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Soil quality assessment based on hybrid computational approach with spatial multi-criteria analysis and geographical information system for sustainable tea cultivation

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Abstract

Long-term intensive tea cultivation is suspected of deteriorating soil quality status and degrading land sustainability. This study aimed to determine the soil quality index of soils in a micro-catchment in Rize Province, Turkey, used for long-term intensive tea cultivation, by means of spatial multi-criteria analysis (SMCA) and standard scoring function (SSF) integrated with geographical information system (GIS) and geostatistics, considering bio-physical-chemical properties of a detailed soil dataset. Soil samples (102) were collected from the surface layer (0–20 cm). In the soil quality index for tea-cultivated soils (TSQI), soil indicators were weighted by an analytical hierarchy. Various indicator units were normalized with the SSF. The TSQI model was divided into five main criteria: (i) physical properties, (ii) chemical properties, (iii) fertility, (iv) biological indicators and (v) soil erosion susceptibility parameters. Principal components analysis (PCA) was applied and minimum dataset (MDS) created to determine the most effective indicators. The spatial distribution pattern of the tea total dataset soil quality index ($TSQI_{TDS}$) and tea minimum dataset soil quality index ($TSQI_{MDS}$) values were statistically similar. $TSQI_{TDS}$ low and very low-class areas accounted for 34.1% of the total area, while $TSQI_{MDS}$ low and very low-class areas constituted 33.6%. These areas, especially those with low soil quality properties, were in the northern and north-western parts of the micro-catchment. $TSQI_{TDS}$ very high and high-class areas accounted for 56.2% of the total area, while $TSQI_{MDS}$ very high and high-class areas were found in 55.3% of the total area. These areas are located in the south of the micro-catchment.

Introduction

Tea is an important product for putting resources into good use, creating employment, supplying raw materials to other industries and providing high added value. Tea production affects the lives of many people and farmers in the Eastern Black Sea Region of Turkey socially, economically and environmentally. As in other countries that cultivate tea, it is a significant source of income for the producers in Turkey. Because the tea plant grows in mountainous and hilly areas with steep slopes, it has a significant economic impact on these regions. It is also a strategic plant with a great potential for creating added value. In Turkey, tea is grown in the provinces of Rize, Trabzon, Artvin, Giresun and Ordu. 20% of all tea production areas in Turkey are in Trabzon, 11% in Artvin and 2% in Giresun and Ordu. As the most important province for tea cultivation, Rize has a 68% share in Turkey's total fresh tea production (ÇAYKUR, 2019; FAO, 2019). A crucial problem for Turkish tea plantations is the decreased soil fertility and quality. Rehabilitation of soils is an important problem for tea cultivating lands around the world. If precautions are not taken, extreme weather events with climate change can further reduce soil quality (Yazıcı, 2021).

To meet the needs of people with fewer costs and higher quality and to plan agricultural practices, institutions are asked to produce solutions. Measuring and reporting the response of individual soil parameters to a particular problem is no longer sufficient for producing solutions (Karlen *et al*., 2003). As the main object of sustainable use, the soil should be considered associated with land management under changing natural conditions. Determining and monitoring the destruction of environmentally important components, that are water, soil and air, with reliable methods is a key step to ensure that the necessary measures can be taken in a timely manner.

In this context, soil quality is its capacity to fulfil its physical, chemical and biological duties continuously and adequately for plants. Continuously fulfilling these physical, chemical and biological duties indicates that the soil is a dynamic living system. This system is explained by a unique balance and interaction between biological, physical and chemical components (Karlen *et al.*, 1997). Creating a sustainable agricultural ecosystem and meeting the needs without adversely affecting the environmental components of the present or the future depends on the reliability of methods of determining soil quality and the applicability of these methods in large areas.

