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BÜLENT TURGUT

SÜMEYYE GÜLER

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# Assessment of soil quality index for different NDVI ranges in a watershed

**Bülent TURGUT**[1,*], **Sümeyye GÜLER**[2]

[1]Department of Soil and Ecology, Faculty of Forestry, Karadeniz Technical University, Trabzon, Turkiye
[2]Department of Silviculture, Faculty of Forestry, Kastamonu University, Kastamonu, Turkiye

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**Abstract:** The aim of this study is to determine the effect of vegetation density on the soil quality index (SQI) in the Godrahav basin, which varies in terms of land use and topographic features. For this purpose, a total of 180 soil samples were taken at depths of 0–20 cm (surface soil) from six ranges of the normalized difference vegetation index (NDVI) in a typical watershed in Artvin (northeast Türkiye). The SQI was used to evaluate and calculate soil quality in the study area. Topographic features (elevation, slope, and aspect), land use, physical properties of the soil (clay content, silt content, sand content, mean weight diameter, aggregation rate, aggregate stability, porosity, bulk density, dispersion rate, field capacity, and wilting point), and chemical properties of the soil (organic matter content, pH, and EC) were used as indicators. The results showed that aggregate stability, aggregation rate, porosity, field capacity, and wilting point water content were highest in the NDVI range of 0.45–0.56 with values of 89.83%, 76.76%, 60.56%, 47.89%, and 33.98%, respectively. Meanwhile, bulk density was lowest in the same NDVI range at 0.81 g $cm^{-3}$. The differences among NDVI ranges in terms of soil properties were statistically significant. SQI values varied significantly ($p < 0.01$) depending on NDVI classes with an increasing trend from the lowest NDVI range to the highest. These results provide a better explanation of the effect of vegetation density on soil quality.

**Key words:** Topographic features, land use, indicator, soil quality

## 1. Introduction

Soil is one of the components of the terrestrial ecosystem and its quality affects ecosystem services. Unmitigated human activities, such as forest degradation (Sanji et al., 2020; Taghipour et al., 2022), intensive tillage on farmlands (Raiesi and Kabiri, 2016; Çelik et al., 2021), and overgrazing on pastures (Amorim et al., 2020) have destroyed the soil's physical and chemical properties and relationships between soil and plants, causing ecological and environmental problems. Maintaining soil quality is key to ensuring environmental stability and the overall maintenance of the biosphere (Zhao et al., 2021).

Soil quality is defined by the Soil Science Society of America as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (as cited by Allan et al., 1995; Karlen et al., 1997). Soil quality can be assessed for both agroecosystems and natural ecosystems. The soil quality index (SQI) is a measure that allows for quantitative and accurate assessment of soil quality. In previous studies, SQI values have been calculated using either the properties of the topsoil (0–25 cm) (Bandyopadhyay and Maiti, 2021; Levi et al., 2021; Mazzon et al., 2021; Marion et al., 2022) or the properties of the soil profile (0–100 cm) (Özşahin et al., 2017; Huang et al., 2021; Gozukara et al., 2022).

There is no method for directly measuring the SQI. Rather, it is indirectly indicated in evaluations of the physical, chemical, and biological properties of soil (Mazzon et al., 2021; Gozukara et al., 2022; Marion et al., 2022). Numerous studies of soil quality evaluation have focused on soil properties but have not described the roles of topographic features and land use, although topographic factors (Maleki et al., 2021) and land use (Alidoust et al., 2018) have control over soil properties on different scales. The estimation of the SQI includes three main steps: the collection of the dataset and description of indicators, the weighting of indicators, and the scoring of subindicators (Liu et al., 2014; Guo et al., 2017; Çomakli and Turgut, 2021; Turgut et al., 2021). While principal component analysis and expert opinion methods are applied to weigh the indicators used in the determination of the SQI (Ciarkowska and Gambus, 2020; Marion et al., 2022), linear or nonlinear methods are used for scoring the indicators (Bandyopadhyay and Maiti, 2021; Mazzon et al., 2021).

* Correspondence: bulentturgut@ktu.edu.tr



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The normalized difference vegetation index (NDVI) is a measure of surface reflectance, and it is used as an indicator of vegetation growth as it is correlated with green leaf biomass and vigor (Tucker et al., 1984). A higher NDVI value signifies healthy and dense vegetation, while lower NDVI values reflect sparse vegetation (Drisya et al., 2018; Gessesse and Melesse, 2019; Khaple et al., 2021). Vegetation alters soil properties as it is a factor in soil formation. There are many studies on the effects of vegetation types on soil properties, and their results have shown that vegetation density improves the soil's physical, chemical, and biological properties (Lu et al., 2014; Li et al., 2021; Sharma et al., 2022). Karaca et al. (2021) determined the SQI values of pasture soils in a semiarid ecosystem with a multiindicator weighting method and they found that there was a significant positive relationship between vegetation density and the SQI. Although there are studies examining the correlations between NDVI values, as an indicator of vegetation density, and soil properties (Banday et al., 2019; Dedeoğlu et al., 2019; Lizaga et al., 2019; Galle et al., 2021), there is a lack of studies determining the relationships between the NDVI and SQI.

Watersheds represent a natural way of dividing the landscape for management and planning purposes, and mountains, valleys, plains, and streams are components of watershed ecosystems (Randhir, 2006). In addition, different land uses such as forest areas, pastures, residential areas, and agricultural areas are seen within the borders of watershed basins. Due to these features, watersheds are unique in terms of the ecosystem services they provide. Thus, determining soil quality allows the monitoring of the sustainability of the ecosystem services of a watershed. The Godrahav basin, chosen as the present study area, has differences in terms of topographic features and land uses. Thus, the Godrahav basin is a suitable area for examining the effects of topographic features and land uses on soil properties. The aims of this study were to determine the soil properties of the watershed, to create distribution maps of those properties, to determine SQI values, to create distribution maps of the SQI, and to determine the relationships between NDVI and SQI values. The difference between this study and previous studies is that, in addition to soil properties, topographic features and land uses are also used here as parameters in determining the quality index values.

## 2. Materials and methods

### 2.1. Study area

This study was conducted in the Godrahav watershed in Artvin Province, Türkiye (Figure 1). According to the international classification system, the Godrahav watershed is in the "large" class with an area of approximately 6750 ha (Kanar, 2014). The direction of the watershed is north to south and it is bordered by Karçal Mountain and the Çoruh River. According to the Turkish State Meteorological Service, the climatic class is semihumid due to total precipitation of 1000 mm and mean temperature of 12 °C.

An elevation distribution map (Figure 2a) was created with 250-m intervals and it showed that the elevation range of 1250–1500 m encompassed 19% of the watershed, while the rates decreased gradually in the ranges above and below that elevation (Figure 2b). As shown in Figure 3a, areas with steep slopes and extremely steep slopes cover 85% of the study area due to the mountainous topography (Figure 3b). Flat and gently sloping areas are located at the bottom of the watershed. As stated above, the watershed is in the north–south direction (Figure 4a); thus, 67% of the watershed faces southeast, west, south, or southwest (Figure 4b). The watershed consists primarily of forest fragments, farmlands, and pastures (Figure 5a). The forest fragments cover 80% of the study area (Figure 5b).

The elevation in the study area ranges between 207 and 2482 m. The common slope groups are steep and extremely steep with mainly east aspect. The main land uses are forest, pasture, and agricultural fields.

