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Assessing Soil Degradation: A Comprehensive Study Using Soil Degradation Index (SDI) in Godrahav Watershed

Toprak Bozulmasının Değerlendirilmesi: Godrahav Havzasında Toprak Bozulma İndeksi (SDI) Kullanılarak Yapılan Kapsamlı Bir Çalışma

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ABSTRACT

Soil degradation is an important problem for watersheds that contain agricultural and natural areas within their border. This study was conducted to assess soil degradation using soil degradation index (SDI). The watershed was divided into transects at 500m intervals in the north-south and the east-west directions. Except for the hard-to-reach points because of topography, disturbed and undisturbed soil samples were taken from 138 sample points at the intersections of the transects. The SDI was calculated using the measured soil parameters including particle size distribution, aggregate stability, aggregation rate, mean weight diameter, dispersion rate, bulk density, porosity, field capacity, wilting point, organic matter content, pH and electrical conductivity. The spatial distribution patterns of these parameters were defined using geostatistical analyses. Slope, elevation, aspect and land use type of the watershed were also mapped using the Geographic Information System (GIS) technique. The results of the study showed that soil degradation can be quantified using an index value, and that basic soil properties can serve as parameters for this index. These parameters affect index values with different weighting, and these weighting values can be calculated by correlation analysis. Moreover, according to the distribution maps, SDI showed spatial variability due to the land use, altitude, and aspect, but it did not vary regularly due to the slope. Based on the findings, it is recommended to implement land use-specific soil management strategies across the watershed. Regular SDI-based monitoring and geospatial analysis can support early detection of degradation and guide sustainable land use planning.

Keywords: Correlation, Physiographic factors, Soil degradation, Soil mapping, Spatial variability

ÖZ

Toprak bozulması, sınırları içinde tarımsal ve doğal alanlar bulunduran su havzaları için önemli bir sorundur. Bu çalışma, bir su havzasında toprak bozulma durumunu değerlendirmek amacıyla Toprak Bozulma İndeksi (SDI) adlı ampirik bir yöntem kullanılarak gerçekleştirilmiştir. Bu amaçla, havza kuzey-güney ve doğu-batı yönlerinde 500 m aralıklarla transektlere bölünmüştür. Topografya nedeniyle ulaşılması zor olan noktalar çıkarıldıktan sonra, transektlerin kesişim noktalarından 138 örnek noktasından bozulmuş ve bozulmamış toprak örnekleri alınmıştır. SDI hesaplamasında tanecik boyu dağılımı, agregat stabilitesi, agregasyon oranı, ağırlıklı ortalama çapı, dispersiyon oranı, hacim ağırlığı, porozite, tarla kapasitesi, solma noktası, organik madde içeriği, pH ve elektriksel iletkenlik gibi parametreler kullanılmıştır. Bu çalışma aynı zamanda bu parametrelerin mekânsal dağılımını belirlemiştir. Havzanın eğim, yükselti, bakı ve arazi kullanımı gibi bazı özellikleri Coğrafi Bilgi Sistemleri (CBS) tekniği kullanılarak haritalandırılmıştır. Jeoistatistiksel teknikler, bu özellikler ve SDI'nin enterpolasyonu için kullanılmıştır. Çalışmanın sonuçları, toprak bozulmasının bir indeks değeri ile ifade edilebileceğini ve temel toprak özelliklerinin bu indeks için parametre olarak kullanılabileceğini göstermiştir. Bu parametreler indeks değerlerini farklı ağırlıklarda etkilemekte olup, bu ağırlık değerleri korelasyon analizi ile hesaplanabilmektedir. Ayrıca, dağılım haritalarına göre SDI, arazi kullanımı, yükseklik ve bakıya bağlı olarak mekânsal değişkenlik göstermiştir; ancak eğime bağlı olarak düzenli bir değişim göstermemiştir. Elde edilen bulgular doğrultusunda, havza genelinde arazi kullanımına özgü toprak yönetim stratejilerinin uygulanması önerilmektedir. SDI temelli düzenli izleme ve mekânsal analizler, bozulmanın erken tespiti ile sürdürülebilir arazi kullanım planlamasına katkı sağlayabilir.

Anahtar Kelimeler: Korelasyon, Fizyografik faktörler, Toprak bozulması, Haritalama, Mekânsal değişkenlik

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Introduction

Soil degradation, defined as the change in physical, chemical and biological properties of the soil resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries (FAO, 2020), leads to the degradation of ecosystem services (Cerretelli et al., 2018). Soil degradation includes erosion (such as soil loss due to deforestation or overgrazing), salinization, compaction, crusting caused by cattle trampling, and waterlogging with impaired water movement (Scanes, 2018).

The soil properties play a crucial role in determining soil health and degradation. Different soil properties directly influence the physical, chemical, and biological characteristics of the soil, which in turn affect its ability to support plant growth, retain water, and nutrient cycle, and resist degradation. Thus, various soil properties, such as soil texture, structure, water holding capacity, organic matter content, soil reaction, and electrical conductivity contribute to the vulnerability of soil to degradation processes (Barcelos et al., 2022; Lorenz et al., 2019; Rabot et al., 2018; Zhang et al., 2022).

A watershed is a topographic unit containing aquatic and terrestrial ecosystems, with various land-use types such as forest, pasture, and agriculture. Watersheds play a major role in the important requirements in human life, such as water supply, and agricultural and animal production. Besides, watersheds are also important for other creatures that benefit from ecosystem services. Godrahav watershed consists of different land-use types. Forestry, animal husbandry, and agricultural production are carried out in the watershed. The problem of soil degradation may disrupt the ecosystem services provided by the watershed.

Researchers reported the main reasons for the soil degradation in the watershed as degraded forest, water erosion, and shifting cultivation (Amundson et al., 2015; Baul et al., 2023; Hattori et al., 2019; Mo et al., 2023). Different methods and models are used to evaluate soil degradation. In many previous studies, the loss of organic matter, decrease in carbon and nitrogen contents, change in particle size distribution, salinization, acidification, compaction, and erosion have been evaluated as degradation separately. For example, plant nutrient deficiency was considered as chemical degradation, and soil compaction as physical degradation.