Soil quality is the ability of soil to perform its functions and deliver multiple ecosystem services, such as maintaining crop productivity, preserving and maintaining water availability and supporting human activities (Tahat *et al.*, 2020). Therefore, the main purpose of soil quality research is to monitor and assess the effects of tillage and other applications on physical, chemical and biological properties, use this assessment as a tool and examine the potentials of soils that indicate their past and present conditions. Moreover, soil quality is determined by dynamic variability and soil properties. For example, the texture is a natural property and cannot change easily. Soil quality is affected by dynamic properties and changes based on soil use and management. Hence, soil quality is a function of agro-climatic factors, hydrogeology and production techniques, and it is determined by many properties like soil depth, water holding capacity, bulk density, available nutrients, organic matter, microbial biomass carbon (MBC), carbon and nitrogen content, soil structure, infiltration rate and crop yield. Because of the correlations between these properties, very few of them have been identified as soil quality indicators, and research on soil quality and its numerical expression has been insufficient (Askari and Holden, 2015). The concept of soil quality was first introduced in the 1990s due to the inadequacy of erosion control activities and the increasing interest in sustainability (Karlen *et al.*, 2003). To explain this concept, we need to know the multiple functions of the soil and better understand the relationship between agricultural activity and soil quality. Recently, soil quality has been associated with soil's role in plant production and environmental health (Gil-Sotres *et al.*, 2005). Today, there are two concepts about soil quality (Karlen *et al.*, 1997; Seybold *et al.*, 1997). The first is the capacity of the soil as a function of its properties (Doran and Parkin, 1994), and the second is the concept of fitness for use (Pierce and Larson, 1993; Acton and Gregorich, 1995). Capacity includes the properties that the soil contains like climate, topography, vegetation and parent material. These properties are indicated by other concepts like texture, slope, structure and colour as measured by soil surveys. Fitness for use is a dynamic concept and is affected by human activity and management. This concept is also often referred to as soil health. Though the boundary between these two concepts is not clear, soil quality is defined as a function of soil properties and soil health is considered the soil's ability to support, protect and develop sustainable plant and animal production, water and air quality and human and animal health.

The tea plant has a major place in herbal production in the Eastern Black Sea Region of Turkey because the most important factors that affect its growth are the climate and soil characteristics. The tea plant can grow in some regions under hot and rainy climatic conditions (Özyazıcı *et al.*, 2011). Regions with minimum annual precipitation of 1250 mm, temperatures ranging from 10–30°C, altitudes up to 2000 m, and a slope of 5–10% are ideal for tea plants. Hence, tea production is limited to a few regions around the world and is extremely sensitive to changes in conditions. Climate change puts the conditions of these limited tea cultivation areas at risk. The Eastern Black Sea region is surrounded by steep and high mountains, disallowing the use of mechanization and hampering the growth of agriculture and animal husbandry at the desired level. Therefore, being very adaptable to the region, the tea plant has great importance for the financial gains of the people in the region. In fact, tea cultivation is carried out in 82 247 ha land in the Eastern Black Sea Region (TUIK, 2021). With a high share in total tea cultivation fields, Rize has more than 125 thousand producers who carry out tea agriculture. So, Rize is a key province for its contribution to both employment and the economy (TUIK, 2020).

Although to the best of our knowledge, despite the economic and strategic significance of tea cultivation for Turkey, there is no detailed soil quality model for it. Agricultural soil quality has recently become an interesting topic for research with increased awareness in agricultural sustainability, reduced agricultural lands due to urbanization and rapid population growth and negative environmental effects. In the current study, the main motivation was to determine the soil quality in the micro-catchment lands with intensive long term tea cultivation in Rize province in the Eastern Black Sea Region under humid ecosystem conditions. So, we determined the soil quality properties of intensive tea cultivation lands in micro-catchment using spatial multi-criteria analysis (SMCA) and standard scoring function (SSF) integrated with the GIS and geostatistic considering the physical, chemical, productivity, biological and erosion susceptibility detailed soil indicators. Therefore, this study can be considered the first peer-reviewed article based on the detailed bio-physical-chemical properties of soil and environmental analyses for tea farming. Besides, the present study contributes to the literature on tea production by outlining the information that will enable the planning of future initiatives that integrate sustainable soil and land management in tea production.

