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CAN THE MEDALUS MODEL BE AN EFFECTIVE TOOL FOR THE IDENTIFICATION OF LAND SENSITIVE TO DEGRADATION AT A LOCAL SCALE (THE POLISH WESTERN CARPATHIANS)?

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Abstract

Land degradation is a complex and pressing global environmental challenge. Addressing the vulnerability of a region to this process requires a multidisciplinary strategy. Land sensitivity to degradation may be evaluated using different approaches according to the scale considered. The Mediterranean desertification and land use (MEDALUS) model has been adapted for the identification of degradation-sensitive land at global and regional scales by virtue of its flexibility. The aim of this study was to evaluate the applicability of the MEDALUS model for the identification of areas sensitive to degradation at the local scale. The Rzepianka catchment (25 km², Polish Western Carpathians) was chosen as a case study. The MEDALUS model was tested using input parameters proposed in the literature, and new parameters affecting land degradation processes at the local scale were introduced. The applicability of this modified MEDALUS model as a tool for the identification of degraded land was evaluated by considering actual changes in the topographic surface detected using the Digital Elevation Model of Difference (DoD) generated from 2011 and 2022 ALS-LIDAR data. This comparison provided an opportunity for discussion of the utility of the MEDALUS model at local scales.

***Keywords**: Land degradation; MEDALUS; Quality indicator; DEM of Difference; GIS; Mountain*

Introduction

Land degradation can result in the overexploitation of soil resources, diminished productivity of ecosystems, changes in vegetation composition, and endangerment of rural livelihoods, and thus poses a significant challenge on the global scale [1]. Land degradation is caused by long-term human impacts on natural systems [2] and is the consequence of complex driving forces, including both natural (climate change, soils, vegetation, and water systems) and socio-economic (human activities, including agriculture expansion, industrialization, intensive urbanization, and the development of infrastructure and communications) factors [3].

Land degradation is a matter of concern for scientists, practitioners, and decision-makers worldwide [4]-[11]. The importance of land degradation has been demonstrated by its inclusion in the United Nations Sustainable Development Goals (SDG) [12], which state that land degradation neutrality should be achieved by 2030. In this context, the identification of degradation-sensitive or degraded land is crucial to achieve this objective.

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Literature reviews [13]-[16] have outlined the different tools and approaches proposed to identify degradation-sensitive or degraded land at global and regional scales. However, a challenge still remains at the local scale, where expert approaches are recommended. The lack of universal guidelines for expert assessments means that the results obtained by different studies are not comparable, which in turn causes difficulties for environmental management. Consequently, a simple and flexible tool or solution that allows the identification of areas sensitive to land degradation at the local scale is required.

The Mediterranean Desertification and Land Use model (MEDALUS) was developed as a research project of the European Union and has become recognized as one of the most important frameworks for estimating degradation-sensitive land [4]. Initially, the model was primarily used in the Mediterranean region [5], [6], [7]; however, the inclusion of new quality indicators has expanded its utility in evaluating the specific conditions of land degradation in other regions [8], [10], [17], [18]. Consequently, the MEDALUS model has been progressively adapted outside the Mediterranean region to include different climate zones [10], [11], [19] at regional scales within large catchment areas [11], [20], across broad geographical regions [8], [21]-[24], and in different countries around the world [5], [9], [10], [25].

The applicability of the model at different scales and climate conditions results from its simplicity and flexibility, as well as its inherent ability to consolidate data from various sources [18], [24], [25], which allows for the modification and inclusion of additional physical variables typical of different study areas. As a result, the model has become widely used on regional scales (study areas often exceed several hundred km²) and the global scale_as mentioned above. In this study, the following research question is addressed: can the MEDAULS model provide an efficient tool for the identification of degradation-sensitive or degraded land at the local scale? The primary research objectives here are therefore to evaluate the usefulness of the MEDALUS model for the identification of such land at local scales, to explore gaps in land degradation assessment methodology, and to present a first attempt to evaluate the applicability of the MEDALUS model to identify local-scale phenomena associated with degradation-sensitive or degraded land. The results of this study have the potential to be used in future research across a range of disciplines in earth and environmental science and will allow close collaboration with different stakeholders and authorities (e.g., landowners, farmers, and forest managers). This research uses a comprehensive approach that can provide valuable insights for soil conservation, land management, vegetation enhancement, and sustainable development in mountain environments.

Materials and Methods

Outline of the MEDALUS model

A combination of indicators is important for the identification and assessment of degraded land. The MEDALUS algorithm considers several variable characteristics describing climate (e.g., rainfall, aridity index, and slope aspect), soil properties (e.g., slope gradient, rock fragments, soil depth, soil texture, and parent material), vegetation (e.g., drought resistance, fire risk, plant cover, and erosion protection), and land management (e.g., population density, land use intensity, and policies). These characteristics are processed as thematic layers [4], [10], [17], [18], [23]. Sensitivity to land degradation within the thematic layer is reflected by values ranging from 1 (lowest sensitivity to land degradation) to 2 (highest sensitivity to land degradation) [4], [9]. The thematic layers are overlain using an algebraic map in Geographic Information Systems (GIS) [4] and are therefore organized into four quality indicators: Climate Quality Index (CQI), Soil Quality Index (SQI), Vegetation Quality Index (VQI), and Management Quality Index (MQI). Finally, these quality indicators are combined into the Environmentally Sensitive Areas Index (ESAI), which enables the identification of degradation-sensitive areas in map form [4], [9].

The advantage of the MEDALUS model is the possibility to modify the main quality indicators, taking into account the availability of data and their adaptation to local conditions [10], [17], [18], [23]. This provides an opportunity to adapt the model to the local scale and address the main objective of this study.

Primary quality indicators and source data

The MEDALUS model requires values describing land degradation sensitivity for the quantitative parameters related to climate, soil, vegetation, and land management. In this study, a scoring system was adopted from fundamental works, such as Kosmas *et al.* [4], Prăvălie *et al.* [10], [23], and Ferrara *et al.* [9]. The application of the model at the local scale, in the present authors' opinion, requires modification of the main quality indicators and the inclusion of parameters that influence the intensity of land degradation at local scales. Therefore, in this study, some parameters important for the assessment of local-scale land degradation intensity were proposed and implemented among the main quality indicators. Following previously established methodology [4], [5], the areas occupied by artificial and aquatic areas were not included in the analysis.

The application of the MEDALUS model at the local scale requires high-quality input data; therefore, this study uses high-resolution data for the required geocomponents (parameters) (Table 1). For GIS analyses, data with a resolution of 1×1 m were used; this represents a previously unexplored resolution of observation in the MEDALUS methodology.