Multivariate models are used based on the approach that more than one type of degradation can be seen in an area. A global evaluation of soil degradation requires sampling and evaluation methodology, and a degradation metric meets the needs and interests of multiple different groups (Hatfield et al., 2017).

Multicriteria decision analysis (MCDA) is an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter (Belton & Stewart, 2002). The MCDA provides a compatible methodological framework for deliberate valuation, which is considered helpful in addressing plural value dimensions related to common goods such as ecosystem services.

The novelty of this study lies in its integrated approach to assessing soil degradation by combining multiple soil physical and chemical properties with topographic and land use variables through a Geographic Information System (GIS)-based multicriteria decision analysis (MCDA). Unlike conventional methods that consider soil degradation components in isolation, this study develops a comprehensive Soil Degradation Index (SDI) to spatially evaluate and classify degradation severity within the watershed. This approach enhances the accuracy and applicability of soil degradation assessments for sustainable land management.

This study was carried out in a watershed to determine the soil properties and their spatial variability and distribution. It was also aimed to calculate the soil degradation index with different weighting methods and determine the spatial variability and spatial distribution of the soil degradation index. Besides, determining the effect of topography and land use differences on soil degradation index is another purpose of the present study. A model was developed using the GIS-based MCDA to determine the spatial distribution of the soil degradation index. Created GIS-MCDA models are based on established soil properties that affect soil productivity. The model was used to classify watersheds of low, medium, and high soil degradation index. The hypothesis was that some topographic factors such as altitude, aspects and slope, and land use correlate to the soil degradation index.

Methods

The Godrahav watershed has a catchment area of 6750 ha and is in the Black Sea Region. It lies in the north-south direction between the Karçal mountains and the Çoruh River (Figure 1A). Its climate is semi-humid with a long-term average rainfall of 1000 mm year-1 and a temperature of 12ºC. The watershed was divided into 500 × 500 m transects, and a total of 274 disturbed and undisturbed soil samples were taken from 138 cross points of transects (Figure 1).

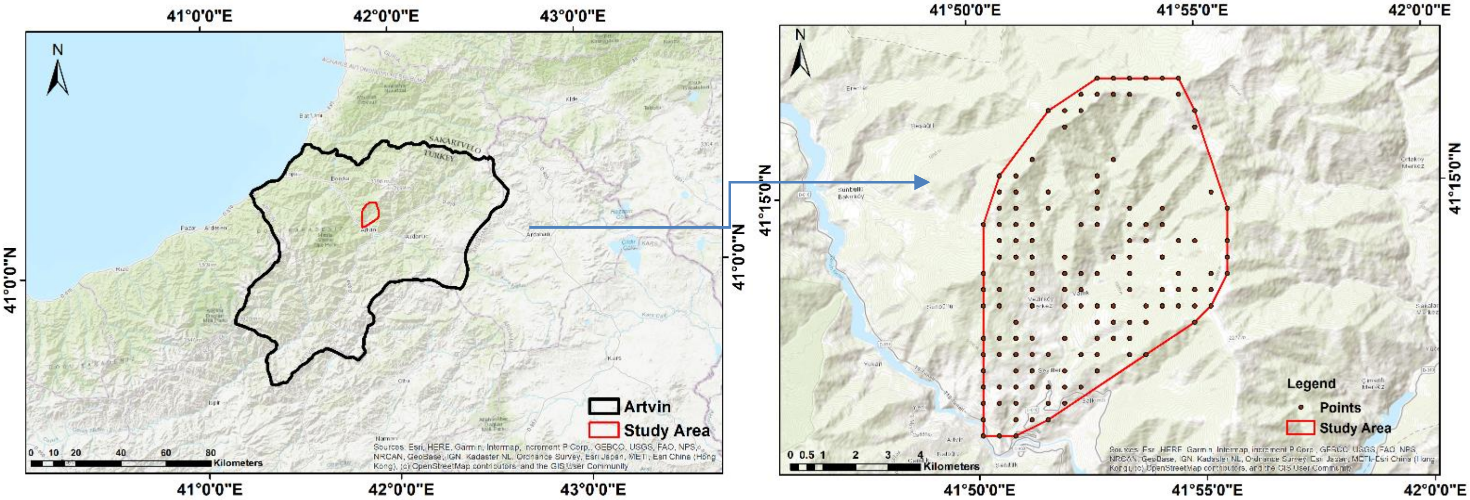


Figure 1.
The geographic position of the study area is named Godrahav watershed in Artvin province, Turkiye. According to the Universal Transverse Mercator system (UTM), the coordinates of the midpoint of the watershed are 37 T, 742040E, 4569701N. B. The sampling points were created with 500x500 m transects to take soil sample