Materials and methods

General study area description

Rize province is located between longitudes 40° 21′ and 41° 25′ E and latitudes 40° 33′ and 41° 20′ N (Fig. 1). The province has an area of 3920 km^2, being mostly mountainous. Rize province is surrounded by Trabzon in the west, Erzurum and Bayburt in the south, Artvin in the east and the Black Sea in the north.

The study area was a micro-catchment in Rize province with an area of approximately 1671.8 ha and an altitude between 0 and 862 m above sea level. The micro-catchment has a mountainous and rugged topography and the slope varies widely (Fig. 2). The south-western parts of the area have lands with gentle to moderate (6–12%) slopes. However, most of the south-eastern and northern regions have steeper slopes, turning into a steep topography further these directions. Also, the slope exposure is toward the northeast and east in most of the area. The areas to the northeast and east of the riverbed have an exposure toward the north-west and east.

Considering geological content, most of the micro-catchment consists of volcanic sedimentary rocks, with a mixture of sandstone-mudstone-limestone in the southeast. Red yellow podzolic soils are distributed throughout the area. These soils are classified as Alisol-Acrisol according to FAO-WRB (2014). Most of the micro-catchment is used for tea cultivation and few lands have forest and pasture areas.

The Black Sea climate is dominant in Rize province. Based on the general characteristics of this climate, the region is cool during

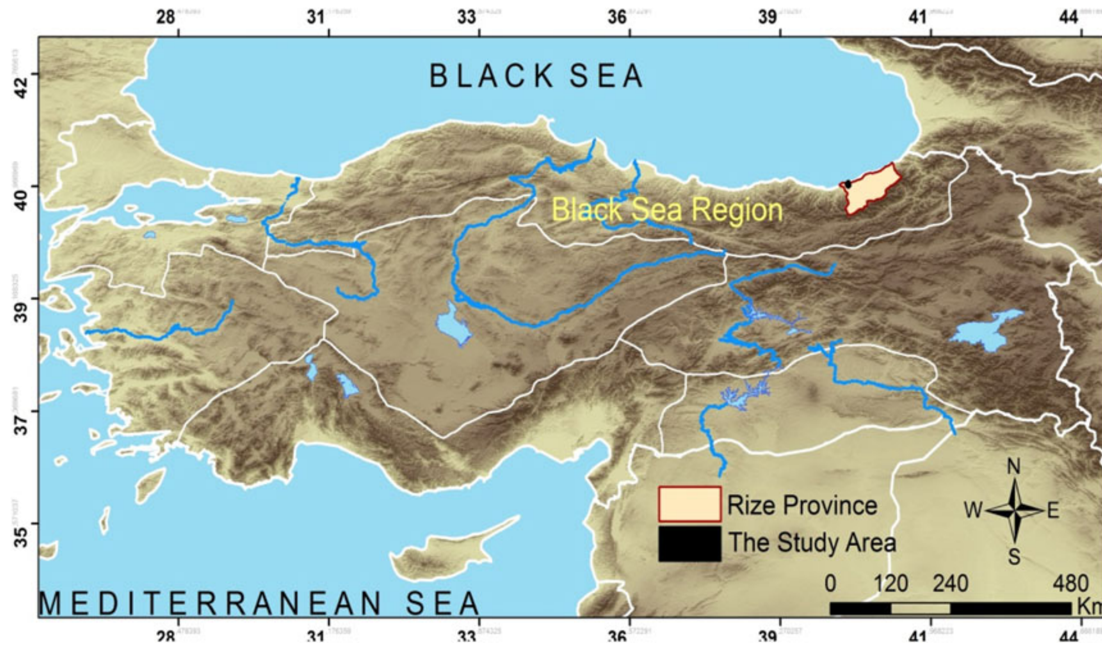

Fig. 1. Location map of the study area.

summer, mild during winter and rainy in almost every season. The biggest factor here is that the mountains extend parallel to the coast. Meteorological data for long term periods show that Rize province has an annual average temperature of 14.3°C, the lowest temperature of 6.5°C and the highest temperature of 23.1°C. The coldest month is January and the warmest is August. Annual precipitation is more than 2300 mm, making Rize the rainiest province in Turkey. Precipitation is evenly distributed across all seasons and there is no dry season. The least precipitation occurs during spring and the most during autumn. Humidity is always above 75%. According to the Newhall simulation model (Van Wambeke, 2000), the soil temperature regime is Mesic, and the soil moisture regime is Perudic.

