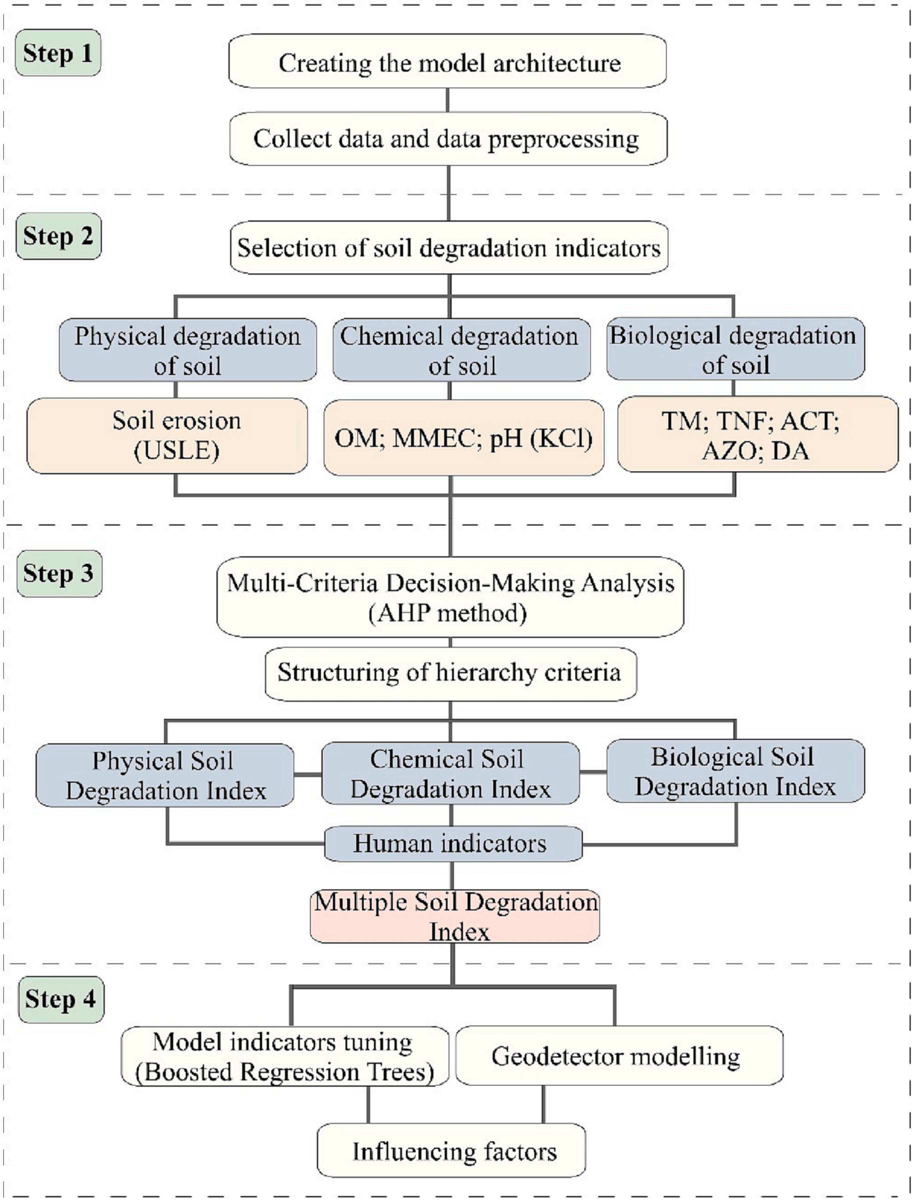

Fig. 2. Architecture of modelling designed to assess MSDI.

indices (Kowalska et al., 2018). Therefore, in this study, a modification of the Multi-Element Contamination Index (MEC) was used (Adamu and Nganje, 2010) to assess soil contamination based on PTE content in the surface layers of the soil. Specifically, the use of MMEC enabled a more accurate assessment of the anthropogenic impact, taking into account the calculated background values for the study area. The values for background PTEs (Table S1) were taken from the results of the project ‘Determination of background values of certain harmful and dangerous substances in soil’ (MEP, 2018), while the categorisation of MMEC was adapted to the classification for the Contamination factor (Table 1). MMEC was calculated based on the following modified formula (Hakanson, 1980):

$$MMEC = \frac{\left(\frac{C_1}{GB_1} + \frac{C_2}{GB_2} + \frac{C_3}{GB_3} + \cdots \frac{C_n}{GB_n}\right)}{n} \tag{2}$$

where C is the content of heavy metals, GB the value of the geochemical background, and n the number of PTEs being studied.

The pH of the soil solution has a great impact on many chemical and biological processes in the soil and is a significant indicator of soil quality. This includes affecting the availability of nutrient microelements, the availability of PTEs, microbiological activity, and SOM decomposition processes (Mengel and Kirkby, 2001). To assess the chemical degradation of the soil, pH values in KCl were used because seasonal variations in values of substitutional acidity are less pronounced.

2.5. *Biological degradation of soil*

Due to their high surface contact with the surroundings, soil microorganisms are highly susceptible to environmental stress, so changes in their abundance and ratio are very good early indicators of soil degradation (Pankhurst et al., 1995). The activity of microorganisms and the formation of their coenoses in soil is influenced by a whole range of abiotic (soil temperature, its humidity, air regime, redox potential, pH, and mechanical properties) and biotic (application of agrotechnical and agrochemical measures) factors. In terms of quantity, bacteria (actinomycetes) are most abundant in soil, followed by representatives of fungi, algae and protozoa, which can serve as indicators of soil degradation

(Miličić et al., 2006). For these reasons, our research included the monitoring of the total number of microorganisms, the number of fungi, the number of specific groups of microorganisms such as ammonifiers and Azotobacter, and the activity of the enzyme dehydrogenase.