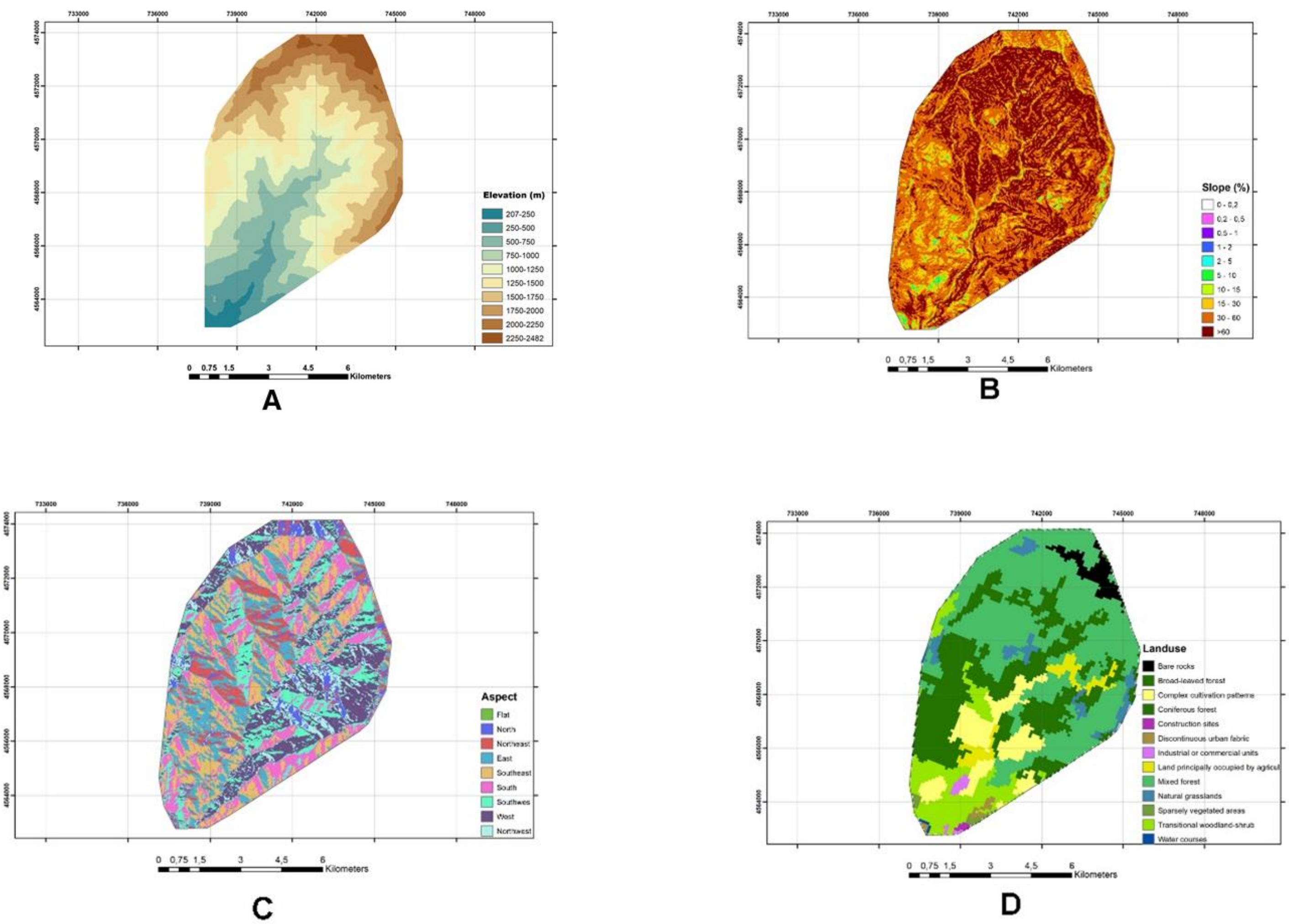


Figure 2.
The landforms and land use of Godrahav watershed. A. Digital elevation model; B. Slope map; C. Aspect map; D. Land use map.

The elevation of the study area varies between 207 m-2482 m (Figure 2A), has a very steep slope (Figure 2B) and mainly the east aspect (Figure 2C). The main land uses are forest, grassland, and agricultural field (Figure 2D).

Soil texture was determined by the Bouyoucos hydrometer method (Gee & Bauder, 1986). Water-stable aggregates were determined using the wet sieving method (Kemper & Rosenau, 1986), and the aggregation rate was calculated accordingly (Turgut & Ateş, 2017). The mean weight diameter and the dispersion rate were also calculated based on standard procedures. Bulk density was determined by the cylinder method (Blake and Hartge, 1986), and total porosity was calculated accordingly (Danielson & Sutherland, 1986). The field capacity and wilting point were determined by applying pressures of 33 kPa and 1500 kPa to the initially saturated samples (Cassel & Nielsen, 1986). Organic matter content was determined by the Smith-Weldon method (Nelson and Sommers, 1983), and pH was measured using a pH meter in a 1:2.5 soil-water suspension (Mclean, 1983). Electrical conductivity was measured by an EC meter (Rhoades, 1983). XLSTAT software was used to calculate descriptive statistics.

The data set was submitted to descriptive statistics (mean, standard deviation, coefficient of variation, maximum and minimum values). The coefficient of variation (CV) of each data set was classified as low variability (CV ≤ 15%), moderate variability (15% < CV ≤ 35%), and high variability (CV > 35 %) (Wilding & Drees, 1983). Geostatistical methods were used to assess the spatial variability of the Soil Degradation Index (SDI) and the soil properties used in its calculation. For visualization purposes, ordinary kriging with an exponential semivariogram model was applied to estimate values across the study area, and the resulting prediction maps were generated using the Kernel Smoothing method. All spatial analyses were conducted using the ArcGIS Geostatistical Analyst extension.

Calculation

Weighting, scoring, and calculation stages were followed to determine the soil degradation index and create the distribution map.

i. Weighting the indicators: In this step, the correlation coefficients between the indicators were determined by Pearson correlation analysis, then the calculation matrix was created by taking the absolute values of the correlation coefficients (Table 1), the correlation coefficients with the indicators themselves were not included in this matrix, and finally, the weighting coefficients were calculated using equation 1.
ii. Scoring the indicators: Indicators were scored with linear functions, such as “more is better”, “optimum range”, and “less is better” (Table 2).
iii. Calculating degradation index: After the variables were scored between 0 and 1, final scores (SDI) were computed using weighting and function scores (Eq. 2). (Güler, 2020)

Table 1.
The matrix model was created by using the absolute values of the correlation coefficients obtained from the Pearson correlation analysis at the stage of weighting the indicators.

	A	B	C	D	N	
A		$\lvert k_{AB}\rvert$	$\lvert k_{AC}\rvert$	$\lvert k_{AD}\rvert$	$\lvert k_{An}\rvert$	
B	$\lvert k_{BA}\rvert$		$\lvert k_{BC}\rvert$	$\lvert k_{BD}\rvert$	$\lvert k_{Bn}\rvert$	
C	$\lvert k_{CA}\rvert$	$\lvert k_{CB}\rvert$		$\lvert k_{CD}\rvert$	$\lvert k_{Cn}\rvert$	
D	$\lvert k_{DA}\rvert$	$\lvert k_{DB}\rvert$	$\lvert k_{DC}\rvert$		$\lvert k_{Dn}\rvert$	
n	$\lvert k_{nA}\rvert$	$\lvert k_{nB}\rvert$	$\lvert k_{nC}\rvert$	$\lvert k_{nD}\rvert$		
Total	$\sum_{i=A}^{n}\lvert k\rvert$	$\sum_{i=B}^{n}\lvert k\rvert$	$\sum_{i=C}^{n}\lvert k\rvert$	$\sum_{i=D}^{n}\lvert k\rvert$	$\sum_{i=n}^{n}\lvert k\rvert$	$\sum\sum\lvert k\rvert$

$$A_A = \frac{\sum_{i=A}^{n}|k|}{\sum\sum|k|} \quad (1)$$

$$SDI = \sum_{i}^{n} w_i \times s_i \quad (2)$$

A_A, the weight of indicator A; |k|, the absolute value of the correlation coefficient between properties.