Soil sampling and analysis

In order to get the most uniform distribution possible, we collected 102 soil samples from the surface depth (0–20 cm) (Fig. 2). Soil sampling was carried out in 2020 and after the tea harvest, to make sure other applications like fertilization did not affect the soil properties. Besides, we took into account different topographic locations and land use/land cover (tea plant) types when collecting the soil samples.

The soil samples were separated from coarse particles, air-dried under laboratory conditions and sieved through a 2 mm sieve. Soil quality status can be evaluated through primary indicators of soil quality that are integrated with soil's physical, chemical and biological properties (Anup and Ghimire, 2019). After they were ready for analysis, we analysed 35 soil quality parameters including physical, chemical and biological properties, plant nutrients and erodibility which indicate susceptibility to erosion. In the soil quality index for Tea Cultivation (TSQI), the indicators are grouped under five categories:

- Physical indicators: sand, clay, silt, bulk density (BD), saturated hydraulic conductivity (HC), field capacity (FC) and permanent wilting point (PWP)
- Chemical indicators: organic matter (OM), $CaCO_3$, electrical conductivity (EC), soil reaction (pH), hydrogen ion content (H) and cation exchange capacity (CEC)
- Nutrient indicators: available phosphorus (AvP), total nitrogen (TN), exchangeable potassium (ExK), exchangeable magnesium (ExMg), exchangeable calcium (ExCa), exchangeable sodium (ExNa), available iron (AvFe), available manganese (AvMn), available copper (AvCu) and available zinc (AvZn)
- Biological indicators: MBC (C_{mic}), basal respiration (CO_2), C_{mic}/CO_2 ratio and metabolic quotient (qCO_2)
- Soil erodibility factors: Aggregate stability (AS), Dispersion ratio (DR), Erodibility ratio (ER), Structure stability index (SSI), Clay ratio (CR) and Crust Formation (CF).

Table 1 shows the analyses of the physical, chemical, biological, productivity and erodibility indicators for determining the soil quality indices of tea cultivation soils.

Structure and stages of the soil quality index model

This study was performed to evaluate the variation in soil quality in tea cultivation fields. To overcome the complex ecological structure of nature, we integrated various methodologies like geographic information system (GIS) techniques, multi-criteria decision analyses (MCDA), SSF, geostatistics, analytical hierarchical processes and principal component analyses. Figure 3 shows the modelling architecture and the correlations between the methods. A soil quality index (SQI) study consists of four stages. The first is modelling the structure and data collection for the database. The second step is selecting soil quality indicators. The third is to gather, score and weight these indicators, obtain total and minimum datasets (TDS-MDS) and process this data to obtain a spatial distribution for SQI changes using GIS and geostatistical techniques. The final step involves evaluating the results of the data analysis.