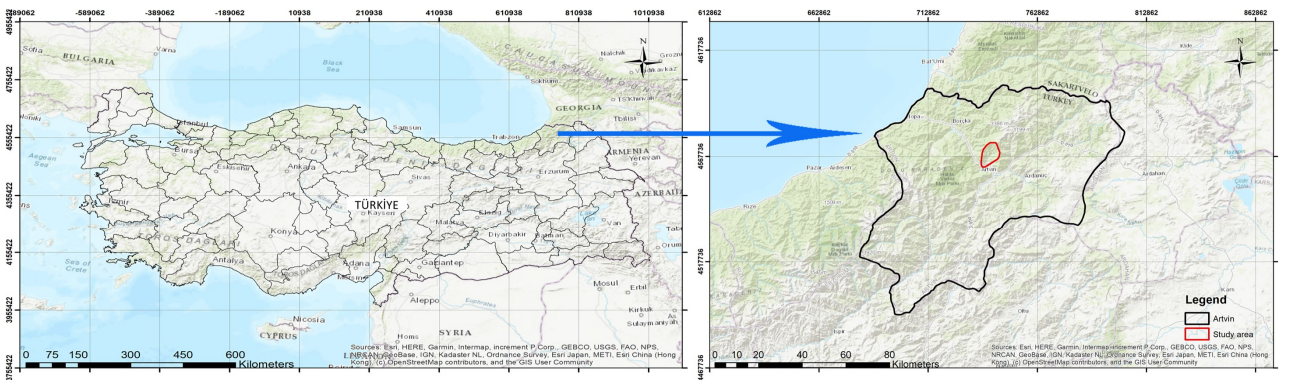



**Figure 1.** Location map of the study area.

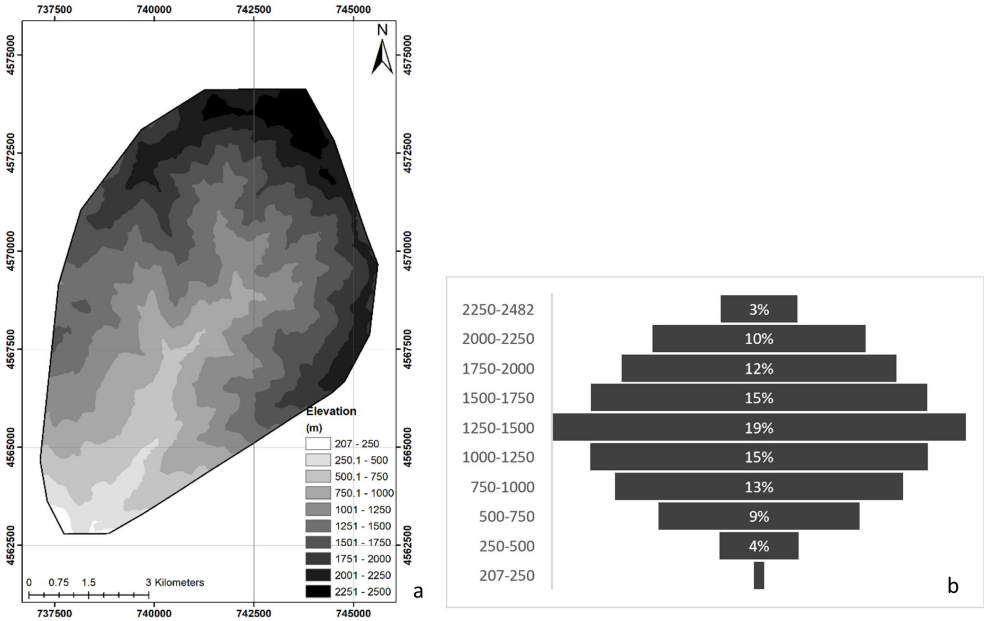



**Figure 2.** (a) Elevation classes and (b) their areal distributions.

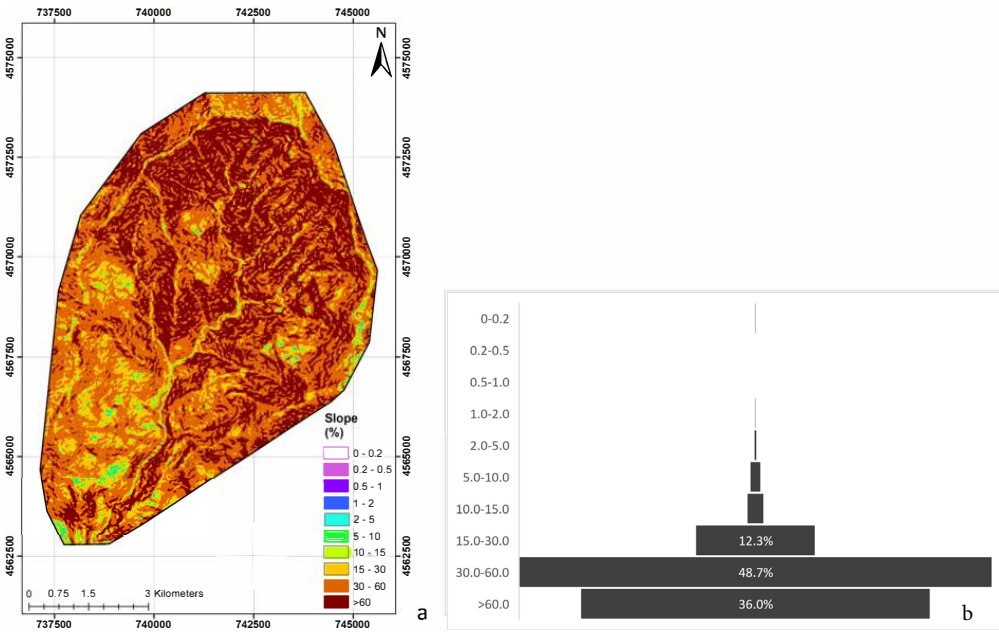



**Figure 3.** (a) Slope classes and (b) their areal distribution.

## 2.2. Method

### 2.2.1. Dataset

The dataset used to determine SQI values included soil properties, topographic features (elevation, slope, and aspect), and land use. The indicators and subindicators, as well as their calculation methods, are given below.

### 2.2.2. Soil properties

The soil properties used as indicators to calculate SQI values were determined based on a literature review (Table 1). According to a previous study, particle size distribution, mean weight diameter, aggregation rate, aggregate stability, porosity, bulk density, dispersion rate,

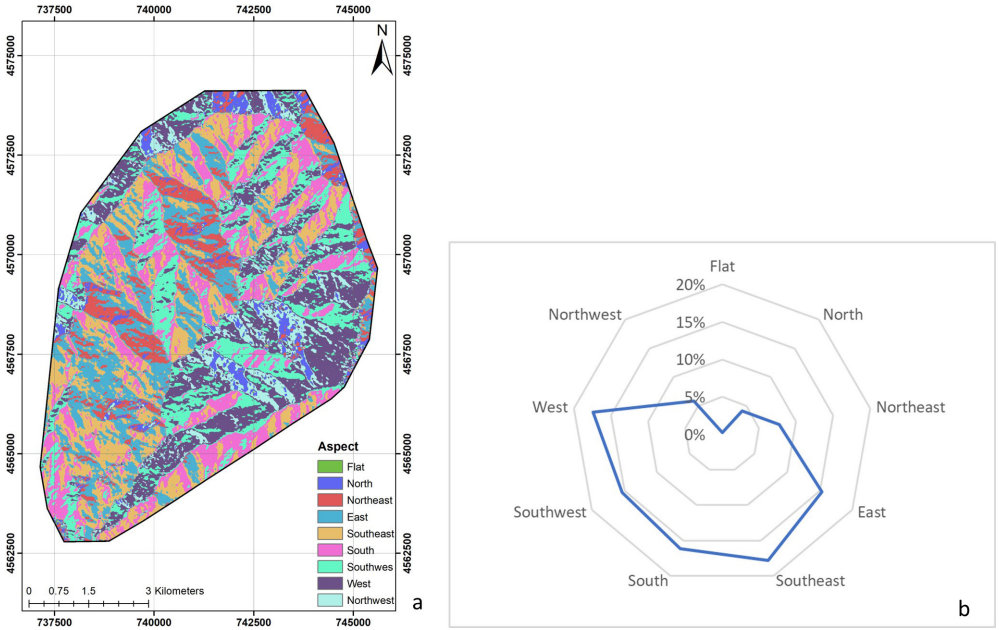



**Figure 4.** (a) Aspect classes and (b) their areal distribution.

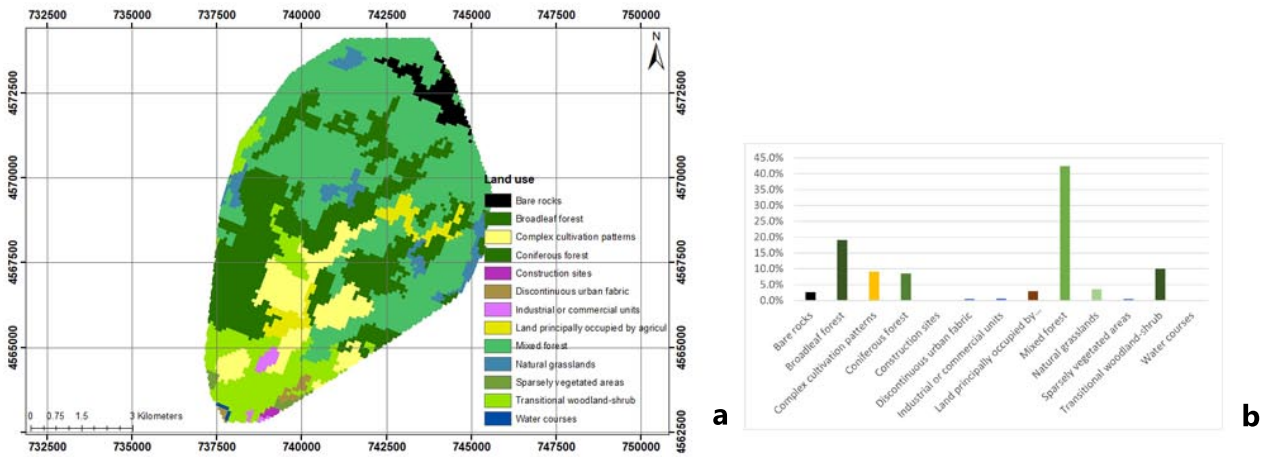



**Figure 5.** (a) Land uses and (b) their areal distribution.

field capacity, wilting point, organic matter content, pH, and electrical conductivity (EC) were the considered indicators. A total of 360 disturbed and undisturbed surface soil samples (0–20 cm) (Samaei et al., 2022) from 180 sample points were collected using a hand driller. Soil samples were taken by bulk method (Rowell, 1994). For this purpose, samples were taken from the selected points at 5-m distances in the north–south and east–west directions for each subsampling point and were mixed (Figure 6). While determining the sampling points, efforts were made to represent all land uses and topographic features (Figure 7). Geographic coordinates were taken by GPS from each sample point. The soil samples were air-dried in the laboratory, stones and plant roots were removed, and the samples were then passed through a 2-mm sieve for further analysis.

