

## Assessment of land sensitivity to degradation using MEDALUS model - a case study of Grdelica Gorge and Vranjska Valley (southeastern Serbia)

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Land degradation is a complex issue caused by diverse drivers, each of which should be considered in the analysis of land sensitivity to degradation. This study identifies the areas most sensitive to land degradation in the Grdelica Gorge and Vranjska Valley, which are unique in terms of natural and socioeconomic conditions. Land-use changes and inappropriate land management have led to serious degradation in this region. The flexible and multifactorial approach of the Mediterranean Desertification and Land Use (MEDALUS) model allowed comprehensive land degradation sensitivity analysis in the study area. The main factors driving soil degradation were assessed by estimating climate quality index, soil quality index, and vegetation quality index, and the main socioeconomic indicators by management quality index and social quality index. The results showed that forest cover is the main factor to contrast land degradation, and even minor adverse changes in forest characteristics, such as structure, canopy cover, health, and quality, could trigger degradation processes. The vegetation quality index was defined in terms of the current vegetation's capacity to protect soil from erosion, drought resistance, and fire risk. Detailed data on forest vegetation cover was obtained from the National Forest Inventory (NFI). The environmentally sensitive area (ESA) index generated through the analysis classified 26.11% of the total study area as critical, 69.53% as fragile, and 2.70% as either prone to or unaffected by degradation processes. According to the ESA index, the areas covered by forests with optimal species composition and high canopy cover were the least susceptible to degradation. The areas under intensive agricultural production without any application of conservation measures were the most susceptible to degradation. Future strategies for optimal land-use patterns are discussed, such as the integration of woody species in croplands to protect soil against degradation and meet human needs in the areas prone to degradation.

**Keywords:** Land Degradation, Sensitivity, MEDALUS, Vegetation Cover, Spatial Analysis

### Introduction

Land degradation and desertification are serious problems causing numerous adverse global and local effects. They impact all spheres of the environment, leading to irrecoverable ecological losses and affecting human well-being (Santini et al. 2010). Degradation processes that occur in arid, semi-arid, and dry sub-humid areas where the productivity of the soil depends on water availability, are referred to as desertifi-

cation (UNCCD 1994). Together with natural causes of the land's sensitivity to degradation and desertification, which are strongly related to climatic features, soil properties, and vegetation types, human activities are usually the direct drivers of degradation and desertification processes (Salvati & Zitti 2008). Changes in land use resulting from human activity represent the common driving force of degradation and desertification processes nowadays.

The transition from forest to other land uses, such as cropland or settlements, is inevitably associated with deforestation, one of the common drivers of degradation, and is a great threat to ecological health in a wide range of environmental and socioeconomic situations (Gharibreza et al. 2020). It generally results in ecological problems, including habitat loss, extinction of species and communities, increased CO<sub>2</sub> emissions, and many others. Human actions can also improve the environment through sustainable land management practices and effective policies (Huang et al. 2020).

A thorough understanding of the land's sensitivity to degradation and desertification is crucial when considering both improvement options and the risk of additional degradation (Olsson et al. 2019). Estimating land sensitivity to degradation and desertification requires an integrated approach and detailed analyses of the interplay of natural and human factors and their role in driving land degradation (Mirzabaev et al. 2015). Accurate estimation is needed to prevent land degradation and support the planning and improvement of land

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Received: May 12, 2021 - Accepted: Feb 21, 2022

**Citation:** Lukić S, Baumgertel A, Obradović S, Kadović R, Beloica J, Pantić D, Miljković P, Belanović Simić S (2022). Assessment of land sensitivity to degradation using MEDALUS model - a case study of Grdelica Gorge and Vranjska Valley (southeastern Serbia). *iForest* 15: 163-170. - doi: [10.3832/ifor3871-015](https://doi.org/10.3832/ifor3871-015) [online 2022-05-07]

Communicated by: Agostino Ferrara

management at any level (Salvati et al. 2012).

Among the available models for assessment of land degradation, the Mediterranean Desertification and Land Use model (MEDALUS) is widely used due to its flexibility in the selection of the main indices of land degradation, its relatively simple application, and its rapid implementation (Kosmas et al. 1999, Salvati et al. 2015, Právělie et al. 2020). The assessment of the environmentally sensitive areas (ESAs) identified by the MEDALUS method was a broader approach guided by several complex and interrelated factors linked to specific local environmental and human-induced conditions (Mirzabaev et al. 2015, Olsson et al. 2019). The spatial distribution of areas with high ESA index values reflects the combined impact of environmental conditions and factors such as demographic trends, the effects of land management, and the quality of environmental policy (Ferrara et al. 2020).

The MEDALUS model was originally developed for the Mediterranean region but has been successfully applied worldwide (Ferrara et al. 2020), in Europe (Contador et al. 2009, Salvati et al. 2015, Právělie et al. 2020), Asia (Dindaroğlu 2015), Africa (Bakr et al. 2012, De Pina Tavares et al. 2015), and South America (Vieira et al. 2015). In Serbia, the MEDALUS model has been applied in certain specific locations (Momirović et al. 2019, Perović et al. 2021).