Climate Quality Index (CQI)

In the original MEDAULS model [4], the CQI was composed of three parameters influencing water availability to plants (precipitation, aridity index, and slope aspect). This approach was generally used in subsequent studies that adapted the MEDALUS model at regional [10], [23] and global [9] scales. To adapt the MEDALUS model to the local scale, this paper obtained the CQI indicator from three parameters: (a) precipitation, (b) aridity index, and (c) slope aspect (Table 1). Precipitation data were obtained by calculating the annual precipitation sums (2021–2022) from the five nearest rainfall stations (Tuchów, Ciężkowice, Pilzno, Jasło, and Gorlice) managed by the Institute of Meteorology and Water Management of the Polish Research Institute (IMGW-PIB). The aridity index characterizes climatic conditions in terms of environmental sensitivity to desertification. In this study, the aridity index was calculated using the database of Trabucco and Zomer [26] combined with the parameters of Ferrara *et al.* [9]. In the present study, the low spatial diversity of this climate characteristic is considered to fully justify the usage of this database for local-scale analyses. The slope aspect is considered an important factor due to its influence on vegetation through variations in humidity levels. According to Kosmas *et al.* [4], among others, southern slopes in the northern hemisphere receive more solar radiation than northern slopes, resulting in higher evapotranspiration and lower soil moisture, and thus underdeveloped vegetation, which increases their vulnerability to degradation. In this study, western and eastern slopes were also included in the analysis as an intermediate between north and south. The CQI, which in this case represents the combination of the precipitation aridity index and aspect, was calculated as the product of these attributes using the following equation:

$$CQI = (\text{Precipitation} \cdot \text{Aridity index} \cdot \text{Slope aspect})^{1/3}$$

The classes and corresponding weighting indices (according to [9], [23]) for the chosen parameters in the assessment of climate quality are summarized in Table 2.

Table 1. Main characteristics of parameters used in the development of indicators (Ind.)

Ind.	Parameter	Original data type/scale	Time period	Data source
CQI	1. Precipitation	database file/vector	2021-2022	Institute of Meteorology and Water Management Polish Research Institute
	2. Aridity index	GeoTiff 30 arc-seconds	1970-2000	Based on Trabucco and Zomer [26]
	3. Slope aspect	las data/1 m spatial resolution DEM	2022	ALS-LIDAR scanning from year 2022*
SQI	4. Parental material	1:50.000	1998	Geological map, Rzepiennik sheet M-34-79-C, [27]
	5. Soil texture 6. Soil groups 7. Soil depth	1:25.000	1956-1977, updated	Soil-agriculture map, Institute of Soil Science and Plant Cultivation, Poland
	8. Slope	las data/1 m spatial resolution DEM	2022	ALS-LIDAR scanning from year 2022*
VQI	9. Erosion protection (vegetation)	vector layer/ digitized on the basis 0.25 m raster size	2018	colour orthophotmaps - Head Office of Geodesy and Cartography Poland
	10. Hillslope shape index	las data/1 m spatial resolution DEM	2022	ALS-LIDAR scanning from year 2022*
	11. Normalized Difference Water Index	raster/10×10m to 1×1m resampling	2021-2022	Sentinel 2 - The Copernicus SENTINEL-2 mission, based on the formula of Gao (1996) [28]
MQI	12. Landslide	1:10.000	2014	landslide map (The Landslide Counteracting System) - Polish Geological Institute-National Research Institute
	13. Land use intensity (SAS)	1:25.000	1956-1977, updated	Soil-agriculture map (Soil-Agricultural Suitability units); Institute of Soil Science and Plant Cultivation; based on the formula of Macias and Bródka (2014) [29]
	14. Field boundary density	vector/recalculated to the density map by line density algorithm in QGIS and to 1m raster resampled	2022	Land and building register system, Head Office of Geodesy and Cartography, Poland

* data from project financed by the National Science Centre in Poland, number: 2021/05/X/ST10/00532

Soil Quality Index (SQI)

To estimate the SQI, one topographic parameter (slope) and four soil parameters (parental material, soil texture, soil groups, and soil depth) were selected (Table 1). This represents the typical set of parameters used in the MEDALUS model at regional and global scales [4], [9] and is considered to be appropriate for local-scale observations. The classes and corresponding weighting indices for the selected parameters in the SQI (according to [4], [9], [23]) are summarized in Table 2. The SQI was calculated as the product of the above-mentioned parameters according to the following equation:

$$SQI = (\text{Parental material} \cdot \text{Soil texture} \cdot \text{Soil groups} \cdot \text{Soil depth} \cdot \text{Slope})^{1/5}$$

Table 2. Characteristics of the 14 quantitative parameters used to obtain the four main quality indicators

Parameter	Class	Description	Score
Climate quality			
1. Precipitation	1	>=650	1
2. Aridity index	1	1-1.25	1
3. Slope aspect	1	N, N, NE, flat areas	1
	2	W and E	1.25
	3	S, SW, SE	1.5

Parameter	Class	Description	Score
Soil quality			
4. Parental material	1	Unconsolidated sediments	1
	2	silicate sedimentary rocks	1.2
	3	mixed sedimentary rocks	1.4
5. Soil texture	1	clay loam, sandy loam, sandy clay loam	1
	2	silty loam	1.2
	3	silty clay, silt	1.6
6. Soil groups	1	cambisol, fluvisol	1
	2	luvisol, podzol	1.3
7. Soil depth (cm)	1	100-150	1
	2	100-50	1.2
	3	50-25	1.6
	4	0-25	2
8. Slope (%)	1	< 6	1
	2	6–18	1.2
	3	18-35	1.5
	4	>35	2
Vegetation quality			
9. Erosion protection	1	Broad-leaved forest; mixed forest,	1
	2	Pastures and grassland; fruit trees and orchards; unpaved roads covered with grass	1.3
	3	Land principally occupied by cropland	2
10. Slope shape index	1	Straight	1
	2	Concave/Convex	1.25
11. Normalized Difference Water Index (NDWI)	1	>0.4	1
	2	0.3-0.4	1.25
	3	0.2-0.3	1.5
	4	0.0-0.2	1.75
	5	<0.0	2
Management quality			
12. Landslide*	1	Stable terrain	1
	2	inactive	1.3
	3	Periodically active	1.6
	4	Active	2
13. Land use intensity**	1	Ls+N+3z	1
	2	2z	1.25
	3	Soil-Agricultural Suitability units 7,12,13,14	1.5
	4	5, 6, 9, 11	1.75
	5	1-4, 8, 10	2
14. Field boundary density ($m \cdot m^{-2}$)	1	0.00	1
	2	0.00-0.02	1.25
	3	0.02-0.03	1.5
	4	0.03-0.04	1.75
	5	>0.04	2

* - the Landslide Counteracting System database, SOPO (Polish acronym), 2018, provided by the Polish Geological Institute-National Research Institute [33] (Mrozek *et al.* 2014).
** - Ls-forest, N-unculivated lands, 2z-3z – classes in grasslands (included unpaved roads covered with grass), 1-14 classes in agricultural areas according to Macias and Bródka [29].