The Bouyoucos hydrometer method was used to determine grain-size distribution (Gee and Bauder, 1986), the wet sieving method was used for aggregate stability (Kemper and Rosenau, 1986), the cylinder method was used for bulk density (Blake and Hartge, 1986), and the Smith–Weldon method was used for organic matter content (Nelson and Sommers, 1983). Mean weight diameter was calculated with Eq. (1) (Van Bavel, 1950),

aggregation rate with Eq. (2), porosity with Eq. (3) (Danielson and Sutherland, 1986), and dispersion rate with Eq. (4). Field capacity and wilting point were determined using a pressure membrane with pressure of 33 and 1500 kPa, respectively (Cassel and Nielsen, 1986). A pH meter (Mclean, 1983) and EC meter (Rhoades, 1983) were used to determine soil reaction and electrical conductivity, respectively.

$$MWD = \sum_{i=1}^{n} x_i y_i \quad (1)$$

Here, MWD is mean weight diameter, $y_i$ is the proportion of each size class by weight with respect to the total sample, and $x_i$ is the mean diameter of the size classes (mm).

$$AR = [\frac{SW - SaW}{SW}] \quad (2)$$

Here, AR is aggregation rate (%), SW is sample weight in aggregate stability, and SaW is sand weight determined by aggregate stability analysis.

$$\text{Soil porosity} = [1 - (\text{bulk density/particle density})] \times 100 \quad (3)$$

**2.2.3. Topographic features**

Topographic features are meaningful in the spatial variability of soil properties due to their roles in soil formation. Thus, topographic features such as elevation, slope, and aspect were used as indicators for determining the SQI. Maps of elevation, slope, and aspect were created with the ArcGIS spatial analysis tool using the Advanced Land Observation Satellite (ALOS) Phased Array Type L-band Synthetic Aperture Radar (PALSAR) digital elevation model (DEM) with spatial resolution of 12.5 m (www.asf.alaska.edu).

**2.2.4. Land use**

Due to land use differences causing variation in soil properties, land use was accepted as an indicator in this study. Data obtained from the 2018 CORINE Project (https://land.copernicus.eu/pan-european/corine-land-cover) were used to map land use in the study area.

**2.2.5. NDVI**

Vegetation dynamics were also determined with the NDVI using Landsat 8 OLI/TIRS C2 Level 2 satellite images downloaded from the United States Geological Survey (https://earthexplorer.usgs.gov). The NDVI was calculated with Eq. (4) (Rouse et al., 1974) using satellite images from July 2019 when the vegetation was its peak.

$$NDVI = \frac{Band_5 - Band_4}{Band_5 + Band_4} \quad (4)$$

**2.2.6. Calculation of SQI**

The SQI was calculated in three steps. First, the weights of every indicator to be employed in the assessment of the SQI were determined. Second, the indicators were normalized using linear scoring. Finally, the SQI was characterized based on the indicators' scores and weights (Huang et al., 2021; Zhang et al., 2022).

**2.2.6.1. Weighting of indicators**

Three main indicators and their subindicators (Table 2) were weighted with the pairwise comparison matrix method based on the analytic hierarchical process

**Table 1.** Studied soil quality indicators and references.

| Soil properties used as indicators | References |
|---|---|
| Clay content | Karaca et al. (2021), Samaei et al. (2022), Ciarkowska and Gambus (2020), Levi et al. (2021), Gozukara et al. (2022) |
| Silt content | Karaca et al. (2021), Samaei et al. (2022), Levi et al. (2021), Gozukara et al. (2022), Turgut et al. (2017) |
| Sand content | Karaca et al. (2021), Samaei et al. (2022), Levi et al. (2021), Gozukara et al. (2022), Turgut et al. (2017) |
| MWD | Raiesi and Kabiri (2016), Çomaklı and Turgut (2021), Turgut et al. (2017) |
| pH | Rahmanipour et al. (2014), Ciarkowska and Gambus (2020), Levi et al. (2021), Huang et al. (2021), Gozukara et al. (2022) |
| EC | Rahmanipour et al. (2014), Levi et al. (2021), Huang et al. (2021), |
| OM | Rahmanipour et al. (2014), Levi et al. (2021), Huang et al. (2021), Gozukara et al. (2022), Turgut et al. (2017) |
| BD | Huang et al. (2021), Zhao et al. (2021), Taghipour et al. (2022) |
| AS | Zhao et al. (2021), Çomaklı and Turgut (2021), Turgut et al. (2017) |
| AR | Çomaklı and Turgut (2021) |
| FC | Zhao et al. (2021), Turgut et al. (2017) |
| WP | Zhao et al. (2021), Turgut et al. (2017) |

MWD: Mean weight diameter; EC: electrical conductivity; OM: organic matter; BD: bulk density; AS: aggregate stability; AR: aggregation rate, FC: field capacity; WP: wilting point.

**Table 2.** Main indicators and their subindicators.

| Main indicators | Subindicators |
|---|---|
| Topographic features | Slope |
| | Elevation |
| | Aspect |
| Soil properties | Clay content |
| | Silt content |
| | Sand content |
| | AS |
| | AR |
| | MWD |
| | BD |
| | Porosity |
| | DR |
| | FC |
| | WP |
| | OM |
| | pH |
| | EC |
| Land use | |

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

preference scale (Saaty, 1980) considering their effects on the SQI. Relative indicators' importance levels were determined based on the opinions of ten experts, who were faculty members studying the SQI and working in the departments of soil science and plant nutrition in agriculture faculties.

**2.2.6.2. Scoring of the indicators**

Expert opinions and a linear function were used as the scoring methods and values ranging from 0 to 1 were assigned. With the expert opinion method, soil scientists who weighted the indicators scored the known land use and aspect as discrete variables considering their effects on soil quality, and then the final score values were created by taking the average of the experts' scores.

Linear scoring options including "more is better," "less is better," and "optimum range" were used for continuous variables such as elevation, slope, and all soil properties (Leite Chaves et al., 2017; Yu et al., 2018; Samaei et al., 2022). With this method, indicators were ranked in ascending or descending order considering their positive or negative effects on soil quality. "More is better" was used to score elevation, organic matter, aggregate stability, aggregation rate, porosity, mean weight diameter, field capacity, and wilting point, while "less is better" was used for slope, bulk density, and dispersion rate. Sand, clay, silt content, and pH were scored in the optimum range (Table 3).

**2.2.6.3. Calculating soil quality index**

Eq. (5) was used to calculate the SQI value for each sampling point (Huang et al., 2021; Gozukara et al., 2022; Zhang et al., 2022).

$$SQI = \sum W_{mi}(W * S_{si}) \quad (5)$$

**2.2.6.4. Mapping indicators and soil quality index**

The kernel smoothing interpolation method was used to create the distribution maps of the soil properties used as indicators of the SQI. Kernel interpolation is a variant of a first-order local polynomial interpolation using ridge regression, which estimates the coefficients of multiple regression models in scenarios where the independent variables are highly correlated (Hilt and Seegrist, 1977), to estimate regression coefficients (ESRI, 2011). Since the independent variables affecting the SQI were correlated with each other, this method was found to be appropriate.

**Table 3.** Linear scoring functions for each category of the indicators.

| Subindicators | Function | x1 | r1 | r2 | x2 | Formula |
|---|---|---|---|---|---|---|
| Elevation (m) | "More is better" | 211 | | | 2429 | |
| OM (%) | | 0.15 | | | 5.90 | |
| AS (%) | | 57.59 | | | 98.91 | |
| AR (%) | | 18.75 | | | 96.75 | |
| Porosity (%) | | 24.69 | | | 87.38 | |
| MWD (mm) | | 0.28 | | | 1.16 | |
| FC (%) | | 15.18 | | | 91.62 | |
| WP (%) | | 8.48 | | | 75.97 | |
| Sand content (%) | "Optimal range" | 0.78 | 30 | 35 | 82.59 | |
| Silt content (%) | | 0.78 | 30 | 35 | 82.59 | |
| Clay content (%) | | 0.78 | 30 | 35 | 82.59 | |
| pH | | 3.79 | 6.8 | 7.2 | 8.00 | |
| Slope (%) | "Less is better" | 7.07 | | | 125.87 | |
| EC (μS $cm^{-1}$) | | 0.00 | | | 6.89 | |
| BD (g $cm^{-3}$) | | 0.03 | | | 1.71 | |
| DR (%) | | 0.19 | | | 92.71 | |

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

ArcGIS software was used to prepare distribution maps of topographic features, land use, soil properties, and SQI.

#### 2.2.7. Statistical analysis

Pearson correlation analysis was used to determine the relationships between indicators. Analysis of variance (ANOVA) was used to determine differences in SQI values in terms of NDVI classes.