This study aims at assessing the sensitivity to land degradation of an area subject to interplay among numerous natural and human factors. In Grdelica Gorge and Vranjska Valley areas, the component of demographic pressure significantly affects land use patterns (Djorović 2005), as well as the quality of land management. In this study, management and social quality indices were analyzed separately in MEDALUS algorithm as proposed by De Pina Tavares et al. (2015) and Vieira et al. (2015), because in addition to natural characteristics, analysis of population dynamics enables to better understand the degradation process and directions of management actions to control degradation (De Pina Tavares et al. 2015). By extraction of demographic com-

ponent from management quality index and its implementation in MEDALUS algorithm as separate layer (social quality index), it could be possible to assess the quality of human interactions with the environment to some extent. The parameters of the ESA indicators, defined in detail below, enabled a thorough investigation of the spatial patterns of sensitivity to land degradation. Areas with high ESA values have been identified as ideal locations for land management interventions, especially to improve the vegetation cover quality and to protect valuable communities in the study area. Rapid and comprehensive identification of the drivers of degradation and alteration of human activities through improved land management and policies enables control of degradation processes to reduce or prevent adverse effects on human well-being and serious disruptions in the environment.

The aim of this study is to: (i) estimate sensitivity to land degradation in an area subject to interplay among numerous natural and human factors using the MEDALUS model; (ii) underline the potentials and value of data provided in Forest Management plans (special or general plans) and National Forest Inventory (NFI) data in environmental modeling; and (iii) identify the areas critically endangered by degradation using Local Moran's I analysis.

## Materials and methods

### Study area

The area of Grdelica Gorge and Vranjska Valley (42° 22' to 42° 55' N; 19° 21' to 20° 00' E) covers 1716.94 km<sup>2</sup> (Fig. 1). This area has a hydrographic network consisting of 137 torrential flows, with a total catchment area of 1700.33 km<sup>2</sup>. Pronounced altitudinal differences over short distances, dissected relief, and steep slopes contribute to an increased potential for degradation processes, particularly erosion. The continental climate of the study area is tempered by the influence of the Mediterranean climate (Perović et al. 2019). The average annual air temperature is 10.9 °C, and the average annual precipitation is 672 mm, based on observations from 1949 to 2017 (RHSS 2018).

The area is characterized by an erodible parent rock with very disturbed and broken layers weathered to different degrees. The most common soil types in the study area are leptosols, cambisols, vertisols, luvisols, and fluvisols (Lukić 2013). The association of Hungarian oak and Turkey oak (*Quercetum frainetto-cerris* Rud. 1949) is the most common forest type at altitudes up to 600 m a.s.l. in the area of Grdelica Gorge and Vranjska Valley. Montane beech forests (*Fagetum moesiaca montanum* Jov. 1953) are present from 800 to 1300 m asl. In the valley of the South Morava River, the most common communities are forests of broom and pedunculate oak (*Genisto elatae-Quercetum roboris* Horv. 1938 s. lat.) and forests of willow and poplar (*Salici-Populetum albae* Drees. 1936 – Tomić 2004). The area is also characterized by the presence of rare and scattered species and communities and the presence of relict and endemic forest communities (Mišić 1981). The area of Grdelica Gorge and Vranjska Valley is socioeconomically underdeveloped and demographically depopulated.

### Methodology

The land degradation sensitivity analysis to identify ESAs was conducted according to the modified MEDALUS model described by Kosmas et al. (1999). This model enabled analyzing both the dominant environmental and human-induced degradation factors that characterize the study area. The analysis was based on five indicators of quality related to the driving forces of land degradation in the area of Grdelica Gorge and Vranjska Valley: climate quality index (CQI), soil quality index (SQI), vegetation quality index (VQI), management quality index (MQI), and social quality index (SoQI).

The proposed ESA Index was evaluated by the five quality indicators, as in eqn. 1:

$$ESA = (CQI \cdot SQI \cdot VQI \cdot MQI \cdot SoQI)^{1/5} \quad (1)$$

The quality indicators were defined by parameters relevant to the study area's sensitivity to land degradation processes. The range of parameter values was weighted according to the sensitivity to degradation and standardized from 1 (low sensitivity) to 2 (high sensitivity). For more accurate weighting of selected parameters, remote sensing data were combined with data from available databases. The analysis excluded the areas under settlements and bodies of water, which encompass 28.46 km<sup>2</sup> and represent 1.66% of the total area of the Grdelica Gorge and Vranjska Valley, hereafter referred to as mask areas. The analyses of CQI, SQI, VQI, MQI, SoQI, and overall ESA were performed in ArcMap® ver. 10.5.1 (ESRI, Redlands, CA, USA).