2.6. Human indicators of soil degradation

Data on the locations of major industrial centres (DI) is taken from the database of potentially contaminated sites in the Republic of Serbia (SEPA, 2018). Euclidean distances from each location are divided into five groups: $\leq$ 2.5 km, 2.5 km $<$ to $\leq$ 5 km, 5 km $<$ to $\leq$ 10 km, 10 km $<$ to $\leq$ 20 km, and a distance $>$ 20 km. The geospatial distribution of PD was taken at 30 arc-second horizontal resolution in accordance with national censuses and population registers (CIESIN, 2018), using the following classification: $\leq$ 50 inhabitants/km^2, 50 $<$ to $\leq$ 100 inhabitants/km^2, 100 $<$ to $\leq$ 300 inhabitants/km^2, 300 $<$ to $\leq$ 500 inhabitants/km^2, and $>$ 500 inhabitants/km^2. The distance from major roadways (DR) was obtained by vectoring the major roads from the topographic map of the study area, while the geospatial distribution was obtained using the Euclidean distance method using the following classification: $\leq$ 500 m, 500 m $<$ to $\leq$ 1000 m, 1000 m $<$ to $\leq$ 2500 m, 2500 m $<$ to $\leq$ 5000 m, and a distance $>$ 5000 m (Table 1).

2.7. Multi-criteria evaluation using the AHP approach

The Analytic Hierarchy Process (AHP) technique is a MCDA proposed by (Saaty, 1980) and is the best way to allocate factors in a hierarchical structure (Pilevar et al., 2020). AHP based on GIS technologies is an important method for assessing the threat of soil degradation as not all indicators contribute equally to it, i.e., their contribution varies from location to location (Sandeep et al., 2021). The indicators of soil degradation studied in this research were hierarchically arranged and assigned criteria relationships, based on a scale of relative importance (Table S2). Each factor was given a comparative weighting, in terms of its impact, based on a review of the relevant literature. It should be noted that PSDI was not included in AHP analysis because one layer was used for this index, i.e., the result of the USLE method. In other words, focusing on an assessment of the target layer (MSDI), we first constructed three criteria relationships for chemical degradation indicators (Table S3) and five criteria relationships for biological degradation indicators (Table S4). Then, a matrix (Table S5; S6) of final criteria relationships (PSDI, CSDI, BSDI, and three human variables) was constructed, which allowed us to generate MSDI for the SWS region. Finally, the reliability of the method was checked by calculating the consistency ratio (CR), the values of which were below 0.1 in each individual hierarchical sorting, which confirms that all matrices were consistent.

2.8. Boosted Regression Trees analysis

In order to assess the impact of important indicators that trigger different soil degradation processes, the Boosted Regression Trees (BRT) model was used. BRT is a machine learning technique used in the analysis of complex nonlinear interactions between environmental indices (Friedman, 2000) and does not require assumptions on data distribution (Lyashevska et al., 2020). The following indices were taken into account in the analyses: C factor, LS factor, R factor, K factor, SOM, MMEC, pH (KCl), TM, TNF, ACT, AZO, DA, DI, PD, and DR. The main parameters of BRT were set to 0.005 (learning rate), 0.5 (bag fraction), 8 (tree complexity) and 10-fold cross-validation. The method was implemented in R software using the ‘gbm’ package, version 2.1 (Ridgeway, 2013). The results of this method are expressed in relative influence (RI), which assesses the optimal number of iterations determined by cross-validation. The greater the influence of the predictor variable, the higher the RI value, with the variables scaled so that the sum is 100. Of course, it should be pointed out that the goal of applying BRT in this study was not to develop predictive models, but to assess and compare the impact of those predictors (indicators) that most affect individual soil degradation processes.

2.9. Geodetector modelling

GDM is a statistical method for the quantitative evaluation of spatial stratified heterogeneity (SSH), (Wang et al., 2010). The key idea of the method is based on the assumption that if an independent variable has an important influence on a dependent variable, then the spatial distribution of the independent variable and the dependent variable should be similar (Zhou et al., 2021). In this study, geospatial heterogeneity between stratified layers, each composed of a series of units or classes, was analysed using two common sub-modules: the factor detector and the interaction detector. In the first case, the factor detector helped us determine the geospatial heterogeneity of the dependent variable (MSDI) and the determinant power of independent variables (PSDI, CSDI, and BSDI) through the q value using the following equation (Wang et al., 2010):

$$q = 1 - \frac{\sum_{h=1}^{l} N_h \sigma_h 2}{N\sigma^2} = 1 - \frac{SSW}{SST} \tag{3}$$

$$SSW = \sum_{h=1}^{l} N_h \sigma h^2 SST = N\sigma^2 \tag{4}$$

where $h = 1, \ldots, L$ is the stratification of variable Y or factor X, N_h and N are the number of units in layer h and the whole area respectively, and σh^2 and σ^2 are the variances of the Y value of layer h and the whole area respectively. SSW and SST are the sum of squares within and the total sum of squares.

In the second case, the interaction detector was used to quantify the interaction between PSDI ($X1$), CSDI ($X2$), and BSDI ($X3$). In this way, we assessed whether the explanatory power of the dependent variable Y (MSDI) increases or decreases in interaction with evaluation factors $X1$, $X2$ and $X3$, or whether the influence of these factors on Y was independent, whereby the relationship between these factors can be divided into five categories (Wang et al., 2010):

$$\text{Weakened, nonlinear (WN)}: \ q(A \cap B) < Min(q(A), g(B)) \tag{5}$$

$$\text{Weakened, unilinear (WU)}: \ min[q(A), g(B)]\langle q(A \cap B) < max[q(A), g(B)] \tag{6}$$

$$\text{Enhanced, bilinear (EB)}: \ max[q(A), g(B)]\langle q(A \cap B) < [q(A), g(B)] \tag{7}$$

$$\text{Independent (I)}: \ q(A \cap B) = q(A) + q(B) \tag{8}$$

$$\text{Enhanced, nonlinear (EN)}: \ q(A \cap B) > q(A) = q(B) \tag{9}$$

3. Results

3.1. Physical soil degradation index

The geospatial distribution of the R factor showed that it was pronounced in the central and western parts of the study area (Fig. S1). In contrast, its geographical distribution in the northeast region was quite low, indicating a direct link between the R factor and the distribution of precipitation. The LS factor was particularly marked in the south and west, which is directly connected to the topographic potential of these areas (Fig. S1). K factor values in the central and western parts of the study area were higher than elsewhere, which indicates more pronounced soil erosion processes in these areas. The C factor indicated that there was greater resistance to erosion processes in the central and western parts of the study area than in the northern and north-eastern parts. In particular, this difference is due to the fact that the surface cover of forest communities in the north and east is far less than in the south and west (Fig. S1).