Where SDI is soil degradation index; w_i is the weighting and s_i is the score of the ith parameter.
The values of the parameters, weight coefficients, and score values used to determine the SDI are given in the supplementary file.
To explain the relationship between SDI and land properties, “zonal statistics as table” ArcTOOL was used.

Table 2.
Functions and function parameters used in the scoring of indicators.

Indicators	Function	x_1	r_1	r_2	x_2	Equation
Electrical conductivity	More is better	0.00			0.69	$f(x) = \frac{(x - x_1)}{(x_2 - x_1)}$
Bulk density		0.19			1.47	
Dispersion rate		13.48			92.71	
Clay content	Optimum range	3.79	30	35	59.56	$f(x) = 1 - \frac{(x - x_1)}{(r_1 - x_1)}; x_1 < x < r_1$
Silt content		0.78	30	35	44.02	$f(x) = 0; r_1 < x < r_2$
Sand content		9.12	30	35	82.59	$f(x) = \frac{(x - r_2)}{(x_2 - r_2)}; r_2 < x < x_2$
pH		3.71	6.8	7.2	7.66	
Aggregate stability	Less is better	57.59			98.91	$f(x) = 1 - \frac{(x - x_1)}{(x_2 - x_1)}$
Aggregation rate		18.75			96.75	
Mean weight diameter		0.28			1.16	
Porosity		24.69			87.38	
Field capacity		15.26			91.62	
Wilting point		8.48			75.97	
Organic matter content		0.15			5.90	

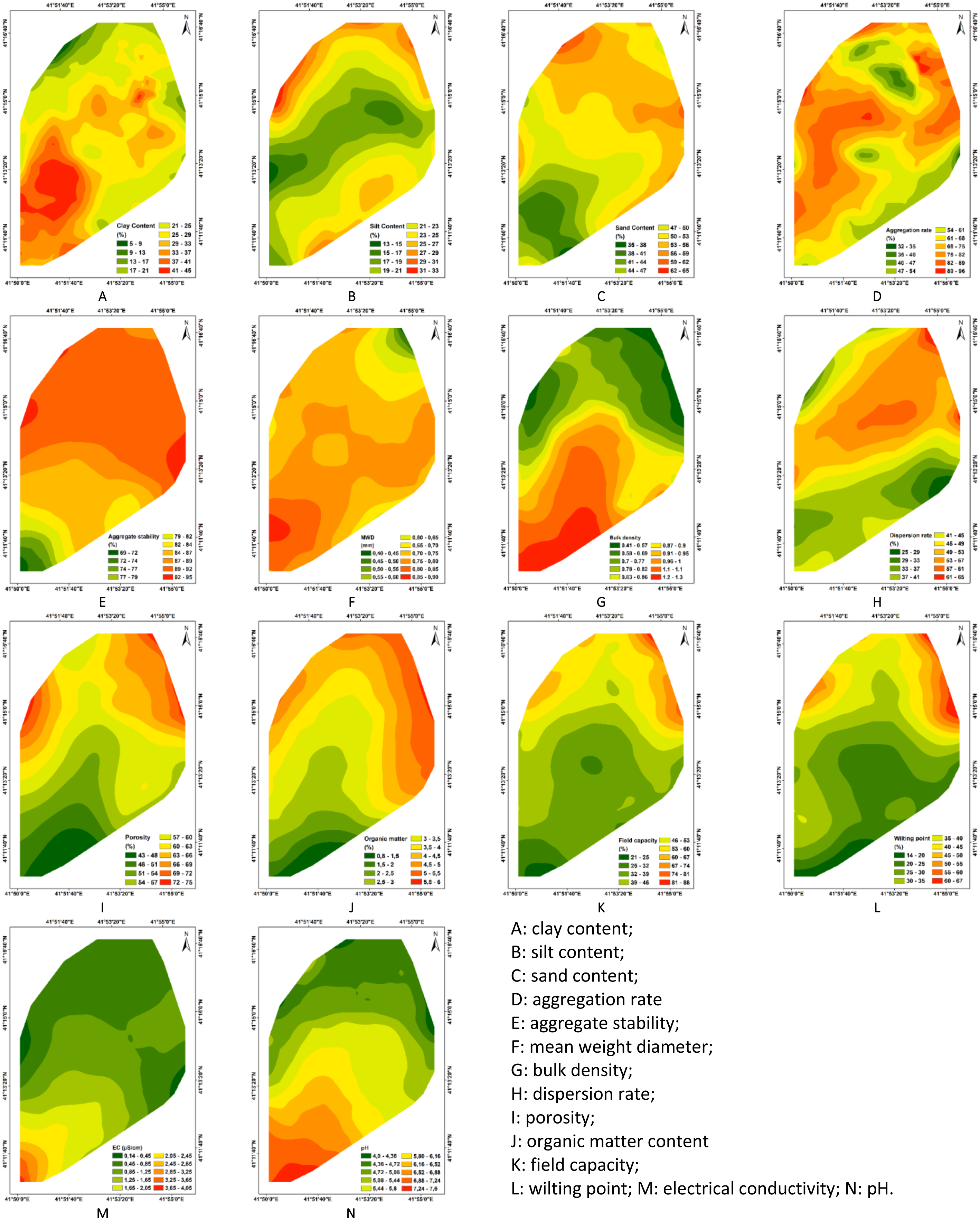
Results and Discussion

The descriptive statistics showed that the range of data was from 3.79 to 59.56% for clay content, from 0.78 to 44.02 % for silt content, from 9.12 to 82.59% for sand content, from 18.75 to 96.75% for aggregation rate (AR), from 57.59 to 98.91% for aggregate stability (AS), from 0.28 to 1.16 (mm) for mean weight diameter (MWD), from 0.19 to 1.47 (g/cm^3) for bulk density (BD), from 13.48 to 92.71% for dispersion rate (DR), from 24.69 to 87.38% for total porosity (f), from 15.26 to 91.62% for field capacity (FC), from 8.48 to 75.97 % for wilting point (WP), from 0.15 to 5.90 % for organic matter content (OM), from 0.0 to 6.89 (μS/cm^1) for electrical conductivity (EC), and from 3.71 to 7.66 for pH. Sand content and AS showed low variability; MWD, BD, f, and pH indicated moderate variability; clay, silt, DR, FC, WP, OM, and EC had high variability (Table 3).