### Climate quality index

The Climate Quality Index (CQI) was represented by four parameters that reflect the impact of climate on degradation pro-

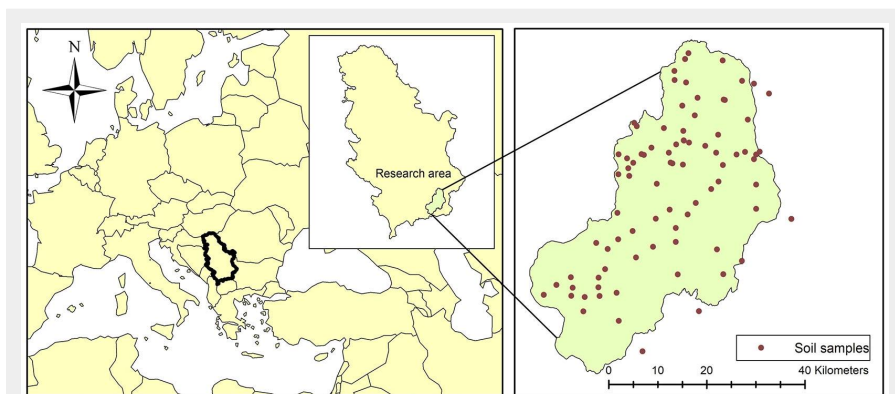


Fig. 1 - Study area of Grdelica Gorge and Vranjska Valley (Southeastern Serbia).

cesses: aridity index (AI), modified Fourier's index (MFI), exposure (E), and rainfall (R). The parameters of CQI were obtained according to the data for period from 1983 to 2016 (RHSS 2018).

The AI was calculated according to eqn. 2:

$$AI = \frac{P}{PET} \quad (2)$$

where  $P$  represents the precipitation, and  $PET$  the potential evapotranspiration, obtained according to the Penman-Monteith method. The MFI was calculated according to eqn. 3:

$$F = \sum_{i=1}^{12} \frac{p_i^2}{P} \quad (3)$$

where  $p_i$  is the rainfall in each month, and  $p$  the annual rainfall, to estimate rainfall aggressiveness (Szilagyi et al. 2016).

The environmental conditions relevant for vegetation growth are represented by  $E$ , which describes solar radiation and temperature conditions, and by  $R$ , the amount of rainfall. Classes and assigned indices for calculating the CQI are presented in Tab. S1 (Supplementary material). The CQI was calculated according to eqn. 4:

$$CQI = (AI \cdot MFI \cdot E \cdot R)^{1/4} \quad (4)$$

#### Soil quality index

The parameters of the SQI were selected based on moisture availability and soil resistance to erosion processes, being these the most important factors for the establishment and survival of vegetation as a permanent erosion control measure. The parameters that define these conditions are: parent material (PM), weighted according to its susceptibility to weathering, which predicts its resistance to erosion (Schaetzl & Thompson 2015); organic matter (OM), the main indicator of soil quality and stability of soil structure, which predicts both the resistance of soil to erosion and water availability to vegetation (Six et al. 2000); soil depth (SD); and slope (S). The original data used to perform this analysis are presented in Tab. S1 (Supplementary material). The data on SQI parameters was obtained according to the 89 soil profiles (Fig. 1). The SQI was calculated according to eqn. 5:

$$SQI = (PM \cdot OM \cdot SD \cdot S)^{1/4} \quad (5)$$

#### Vegetation quality index

Vegetation was analyzed for its capacity to protect soil from erosion, drought resistance, and fire risk. The VQI was calculated by four standard parameters (Kosmas et al. 1999): plant cover (PC), erosion protection (EP), drought resistance (DR), and fire risk (FR).

PC was obtained from the normalized difference vegetation index (NDVI) commonly used to assess vegetation cover (Mohamed 2013). EP was defined by combining

CORINE Land Cover data (CGLS 2012) and National Forest Inventory data (NFI 2009). General data on land cover were obtained from CORINE and adjusted according to more specific data on forest type (deciduous, coniferous, or mixed) and stand conservation (conserved, thinned, or devastated stand) obtained from NFI.

Stand conservation describes the degree of canopy stocking, the proportion of principal and minor tree species, and the health, risks, and quality of the stand in the inventory unit.

A conserved stand is characterized by a dense to complete canopy (1.0-0.6), good tree health, good-quality trees, and a favorable ratio of principal and minor tree species. A thinned stand is characterized by an incomplete canopy (0.4-0.6), good tree health, and good-quality trees, but a less favorable ratio of principal and minor tree species. A degraded stand is characterized either by a broken canopy (below 0.4), by poor tree health and poor-quality trees or by a completely unfavorable ratio of principal and minor tree species (favoring minor species over the principal species).