Using the USLE method, the surfaces affected by each level of PSDI (Fig. 3) were calculated. In the SWS region, which occupies about 27,000 km^2, PSDI had no major impact across about 67% of the area. About 11% of the region was at moderate risk from PSDI, while there was high and very high risk from PSDI across just over 22% of the region, i.e., about 6,000 km^2 (Table S7). Essentially, our results indicated that PSDI gradually increased from east to west with obvious zonal characteristics. It was mainly characterised as low and very low risk in the northwest and southeast of the study area, while high and very high risk from erosion processes was most common in the western and central parts of the SWS region, as a consequence of the distinct topographic potential, unstable precipitation, and shallow, skeletal soils with low SOM content. In particular, a significant threat from erosion processes was identified in the wider area of the Kolubara District in the north, the hilly/mountainous terrains of the Zlatibor, Raška and Moravica districts in the southwest, and the agricultural areas of the Šumadija District in the north.

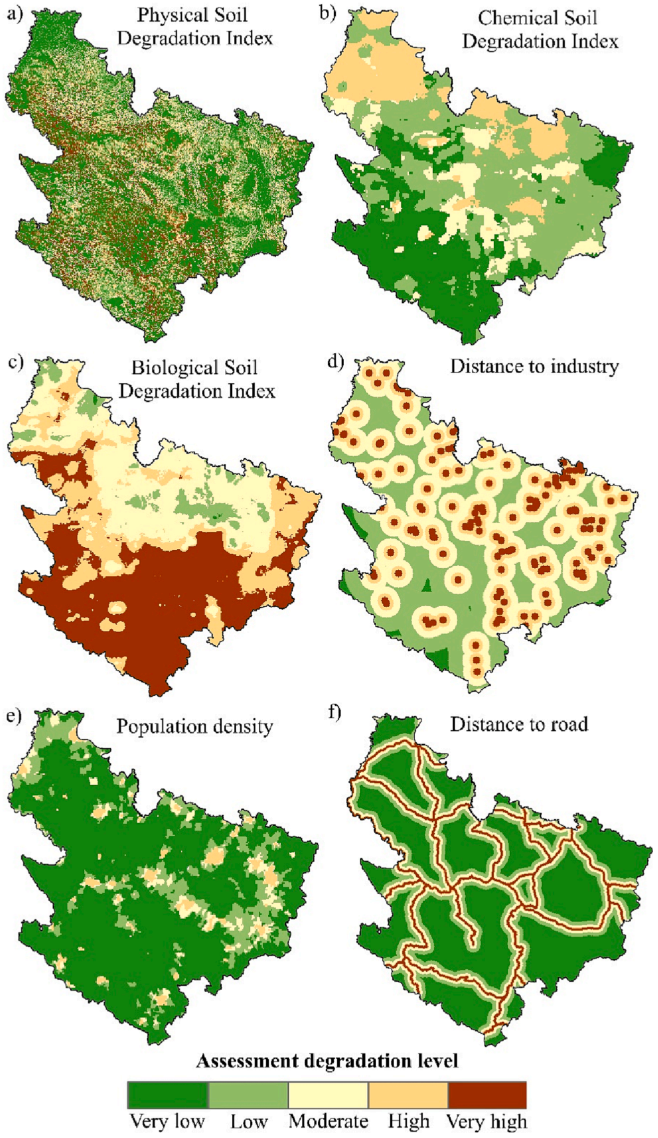

Fig. 3. Soil degradation indicators in the SWS region: a) Physical Soil Degradation Index; b) Chemical Soil Degradation Index; c) Biological Soil Degradation Index; d) Distance to industry; e) Population density; f) Distance to road.

3.2. *Chemical soil degradation index*

Low SOM content (1–3%) was found in the northern and eastern areas of the SWS region, while an increase was recorded in the southwestern part of the study area, which is a consequence of how the soil resources are used. In addition, high SOM levels (>10%) were also noticeable in western and central parts of the SWS region (Fig. S3). High MMEC values (<3) were found at the local level, primarily in the western and north-western parts of the SWS region, as well as in some central parts. These central parts abutted medium-value areas that were interconnected by narrow bands, while the rest of the SWS region had lower values, with eastern peripheral parts of the study area particularly prominent and also, to a lesser extent, southern peripheral areas. The geospatial pattern for pH (KCl) values was very similar to values for MMEC, i.e., the highest values were in the west and central parts of the SWS region with interconnected areas with moderate values (Fig. S3).

Using an MCDM approach based on GIS technologies, three indicators (SOM, MMEC, and pH (KCl)) were integrated for the geospatial mapping of CSDI in the SWS region. The threat posed by chemical soil degradation was low or very low across 71% of the entire SWS region, while about 12% was at moderate risk, and approximately 17% of the study area was at high risk (Table S7). Essentially, the geospatial representation of CSDI clearly distinguished two large entities: the first in the north and the border area of the north-eastern part, where a high impact was noted, and the second in the south-west of the SWS region, where the impact was very low (Fig. 3).

3.3. *Biological soil degradation index*

The geospatial distribution of individual indicators of biological degradation highlighted their low impact on soil degradation in northern parts of the SWS region (Fig. S4), with the abundance of ACT and TNF partially increasing towards central areas, especially in the valleys of large rivers. In contrast, there was a pronounced risk of soil degradation in all the hilly/mountainous areas of the SWS region (Fig. S4).

Using the AHP of the hierarchical relationship between the examined indicators of biological soil degradation, a BSDI was created (Fig. 3). In general, some form of biological degradation was observed across the entirety of the SWS region, with a very high value found across 41% of the region, mainly affecting mountainous areas in southern parts of the SWS region, but also to a certain extent the western parts of the Zlatibor and Mačva districts (Table S7; Fig. 3). High values were particularly characteristic of the perimeters of the alpine areas in the southern part of the SWS region (25%), while moderate values were mostly found in the central and southern parts of the region (29%). Very low and low values were widespread in the valleys of large rivers in the central part of the SWS region, as well as in the peripheral parts of the Mačva District towards the Sava and Drina rivers in the north and west (Table S7; Fig. 3).