Vegetation Quality Index (VQI)

The VQI was analyzed using the following parameters: (a) erosion protection, including the type of vegetation cover; (b) the Normalized Difference Water Index (NDWI); and (c) the slope shape index, which allows the detection of areas more prone to erosion (Tables 1, 2). The categories of erosion protection used were assessed based on Prăvălie *et al.* [23] in relation to LULC data obtained from 2018 color orthophotomaps and local environmental conditions [28], [29], [30].

The NDWI index is considered to be a valuable parameter at the local scale because it helps to identify arid areas that are more vulnerable to land degradation due to overdrying. The NDWI index was calculated based on the Gao formula [28] using Sentinel 2 satellite image data specifically for the beginning of the vegetation period (May 2021 and 2022). NDWI categories were assigned according to the guidelines provided by Gulácsi and Kovács [31], where NDWI <0 indicates very strong drought and >0.4 indicates no drought. The hillslope shape index is also considered a valuable parameter for land degradation assessment and is integrated in the local-scale MEDALUS model proposed herein. The hillslope shape index allows the identification of agricultural terraces and areas of hillslopes dominated by terraces, thereby identifying regions that are less susceptible to land degradation. Terraced slopes are characterized by approximately 40% less denudation than non-terraced slopes [32]. The hillslope shape index was calculated using the profile curvature method implemented in the QGIS program based on the 1 m resolution DEM described above. The VQI was calculated according to the following formula:

$$VQI = (\text{Erosion protection} \cdot \text{NDWI} \cdot \text{Hillslope shape index})^{1/3}$$

Management Quality Index (MQI)

The MQI was analyzed in terms of quality management and the degree of anthropogenic impact on land degradation. Three parameters were included in this indicator: (a) landslide activity, (b) land use intensity, and (c) field boundary density (Tables 1, 2). Landslide activity, as a component of the MQI, was introduced by Momirović *et al.* [8] as a major criterion for landslide hazard and susceptibility assessment in land degradation (Table 1). Land use intensity influences the land degradation process and is strongly connected to policy management. Land use intensity was evaluated based on soil agricultural suitability (SAS) units (Table 1). The categories of SAS are associated with the utility of agriculture in terms of grassland and arable land. More productive SASs are used more intensively for agricultural purposes, and consequently, they are more susceptible to land degradation [29]. The final parameter in the MQI is the field boundary density. Field boundaries, such as ploughed furrows and unpaved roads covered with grass, often create incisions that facilitate concentrated linear water flow, thereby accelerating land degradation processes [34].

Therefore, in the present study, this parameter is considered valuable for the identification of degradation sensitivity and is included in the local-scale MEDALUS model. The MQI is determined by multiplying the above parameters, which indicate the sensitivity to degradation, according to the following equation:

$$MQI = (\text{Landslide} \cdot \text{Land use intensity} \cdot \text{Field boundary density})^{1/3}$$

Areas sensitive to degradation

The Environmentally Sensitive Areas Index (ESAI) was computed as the geometric mean of the four indicators, including both natural factors and human activities, according to the following equation:

$$ESAI = (CQI \cdot SQI \cdot VQI \cdot MQI)^{1/4}.$$

The catchment area was classified into four main classes (not affected - N; potentially affected - P; fragile - F; critical - C) and eight subclasses (N, P, F1, F2, F3, C1, C2, and C3) of sensitivity to degradation, defined according to widely applied thresholds and classification systems [19], [23], [35]. The spatial distribution of the classes and their proportion in the catchment area allowed the assessment of the spatial sensitivity of the land to degradation and the application of the MEDALUS model for the detection of degradation-sensitive land.

Factors responsible for predicting degradation-sensitive areas

To explore which factors play a key role in predicting degradation-sensitive land areas in the local-scale MEDALUS model, statistical analyses were applied. The relationships between (a) 14 basic parameters and the main quality indicators (SQI, CQI, VQI, MQI) and (b) the main quality indicators and the ESAI were determined using spatial correlation analysis. The non-parametric Spearman correlation coefficient was applied. The coefficient lies within the range of +1 to −1, where a positive correlation indicates a strong direct relationship between two parameters and a negative correlation denotes an opposing relationship. A correlation coefficient value of zero indicates that the two parameters are not dependent on each other. Statistical analyses were performed based on scripts in the R language, which were implemented into QGIS software.

Verification of degradation-sensitive areas identified using the MEDALUS model

The MEDALUS model has been applied worldwide to predict areas sensitive to degradation or desertification. However, to the best of the present authors' knowledge, no literature containing information about the validation phase of the model to justify its applicability in practice has been published. In order to fill this gap, the present study attempted to carry out the verification stage of the MEDALUS model at the local scale, using high-resolution (1 m) data. Considering the complexity of degradation issues, an indirect approach was proposed. In the study area used, degradation was observed to be strongly associated with erosion and accumulation processes, which in turn influence the topographic surface. Therefore, in this study, the results of the MEDALUS model were compared with a DEM of Difference (DoD; 1 m spatial resolution). This comparison was made using two collections of Airborne Laser Scanning–Light Detection and Ranging (ALS-LIDAR) data from 2011 (with a point density of 4-6 pts/m², obtained from the Head Office of Geodesy and Cartography in Poland) and 2022 (with a point density of 20–30 pts/m², a project funded by the National Science Centre in Poland). Both scans were carried out to the same standard, resulting in a 15 cm vertical accuracy for each measured point (in fact, the maximum elevation ground error at each point is 30 cm or less). It was assumed that the correspondence between the areas identified by the MEDALUS model as degradation-sensitive and the areas in which surface changes occurred would confirm the usefulness of the model. Convergence was evaluated by crosstabulation analysis, supported by spatial correlation analysis using a Spearman R coefficient calculated in the R language.

The study area

The catchment unit used (the Rzepianka catchment) was chosen because it allows an integrative spatial analysis, linking the combination of topographic, geological, soil, vegetation, and climatic conditions [36], [37]. With an area of 45 km², the Rzepianka catchment is in the Ciężkowickie Foothills of the Polish Western Carpathians between 257 and 404 m a.s.l. (Fig. 1).