Table 3.
Descriptive statistics of soil properties (n=137) used as indicators for determining soil degradation index.

Properties	Min	Max	Mean	Standard deviation	Coefficient of variation
Clay (%)	3.79	59.56	29.24	10.76	36.80
Silt (%)	0.78	44.02	22.02	10.41	47.28
Sand (%)	9.12	82.59	48.74	13.82	28.35
AR (%)	18.75	96.75	69.81	18.78	26.90
AS (%)	57.59	98.91	86.97	8.15	9.37
MWD (mm)	0.28	1.16	0.76	0.14	18.42
BD (g cm^{-3})	0.19	1.47	0.91	0.29	31.87
DR (%)	13.48	92.71	44.15	18.01	40.79
f (%)	24.69	87.38	57.10	11.96	20.95
FC (%)	15.26	91.62	41.47	15,31	36.92
WP (%)	8.48	75.97	30.32	12.66	41.75
OM (%)	0.15	5.90	3.41	1.60	46.92
EC (μS/cm^1)	0.00	6.89	1.28	1.22	95.90
pH	3.71	7.66	5.77	1.01	17.50

The variation of soil properties depending on the physiographic characteristics of the basin and the differences in land use is seen in the distribution maps (Figure 3). Clay content, electrical conductivity and pH were low in the upper zones of the basin and high in the accumulation zones due to runoff. On the other hand, organic matter was high in forest areas and low in agricultural areas and settlements. Other soil properties, such as aggregate stability, porosity, bulk density, varied across the basin depending on the associated properties.



A: clay content;
B: silt content;
C: sand content;
D: aggregation rate
E: aggregate stability;
F: mean weight diameter;
G: bulk density;
H: dispersion rate;
I: porosity;
J: organic matter content
K: field capacity;
L: wilting point; M: electrical conductivity; N: pH.

Figure 3.
Distribution maps of soil properties used as indicators in the Godrahav watershed.

The soil properties and Soil Degradation Index (SDI) values obtained in this study are consistent with findings from similar research conducted in the Black Sea Region of Türkiye. For instance, in the Deviskel Stream Watershed located in Borçka, Artvin, a study investigating the effects of different land use types on soil properties found that agricultural lands had an average organic matter content of 6.20%, a pH of 7.22, and an electrical conductivity of 448.99 µS/cm. These values were considerably higher compared to forest and pasture areas, indicating the significant impact of agricultural practices on soil characteristics (Erdoğan & Yavuz, 2021).

Similarly, a study conducted around Kaz Lake in Tokat Province reported significant changes in soil properties following drainage activities. Notably, the clay content ranged between 25.40% and 62.90%, with an average of 50.65%. The authors emphasized that such high clay content may negatively affect water infiltration and plant growth (Acir et al., 2021).

In addition, a study carried out in the Alaca Watershed revealed that the spatial distribution of soil organic carbon (SOC) stocks was influenced by both land use and topographic features. Higher SOC stocks were reported in forested areas, while lower values were observed in agricultural lands, confirming the role of land cover in shaping soil carbon dynamics (Yılmaz, 2021).

These findings corroborate the current study's results, suggesting that land use and physiographic factors such as elevation and slope play a crucial role in shaping soil quality and degradation patterns in the Black Sea Region

Weights of indicators

The weights determined using the absolute values of the binary correlation coefficient are given below (Table 4). pH had the highest weight coefficient, followed by Pb, f, OM, FC, clay, sand, WP, EC, MWD, DR, AS, AR, and silt, respectively. Since the weight coefficient was determined by dividing the absolute value of the correlation coefficient of each property by the total correlation absolute value, the weighting values were in the same order (Table 5).

Table 4.
Absolute values of correlation coefficients were obtained from Pearson correlation analysis performed among soil properties.

Indicator	Clay	Silt	Sand	AR	AS	MWD	P_b	DR	F	FC	WP	OM	EC	pH
Clay		0.13	0.63	0.38	0.31	0.35	0.29	0.28	0.27	0.12	0.04	0.29	0.36	0.53
Silt	0.13		0.62	0.07	0.05	0.03	0.13	0.36	0.1	0.17	0.1	0.1	0.1	0.11
Sand	0.63	0.62		0.32	0.25	0.27	0.13	0.51	0.16	0.01	0.1	0.17	0.18	0.32
AR	0.38	0.07	0.32		0.02	0.27	0.23	0.05	0.22	0.37	0.51	0.13	0.06	0,02
AS	0.31	0.05	0.25	0.02		0.22	0.31	0.04	0.1	0.19	0.03	0.27	0.44	0.45
MWD	0.35	0.03	0.27	0.27	0.22		0.26	0.48	0.28	0.04	0.04	0.1	0.29	0.38
BD	0.29	0.13	0.13	0.23	0.31	0.26		0.11	0.83	0.65	0.57	0.65	0.33	0.69
DR	0.28	0.36	0.51	0.05	0.04	0.48	0.11		0.22	0.02	0.03	0.13	0.23	0.25
f	0.27	0.1	0.16	0.22	0.1	0.28	0.83	0.22		0.48	0.43	0.5	0.21	0.54
FC	0.12	0.17	0.01	0.37	0.19	0.04	0.65	0.02	0.48		0.81	0.62	0.2	0.52
WP	0.04	0.1	0.1	0.51	0.03	0.04	0.57	0.03	0.43	0.81		0.6	0.01	0.37
OM	0.29	0.1	0.17	0.13	0.27	0.1	0.65	0.13	0.5	0.62	0.6		0.16	0.57
EC	0.36	0.1	0.18	0.06	0.44	0.29	0.33	0.23	0.21	0.2	0.01	0.16		0.52
pH	0.53	0.11	0.32	0.02	0.45	0.38	0.69	0.25	0.54	0.52	0.37	0.57	0.52	
$\sum$	3.98	2.07	3.67	2.65	2.68	3.01	5.18	2.71	4.34	4.20	3.64	4.29	3.09	5.27

$$\sum = \mathbf{50.78}$$

AR: aggregation rate; AS: aggregate stability; MWD: mean weight diameter; BD: bulk density; DR: dispersion rate; f: porosity; FC: field capacity; WP: wilting point; OM: organic matter content; EC: electrical conductivity.