3.4. *Multiple soil degradation index*

Based on the 19 analysed degradation indicators, a multiple soil degradation index (MSDI) was obtained, which highlighted significant geospatial differences in terms of soil sensitivity to degradation across the SWS region. According to the MSDI classification, about 11,000 km^2, accounting for about 41% of the total land area, fell into the very weak to weak category in terms of the threat from total forms of degradation. Large areas, totalling about 12,000 km^2 or 44% of the study area, can be classified as moderate in terms of MSDI values, representing the primary level of degradation, while high and very high MSDI values were local in character and covered almost 15% of the territory (Fig. 4; Table 2). Regionally, the most critical MSDI categories were mainly found in the northern, central, and southern parts of the SWS region, where the synergistic effect of physical and chemical soil degradation can be seen. Therefore, this area can be considered at threat ecologically, which is above all a result of the destruction of natural vegetation, especially

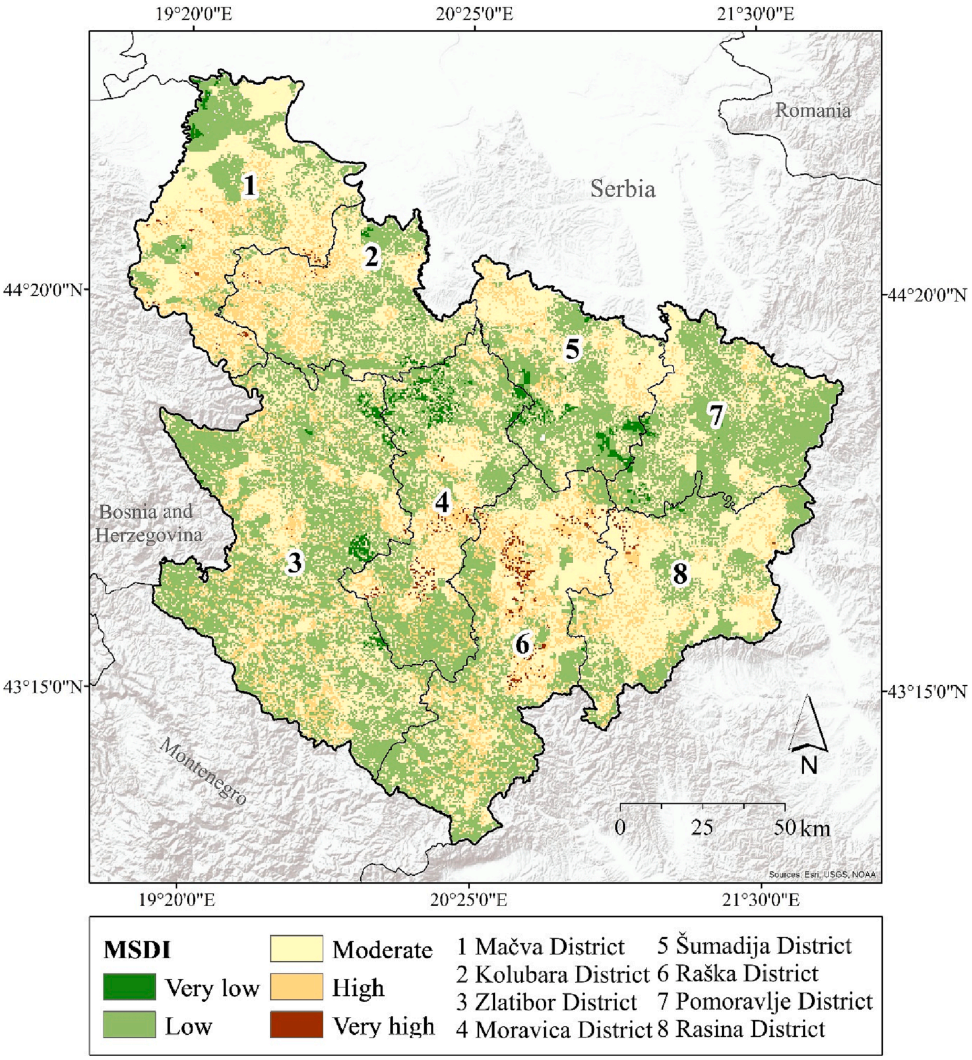

Fig. 4. Multiple Soil Degradation Index in the SWS region.

Table 2
Spatial distribution of MSDI in the SWS region.

Multiple Soil Degradation Index	km^2	%
Very low	462.81	1.75
Low	10453.30	39.46
Moderate	11706.06	44.19
High	3629.48	13.70
Very high	241.35	0.91
Total	26493.00	100.00

forests, but also soil erosion, agricultural activities, and an increase in PTE content in the soil.

It should be emphasised that, in terms of geospatial distribution, MSDI values are comparatively low compared to the individual indices (PSDI, CSDI, and BSDI) as these take into account the current state of the soil, while MSDI provides a comprehensive analysis of all the pressures on the soil area.

3.5. The contribution of influencing factors

The results suggest that the RI of the indicators is different, which points to variability in the form of the degradation indicators in the SWS region (Fig. 5). On average, the most important indicators of physical soil degradation were the C factor with an impact of approximately 58%, the LS factor with close to a 22% impact, and the R and K factors with an impact of approximately 10%. SOM had the greatest relative impact on chemical degradation with an impact of approximately 49%, while the impact of MMCE was estimated at 39% and that of pH (KCl) a mere 12%. The percentage impact of the biological indicators from highest to lowest was as follows: TM, TNF, ACT, AZO and DA, with an average impact of 30%, 30%, 17%, 12% and 12%, respectively. In terms of the human indicators, the highest rate of contribution was DI and PD, with an impact of approximately 42%, while the impact of DR was relatively low, at just under 15% (Fig. 5).