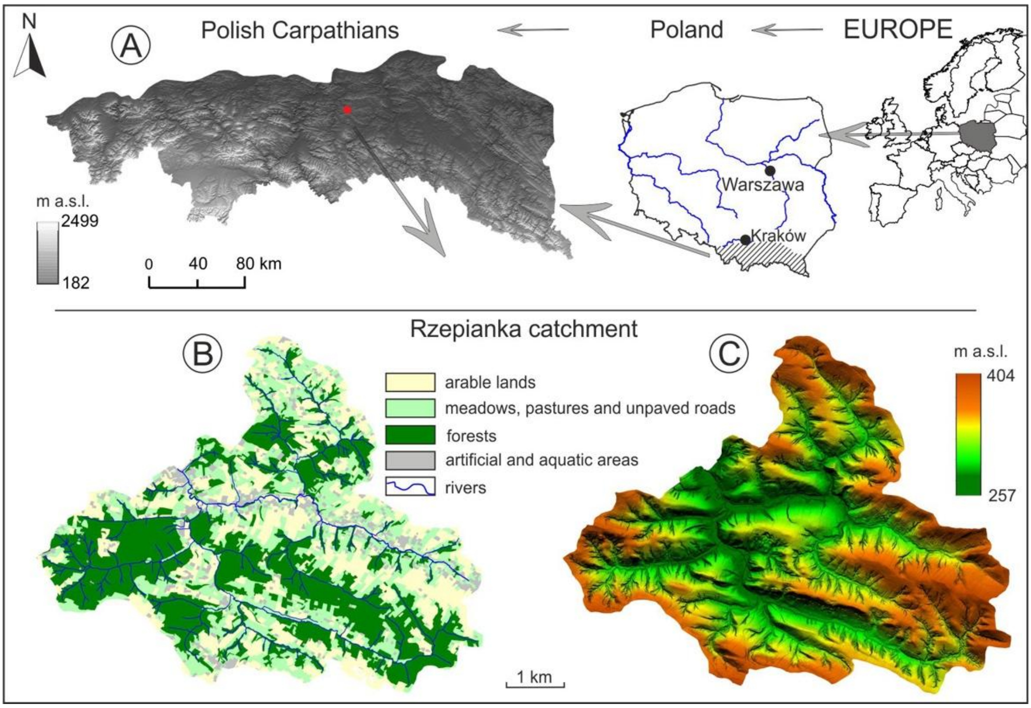

Fig. 1. The study area in the Polish Carpathians. A - Location of the research area. B - Land use/cover of the research area. C - Relief of the research area

The main stream is a tributary of the Biała Dunajcowa river. Investigations were carried out on the upper part of the catchment area, covering an area of 25.1 km². The geological composition of the area consists of flysch sandstones and shales belonging to the Silesian Nappe, which significantly influence the relief of the catchment [38]. The topography is predominantly gentle, with only a small percentage of the area (less than 14%) characterized by steep slopes exceeding 35%. The upper Rzepianka catchment is located in a temperate climate zone [39] with a mean annual precipitation of 700 mm and a mean annual temperature of 8°C (1991–2020; IMGW-PIB). Silty loess-like deposits support the formation of Luvisoils. The foothill zone is mainly covered by deciduous forests of hornbeam, oak, lime, and beech. In 2018, arable land accounted for 24.5% of the land area of the catchment, forests covered 40.7%, meadows and pastures 33.4%, and artificial and aquatic areas 1.4%. An important feature of the landscape of the area is highly fragmented agricultural land, typical of the Polish Carpathian Foothills [40], which results in a dense network of unpaved access roads to the fields, often covered with grass. The upper Rzepianka catchment was inhabited by approximately 1800 people in 2018 (estimate based on the Central Statistical Office of Poland). The catchment area is well-connected by road to the nearby district towns of Gorlice (with a population of 27,000 inhabitants) and Tarnów (with a population of 110,000).

Results

Use of the MEDALUS model at local scales - Spatial distribution of quality indicators

Table 3 presents the primary quality indicators (SQI, CQI, VQI, and MQI), showing the percentage and area (km²) of land area accounted for by each quality class, together with the corresponding criteria established by Kosmas *et al.* [4] and Prăvălie *et al.* [23].

Table 3. Main quality indicators: Climate Quality Index (CQI), Soil Quality Index (SQI), Vegetation Quality Index (VQI), and Management Quality Index (MQI), including scores, area within the Rzepianka catchment, and percentage content within the Rzepianka catchment.

Indicator	Class	Quality description	Score range	Total area	
				km^2	%
CQI	1	high quality	<1.15	14.25	56.7
	2	moderate quality	1.15-1.81	10.53	41.9
	3	low quality	>1.81	0.00	0.0
	artificial and aquatic areas			0.34	1.4
SQI	1	high quality	<1.13	1.43	5.7
	2	moderate quality	1.13-1.45	20.28	80.7
	3	low quality	>1.46	3.06	12.2
	artificial and aquatic areas			0.34	1.4
VQI	1	high quality	<1.13	1.68	6.6
	2	moderate quality	1.13-1.38	17.27	68.8
	3	low quality	>1.38	5.82	23.2
	artificial and aquatic areas			0.34	1.4
MQI	1	high quality	<1.25	8.77	34.9
	2	moderate quality	1.25-1.5	10.84	43.2
	3	low quality	>1.51	5.16	20.5
	artificial and aquatic areas			0.34	1.4

Source: Own elaboration of the authors

The spatial distribution of every basic parameter and the main quality indicators are shown in Figs. 2 and 3. In terms of the CQI, a significant part of the study area (56.7%, i.e., 14.25 km²) has a high climate quality. An area of 10.53 km², corresponding to 41.9% of the total area, is characterized by moderate climate quality (Table 3). In general, the study site lacks areas with high land degradation potential, which can mainly be explained by its precipitation and aridity index, which, according to existing methodology [4], [9], [23], classifies the entirety of the studied catchment in the lowest score. As a result, the slope aspect was determined to be the primary factor influencing the CQI (Table 4). In terms of the SQI, the data obtained showed that sites characterized by a high soil quality index cover approximately 5.7% of the total area, equivalent to 1.43 km². Moderate soil quality covered a significant part of the study area (80.7%, i.e., 20.28 km²), and 12.2% of the total area (3.06 km²) exhibited a low soil quality. Higher pressure of soil conditions was identified in different places across the catchment area, mainly on slopes used for agricultural purposes. Considering the constituent parameters of the SQI, the higher potential for land degradation can be attributed to soil texture (silt and silty clay), as well as the shallow soil depth at specific sites (Table 4, Fig. 2; sites 5 and 7).