## 3. Results and discussion

### 3.1. Weights of the indicators

Indicator weights obtained in accordance with expert opinions were as follows: among the main indicators, soil properties were considered the most important soil quality indicator with a weight value of 0.444, followed by land use (0.320) and topographic features (0.236), respectively.

Organic matter had the highest weight (0.141) among soil property subindicators, followed by bulk density (0.108), aggregate stability (0.100), clay content (0.082), electrical conductivity (0.080), pH (0.078), aggregation rate (0.074), porosity (0.065), field capacity (0.062), dispersion rate (0.058), mean weight diameter (0.056), wilting point (0.056), sand content (0.022), and silt content (0.020). The weights of the landform subindicators were 0.513, 0.252, and 0.236 for slope, elevation, and aspect, respectively (Table 4).

### 3.2. Scores of the indicators

According to expert opinions, the score ranking of land use types was as follows: natural pasture (1), coniferous forest (0.8), broadleaf forest (0.8), mixed forest (0.7), transitional woodlands-shrubs (0.5), sparsely vegetated areas (0.4), land principally occupied by agriculture (0.4), complex cultivation patterns (0.3), discontinuous urban fabric (0.1), industrial or commercial units (0.1), bare rock (0.1), and water (0.1). The score ranking of aspect was as follows: north (1), northeast (0.8), northwest (0.8), east (0.6), southeast (0.4), southwest (0.4), west (0.4), and south (0.2) (Table 5). Sample graphics showing the score values of other indicators obtained from the "more is better," "optimum range," and "less is better" functions corresponding to measurement values are provided in Figure 8.

### 3.3. NDVI classes

Considering previous studies, six NDVI classes were created in the study area, with values from -1 to 0 indicating water surface and values from 0 to 0.2 indicating bare soil (Essaadia et al., 2022), while the ranges of 0.2–0.23, 0.23–0.36, 0.36–0.45, and 0.45–1 indicated vegetated lands ranging in coverage from weak vegetation cover to higher vegetation cover, respectively (Figure 9a) (Turgut and Turgut, 2022). The NDVI range encompassing the largest area (37.99%) in the studied basin was 0.36–0.45, while values of <0 accounted for the smallest area (0.01%) (Figure 9b).

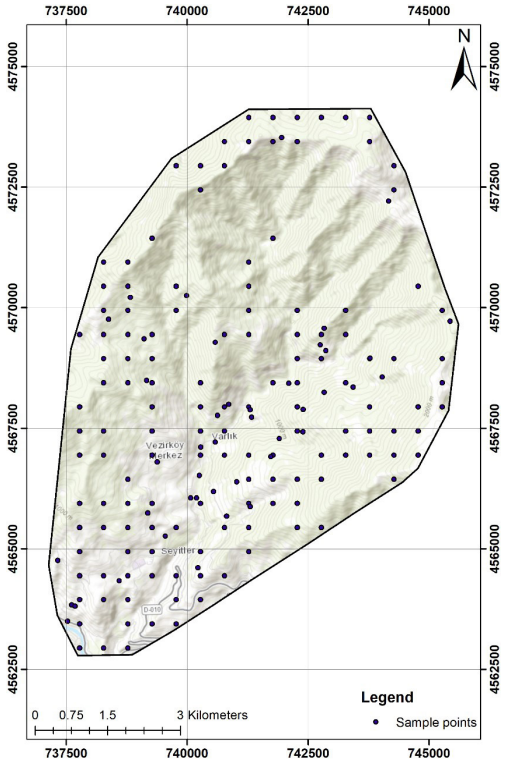



**Figure 6.** Soil sampling pattern.

### 3.4. Descriptive statistics of indicators

The descriptive statistics of the indicators are shown in Table 6. The study area is in the class of very steep slope with an average slope of approximately 48%, and the average elevation is 1230 m. Approximately 30%, 22%, and 48% of the soil composition was clay, silt, and sand, respectively. These results indicated that the soil texture in the study area was sandy clay loam. In terms of soil structure, average aggregate stability, aggregation rate, mean weight diameter, and dispersion rate were found to be 86%, 67%, 0.77 mm, and 41.85%, respectively. The range of bulk density was 0.19–1.71 g $cm^{-3}$ and porosity was 24.69%–87.38%. In terms of soil moisture characteristics, field capacity ranged between 15.18% and 91.62%, while wilting points were between 8.48% and 75.97%. The electrical conductivity range, pH, and organic matter were 0–8.89 µS $cm^{-1}$, 3.71–8.00, and 0.15%–5.90%, respectively.

Pearson correlation results showed that strong positive correlations existed between clay and mean weight diameter, sand and dispersion rate, aggregate stability and elevation, organic matter and porosity, organic matter and field capacity, organic matter and wilting point, organic matter and elevation, porosity and field capacity, porosity and wilting point, and porosity and elevation. However, strong negative correlations were observed between clay and sand, organic matter and bulk density, bulk density and porosity, and pH and elevation (Figure 10).

### 3.5. Distribution of soil properties in the study area

Soil properties in watersheds show spatial variability due to erosion and accumulation zones caused by topography (elevation, slope, aspect), and land use differences (le Bissonnais et al., 2002; Ffolliott et al., 2013; Selassie et al., 2015; Zuo et al., 2020). The variation of soil properties in the watershed can be explained by this general principle. The spatial variability map obtained in this study indicates that soils high in clay content were found in the lower part of the watershed (Figure 11a). However, the sand content was found to be higher in the watershed division parts (Figure 11b). The silt content did not show any spatial dependence (Figure 11c). The properties used in the evaluation of soil structure also varied according to the topographic features of the basin; aggregate stability was higher in the upper part of the basin (Figure 12a), and the aggregation rate (Figure 12b) and mean weight diameter (Figure 12c) were higher in the accumulation zones. Porosity and bulk density showed inverse distributions. While bulk density was higher in the accumulation zone (Figure 13a), porosity was higher in the upper part (Figure 13b). The dispersion rate was high in areas with high sand content (Figure 13c). Water retention capacity also varied




**Figure 7.** Photographs of fieldwork (a and b - sloping land; c and d - flat land).

across the basin; both field capacity (Figure 14a) and wilting point (Figure 14b) were higher in the upper part of the basin and lower towards the bottom of the basin. The organic matter content was higher in the upper parts of the basin, which are covered by forest and pasture (Figure 15a). The electrical conductivity (Figure 15b) and pH (Figure 15c) were higher in the accumulation zone of the basin, as expected.

**Table 5.** Scores of the indicators obtained from expert opinions.

| Indicators | Parameters | Score |
|---|---|---|
| Land use | Natural pastures | 1 |
| | Coniferous forest | 0.8 |
| | Broadleaf forest | 0.8 |
| | Mixed forest | 0.7 |
| | Transitional woodlands-shrubs | 0.5 |
| | Sparsely vegetated areas | 0.4 |
| | Land principally occupied by agriculture | 0.4 |
| | Complex cultivation patterns | 0.3 |
| | Discontinuous urban fabric | 0.1 |
| | Industrial or commercial units | 0.1 |
| | Bare rocks | 0.1 |
| | Water | 0.1 |
| Aspect | North | 1 |
| | Northeast | 0.8 |
| | Northwest | 0.8 |
| | East | 0.6 |
| | Southeast | 0.4 |
| | Southwest | 0.4 |
| | West | 0.4 |
| | South | 0.2 |

**Table 4.** Weights of the main indicators and subindicators used to calculate soil quality index (SQI).

| Main indicators | Weight | Subindicators | Weight |
|---|---|---|---|
| Soil properties | 0.444 | OM | 0.141 |
| | | BD | 0.108 |
| | | AS | 0.100 |
| | | Clay content | 0.082 |
| | | EC | 0.080 |
| | | pH | 0.078 |
| | | AR | 0.074 |
| | | Porosity | 0.065 |
| | | FC | 0.062 |
| | | DR | 0.058 |
| | | MWD | 0.056 |
| | | WP | 0.056 |
| | | Sand content | 0.022 |
| | | Silt content | 0.020 |
| Land use | 0.320 | - | - |
| Topographic features | 0.236 | Slope | 0.513 |
| | | Elevation | 0.252 |
| | | Aspect | 0.236 |

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

**Table 6.** Descriptive statistics of indicators used to calculate soil quality index (SQI).

| Indicator | Minimum | Maximum | Mean | Standard deviation | Coefficient of variation |
|---|---|---|---|---|---|
| Slope (%) | 7.07 | 125.87 | 47.55 | 20.37 | 42.84 |
| Elevation (m) | 211 | 2429 | 1230 | 538 | 43.74 |
| Clay content (%) | 3.79 | 59.56 | 29.32 | 10.87 | 37.07 |
| Silt content (%) | 0.78 | 56.35 | 22.30 | 10.24 | 45.92 |
| Sand content (%) | 9.12 | 82.59 | 48.38 | 13.63 | 28.16 |
| AS (%) | 57.59 | 98.91 | 85.95 | 8.08 | 9.40 |
| AR (%) | 18.75 | 96.75 | 67.45 | 19.44 | 28.82 |
| MWD (mm) | 0.28 | 1.16 | 0.77 | 0.14 | 17.85 |
| DR (%) | 7.21 | 92.71 | 41.85 | 17.87 | 42.71 |
| BD (g $cm^{-3}$) | 0.19 | 1.71 | 0.95 | 0.30 | 31.57 |
| Porosity (%) | 24.69 | 87.38 | 56.04 | 12.30 | 21.95 |
| FC (%) | 15.18 | 91.62 | 40.83 | 15.08 | 36.93 |
| WP (%) | 8.48 | 75.97 | 30.09 | 12.42 | 41.27 |
| EC (µS $cm^{-1}$) | 0.00 | 6.89 | 1.38 | 1.21 | 87.63 |
| OM (%) | 0.15 | 5.90 | 3.39 | 1.55 | 45.69 |
| pH | 3.71 | 8.00 | 5.88 | 1.04 | 17.60 |