3.6. Spatial stratified heterogeneity of soil degradation

Our research found that PSDI exhibited strong SSH in the SWS region and explained about 55% of the geospatial variation of MSDI (Fig. 6a), followed by CSDI with an impact of approximately 15%, and BSDI with only a 6% impact. PSDI was also dominant in all regions of the study area, with *q* being the most pronounced in the Zlatibor (0.75) and Pomoravlje Districts (0.67). On the other hand, more significant *q* values for CSDI were obtained for the Šumadija (0.31) and Kolubara Districts (0.30), while BSDI was more frequent in the Kolubara (0.18) and Rasina Districts (0.17; Fig. 6a). In essence, these results coincided with the patterns of the most influential physical form of degradation, occurring in areas with a marked interaction between topography and land use, while the impact of chemical degradation was marked mainly around

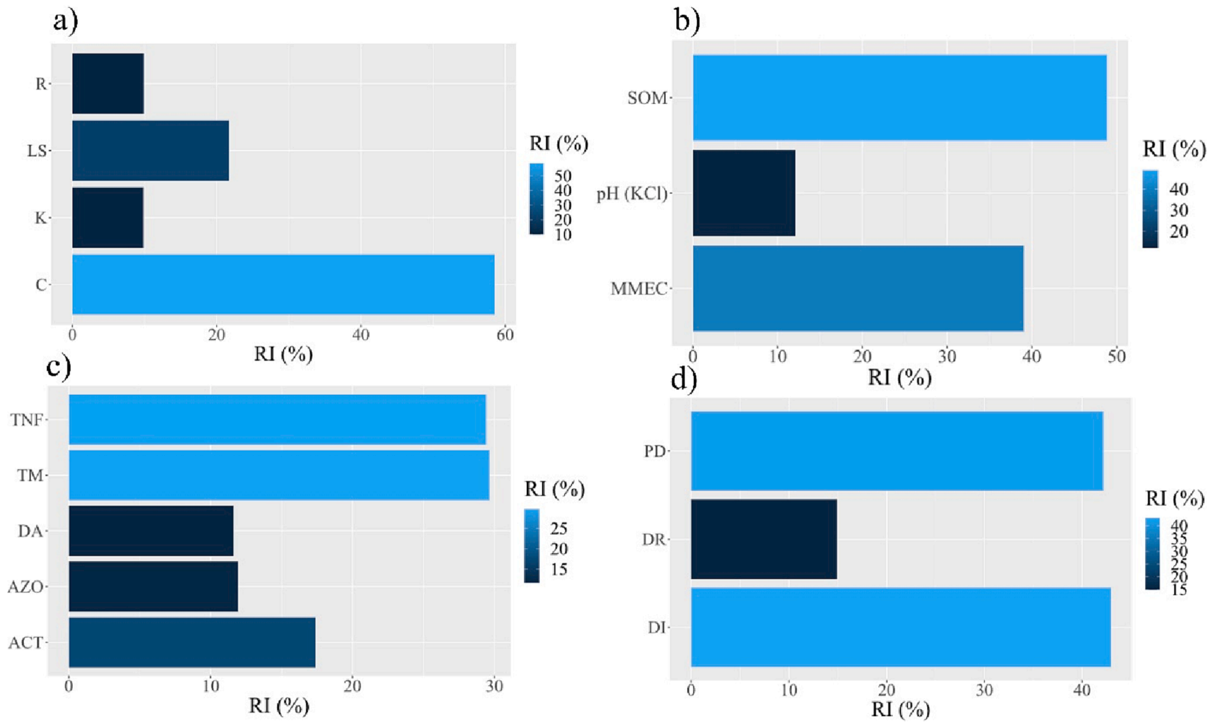

Fig. 5. Relative importance of the indicators: a) physical degradation indicators, b) chemical degradation indicators, c) biological degradation indicators, d) human indicators.

mining centres and areas with intensive agricultural production.

In addition, the interaction between the determinant power of the influence of PSDI, CSDI, and BSDI on the geospatial dynamics of MSDI was quantified and compared. The interactions were mainly EB and EN (Fig. 6b) and their impact on MSDI was greater than the impact of individual degradation indices. In short, the impact of PSDI, CSDI, and BSDI on soil degradation in the SWS region was not independent, but the impact of the interaction of the degradation indices was stronger than the sum of their separate effects (EN), i.e., their interactive effect was greater than each individual effect (EB). At the same time, our results showed that the interactions between PSDI and CSDI had the greatest explanator power, reaching 72%, PSDI ∩ BSDI explained 56%, and the interaction between CSDI ∩ BSDI had an explanator power of 42% (Fig. 6b).

4. Discussion

4.1. Impacts of physical degradation

According to (Panagos et al., 2015), European mean annual soil loss amounts to approximately 2.46 t ha^{-1} yr^{-1}, which is 1.6 times higher than the average soil formation rate (Verheijen et al., 2009). Accordingly, approximately 12.7% of European soils are affected by a moderate to high erosion rate, whereby their losses can be classified at over 5 t ha^{-1} yr^{-1} (Panagos et al., 2016). In the SWS region, our research indicates that this percentage is even higher, i.e., that as much as 33% of the region can be classified as above this threshold. However, if we bear in mind that the tolerance threshold level of soil in central Serbia is about 2 t ha^{-1} yr^{-1} (Đorović, 1975), close to 56% of the SWS region can be considered safe. Soil protection measures should certainly be undertaken across 22.43% of the SWS region, where the estimated soil losses are serious (soil losses above 10 ha^{-1} yr^{-1}). In particular, this applies to the western, central, and southern parts of the SWS region, where the removal of soil material from slopes and its transport to riparian areas and foothills is an extremely widespread phenomenon, which is a consequence of the significant degradation of forest communities, but also the degradation of pasture and meadow land (Perović et al., 2021).

The most serious problems with soil erosion (PSDI) in this part of Serbia are connected to land cultivation, especially in the hilly/mountainous regions, primarily due to deforestation, without taking into account the land configuration and other natural conditions (Petković et al., 1999). Following on from this, this research also indicates that the vegetation cover-management factor (C) is the most influential factor in terms of physical soil degradation in the SWS region with an impact of about 58% (Fig. 5). Soil erosion is known to be influenced by several factors, with the C factor recognised as the key erosion factor (Chen et al., 2021; Manojlović et al., 2021), and as such has a significant impact on soil losses and can positively affect the properties of soil erodibility, slow down surface runoff, promote infiltration, stabilise soil, and impact the state of SOM in soil (Gocić et al., 2020; Tang et al., 2020).

The impact of high topographic potential (LS factor), the RI of which is estimated at approximately 22% (Fig. 5), is most visible in the southwest of the SWS region, where significant soil losses were recorded, despite the relatively high forest cover and elevated SOM content (Fig. S3). Several other studies also indicated that topography significantly influences erosion intensity (Sahour et al., 2021; Wang et al., 2022). Namely, the topography of this part of Serbia has a major impact on land use, as well as on factors that contribute to soil erosion (Kostadinov et al., 2006), and also soil management techniques. Almost all arable land on slopes of 3–5% is exposed to the influence of weak erosion processes, while on slopes above 15% moderate erosion processes begin (MAFWM, 2018), with the steepest slopes often creating landslides and avalanches, damaging the vegetation cover and increasing soil erosion (Ristić et al., 2011).