Table 5.
Total correlation coefficients of indicators calculated with absolute values of correlation coefficients, and weights of indicators.

Indicator	Σ correlation coefficient	Weight of indicator	Indicator	Σ correlation coefficient	Weight of indicator
Clay	3.98	0.078	DR	2.71	0.053
Silt	2.07	0.041	f	4.34	0.085
Sand	3.67	0.072	FC	4.20	0.083
AR	2.65	0.052	WP	3.64	0.072
AS	2.68	0.053	OM	4.29	0.084
MWD	3.01	0.059	EC	3.09	0.061
BD	5.18	0.102	pH	5.27	0.104

AR: aggregation rate; AS: aggregate stability; MWD: mean weight diameter; BD: bulk density; DR: dispersion rate; f: porosity; FC: field capacity; WP: wilting point; OM: organic matter content; EC: electrical conductivity.

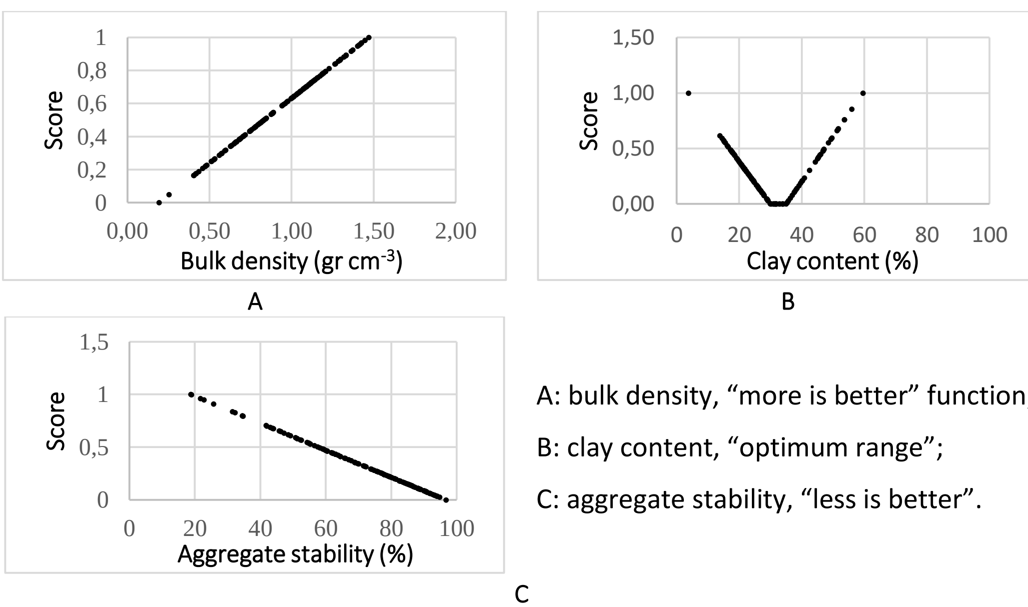
Scores of indicators

The scores were calculated for each indicator using the functions specified in methods. Here are examples of functions (more is better, optimum range, and less is better) used (Figure 4).

Soil Degradation Index

The SDI varied between 0.297 and 0.620 in the basin. According to the values obtained by the ratio of SDI classes to the whole area, SDI values in the range of 0.422–0.455 were seen to be the most common class, followed by 0.389–0.422, 0.455–0.488, 0.356–0.389, and 0.323–0.356, respectively (Figure 5). It can be said that a significant portion of the basin land (95%) is below 0.5 on the 0–1 scale (Figure 6). This indicates that while soil degradation is present, it has not yet reached critical levels in most parts of the basin.

Similar SDI distributions were reported by Yılmaz and Korkanç (2021) in the Devrekani Basin (Kastamonu), where over 85% of the land had SDI values below 0.6. Their study also found that agricultural practices and topographic position were the major drivers of spatial variability in degradation. Likewise, in the Arhavi watershed (Artvin), Gürsoy and Şahin (2020) identified low to moderate SDI values predominantly in forest and pasture lands, but observed significant increases in SDI in settlement and agriculture-dominated zones. These studies emphasize that although natural landscapes maintain relatively better soil quality, human-induced activities such as tillage and deforestation markedly elevate SDI levels.



A: bulk density, “more is better” function;

B: clay content, “optimum range”;

C: aggregate stability, “less is better”.

Figure 4.
Graphs show the relationship between the measurement values of the indicators and the score values calculated with linear functions.

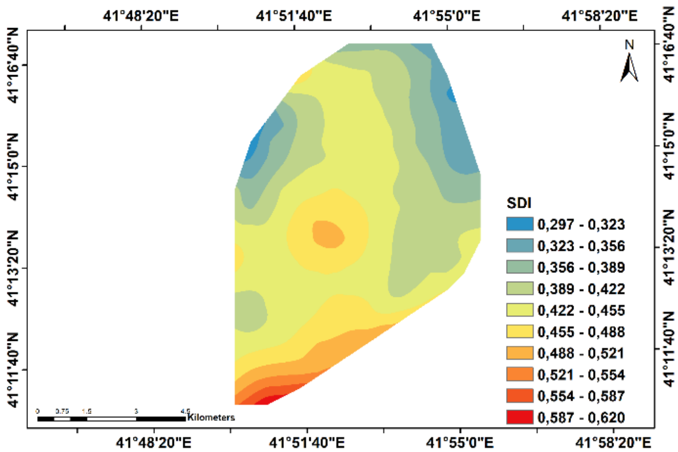


Figure 5.
Spatial distribution map of soil degradation index in Godrahav watershed.