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

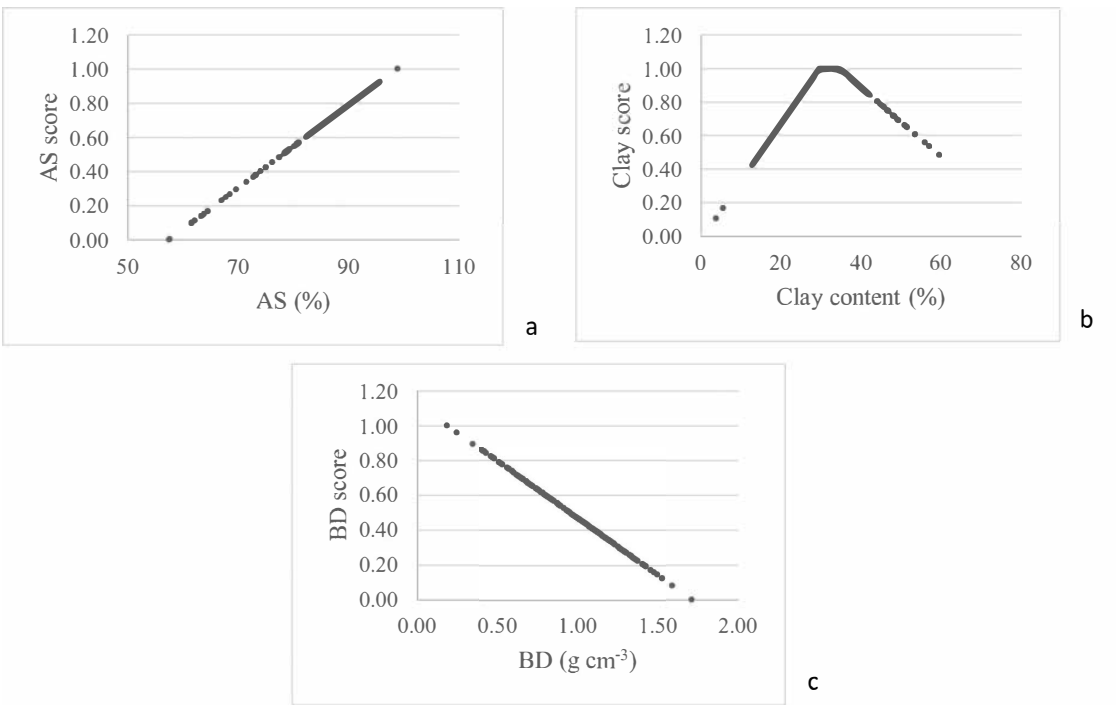



**Figure 8.** Graphs showing the relationships between the measurement values of the indicators and the score values calculated with linear functions: a) aggregate stability (AS), "more is better" function; b) clay content, "optimum range"; and c) bulk density (BD), "less is better."

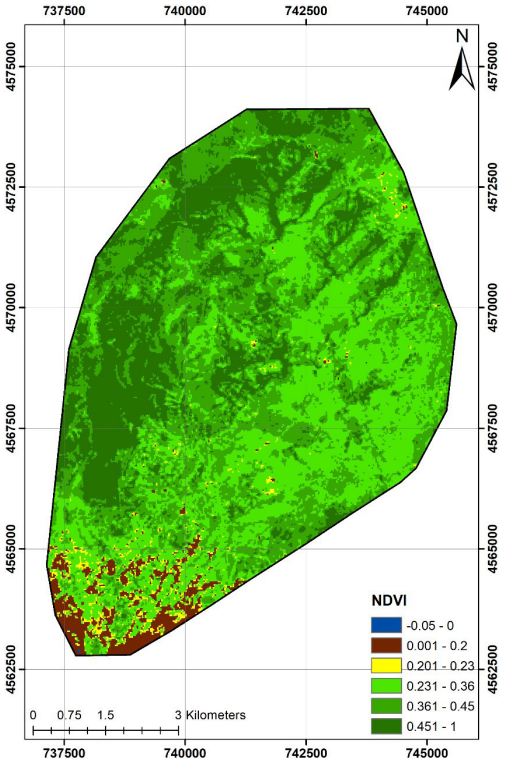



**Figure 9.** (a) NDVI classes of the study area and (b) their areal distribution.

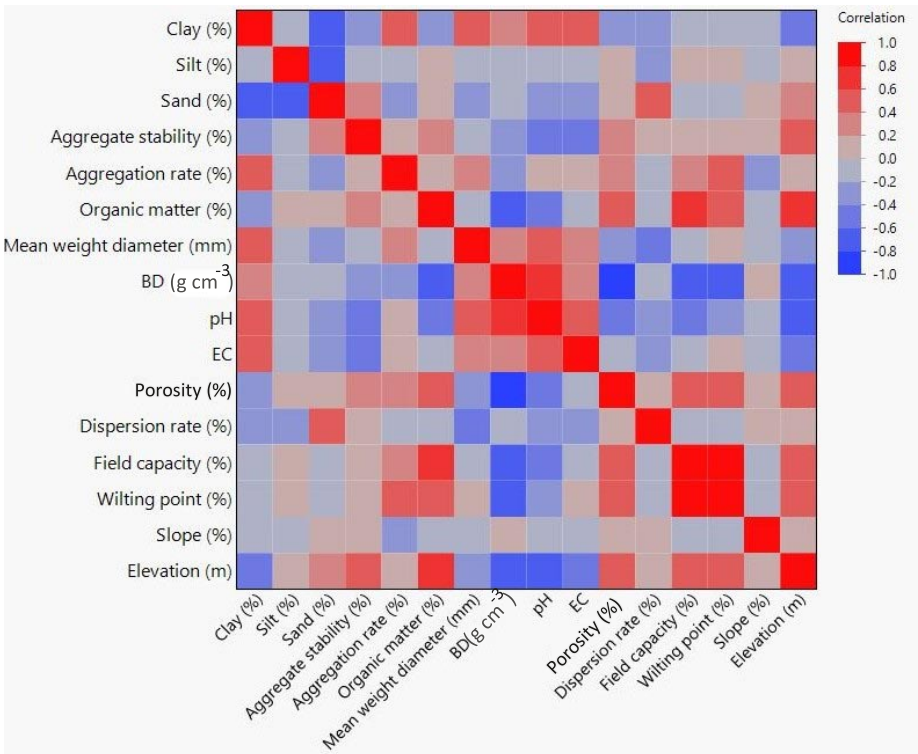



**Figure 10.** Pearson correlation coefficients of indicators (red represents a strong positive correlation while blue represents a strong negative correlation).