Erosion processes (PSDI) are present in the northern and central parts of the SWS region, especially on agricultural soils, which is traditionally the main land use activity in this part of Serbia (Belanović et al., 2013). Since, in most cases, soil losses that occur in areas with pronounced agricultural activities are higher than the rate of soil formation, this partly explains the increase in costs associated with agricultural production, the decrease in crop yields, and also the

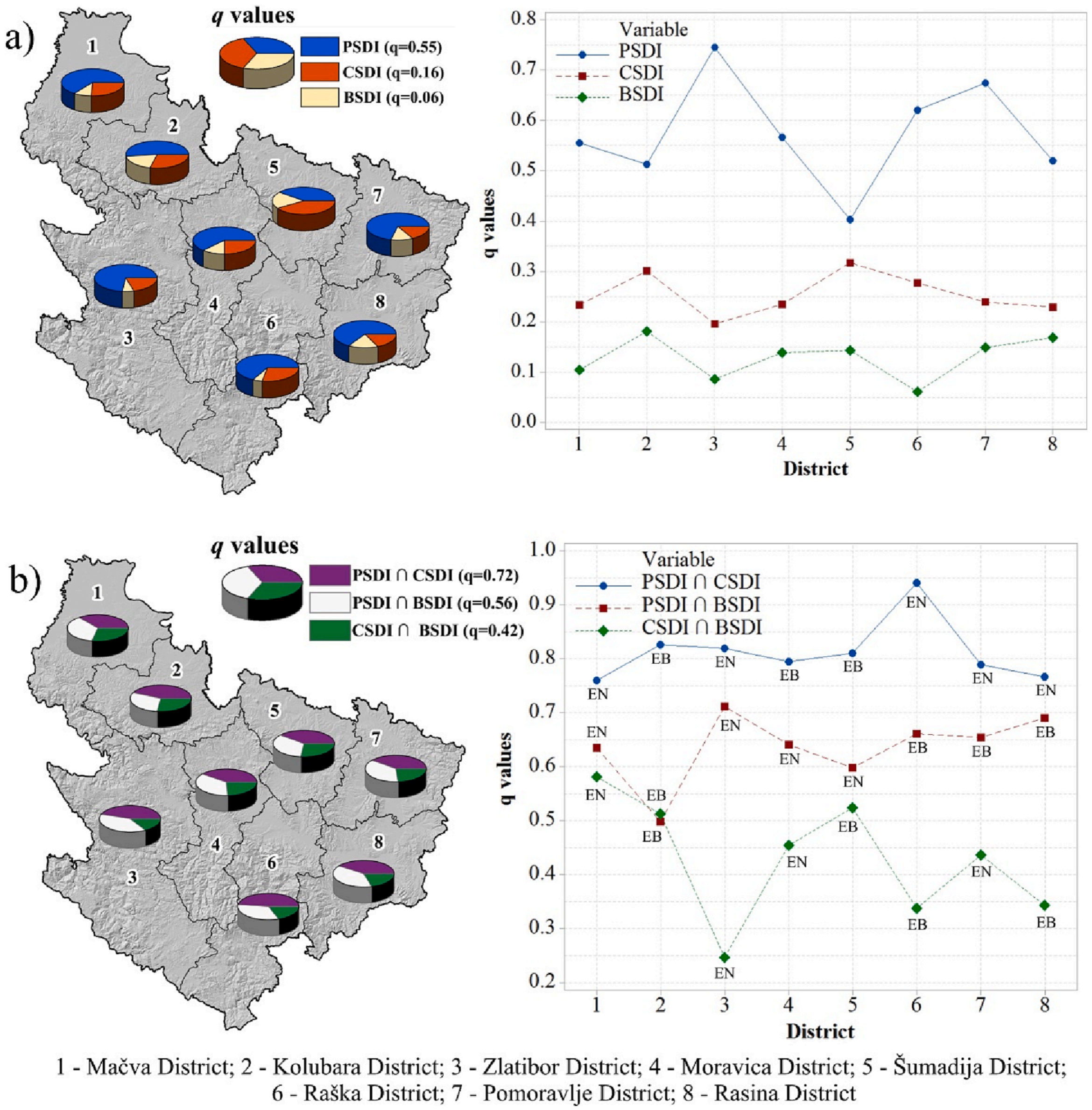

Fig. 6. a) Factor detector results (p value $<$ 0.01); b) Interaction detector results (p value $<$ 0.01).

abandonment of agricultural land in many rural parts of the SWS region (Gajić et al., 2021). At the same time, these areas have significantly less SOM (on average 1–2%), due to increased mineralisation, inadequate crop management practices, and crop rotation systems (Pavlović et al., 2017).

The soils in the southern part of the SWS region are characterised by low resistance to erosion processes, i.e., instable soil structure and a decrease in the infiltration rate and available water capacity in the soil (Perović et al., 2021). The development of erosion processes (PSDI) in the SWS region is also significantly influenced by the geological substrate, which often comprises shale, flysch and sandstone (Pavlović et al., 2017). These formations disintegrate relatively easily, creating loose material that is very susceptible to erosion processes. Of course, it should be stated that the western part of the region is characterised by a serpentine substrate (Pavlović et al., 2017; Čakmak et al., 2018). At lower altitudes in these areas, it is mostly cambisols that are formed, while at higher altitudes there are shallow rankers and lithosols and their resistance to erosion processes is very low.

4.2. Impacts of chemical degradation

The research showed that at 49% SOM has the greatest impact on the CSDI of the study area (Fig. 5), which is in line with accepted beliefs about its impact on soil degradation (Krull et al., 2004; Nascimento et al., 2021). In the SWS region, the geospatial distribution of SOM is clearly linked to altitude. This is directly related to intensive agricultural production and land use systems in those parts of the region at altitudes below 500 m a.s.l. (Fig. S3), which are characterised by large and constant SOM losses. High SOM levels are characteristic for mountainous parts of the SWS region. These areas also have a very high organic carbon content (Kadović et al., 2012) and, often, reduced mineralisation processes (Brzostek et al., 2014), primarily in the surface layer of forest soils, which have high water retention capacity thanks to the strong organic layer. On the other hand, moderate SOM levels are mainly related to areas with extensive agricultural production at altitudes of 500 to 800 m a.s.l., as well as in the valleys of large rivers (Fig. S3).