Weighting indices for stands' capacity to protect soil from erosion are basically defined according to Salvati & Bajocco (2011) and Contador et al. (2009) who assigned weighting indices for vegetation classes derived from the CORINE Land Cover map. Erosion protection function of forest cover depends mostly on canopy cover closure and species composition (Vatandaşlar et al. 2020), species-specific functional traits (Seitz et al. 2016), species richness (Salvati et al. 2015, Song et al. 2019), etc.

We used the data on forest type and stand conservation obtained from NFI to slightly adjust the weighting indices, taking into account that the stand conservation parameter defined through the degree of canopy stocking, tree health and quality, and the ratio of principal and minor tree species affects the stand's ability to protect the soil from erosion. The weighting indices used to perform this analysis are given in Tab. S2 (Supplementary material).

DR was obtained through CORINE Land Cover data by grouping land cover types (see Tab. S1 in Supplementary material). FR was obtained by combining CORINE Land Cover and NFI data. Data on the stand unit in the NFI contain information on the mixture of tree species in the stand. The flammability of the forest depends on the stand structure, the biological and ecological characteristics of each species in the mixture, and their relationships (Vasić 1992, Fernandes 2009, Xanthopoulos et al. 2012). Stands in the Republic of Serbia are divided into six classes of flammability (Vasić 1992), from the least endangered class (VI category, or very low flammability), which includes bare lands, to the most endangered class (I category, or extremely high flammability), which includes pine and larch forests (see Tab. S1 in Supplementary ma-

terial for the original data).

The VQI was calculated according to eqn. 6:

$$VQI = (PC \cdot EP \cdot DR \cdot FR)^{1/4} \quad (6)$$

#### Management quality index

Management quality reflects the human contribution to land degradation in the environment. It was analyzed by assessing the impact of land-use patterns on the environment, represented as land-use intensity (LUI) and policy enforcement (PE), which characterizes the extent of implementation of existing environmental regulations. The LUI map was obtained by grouping CORINE Land Cover data into three categories according to Právělie et al. (2017). Policy enforcement was obtained by integrating CORINE data with data on the forest primary function derived from the NFI. The primary function is either determined in advance as a legal requirement or determined subsequently based on specific criteria such as slope steepness, closeness of water source, road network, or industrial area, population density etc. Classes and assigned indices for calculation of the MQI according to Právělie et al. (2017) are presented in Tab. S1 (Supplementary material). The MQI was calculated according to eqn. 7:

$$MQI = (LUI \cdot PE)^{1/2} \quad (7)$$

#### Social quality index

Social quality was analyzed by assessing the pressure of human actions on the ecosystem that leads to land degradation and desertification. Two main parameters were used: population density (PD) and old age index (OAI). PD represents the total population per unit area and is closely related to the level of human pressure on natural resources (De Pina Tavares et al. 2015). The OAI represents the ratio of the number of inhabitants older than 65 years of age to the total number of inhabitants (Kosmas et al. 2014) and emphasizes the number of older people in relation to the total population (De Pina Tavares et al. 2015). Older people puts more pressure on natural resource by applying tillage techniques and breeding livestock in obsolete manner which usually adversely impact the soil and vegetation condition. Classes and assigned weights of indices for calculation of SoQI, according to De Pina Tavares et al. (2015), are presented in Tab. S1 (Supplementary material).

The SoQI was calculated according to eqn. 8:

$$SoQI = (PD \cdot OAI)^{1/2} \quad (8)$$

#### Statistical analysis

Spatial correlation was performed to identify collinearity among quality indices

**Tab. 1** - Quality indices CQI, SQI, VQI, MQI and SoQI distribution by quality classes.

Indices	Class range	Class	Class area (km <sup>2</sup> )	Class area (%)
Climate quality index (CQI)	< 1.3	high	970.25	56.51
	1.3-1.5	medium	643.86	37.50
	> 1.5	low	74.37	4.33
Soil Quality Index (SQI)	< 1.13	high	19.26	1.12
	1.13-1.45	medium	1161.42	67.64
	> 1.45	low	507.80	29.58
Vegetation Quality Index (VQI)	< 1.13	high	98.45	5.73
	1.13-1.41	medium	1065.87	62.08
	> 1.41	low	524.82	30.57
Management Quality Index (MQI)	< 1.25	high	1294.13	75.37
	1.25-1.5	medium	86.87	5.06
	> 1.5	low	308.22	17.95
Social quality index (SoQI)	< 1.3	high	308.04	17.94
	1.3-1.4	medium	212.22	12.36
	> 1.4	low	1168.22	68.04
Mask areas	-	-	28.46	1.66
Total area	-	-	1716.94	100.00