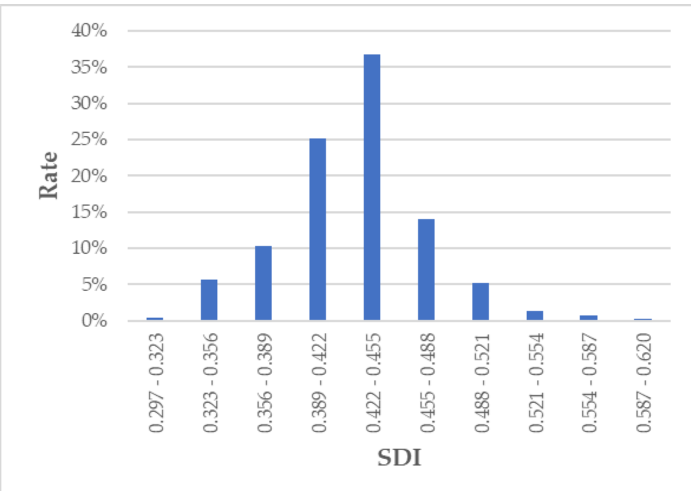


Figure 6.
Proportions of Soil degradation index (SDI) classes in Godrahav watershed

The consistency of SDI values with findings from different parts of the Black Sea region confirms that basin-specific factors such as slope, vegetation cover, and land management practices play crucial roles in soil degradation processes (Aydın & Kara, 2019; Yıldız et al., 2017).

To understand the reasons for the change of the SDI in the study area, it was associated with the watershed characteristics, such as land use differences, topographic factors, and cover rate.

The effect of land use on SDI

The first watershed characteristic that affects the SDI is the differences in land use. The area with the highest SDI is the settlement (0.54) followed by the waterside (0.53) used for recreational activities. These areas are followed by agriculture (0.46), forest (0.43) and meadow (0.39), respectively (Figure 7). Human settlement activities are often associated with land degradation through the depletion of essential soil nutrients (e.g., nitrogen, phosphorus) and the accumulation of pollutants such as heavy metals and other chemical residues (Asare et al., 2021; Fenger-Nielsen et al., 2019; Šmejda et al., 2018). Management practices such as soil tillage and field traffic in the agricultural areas lead to negative changes in soil properties (Poesen, 2018; Tian et al., 2023; Wang et al., 2023) and an increase in SDI.

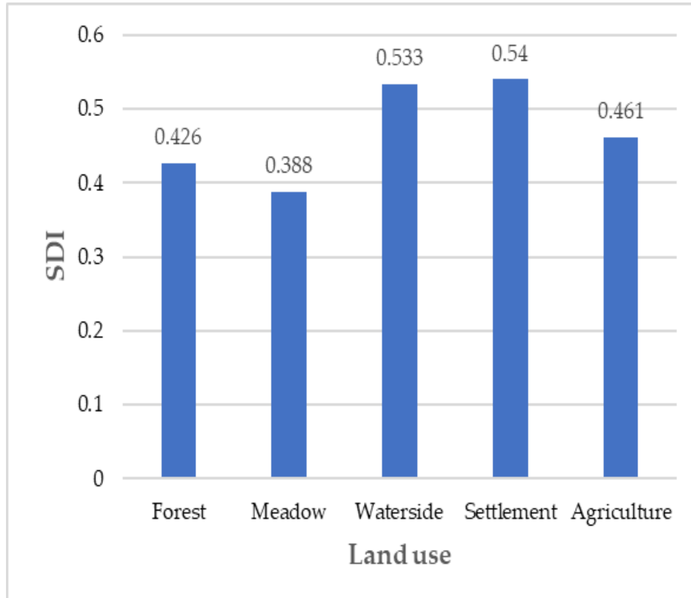


Figure 7.
Variation of the soil degradation index (SDI) in the study area according to land use.

Factors causing soil degradation in the forest are reduction in plant cover, decrease in soil fertility, weak soil structure, erosion, recurrent forest fire, and reduction of beneficial microorganisms (Bax & Francesconi, 2018; Guo et al., 2019; Navarro Rau et al., 2023; Roth et al., 2023; Sabogal, 2012). The low human activities in the forest of the study area have prevented these factors. For this reason, it is expected that the SDI will be low in this area. The same situation has been observed in meadow areas, the low grazing pressure has prevented the negative changes in the soil properties, and accordingly, the SDI is also placed in the low class.

According to this result, land use practices can significantly impact soil degradation, leading to changes in soil degradation indices (Buraka et al., 2023; Leul et al., 2023; Zahedifar, 2023). Like our results, the researchers report that the soil degradation problem was less common in forest and meadow areas than agricultural fields (Kidron et al., 2010; Leul et al., 2023; Moebius-Clune et al., 2011; Yousefi et al., 2016; Zhang et al., 2019).

The effect of altitude on SDI

Altitude constitutes another watershed characteristic that exerts an influence on the Soil Degradation Index (SDI). As altitude increases across the watershed (Figure 8), a concomitant reduction is observed in the SDI values. The regions characterized by lower altitudes within the watershed exhibit a heightened susceptibility to human activities such as settlements and recreation due to their enhanced accessibility. Consequently, these areas are marked by the presence of settlements and extensive agricultural fields. Conversely, the areas dominated by forest and meadows situated at higher altitudes remain relatively less accessible, playing a pivotal role in the preservation of their innate natural attributes. Within these elevated natural zones, distinguished by their high altitudes, the soil demonstrates a noteworthy organic matter content as well as significant total nitrogen levels, finer soil texture, and a more stable aggregate structure (Mujiyo et al., 2022; Zhu et al., 2020). Consequently, soil degradation in these elevated natural areas is notably limited Our results are consistent with previous studies that reported a gradual increase in soil degradation from higher to lower altitudes (Wang et al., 2020).

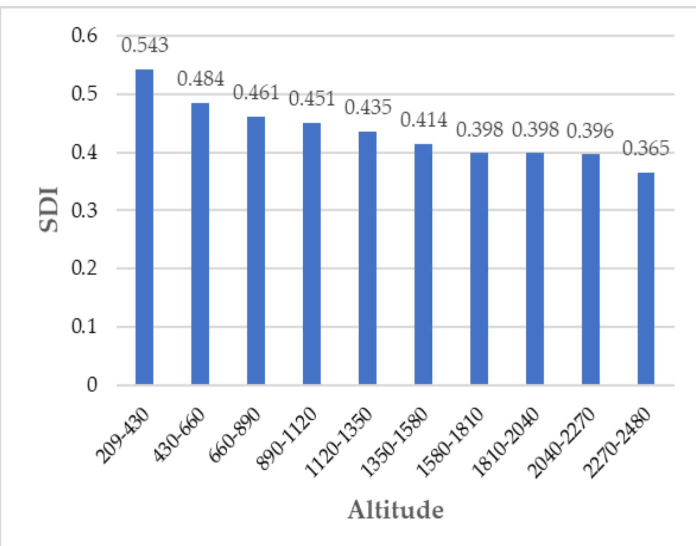


Figure 8.
Variation of the soil degradation index (SDI) in the study area according to altitude.