The geospatial distribution of MMEC, the RI of which was estimated at about 40% (Fig. 5), is mainly caused by the geological origin of PTEs, as well as an anthropogenic influence. Based on the results, it can be noted that the values only rarely fall into the category of high impact of pollution (values above 3), (Fig. S3), with the highest value 3.27, which represents areas with serious pollution. Even though the areas that are characterised by elevated MMEC values indicate the influence of the geological substrate on the origin of PTEs, certain higher values can be attributed to the fairly wide area that was taken into account when calculating the background, which leads to the appearance of outliers and their possible misinterpretation (Mrvić et al., 2011). High values of MMEC are present in the western part of the SWS region (the Zlatibor District), primarily due to elevated levels of Ni and Cr (Fig. S2), which are closely linked to serpentines in that area (Antić-Mladenović et al., 2019). Also, a connection between these two elements was observed in the central parts of the region, which is explained by the influence of sediment transport from the area of the Zlatibor massif to the alluvial plains (Čakmak et al., 2018; Antić Mladenović et al., 2019). A second area with elevated MMEC values is on the western edge of the Mačva District and is also mainly a result of the geological substrate, but also mining activities (elevated values: As, Hg, Pb and Zn), (Belanović Simić et al., 2022; Fig. S2). Specifically, geologically speaking, this region is where two geological blocks meet - the Jadar Block terrane and the Drina Element (Pavlović et al., 2017), which has resulted in large ore deposits, especially of Pb, Zn and Sb, with As occurring as an accompanying element (Fig. S2).

The SWS region is characterised by low soil pH, with 43% of central agricultural areas classified as having highly acidic and acidic soils (Ličina et al., 2011). The comparative geospatial distribution of Ni and Cr content (Fig. S2) and MMEC with pH (KCl) values (Fig. S3) clearly indicates the dependence between these parameters. The highest pH (KCl) values were recorded in those very areas that are dominated by serpentinite as the geological substrate or river sediment, with weakly acidic and neutral soils forming on such a substrate (Vicić et al., 2014). The absence of any geospatial correspondence between MMEC and pH (KCl) in the Mačva District supports this claim since in this area MMC is not caused by Cr and Ni values. Additionally, in the central region, on the border between the Morava and Raška districts, a large area with low pH (KCl) values is clearly visible, which is also the result of the geological substrate since the area is dominated by sericite shales, phyllites, and phyllitomica schists (Pavlović et al., 2017). In the extreme west of the SWS region, higher pH values (KCl) were determined because this area is closely linked to the alluvial sediment of the Sava River. This is characterised by higher Ni and Cr content and the sediment originated from the serpentine substrates of the southern tributaries of the Sava, as well as sediments from Fruška Gora (Pavlović et al., 2019).

The most pronounced impact on CSDI according to the geospatial distribution (Fig. 5) was had by SOM, as has been established in earlier studies (Krull et al., 2004). The chemical degradation of soil is most marked in the Mačva, Šumadija and Pomoravlje districts. In addition, in the west of the Zlatibor District and in the valleys of large rivers, CSDI values are elevated, although in the AHP hierarchical structure they are significantly reduced due to the impact of high pH values, which results in the immobilizing of certain PTEs. Based on prevalence, high level CSDI values account for approximately 17% (Table S7), which is a slightly higher percentage than chemically degraded soils in Europe (Oldeman, 1992).

4.3. Impacts of biological degradation

TM and TNF have the greatest effect on BSDI with an average impact of 30% (Fig. 5). The abundance of TM in the SWS region is predominantly associated with the geospatial distribution of arable land at lower altitudes and lower SOM values (Tian et al., 2021), which indicates the importance of SOM composition for the abundance of microorganisms. Moreover, due to the use of fertilisers, especially organic ones, and pesticides in the northern parts of the SWS region, a better supply of microorganisms with nutrients was recorded, which increases their abundance as well as DA. In addition, the regular cultivation of soil in the north of the region allows a favourable soil air-to-water ratio, which is one of the conditions for the normal development of microorganisms.

In the north of the SWS region, a greater abundance of AZO and ACT was recorded, with ACT observed as occupying a larger area, especially in areas around large rivers and in soils with higher pH values (Narendrula-Kotha and Nkongolo, 2017). A decrease in the abundance of TM was observed at higher altitudes, which was particularly pronounced for ACT in areas above 300–500 m a.s.l., and is a result of the shorter vegetation period, less readily degradable SOM characterised by a wide C/N ratio, and lower average temperatures (Tian et al., 2021). Additionally, the decreased abundance of microorganisms (especially ACT and TNF) observed in the Zlatibor District is a consequence of the high Ni and Cr content (Khan and Sculliom, 2002).

In terms of TNF, the greatest abundance was found in central areas of the SWS region, while the geospatial distribution coincides with ACT. In addition, their abundance increases at higher altitudes, with lower soil pH and forest communities (Narendrula-Kotha and Nkongolo, 2017), with the SOM of such soils being rich in lignin (Arora and Sharma, 2010).

In general, geospatially speaking, low and very low risk of biological degradation (BSDI) is most prevalent in areas below 300 m a.s.l. characterised by intensive agricultural production and in river valleys. As altitude increases, so too does the threat degree of BSDI due to the influence of climatic factors, SOM quality, and erosion processes. An increased degree of degradation from BSDI is also clearly distinguishable in areas with elevated levels of PTEs (Khan and Sculliom, 2002), primarily in the west of the Zlatibor and Mačva districts.

4.4. Multiple soil degradation assessment

In this study, it was found that about 59% of the SWS region is degraded by the synergistic effects of PSDI, CSDI, and BSDI (Table 2). Given the geospatial pattern of total degraded areas, the results are in relative accordance with previous studies and other analyses, which indicate that about 80% of the land area in Serbia is affected by various forms and categories of soil degradation (Ristić et al., 2012), whereby soil erosion alone has an impact on the degradation of 80% of agricultural soils (Ličina et al., 2011; Pavlović et al., 2017). Furthermore, our results are in line with data on the status of soil in the EU, where 60–70% is degraded due to unsustainable land management (EC, 2020; Panagos et al., 2022). It should be emphasised that moderate degradation is affecting about 44% of the study area and these are areas where any disturbance in the balance between the environment and anthropogenic activities can lead to accelerated soil degradation. High and very high degradation was estimated across 15% of the study area, mainly in areas used for agricultural production, which requires the application of conservation measures with the aim of sustainable land management.