Table 4. Statistical relationships between quantitative parameters influencing land degradation and the main quality indicators (SQI, CQI, VQI, and MQI)

Numbers related to Fig. 2	Parameter *	CQI	SQI	VQI	MQI
3	Slope aspect	0.92	0.00	0.06	0.04
4	Parental material	0.01	0.29	0.13	0.00
5	Soil texture	-0.07	**0.44**	0.12	0.24
6	Soil groups	-0.03	0.30	0.22	0.20
7	Soil depth	0.08	**0.76**	0.09	0.03
8	Slope	-0.04	0.32	-0.24	-0.29
9	Erosion protection by vegetation	0.10	0.03	**0.81**	0.39
10	Hillslope shape	-0.04	0.08	-0.08	-0.10
11	NDWI	0.06	0.02	**0.56**	0.27
12	Landslide	0.04	0.04	-0.09	0.14
13	Land use intensity	0.12	0.03	0.48	**0.69**
14	Field boundary density	-0.04	0.06	0.10	**0.68**

* excluding precipitation and aridity layers – 1, 2 (no variability in the catchment area); Source: Own elaboration of the authors

The estimation of sensitivity to land degradation based on the VQI revealed extensive areas with moderate and low vegetation quality, accounting for 92% of the total area (Table 3). This is ascribed to the inadequate erosion protection by vegetation, primarily in areas occupied by cropland (Table 4, Fig. 2; site 9).

The assessment of human impact on land sensitivity to degradation by MQI showed that 34.9% of the catchment area has a high management quality. Areas with poor management quality (moderate and low quality), with a total area of 63.7% (Table 3), dominate the catchment. The high density of field boundaries (which tends to concentrate linear water flow and accelerate degradation processes) together with the quality of agricultural soils (which affects the intensity of land use for agricultural purposes) have been diagnosed as two major factors influencing the detection of degradation-sensitive areas (Table 4, Fig. 2; sites 13 and 14, and Fig. 3).

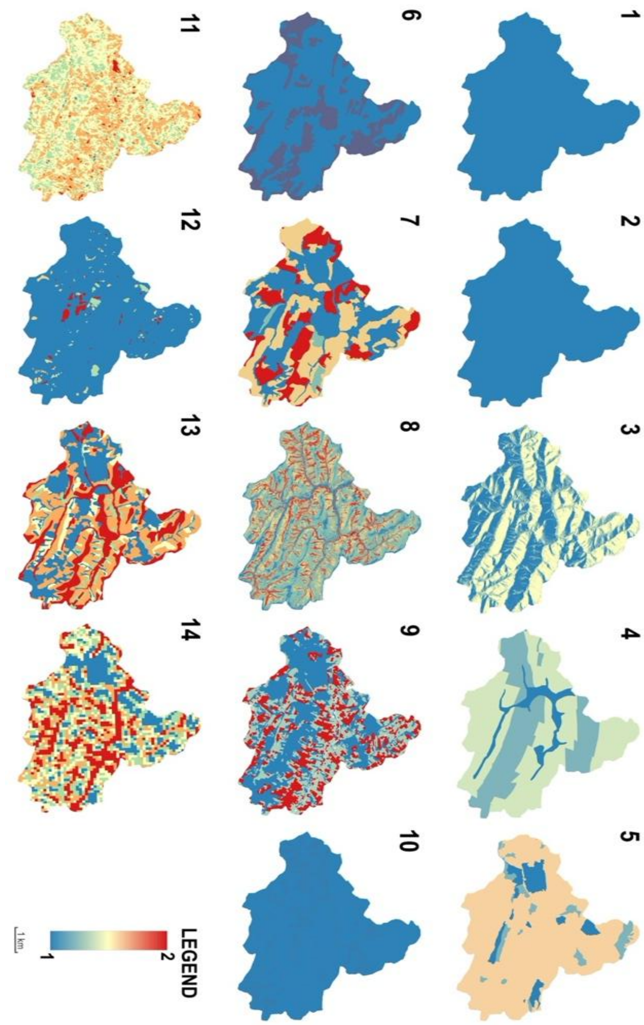

Fig. 2. Spatial distribution of quantitative parameters related to climate (1 - precipitation, 2 - aridity index, 3 - slope aspect); soil (4 - parental material, 5 - soil texture, 6 - soil groups, 7 - soil depth, 8 - slope); vegetation (9 - erosion protection by vegetation, 10 - hillslope shape index, 11 - Normalized Difference Water Index); and land management (12 - landslide, 13 - land use intensity, 14 - field boundary density) in unclassified forms (legend: 1 - lowest sensitivity to land degradation; 2 - highest sensitivity to land degradation)

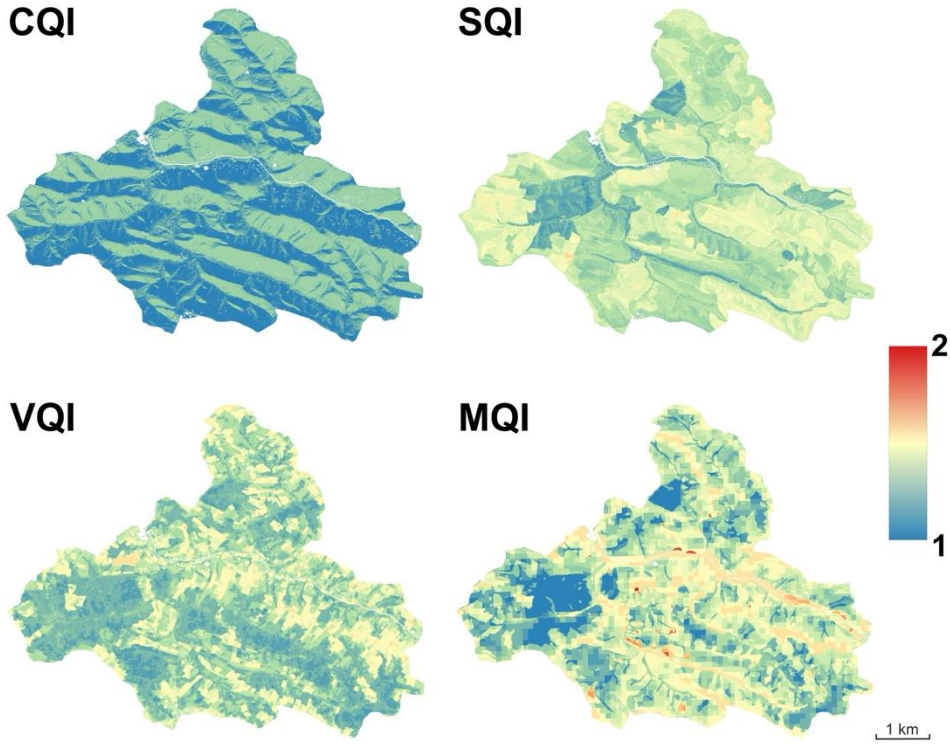

Fig. 3. Spatial distribution of Climate Quality Index (CQI), Soil Quality Index (SQI), Vegetation Quality Index (VQI), and Management Quality Index (MQI) in unclassified forms (legend: 1 - lowest sensitivity to land degradation; 2 - highest sensitivity to land degradation)