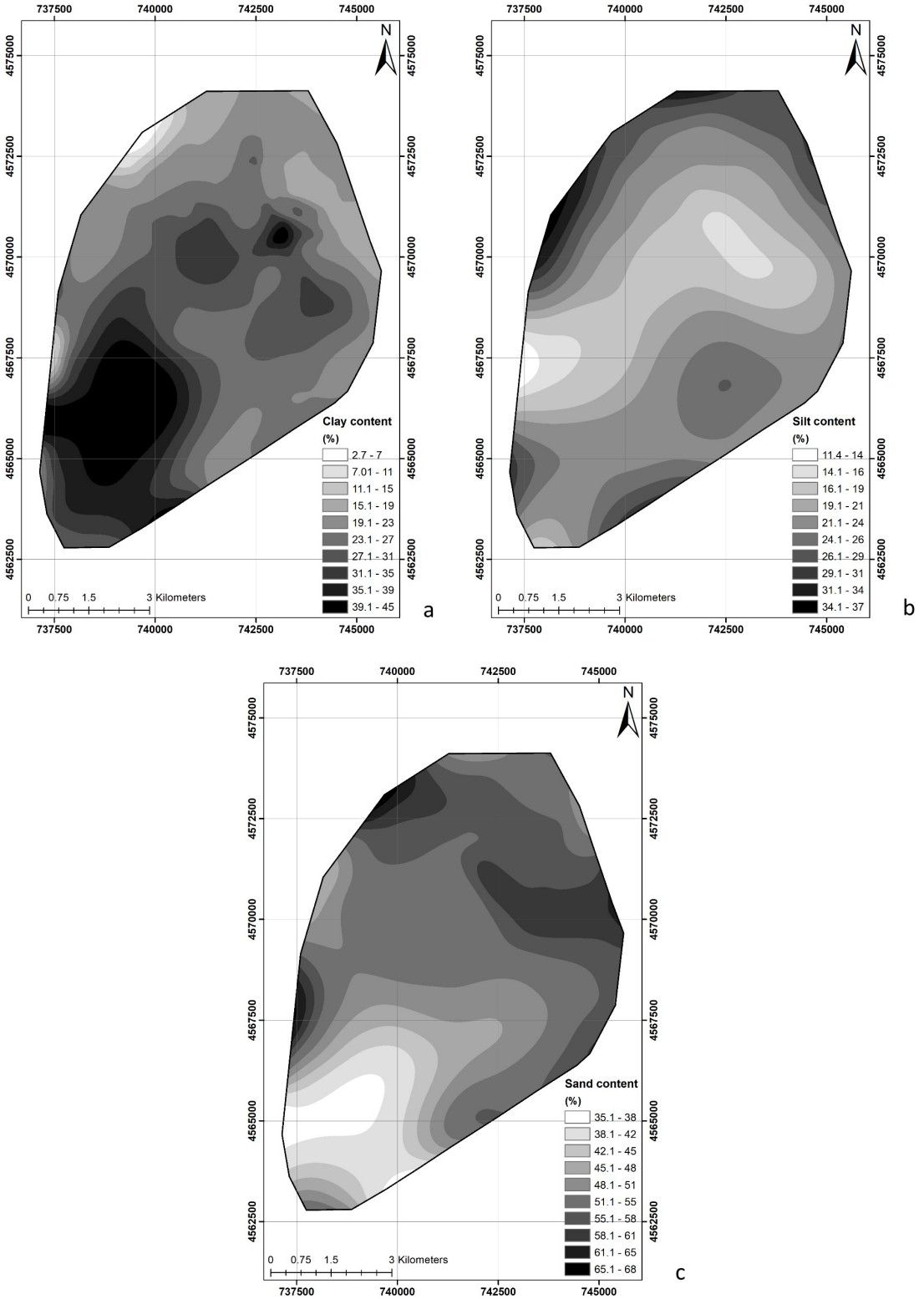



**Figure 11.** Spatial distribution of the (a) clay, (b) silt, and (c) sand contents in the watershed.

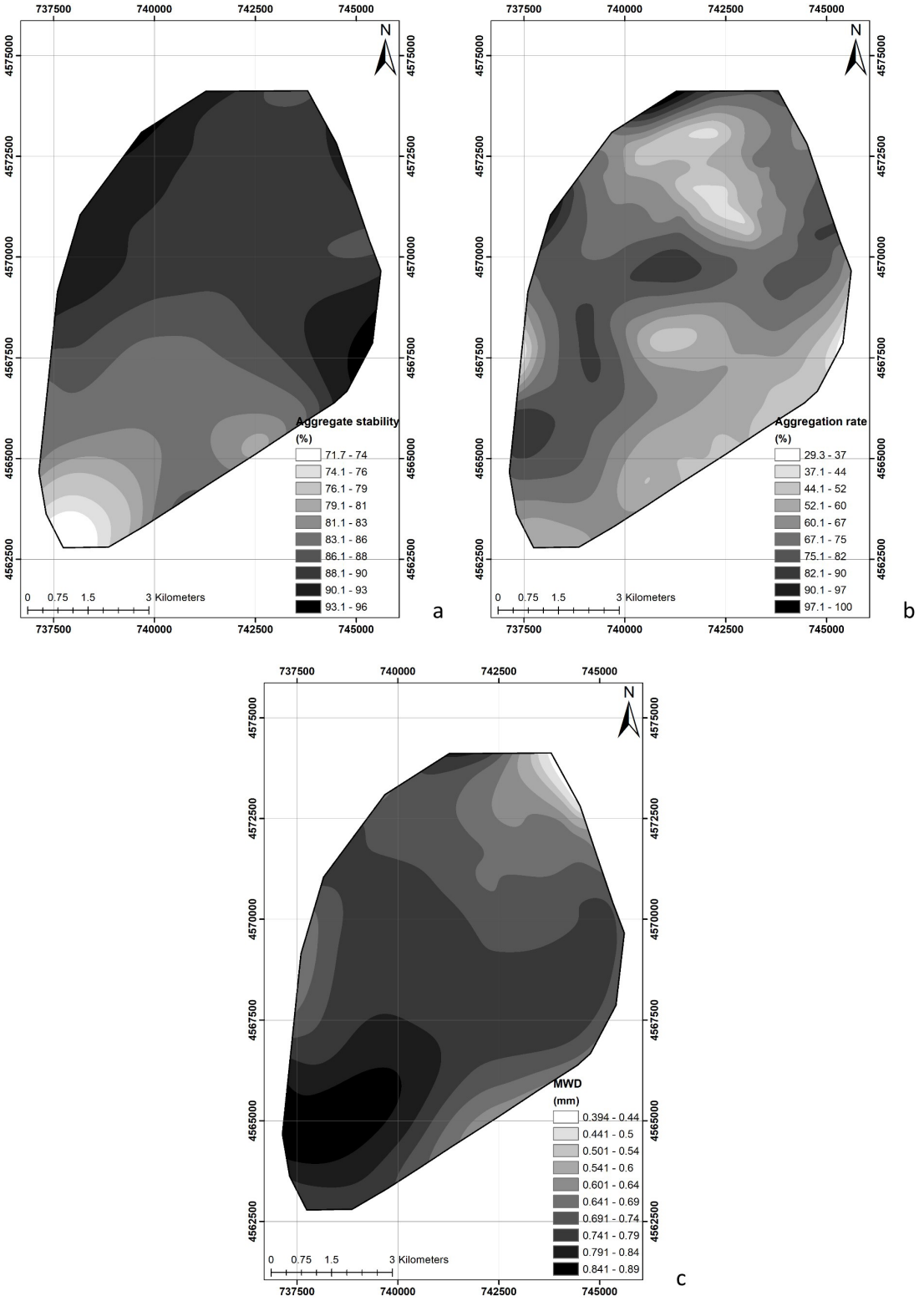



**Figure 12.** Spatial distribution of the (a) aggregate stability, (b) aggregation rate, and (c) mean weight diameter (MWD) in the watershed.