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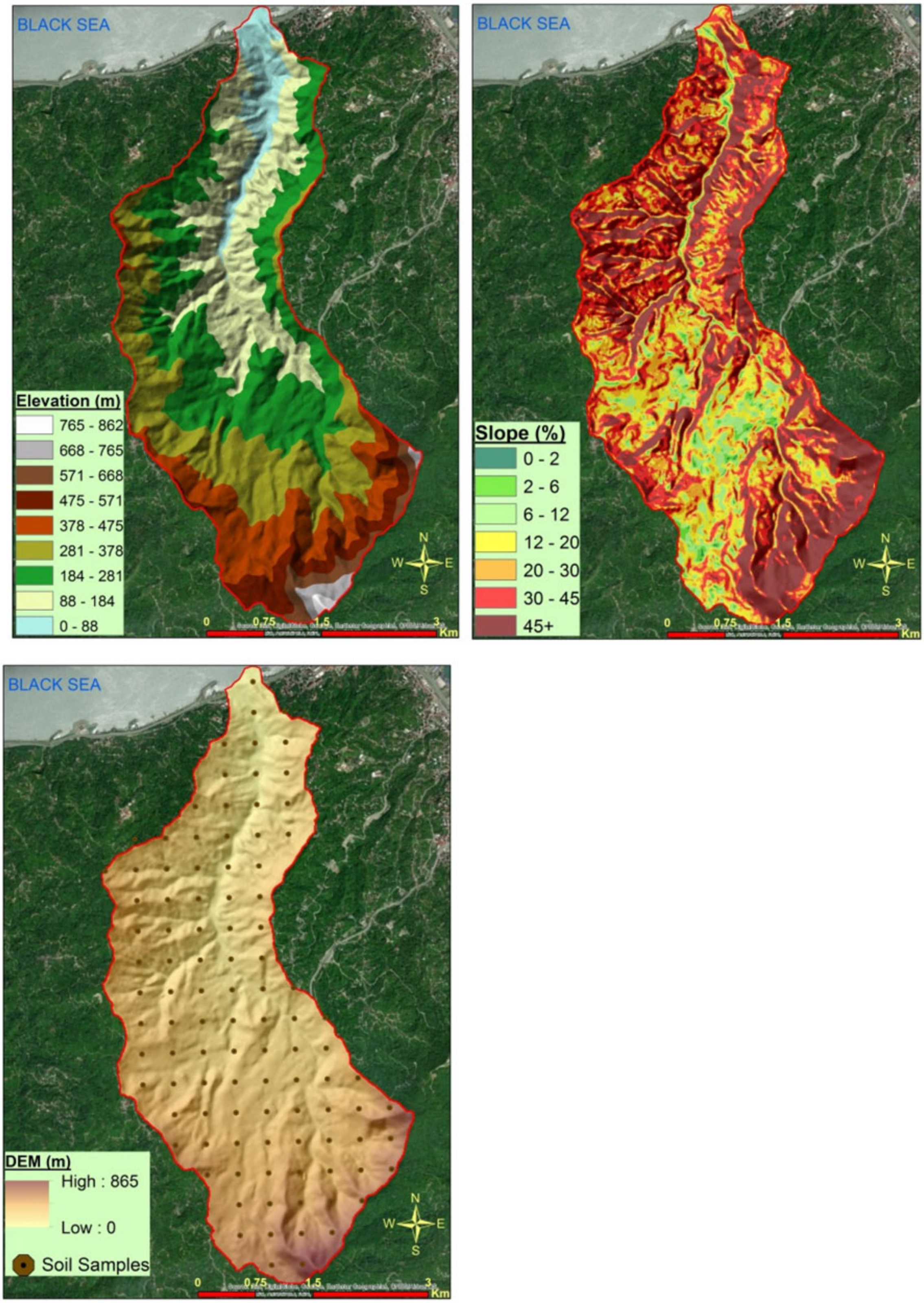

Fig. 2. Elevation, slope and soil sample maps of the study area.

Weighting process- multi-criteria decision-making analysis and soil quality scoring-SSF

Multi-criteria decision-making analysis (MCDA) methods offer numerous methodologies to effectively help decision-makers in complex problems with multiple, conflicting criteria. Analytical Hierarchy Process (AHP) is a mathematical MCDA method developed by Saaty (2008) and frequently used in the literature (Dengiz *et al*., 2020; Özkan *et al*., 2020; Karaca *et al*., 2021). It

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Table 1. Protocol measurements for indicators selected in the study