Degradation-sensitive areas

The final land degradation sensitivity map (Fig. 4; site 1) was generated by categorizing the ESAI index into four sensitivity classes (Table 5), which were organized based on their respective sensitivity levels: non-affected (N), potentially affected (P), fragile (F1, F2, and F3), and critical (C1, C2, and C3) regions. The impact of the main quality indicators (SQI, CQI, VQI, and MQI) on the ESAI is presented in Table 5.

Table 5. Classes of land sensitivity to degradation in the Rzepianka catchment (description adapted from Salvati and Bajocco [35] (2011) and Prăvălie *et al.* [23] (2017)

Category	**Description**	**Score range**	**Area**	
			km^2	%
N	No sensitive/very low sensitive*	<1.17	4.00	15.9
P	Low sensitive areas*	1.17-1.22	4.43	17.6
F1	Medium sensitive areas*	1.23-1.26	4.72	18.8
F2		1.27-1.32	6.69	26.7
F3		1.33-1.37	3.41	13.6
C1	High and very high*	1.38-1.41	1.11	4.4
C2		1.42-1.53	0.41	1.6
C3		>1.53	0.00	0
Artificial and aquatic areas			0.34	1.4
Total			25.11	100

* sensitive areas to land degradation, Source: Own elaboration of the authors

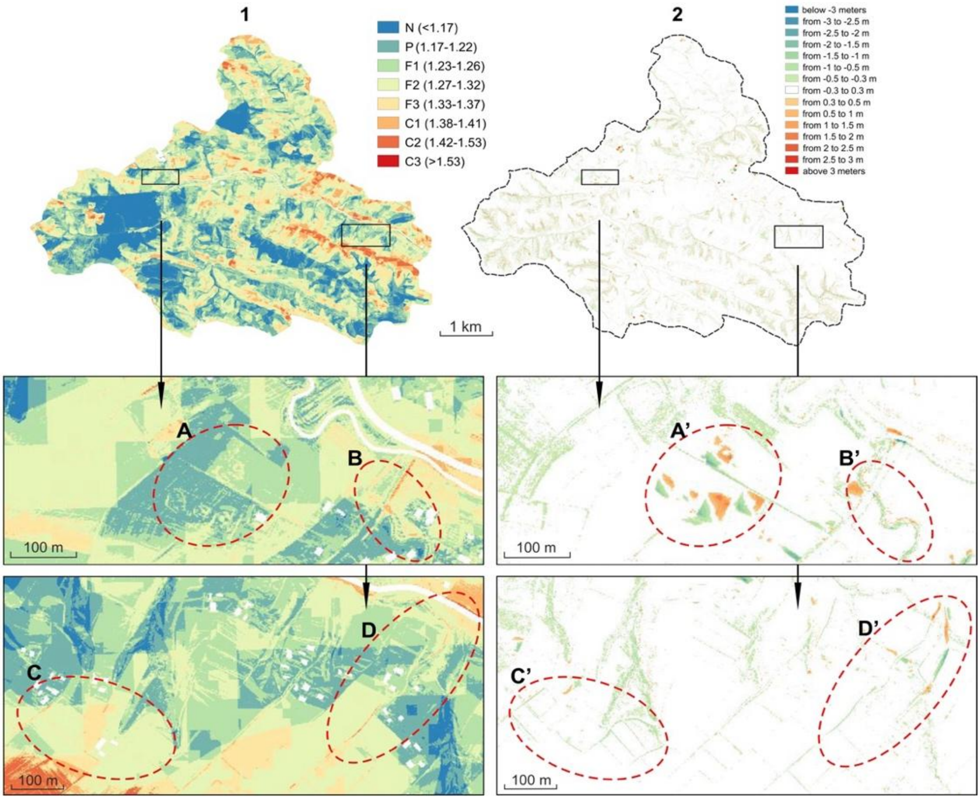

Fig. 4. (1) ESAI: non-affected (N), potentially affected (P), fragile (F1, F2, and F3), and critical (C1, C2, and C3). (2) Changes in the terrain surface determined by the DoD model and comparison of selected fragments of ESAI map with the DoD model (AA', BB', CC', DD')

The results obtained clearly show that approximately two-thirds of the study area (63.08%) falls into the fragile classes, particularly the F2 class. In addition, 17.6% of the study area is classified as potentially affected, while 15.9% is classified as non-affected by degradation. These results suggest that only 6% of the Rzepianka catchment area is classified as critical, typically corresponding to the C1 class.

The data presented in Table 6 indicate that the ESAI is mainly related to the MQI and VQI (0.66 and 0.61, respectively), whereas the CQI and SQI have a more moderate influence (0.39 and 0.34, respectively).

Table 6. Statistical relationships between the main quality indicators (SQI, CQI, VQI, and MQI) and ESAI

	CQI	SQI	VQI	MQI	ESAI
CQI	1.00	0.01	0.07	0.05	0.39
SQI	0.01	1.00	0.07	0.00	0.34
VQI	0.07	0.07	1.00	0.33	**0.61**
MQI	0.05	0.00	0.33	1.00	**0.66**

Source: Own elaboration of the authors

According to the ESAI, areas of critically degradation-sensitive land are situated in the eastern and northern parts of the catchment area and correspond to intensively cultivated areas, in which more productive soils with silty and silty clay textures are more affected by degradation processes; this is reflected in soil depth reduction (Figs. 2 and 4; site 1).

Spatial assessment of the Environmentally Sensitive Areas Index and its relationship to the DoD model – verification of the MEDALUS model

Comparisons between the classes of the ESAI and the DoD model were intended to verify the local-scale usefulness of the MEDALUS model. The results of this validation procedure are presented in Figure 4.

The correlation between the final ESAI classes and the intervals classified by the DoD was 0.09, suggesting a weak relationship between these data. The absence of a statistical relationship does not, however, suggest that there is no relationship. Changes in the topographic surface reflected by the DoD model in the range −30 to +30 cm are evident (Fig. 5) and affect approximately 90% of the catchment area. Taking into account the cross-tabulation analyses, more than 83% of the ESAI classes were included in this range of the DoD model. Such changes, even when they affect a significant part of a catchment area, are difficult to interpret because they are included in the range corresponding to the potential maximum measurement error of the DoD model (Fig. 5).