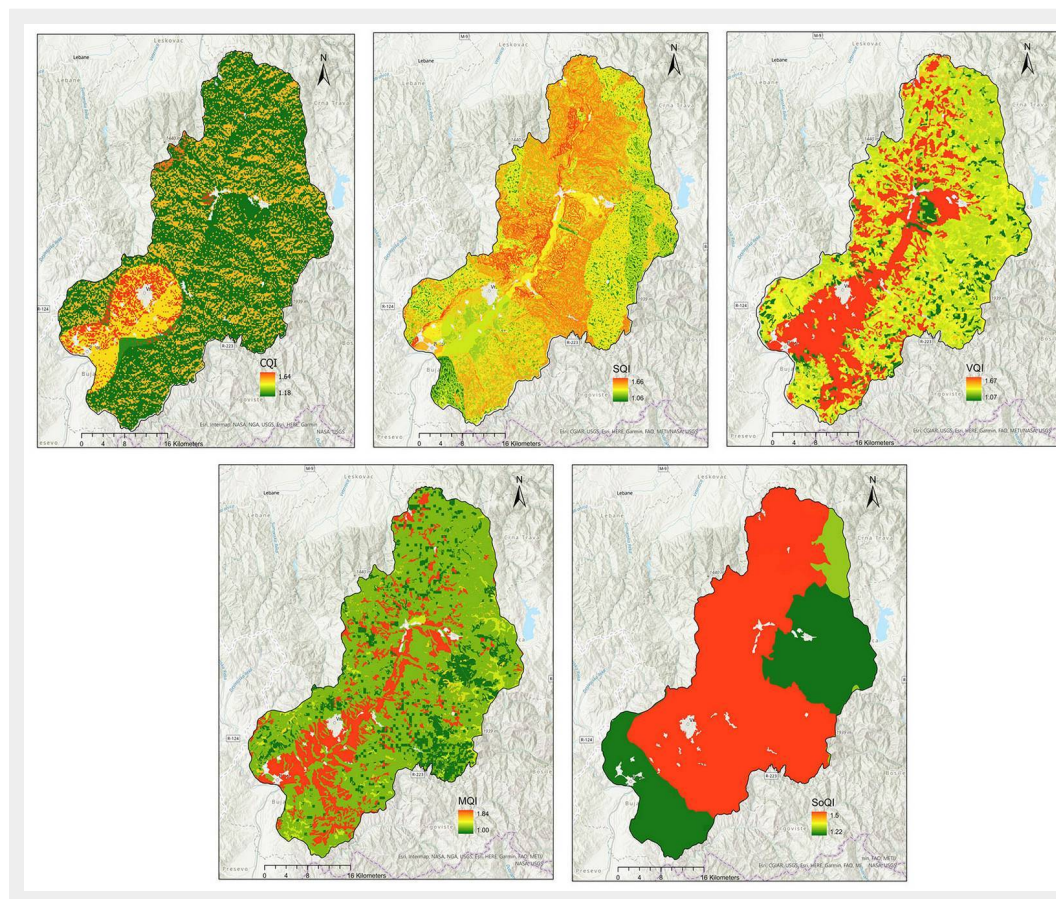
**Results and discussion**

*Climate quality index*

The CQI shows that most of the studied area is high quality (56.51%), while 37.50% is medium quality (Tab. 1). The high CQI in the northern and central parts of the study area could be correlated with favorable air temperature and precipitation conditions, mediated by the Kukavica and Ostrozub mountains (Fig. 2). Such favorable conditions are reflected in the good health of the stands and the presence of preserved rare and endemic communities such as *Lauroceraso-Fagetum montanum* Jov. 1967. High to medium climate quality in the southern and southeastern parts of the study area results from less steep terrains allowing warmer air masses to break through from the Mediterranean (Perović et al. 2019). This part of the study area is also characterized by the presence of endemic species of the Balkan Peninsula such as *Acer intermedium* Panč., which forms in this area the specific communities *Fagio-Aceri intermediae-colurnetum* Jov. 1955 and *Quercus-Aceri intermediae-colurnetum* Miš. et Din. 1971 (Mišić 1981). The southwestern and central parts of the study area along the wider portions of the South Morava River (4.33% of the studied area) are of low climate quality. Significant drivers of degradation processes in this part of the studied area are temperature extremes and the irregular distribution of precipitation (Kostadinov et al. 2018) with frequent high-intensity showers.

(CQI, SQI, VQI, MQI, SoQI) and correlation of each index with ESA value. The analysis was performed with the Band Collection Statistics tool in ArcMap® ver. 10.5.1 (ESRI, Redlands, CA, USA). The spatial distribution of ESA patterns was obtained using Anselin Local Moran's I analysis (Anselin 1995). The analysis identi-

fied statistically significant clusters of high and low ESA values as well as outliers exhibiting ESA values statistically different from their neighbors. The analysis was performed in ArcGIS® Pro ver. 2.6 (ESRI, Redlands, CA, USA) and tested using 999 permutations with a significance level of 0.05.