The effect of slope on SDI

The SDI values exhibited variations based on the gradient of slopes within the research area. The alteration in SDI with respect to distinct slope categories is illustrated in Figure 9. Corresponding to an escalating incline across the watershed, a progressive decrease in SDI is observed. The 0-18 slope class yielded the highest SDI value (0.439), whereas the >100 slope class displayed the lowest value (0.422) (Figure 9). This disparity can be attributed to the infrequent occurrence of human activities in rugged terrains. Consequently, these steep terrains are predominantly covered by forests, thereby affording protection against soil erosion (Šamonil et al., 2023; Wiśniewski & Märker, 2019) and losing organic matter content (Pan et al., 2023). Erosion, a well-acknowledged agent of environmental degradation (Wiśniewski & Märker, 2019), is mitigated through this natural safeguard.

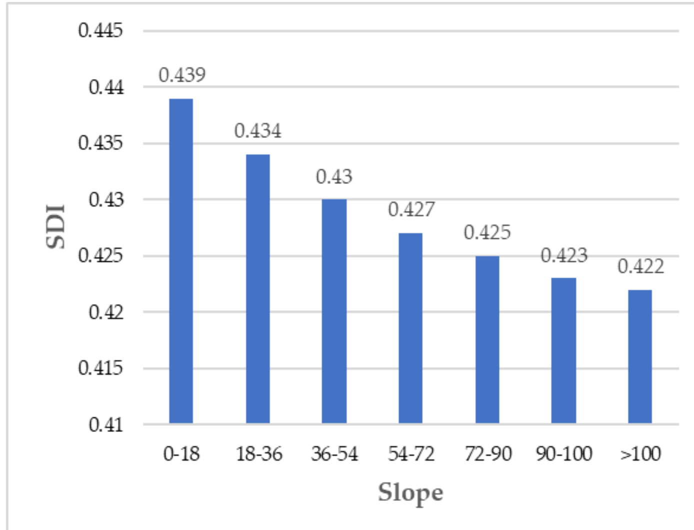


Figure 9.
Variation of the soil degradation index (SDI) in the study area according to the slope.

The effect of aspect on SDI

SDI showed variability across different aspects within the watershed. The most elevated SDI values were observed in east-facing regions, contrasting with the lowest values recorded in northeast-facing areas. Stated differently, throughout the watershed, shaded zones exhibited lower SDI values compared to sun-exposed areas (Figure 10). This phenomenon can be attributed to the augmented vegetation density on the northern and western facets of the land, resulting from diminished evaporation rates (Griffiths et al., 2009; Han et al., 2022). Greater vegetation density is associated with increased levels of organic matter and clay content, primarily attributed to reduce erosion rates (Tian et al., 2023). Consequently, it is normal for regions displaying lower Soil Degradation Index (SDI) values in the northern and western peripheries of the study area to exhibit broader spatial coverage. Although it varies depending on the climate and land use, this is a common phenomenon, as supported by our findings, and aligns with previous research (Lenka et al., 2013), which also reported diminished degradation parameters in north-facing areas.

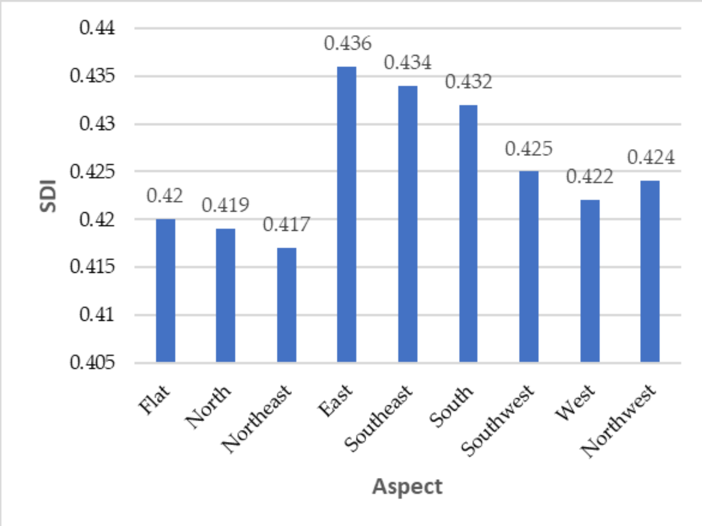


Figure 10.
Variation of the soil degradation index (SDI) in the study area according to the aspect.

Conclusion

While this study provides a comprehensive framework for assessing soil degradation through the Soil Degradation Index (SDI), it lacks a clear articulation of practical recommendations for decision makers. Identifying degraded zones is valuable, yet the study could be strengthened by translating these findings into actionable land management strategies. For instance, in areas with high SDI values, specific restoration techniques such as organic matter amendment, conservation tillage, or afforestation could be suggested. Moreover, land use planning decisions could benefit from prioritizing conservation in highly degraded areas and limiting intensive agriculture or construction in zones with vulnerable soils.

Additionally, the study does not fully address the limitations of the SDI approach. One key limitation is the potential subjectivity in assigning weights to soil parameters, even when supported by correlation analysis. The empirical scoring functions, though useful, may not fully capture the complexity and interactions of soil processes across diverse landscapes. To improve robustness, future studies could incorporate machine learning algorithms or multi-criteria decision analysis (MCDA) to refine parameter weighting and scoring. Another limitation is the temporal static nature of the data; soil degradation is a dynamic process, and repeated sampling or remote sensing integration over time would allow for monitoring trends and evaluating the effectiveness of management interventions.In conclusion, while the SDI provides a valuable snapshot of soil health, future research should enhance its predictive and prescriptive power by integrating socio-economic factors, land management histories, and time-series data. This would help guide sustainable land use policies and adaptive management practices more effectively.

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