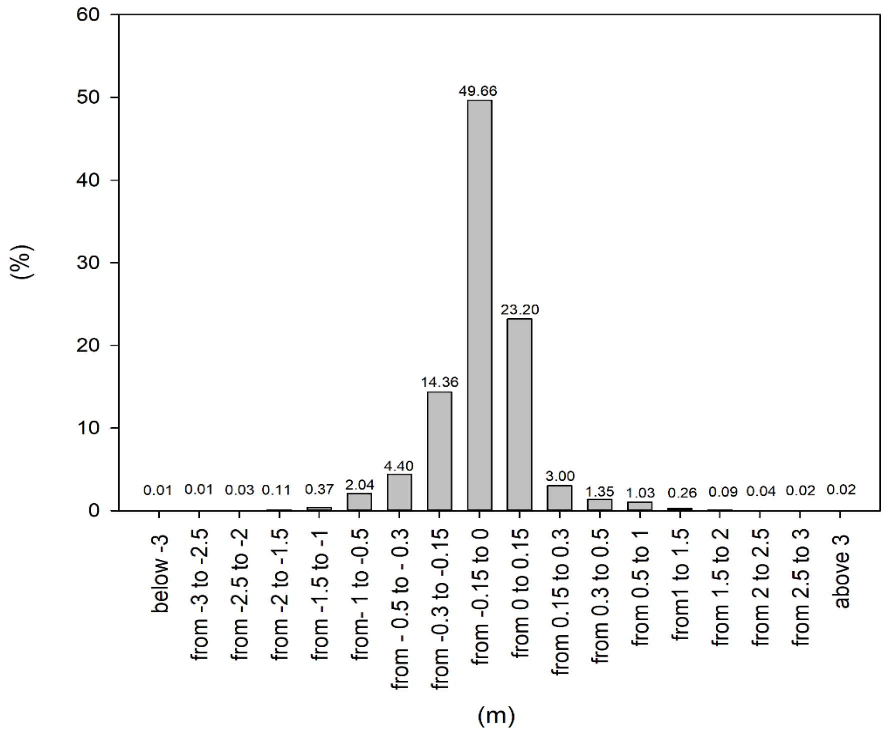

Fig. 5. Topographic surface changes in the upper Rzepianka catchment based on the DoD model

Changes in the topographic surface that exceed the potential measurement error of the DoD models are less noticeable and affect approximately 10% of the catchment area. A lowering of the topographic surface by more than 30 cm occurred in 7% of the area analyzed, whereas an increase in the elevation of the topographic surface of the same value occurred in 3% of the area. The detailed analysis of four case studies (Fig. 4) representing the nature of surface changes and their relation to ESAI gives valuable insights into the use of the DoD in verifying data. The first case (Fig. 4, AA') represents a catchment area in which residential and commercial development is taking place. The leveling of the land required for each building results in significant ground remodeling. In such locations, excavations and embankments appear similar to those along newly constructed local roads. The ESAI map does not predict these frequent changes and has identified such areas as potentially affected by (class P) and fragile to (class F1) land degradation. The second case (Fig. 4 BB') represents parts of a catchment in which the main stream bed is visible in the DoD model with a dominant contribution from erosion. The ESAI model recognizes such areas as partially sensitive to degradation (classes F1–F3), but only in relation to steep deforested banks. The remaining two cases represent a significant relationship between the final ESAI and DoD. The third case (Fig. 4, CC') represents the fragile (classes F2 and F3) and critical (classes C1, C2) areas of degradation, corresponding to significant changes in the real surface detected by the DoD model (lowering to −0.5 m). This case study emphasizes the influence of human activity in relation to changes in surface topography resulting from the development of agricultural terraces. The fourth case (Fig. 4, DD') represents parts of the catchment in which surface changes are related to the functioning of rural (unpaved) roads. The ESAI classifies unpaved roads, mostly covered with grass, and their surroundings as vulnerable to degradation (class C1–C3), consistent with DoD data (fragments with erosion on the slopes and accumulations in the unpaved road holweg - the thickness exceeds half a meter).

Discussion

Use of the MEDALUS model for detection of degradation-sensitive areas at regional and global scales

The MEDALUS model was developed to identify a specific and delimited unit in which environmental and socioeconomic factors are not in balance or not sustainable for a particular environment, with the objective of introducing appropriate policies to mitigate these processes [4], [9]. The first tests of the MEDALUS methodology [4] were carried out in the Mediterranean regions, including Greece [4], Portugal [41], and Italy [5]. The efficiency, reliability, and flexibility of the model in selecting relevant indicators and integrating data from different sources [23], [24], [25] has led to its wider application outside of the Mediterranean region. Thus, the MEDALUS approach has been adapted for analysis at regional scales, for example, in Romania [8], [10], [11], [19], [23], where new quality indicators were incorporated into its methodology. More recently, the applicability of the MEDALUS algorithm has been updated and demonstrated on a global scale [9]. The application of this model, based on consistent data sources, spatial resolution, and methodology, provides a unique opportunity to indirectly compare the average values of the ESAI across large geographical regions and offers valuable information about "regional hotspots" [42], [43], [44] that require more detailed analyses. According to previous studies, the regions of Central and Eastern Europe (including the Carpathians, where the study area is located) are experiencing an increase in climatic aridity, a higher frequency of forest fires, local instances of soil degradation, and varying levels of anthropogenic pressures. Changes in the climatic conditions of land degradation and desertification indicated by the MEDALUS model have been confirmed by many local studies. Analyses by Kędra and Szczepanek [45] showed an increase in the mean annual temperature in the Polish Carpathians for both the periods 1961–2010 and 1981–2010 (0.29 and 0.35°C per decade, respectively); this significant increase shows a close agreement with the results reported in Spinoni *et al.* [43], in which the Carpathians were considered as a whole region. Similarly, Bokwa *et al.* [44] studied the Carpathian Foothills (200–400 m a.s.l.), similarly to the present study, revealing that this region exhibits the highest mean annual air temperature along the entire altitudinal gradient in the Polish Carpathians. Furthermore, climate change has led to prolonged summer droughts [44], characterized by increased evapotranspiration and reduced soil water availability [46]. These phenomena, combined with human activities, can lead to major changes in the landscape [47], [48], [49], [50] and can strongly affect land degradation [51], [52]. Therefore, by considering environmental changes diagnosed at the local scale, the applicability of the MEDALUS model for the identification of local-scale areas vulnerable to degradation was evaluated.