**Fig. 2** - Spatial distribution of quality indices CQI, SQI, VQI, MQI and SoQI.

### Soil quality index

The SQI of the majority of the studied area (67.64%) resulted to be medium quality, 29.58% of the area was low quality, and only 1.12% of the area was high quality. The central, northern, and western parts of the study area showed low SQI values (Fig. 1). The central part is characterized by parent rocks prone to weathering, mostly shale, sandstones, and conglomerates (Tanasijević 1956, Schaetzl & Thompson 2015). The fragility of the soils formed on parent rock prone to weathering is further increased by the absence of permanent vegetation cover, especially on steep slopes. In such conditions, soils can neither maintain productivity nor resist erosion (Gharibreza et al. 2020). The southern and eastern parts of the area showed medium SQI values. The eastern part of the study area is characterized by soils with a higher organic matter content formed mostly on granites and granodiorites (Tanasijević 1956). The reduced susceptibility of those parent rocks to weathering (Schaetzl & Thompson 2015) and higher organic matter content offering increased soil structure stability (Six et al. 2000) results in higher soil resistance to degradation. In the southern part of the study area, soils are deep, which is likely a result of less pronounced relief and moderate slopes, among other reasons, considering that slope is strongly negatively correlated to soil depth (Mehnatkesh et al. 2013).

### Vegetation quality index

The VQI assessment showed that about one-third (30.57%) of the study area is characterized by low vegetation quality, 62.08% of the total study area exhibited medium vegetation quality, and 5.73% had high vegetation quality (Tab. 1). Low vegetation quality mostly corresponds to areas of intensive agriculture and high population pressure. These areas are situated along the entire course of the South Morava River, especially in the southern parts where the river broadens in the valley, creating favorable conditions for agricultural activities. Conventional agricultural production, the dominant land-use pattern in this part of the study area, is characterized by agricultural activities mostly carried out without conservation measures (Fig. 1). Conservation measures in agriculture include the cultivation of a cover crop providing sufficient protection against degradation (López-Vicente et al. 2020). In addition, low vegetation quality is a consequence of the absence of natural forest vegetation in this part of the study area. The areas with a high vegetation quality are small and isolated throughout the study area (Fig. 1). Transitional areas of forests and shrubland belong to the categories of vegetation most resistant to drought (Contador et al. 2009, Prävälje et al. 2017) and less prone to fire risk (Contador et al. 2009, Fernandes 2009, Xanthopoulos et al. 2012). The resistance to fire is especially important in areas

**Tab. 2** - Classes of Environmentally Sensitive Areas (ESA) in the area of Grdelica Gorge and Vranjska Valley.

ESA Class	Subclass	Score range	Total area (km <sup>2</sup> )	Total area (%)
Unaffected	N	≥ 1.00 ≤ 1.170	1.33	0.08
Potential	P	> 1.170 ≤ 1.225	45.10	2.62
Fragile	F1	> 1.225 ≤ 1.275	255.11	14.86
	F2	> 1.275 ≤ 1.325	542.23	31.58
	F3	> 1.325 ≤ 1.375	396.43	23.09
Critical	C1	> 1.375 ≤ 1.425	173.76	10.12
	C2	> 1.425 ≤ 1.530	158.08	9.21
	C3	> 1.530	116.43	6.78
Mask area	-	-	28.46	1.66
Total	-	-	1716.94	100.00

with high population pressure. The areas of high vegetation quality include preserved rare and endemic communities in areas of low population pressure, mostly at higher altitudes, at small and isolated sites. The dominant vegetation type in the medium-quality areas is deciduous forests representing the natural vegetation of the study area. Although natural, deciduous forests have a reduced potential to provide sufficient soil protection during the non-growing season (Contador et al. 2009). Deciduous forests are not greatly endangered in terms of drought resistance and fire risk. Natural grasslands and pastures are also of medium vegetation quality.

### Management quality index

The high management quality estimated for 75.37% of the study area could be related to the implementation of sustainable management policies, mainly in the nature protection and forestry sector. The areas of high management quality coincide with forests, natural grasslands, and pasture areas where agricultural activities are absent (Fig. 1). Sustainable management practices are mostly implemented in these areas, such as protection regimes, where rare and endangered forest communities are present. The low management quality covers 17.95% of the area and is mainly located on agricultural and bare land (Tab. 1), where conservation measures are lacking. The absence of conservation measures is a contradiction of sustainable management practice (Mehmet Tuğrul 2020).

### Social quality index

The SoQI analysis showed that 68.04% of the study area has low social quality (Tab. 1). The areas of low social quality are inhabited by a population largely over 65 years of age, which indicates a high proportion of older people relative to the total population (De Pina Tavares et al. 2015, Perović et al. 2021). In addition, the population density in the areas of low social quality is greater than 100 inhabitants per square kilometer, which adversely affects the social quality index of the entire area. Anthropogenic impact, expressed in terms of population density, reflects the level of human pressure on natural resources (De Pina Tavares et al. 2015). Human pressure on cropland, especially land without a clearly defined management policy, can directly adversely affect the soil condition (Prävälje et al. 2017). The eastern parts of the study area (covering 17.94% of the total study area) are high social quality as a consequence of their lower population density (Fig. 1).