Furthermore, this study indicates that PSDI, i.e., the potential risk to soil from erosion processes, is the most influential indicator of the geospatial frequency of MSDI in the SWS region ($q = 0.55$). This is certainly to be expected, given that the main form of soil degradation at the global level is soil erosion (Oldeman et al., 1991; Borrelli et al., 2020). Namely, soil erosion as the most dominant and widespread form of soil degradation in Europe (Gobin et al., 2004; Panagos et al., 2015), including areas of the Mediterranean (Borrelli et al., 2017; Ferreira et al., 2021) and the Balkan Peninsula (Blinkov, 2015), affects biodiversity in soil and the capacity to provide ecosystem services by changing the characteristics and properties of the soil, thus endangering the stability of the supply of energy, food, and water.

The interactivity of PSDI ∩ CSDI ($q = 0.72$) is most pronounced in the hilly/mountainous areas of the SWS region, where a lower SOM content was observed, primarily in the Raška District, but also in areas with elevated MMEC values, as is the case with the Zlatibor District. Soil erosion in these areas carries away not only nutrients, but also PTEs. Regardless of the origin of PTEs in soil (natural or anthropogenic), those in suspended soil particles reach riparian areas, foothills and water accumulations through surface runoff and deposition processes. The least interaction of these two indices is in the Mačva District due to the distinctly flat landscape with very weak erosion processes (Fig. 6b). Interaction between PSDI and BSDI ($q = 0.56$) was also observed in all the hilly/mountainous areas of the SWS region (Fig. 6b). Erosion processes contribute to a reduction in biological diversity due to the loss of the surface layer of soil, i.e., these processes significantly change the composition and diversity of microorganisms in the soil. Marked interaction between CSDI and BSDI was observed in the lowlands of the Mačva, Šumadija and Kolubara districts, primarily due to anthropogenic activities (agricultural production and mining with associated industry), leading to reduced SOM content, increased acidification, and ultimately to a reduction in DA and ACT.

In light of the achievement of SDG 15.3, which defines the quality of soil resources needed to sustain ecosystem functions and services, the findings of this study draw attention to the need for better soil management in the SWS region, which is critical for strengthening scientific, technical and policy support for the implementation of international and national strategies in soil conservation.

5. Study limitations and recommendations

Although significant results were obtained through the research in this study, there are certain limitations. Namely, the research included three basic soil degradation patterns in the Western Serbia and Šumadija region (SWS), but some other forms and indicators of soil degradation were omitted, such as wind erosion and the impact of soil acidification processes, which could, to some extent, contribute to a better understanding of multidimensional soil degradation patterns. In addition, the application of specific multiple indices can lead to a lack of individual information during the aggregation of multidimensional indicators into a one-dimensional index (Prince et al., 2018).

This research included mainly quantitative methods, while future studies should also take into account qualitative factors in order to deepen understanding of the complex soil degradation mechanisms. Furthermore, in order for the USLE method to be optimised for local environmental conditions, it is recommended that factors be adjusted and modified based on the specific characteristics of the area being investigated. In this sense, this study did not discuss the factors of the USLE method in detail, bearing in mind that the advantages and disadvantages of this method are well known and have already been described in detail in scientific literature (Benavidez et al., 2018; Alewell et al., 2019). Instead, this study focused on a comprehensive geospatial analysis of the most important processes and indicators of degradation in the study area. Therefore, the values obtained by the USLE method can only be considered as indicators of general soil erosion (PSDI) and not as a parameter for a precise estimation of soil loss. It should also be noted that both in general and also in Serbia, there is a general lack of systematic monitoring of degraded areas within a harmonised monitoring program, which makes it much more difficult to study spatial and temporal trends and the extent of soil degradation from both a scientific and professional point of view.

6. Conclusions

This study, which implemented the new concept of multiple soil degradation indices (MSDI), thus enabling the simultaneous integration of several environmental factors acting separately or synergistically, provided concrete answers to the research questions set out at the beginning concerning the state and geospatial distribution of physical (PSDI), chemical (CSDI), and biological (BSDI) degradation, i.e. a comprehensive assessment of soil sensitivity to degradation in the case study area of SWS.

The results of this study showed that the dominant indicator of physical soil degradation is the C factor with an impact of about 58%, that SOM has the greatest relative impact on chemical degradation at approximately 49%, and that total microflora and total number of fungi have the greatest impact of the biological degradation indicators at approximately 43%. In addition, the results of this study indicate that 59% of the study area is currently degraded by the synergistic effects of multiple factors of physical, chemical, and biological soil degradation (MSDI), with about 44% comprising areas that are at risk of accelerated soil degradation due to environmental degradation caused by anthropogenic activities. Analyses showed that physical degradation or soil erosion has the greatest impact on soil degradation in the SWS study area, with an average impact of 55%, followed by chemical degradation at 16%, while biological degradation only had a 6% impact.

The methodological framework applied in this research enabled a better insight into the various forms and indicators of soil degradation, their impact, and the easier identification of the interaction between them, and possible environmental consequences in the study area. In the future, this methodological framework can be improved by taking into account other indicators of soil degradation such as wind erosion, soil acidification processes, which can expand the definition of multidimensional patterns in soil degradation.

CRediT authorship contribution statement

Veljko Perović: Conceptualization, Methodology, Data curation, Software, Writing – original draft. **Dragan Čakmak:** Methodology, Writing – original draft. **Olivera Stajković Srbinović:** Writing – review & editing. **Vesna Mrvić:** Conceptualization. **Snežana Belanović Simić:** Conceptualization, Writing – review & editing. **Marija Matić:** Writing – review & editing. **Dragana Pavlović:** Writing – review & editing. **Darko Jaramaz:** Writing – review & editing, Visualization. **Miroslava Mitrović:** Writing – review & editing. **Pavle Pavlović:** Supervision, Methodology, Conceptualization, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110096.

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