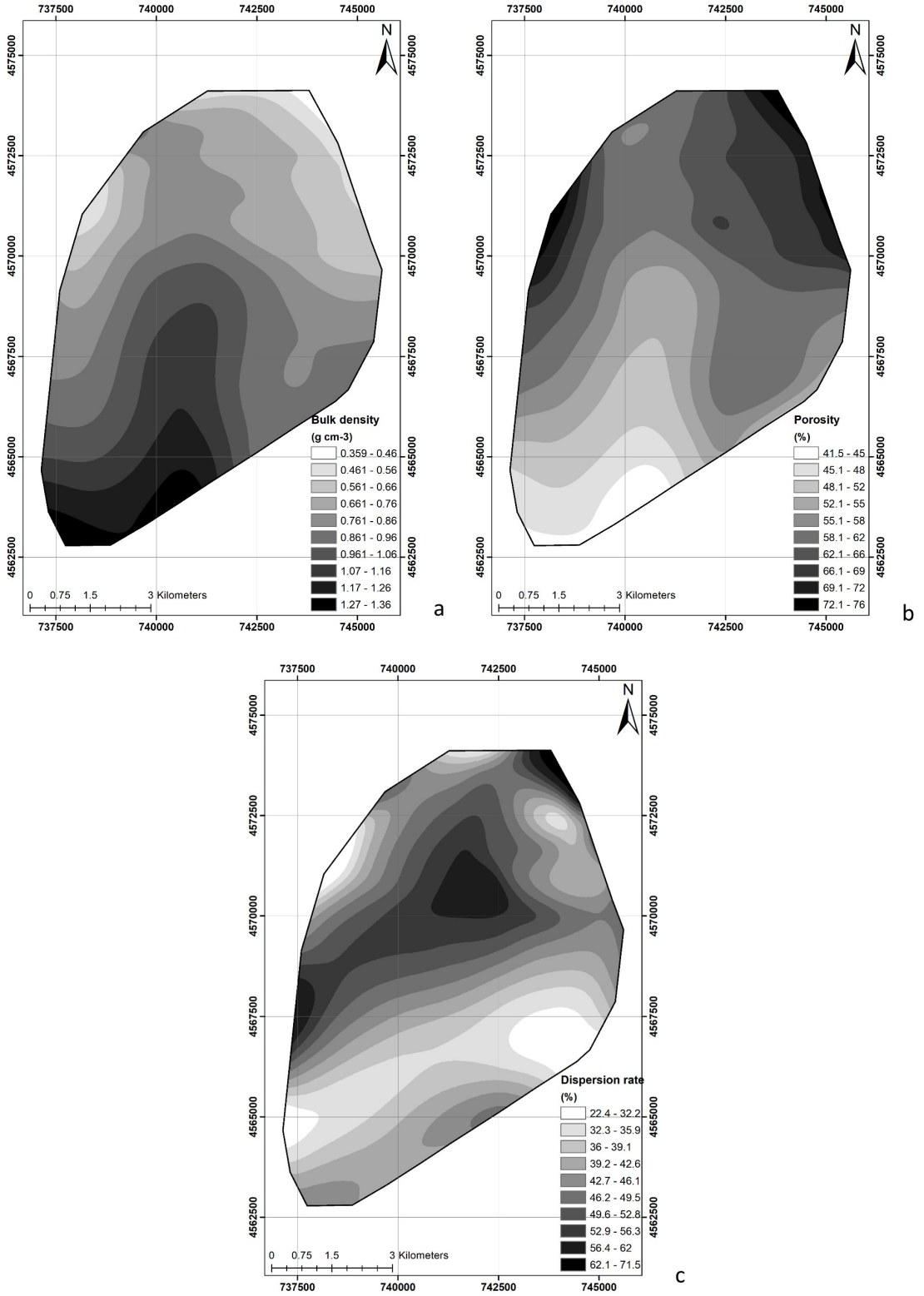



**Figure 13.** Spatial distribution of the (a) bulk density, (b) porosity, and (c) dispersion rate in the watershed.

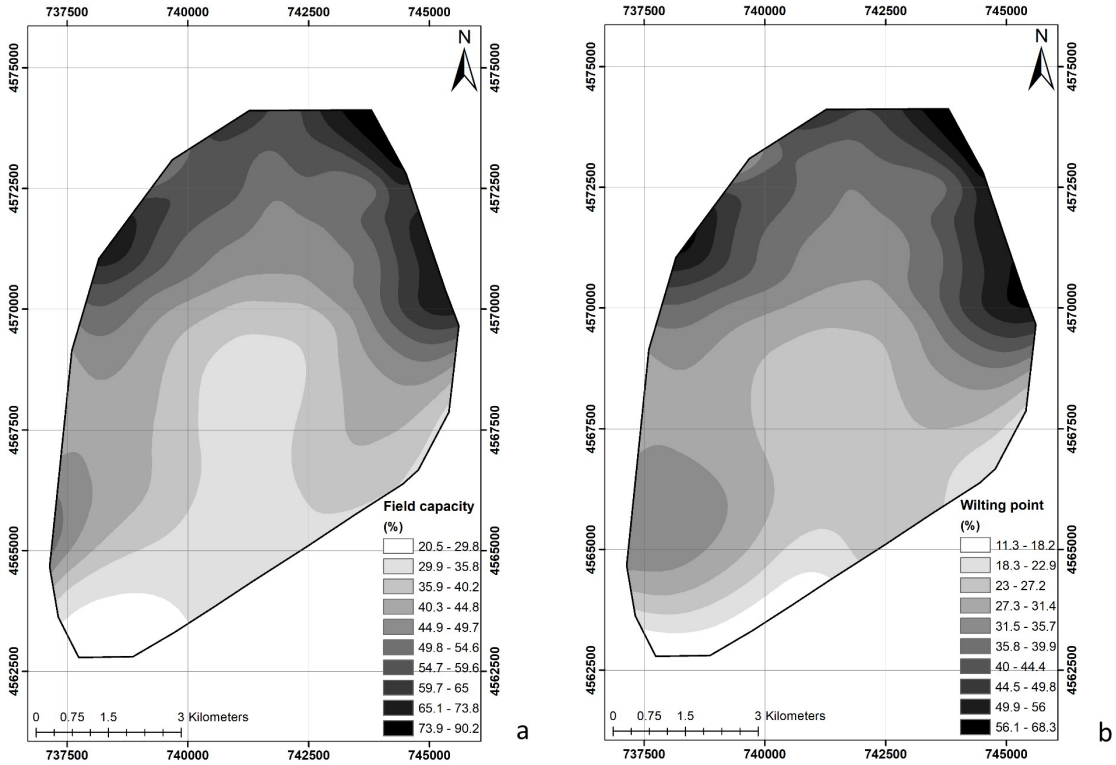



**Figure 14.** Spatial distribution of the (a) field capacity and (b) wilting point in the watershed.

### 3.6. Changes in soil properties depending on NDVI

This section addresses changes in soil properties due to NDVI classes. The ANOVA results indicated that the differences among NDVI classes in terms of mean weight diameter, dispersion rate, and clay, sand, and silt contents were not significant. However, organic matter content, aggregate stability, aggregation rate, bulk density, porosity, field capacity, wilting point, and pH changed significantly with NDVI classes (Table 7). While the highest organic matter was obtained from the highest range of NDVI values, it gradually decreased and reached the lowest value in the lowest range of NDVI. Researchers previously indicated that the main source of soil organic matter is vegetation residue (Rowell, 1994; Baldock and Nelson, 2000; Karaman et al., 2012), The greater soil organic matter content in the area with higher NDVI values can be explained by the vegetation density. The highest aggregate stability was obtained from the NDVI range of 0.45–0.56, and it decreased gradually with decreasing NDVI. The aggregation rate was also highest in the NDVI range of 0.45–0.56, but its decrease was not gradual. Bulk density increased with decreasing NDVI range. However, porosity showed a decreasing trend with decreasing NDVI values. Soil aggregate formation and stability are profoundly influenced by soil organic matter content (Li et al., 2023). High values of structural parameters are expected in areas with high NDVI values, which are an indicator of vegetation density. Field capacity and wilting point also dropped gradually due to decreasing NDVI values. As a result of the positive relationship between soil organic matter and soil moisture characteristics (Rasa et al., 2018; Wang et al., 2019), field capacity and wilting point moisture contents were higher in areas with high NDVI values. Depending on the increase in NDVI value, pH values tended to decrease.

### 3.7. Distribution of SQI values in the watershed

Values of the SQI increased in locations near the watershed division, mainly covered by pastures and forests (Figure 16). This may be due to the higher values of the quality indicators in pasture areas with large fine root systems and in forest areas with litterfall. Meanwhile, pasture and forest were least affected by human activities, resulting in better soil quality. Alteration of forest and pasture ecosystems into agriculture and settlements resulted in a significant decrease of the SQI. These results showed that pasture and forest areas with higher vegetation coverage had positive effects on soil quality relative to agricultural lands and settlements. These results agree with those of previous studies (Leite Chaves et al., 2017; Yu et al., 2018; Samaei et al., 2022). A more reliable SQI distribution map could be generated by increasing the sampling points, but limited research possibilities did not allow that in the present study.