Use of the MEDALUS model for detection of areas sensitive to degradation at the local scale

According to Prăvălie *et al.* [23], it is possible to improve the methodology of the MEDALUS model and successfully apply it in other regions known to be susceptible to land degradation. By adapting the method to specific environmental conditions, it becomes possible to investigate the spatial sensitivity of the land degradation process in a small catchment area using high-resolution data. Thus far, the only investigation of land degradation sensitivity using high-resolution data (1:10.000) within the ESAI framework was conducted in Czechia [19]. The results of that study indicate that the sensitivity of land to degradation in the Czech Republic is only slightly lower than that in the Mediterranean and southeastern Europe.

In this study, results obtained using the MEDALUS model (ESAI) indicate a medium (fragile) land sensitivity to degradation processes of over 60% at the scale of the Rzepianka catchment. These results confirm a lower sensitivity to land degradation relative to similar studies conducted in Czechia [19], Romania [23], and Serbia [11], [22], which may indicate the influence of a temperate climate.

In the Polish Western Carpathians, DoD data were successfully used to assess the extent of local land surface degradation, determining the impact of human activities [53] and the intensity of natural processes [54]. However, the authors did not find any studies in which high-resolution terrain data were used to verify the results of land degradation using models. Therefore, one of the major issues addressed in this study was the attempt to verify the results of the MEDALUS model using the high-resolution DoD model. The results of this verification showed that the statistical relationship between the ESAI and the DoD model at the catchment scale was low (R=0.09). However, a more detailed analysis allowed some general statements to be made regarding this issue. In general, the DoD model accurately evaluates changes in the topographic surface over the last decade. Most of the changes can be seen in the range of −30 to +30 cm. Despite the fact that this range corresponds to the maximum error of the DoD measurement, it can be shown that surface changes are related to the polygons corresponding to the ESAI classes C1–C3 (critical land degradation), which primarily reflect arable fields in which the soil profile has been reduced in the range of 0–30. The relationships between ESAI and DoD observed in these areas, where changes in surface topography exceed 30 cm (out of the error range), show that the ESAI provides relatively accurate estimations of changes in the surface topography associated with erosive transformations within the riverbed channels, but also with agricultural terracing and the unpaved road network and its surroundings.

The implementation of the MEDALUS methodology in the study area, based on available high-resolution spatial data for soil, climate, vegetation, and management systems, was adapted to the local conditions. This has resulted in the development of a viable method for identifying lands at risk of degradation. The results obtained also confirm the usefulness of the MEDALUS model as an effective tool for conducting simulations that facilitate sustainable land management in areas susceptible to degradation processes, including small catchments. Furthermore, the identification of areas more susceptible to degradation will improve spatial planning, and the data derived from these analyses can be valuable for future research in various disciplines of earth and environmental sciences. Consequently, these results can serve as a basis for planning landscape management in the coming decades and for improving analytical standards in analogous studies conducted in different geographical zones, especially in temperate regions.

The use of consistent methodology, such as the MEDALUS approach, is important for comparative analysis. In the geographical region where the study area was located, previous work has evaluated land degradation using different approaches. For example, Kędra and Szczepanek [45](2019) indicated that changes in LULC since 1990 indicate both present-day land degradation and continued future risks of degradation. Their study highlighted the need for sustainable management practices in mountainous regions to mitigate or prevent degradation due to ongoing intensive urbanization. Similarly, Ćwik and Hrehorowicz-Gaber [55] demonstrated the vulnerability of mountain rural regions to unsuitable land development, particularly as a result of unplanned and uncontrolled settlement growth. To identify areas most vulnerable to land degradation, Bucała-Hrabia [56] analyzed LULC patterns in catchment areas in the western part of the Carpathians using recommended guidelines for assessing land degradation in accordance with the UN Sustainable Development Goals. Other interpretations of changes in land cover in the context of land degradation have also been proposed; for example, the abandonment of agricultural land may lead to land improvement, whereas settlement development and the transformation of forest areas into grassland have contributed to land degradation. The use of different approaches may lead to results that are not fully comparable, which may in turn result in inconsistent and/or inappropriate environmental management decisions. Using a single model, e.g., MEDALUS, can limit these issues and support environmental management at different scales, from local to global.

Conclusions

The results of this study have shown that the MEDALUS model allows a pragmatic exploration of the spatial sensitivity of land degradation processes at local scales using high-resolution data. Furthermore, the model can be easily adapted both to the specific environmental conditions of the Polish Carpathians and to the available data on this region. By replacing certain parameters within the four main quality indicators with other relevant parameters (e.g., NDWI), a more accurate estimation of these quality indicators was facilitated. The ESAI results obtained show that only 6.0% of the study area is classified as critical in terms of land degradation, whereas 63.08% is classified as fragile, 17.6% as potentially affected, and 15.9% as non-affected by degradation. These results confirm that the study area exhibits a lower sensitivity to land degradation than similar regions in Czechia. In addition, a positive impact on the final ESAI was obtained by adding new elementary maps (parameters) to the model, i.e., slope shape and plot boundary density (field boundary density). As a result, changes in agricultural terraces, field boundaries, and shapes around local unpaved roads are visible in the DoD and predicted by the ESAI.

In summary, both the ESAI and DoD enable mutual verification, and it can be confirmed that the ESAI considers some forms of anthropogenic activity, whereas the DoD takes into account all landform changes. ESAI provides a prediction, while DoD is the result of real changes. ESAI indicates areas predisposed to land degradation and therefore identifies more rapid erosion processes, whereas DoD indicates areas in which significant changes have already occurred.

Qualitative analysis between ESAI and DoD confirmed that the degraded areas identified by the MEDALUS model are registered on DoD; however, this relationship refers only to part of the area. Quantitative analysis (cross-correlation analysis) indicated relationships between ESAI and the DoD model; however, due to the fact that a significant part of the ESAI classes are covered by classes within the error range of the DoD model (from −0.3 to 0.3 m), the spatial correlation between the two cannot be conclusively established. It is assumed that the DoD, with lower vertical error, would allow for a more detailed quantitative validation of the MEDALUS model. Further research is required to address this issue.

Overall, the results of this study have demonstrated the effectiveness of the MEDALUS model as a valuable tool for carrying out simulations to promote sustainable land management, particularly in areas vulnerable to degradation processes, such as small catchments. By identifying areas with higher vulnerability to degradation, it will be possible to improve land management planning efforts through the optimized design of restoration and rehabilitation measures, ultimately promoting more appropriate development.

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