### Environmentally sensitive area index

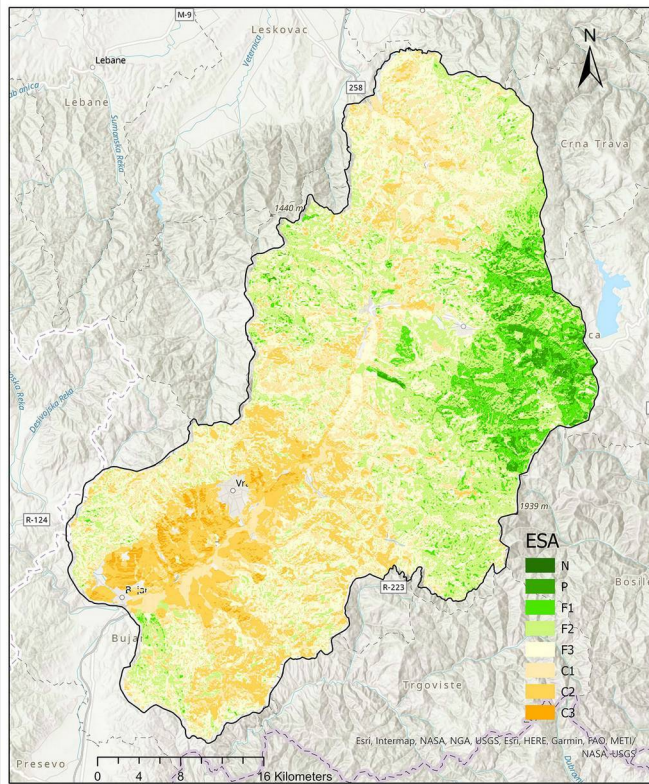
According to the synthesis map of the ESA index (Fig. 3), the majority of the Grdelica Gorge and Vranjska Valley (69.53%, or 1,193.78 km<sup>2</sup>) was classified as fragile (F1, F2, and F3). One-third (31.58%) of the total investigated area (542.23 km<sup>2</sup>) was in the subclass F2.

The highest sensitivity classes (C) represent one-quarter (26.11%) of the total area of Grdelica Gorge and Vranjska Valley, or

**Tab. 3** - Spatial correlation matrix of quality indices and ESA.

-	CQI	SQI	VQI	MQI	SoQI	ESA
CQI	1.000	-0.023	0.149	0.147	0.065	0.529
SQI	-	1.000	0.051	-0.120	0.209	0.347
VQI	-	-	1.000	0.275	0.147	0.675
MQI	-	-	-	1.000	0.023	0.536
SoQI	-	-	-	-	1.000	0.448
ESA	-	-	-	-	-	1.000

**Fig. 3** - The synthesis map of ESA index in the area of Grdelica Gorge and Vranjska Valley.



maritime climate, these factors suggested that the southern part of the study area would be less susceptible to degradation. However, intensive agriculture is the dominant land use therein, precisely due to the favorable environmental conditions. Intensive agriculture leads to soil depletion by overexploitation, loss of soil organic matter (Gomiero 2016) and acceleration of erosion processes (Gharibreza et al. 2020). In addition, agricultural management policies are insufficiently implemented in this area.

As a consequence, the area is characterized by high sensitivity to degradation (Fig. 2). The overlooked importance of sustainable agricultural measures and insufficiently implemented regulatory measures in conventional agricultural practices lead to serious land degradation (Gomiero 2016). A significant positive correlation between the MQI and ESA index ( $r = 0.536$ ) in the study area indicates the importance of sustainable land management in controlling land degradation. Statistically significant clustering of high ESA index values coincides with areas of low management, social, and vegetation quality (Fig. 3). These areas are located in the valley along the South Morava River course in the southern part of the study area, or are scattered on pronounced relief and steep slopes in the northern part of the study area. The lack of forest vegetation due to intensive agriculture and high population pressure in the southern part of the study area has also contributed to higher land susceptibility to degradation. A positive correlation between MQI and VQI ( $r = 0.275$  – Tab. 3) indicates the importance of proper land management in the maintenance of natural vegetation cover, especially forest cover which is the most effective vegetation type for controlling land degradation (Salvati et al. 2015).