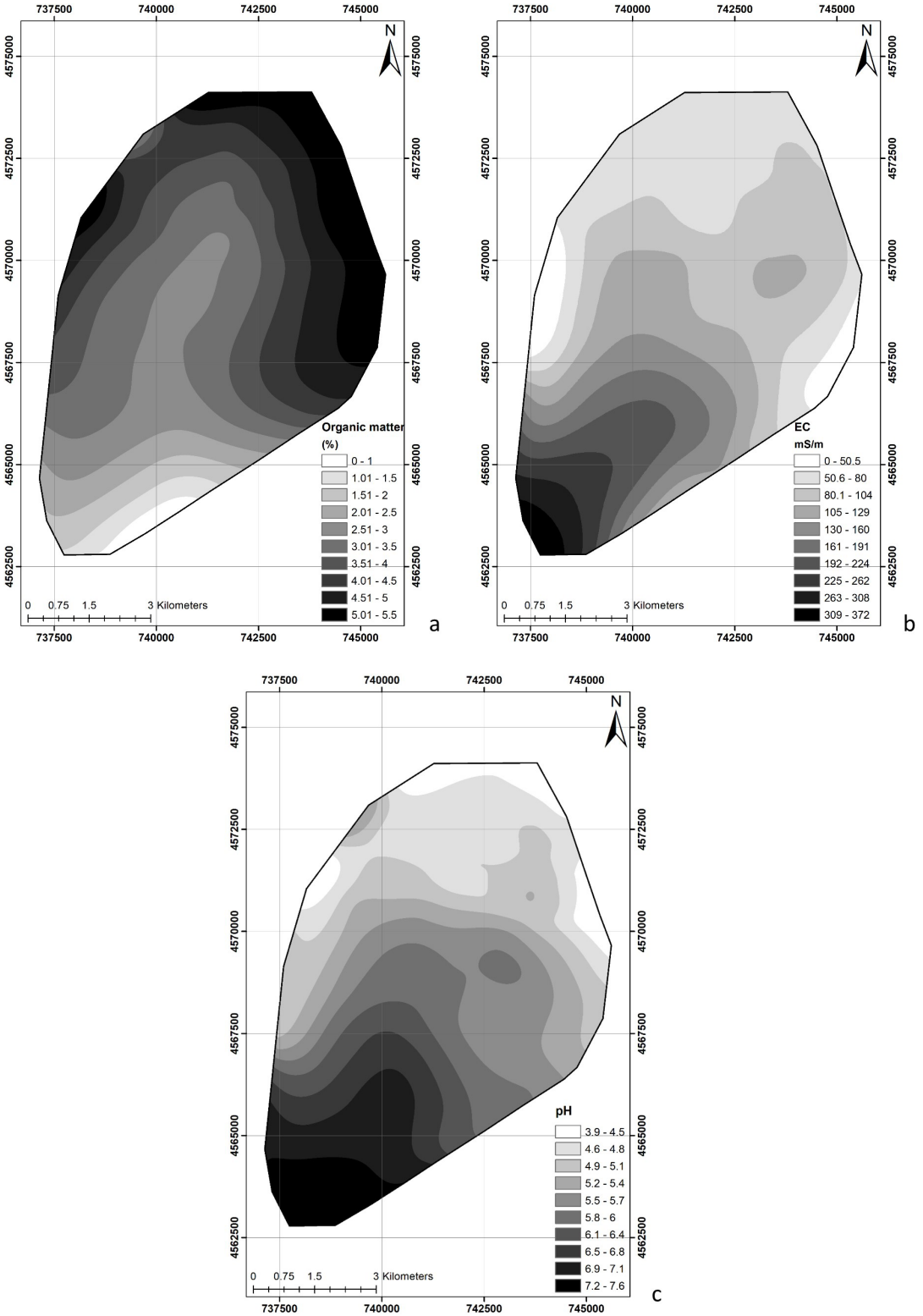



**Figure 15.** Spatial distribution of the (a) organic matter, (b) EC, and (c) pH in the watershed.

**Table 7.** ANOVA results.

| Soil properties | NDVI classes | | | | | F values |
|---|---|---|---|---|---|---|
| | 0–0.20 | 0.20–0.23 | 0.23–0.36 | 0.36–0.45 | 0.45–0.56 | |
| Clay | 31.72 | 30.23 | 29.68 | 28.32 | 29.54 | 0.328 ns |
| Silt | 28.72 | 24.81 | 21.74 | 21.23 | 22.58 | 1.641 ns |
| Sand | 39.56 | 44.96 | 48.59 | 50.45 | 47.88 | 1.907 ns |
| AS (%) | 79.71 C | 79.30 C | 84.80 BC | 87.43 AB | 89.83 A | 6.222** |
| AR (%) | 62.10 b | 71.63 ab | 63.85 b | 67.86 ab | 76.76 a | 2.533* |
| MWD (mm) | 0.80 | 0.82 | 0.77 | 0.76 | 0.76 | 0.399 ns |
| BD (g $cm^{-3}$) | 1.20 A | 1.19 AB | 0.97 AC | 0.92 BC | 0.81 C | 5.718** |
| Porosity | 47.55 B | 46.98 | 55.61 AB | 57.24 AB | 60.56 A | 3.814** |
| Dispersion | 41.05 | 42.70 | 40.17 | 40.44 | 49.63 | 1.558 ns |
| FC | 28.67 B | 33.09 B | 40.47 AB | 41.11 AB | 47.89 A | 3.702** |
| WP | 20.95 B | 22.76 AB | 30.65 AB | 30.52 AB | 33.98 A | 3.24* |
| OM | 1.50 B | 2.34 AB | 3.52 A | 3.70 A | 3.50 A | 7.362** |
| pH | 7.07 A | 6.74 AB | 5.95 B | 5.72 B | 5.33 C | 9.406** |
| EC | 2.10 | 1.33 | 1.49 | 1.29 | 1.04 | 1.970 ns |

MWD: Mean weight diameter; EC: electrical conductivity; OM: organic matter; BD: bulk density; AS: aggregate stability; AR: aggregation rate, FC: field capacity; WP: wilting point.
Values in rows followed by different letters are statistically significantly different. ns: Nonsignificant; *, **: significant at $p < 0.05$ and $p < 0.01$, respectively.

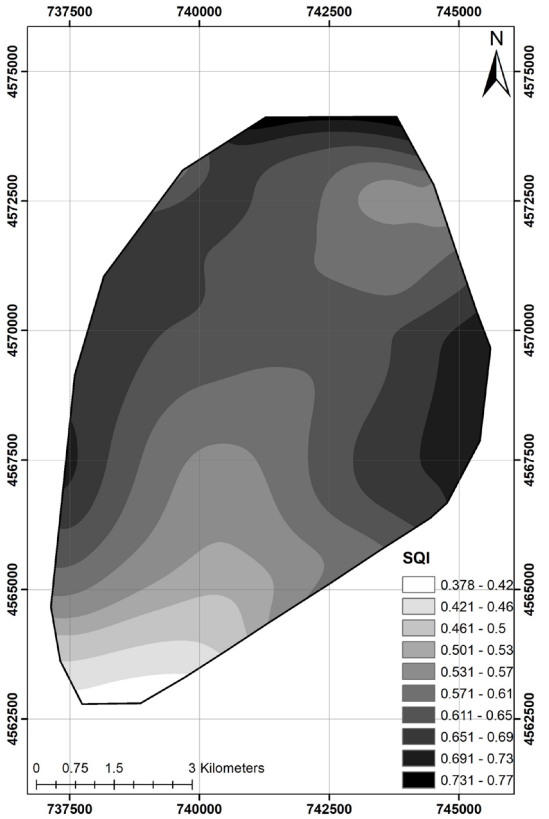



**Figure 16.** Distribution map of SQI values.

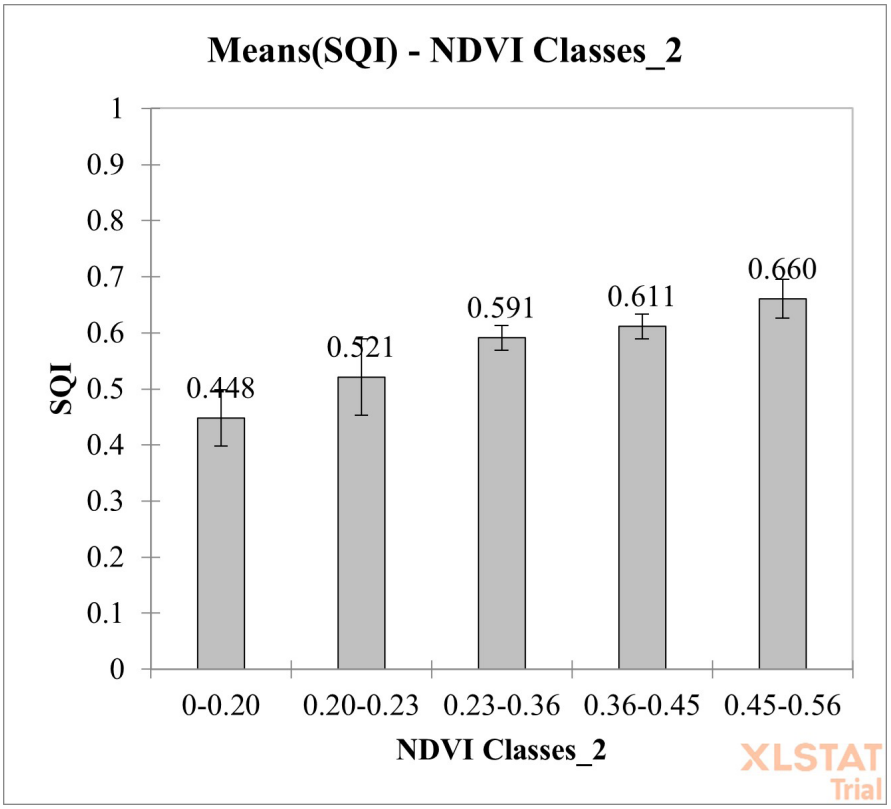



**Figure 17.** Comparison of NDVI classes in terms of SQI.

### 3.8. SQI values of different NDVI classes

The soil in the study area was divided into six NDVI ranges: -1 to 0, 0 to 0.2, 0.2 to 0.23, 0.23 to 0.36, 0.36 to 0.45, and 0.45 to 1. Using these six ranges of the NDVI, SQI values were calculated separately. The SQI values were ranked as follows: 0.45–1, 0.36–0.45, 0.23–0.36, 0.20–0.23, and 0–0.20 (Figure 17). The results showed that the soil quality of the SQI range of 0.45–1 was highest, while the quality of the 0–0.20 range was the worst. Differences among NDVI classes were statistically significant (F: 13.596; $p < 0.01$). The NDVI gives a quantitative estimation of vegetation growth and biomass (Wu et al., 2016), and high NDVI values indicate higher vegetation density. Plants and their roots, accepted as the main source of soil organic matter, improve the soil's physical and chemical properties (Baver et al., 1972; Rowell, 1994). For this reason, it is to be expected that the SQI will be higher in areas with higher NDVI values.

## 4. Conclusion

In this study, unlike previous studies using only soil properties, topographic features and land use were also used as criteria in the calculation of the SQI. It was demonstrated that expert opinion is an alternative method for scoring discrete variables in calculating the SQI. Spatial variabilities in soil physical and chemical properties, topographic features, and land use in the study area were evaluated to reveal their effects on the SQI in the watershed. The significant differences among NDVI ranges in terms of SQI indicated that vegetation coverage and density increase SQI values. This finding supports the general belief that soil quality is high in forest and pasture ecosystems. Limited research opportunities did not allow more soil properties to be examined, such as plant nutrient status or microbiological properties. It is thought that future studies to be carried out in different locations, where climatic factors, bedrock properties, plant nutrient

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