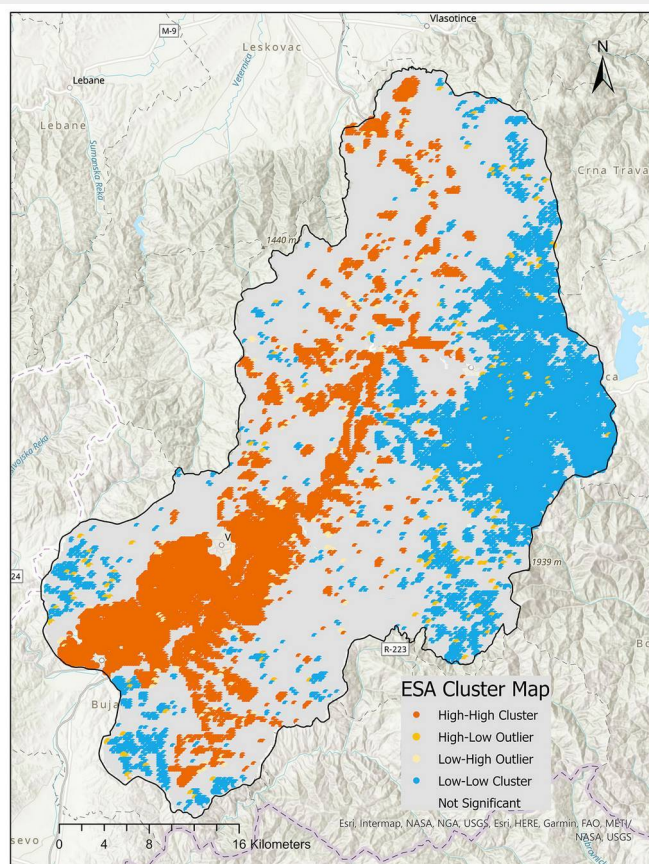
The areas of low sensitivity to land degradation (NP, P, and F1) are located in the eastern part of the study area and include high-altitude areas protected by forest vegetation. Statistically significant clustering of low ESA index values also coincides with eastern areas characterized by medium vegetation quality, high to medium management quality, and high social quality (Fig. 4). The lower sensitivity to degradation in these areas is probably a consequence of more favorable climatic conditions (lower air temperatures and higher precipitation). Particularly low sensitivity to land degradation is shown by small, scattered areas throughout the eastern part of the study area, which are characterized by the presence of undisturbed, natural autochthonous forests. The low population pressure in this area is the main reason of such forest remains. The sustainable forest management carried out in this area allows a higher canopy cover which mitigates both water and wind erosion and permits a large accumulation of soil organic matter. Further, soil organic matter affects the aggregation and stability of the soil structure

448.28 km<sup>2</sup>. Subclass C1 covers 10.12% of the total area (173.76 km<sup>2</sup>). Classes N and P are the least represented in the investigated area, covering 0.08% and 2.62% of the total area, respectively (Tab. 2).

According to the ESA index, the areas

most sensitive to degradation processes are located in the southern part of the study area, which is characterized by a wide river valley, milder slopes, and deeper soils compared to the northern part. Combined with the favorable impact of a milder

**Fig. 4** - Spatial pattern of ESAs to degradation in Grdelica Gorge and Vranjska Valley.



and is generally an indicator of soil quality that decreases soil susceptibility to degradation. A strong positive correlation was observed between the ESA index and VQI ( $r = 0.675$ ), suggesting the importance of vegetation cover in controlling land degradation in the study area.

## Conclusions

Various factors are driving the degradation in the area of Grdelica Gorge and Vranjska Valley. The MEDALUS model, which allows adjustment to local conditions and data availability, was applied for land degradation sensitivity analysis. The results indicate that most of the Grdelica Gorge and Vranjska Valley area is susceptible to land degradation, largely depending on the type and quality of the vegetation cover. Forested areas with optimal species composition and high canopy cover are the least sensitive to degradation, while areas under intensive agricultural production are the most sensitive. The areas of intensive agriculture are also under high population pressure and are insufficiently managed in terms of conservation measures, leading to greater sensitivity. Forests in this area are generally well managed in contrast to agricultural land.

According to our results, 95.64% of the Grdelica Gorge and Vranjska Valley area falls into the fragile and critical sensitivity classes. Of the total area, 69.53% is considered fragile, and 31.58% belongs to the F2 subclass; 26.11% of the area is considered critical, and 10.12% is in the C1 subclass. These results can help administrators develop strategies for optimal land-use patterns. In the areas most endangered by degradation, mandatory application of conservation measures alongside agricultural production should be taken as an appropriate management practice. The protective effect of vegetation against degradation support the incorporation of woody species in agricultural production, thus protecting against land degradation and addressing the socioeconomic needs of the population living in the investigated area.

## Acknowledgments

This work was carried out as part of the project “Investigation of Climate Change and Its Environmental Impact: Monitoring of Impact and Adaptation and Mitigation” (III43007 2011-2018), funded by the Ministry of Education, Science, and Technological Development of the Republic of Serbia (contract no. 451-03-9/2021/14/2000169).

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## Supplementary Material

**Tab S1** - Parameters of quality indices: CQI, SQI, VQI, MQI and SoQI classes, corresponding weights, and data sources.

**Tab S2** - Weighting indices for the ability of stands to provide erosion control.

**Link:** [Lukic\\_3871@suppl001.pdf](mailto:Lukic_3871@suppl001.pdf)