Parameters	Unit	Protocol	Reference
Aggregate stability (AS)	%	Wet sieving	Kemper and Rosenau (1986)
Dispersion ratio (DR)	%	DR = $(a/b) \times 100$	Lal and Elliot (1994)
Erodibility ratio (ER)	%	ER = $(a/b) \times (A/c) \times 100$	Lal and Elliot (1994)
Structure stability index (SSI)	%	$SSI = \sum a - \sum b$	Lal and Elliot (1994)
Clay ratio (CR)	%	CR = $(100-c)/c$	Bouyoucos (1935)
Crust Formation (CF)	%	CF = %OM × 100/clay% + silt%	Pieri (1989)
Texture (clay, silt and sand)	%	Hydrometer method	Bouyoucos (1951)
Bulk density (BD)	gr/cm^3	Undisturbed condition	Blake and Hartge (1986)
Field capacity (FC)	%	Water retention at 33 kPa matric potentials	Klute (1986)
Permanent wilting point (PWP)	%	Water retention at 1.500 kPa matric potentials	Klute (1986)
Available water capacity (AWC)	%	Calculation (difference between FC and WP)	Klute (1986)
Hydraulic conductivity (HC)	(cm/h)	Soil's saturated condition	Oosterbaan and Nijeland (1994)
Organic matter (OM)	%	Walkley-Black wet digestion	Nelson and Sommers (1982)
pH	1:2.5	(w:v) soil-water suspension	Soil Survey Staff (1993)
Electrical conductivity (EC)	dS/m	(w:v) soil-water suspension	Soil Survey Staff (1993)
Calcium carbonate ($CaCO_3$)	%	Scheibler calcimeter	Soil Survey Staff (1993)
Available phosphorus (AvP)	mg/kg	Bray and Kurtz	Kacar (1994)
Total nitrogen (TN)	%	Kjeldahl	Bremner and Mulvaney (1982)
Ammonium acetate (NH_4OAC–K), calcium (Ca), magnesium (Mg) and sodium (Na)	cmol/kg	Ammonium acetate extraction, flame spectrometry detection	Soil Survey Staff (1993)
Cation exchange capacity (CEC)	cmol/kg	Ammonium and sodium acetate extraction, flame spectrometry detection	Soil Survey Staff (1993)
Diethylenetriamine pentaacetate (DTPA)–copper (Cu), iron (Fe), manganese (Mn), zinc (Zn)	mg/kg	DTPA extraction, atomic absorption spectrometry (AAS) detection	Lindsay and Norvell (1978)
Microbial biomass carbon (C_{mic})	mg C/g dry soil	substrate-induced respiration method	Anderson and Domsch (1978)
Basal respiration (BR)	μg CO_2-C/g dry soil	at field capacity (CO_2 production at 22°C without addition of glucose) was measured,	Anderson (1982)
Microbial biomass (Cmic)/carbon dioxide (CO_2) ratio	unitless	dividing the CO_2-C released from the sample in 1 h by the biomass C	Santruskova and Straskraba (1991)
Metabolic quotient (qCO_2)	unitless	From calculation; (μgCO_2/mgCmic/d = BRrates/Cmic)	Anderson and Domsch (1978)

a is the percentage of silt plus clay in suspension, b is the percentage of silt plus clay dispersed with chemical agent, A is the field capacity, c is the percentage of clay dispersed with chemical agent.

considers the priorities of the group or the individual and evaluates qualitative and quantitative variables together with pairwise comparisons (Saaty, 2008). Saaty (1977) suggested a comparison consisting of values ranging from 1 to 9 that described the degree of importance. Using these comparison matrices, we weighted the soil properties with AHP according to their importance level.

Depending on the correlation level of each factor of the criteria with the soil quality processes, the weight scores were determined using the SSF. When selecting the physical, chemical, productivity and biological indicators of soil quality index for tea cultivation, we took into account many of the previous studies (Kacar, 1984; Özyazıcı *et al*., 2010, 2013; Saygın *et al*., 2017; Dengiz *et al*., 2020; Karaca *et al*., 2021). We also considered some physical quality factors that indicate erosion susceptibility like dispersion ratio, erodibility ratio and structural stability index, as suggested by Dengiz *et al.* (2020). Because of the high precipitation and the steep slopes in the area, the destruction of the surface soil by the vegetation can cause the soil to be replaced by erosion. To convert the soil quality indicators for tea cultivation to unitless values and to obtain scores between 0–1, we used SSF as given in Table 2. Generally, there are 3 scoring functions (Karlen and Stott, 1994; Wymore, 1993). Here, a high score for the parameter indicates a positive relationship between the soil quality and the parameter (more is better-MB), so positive SSF is used. In the other

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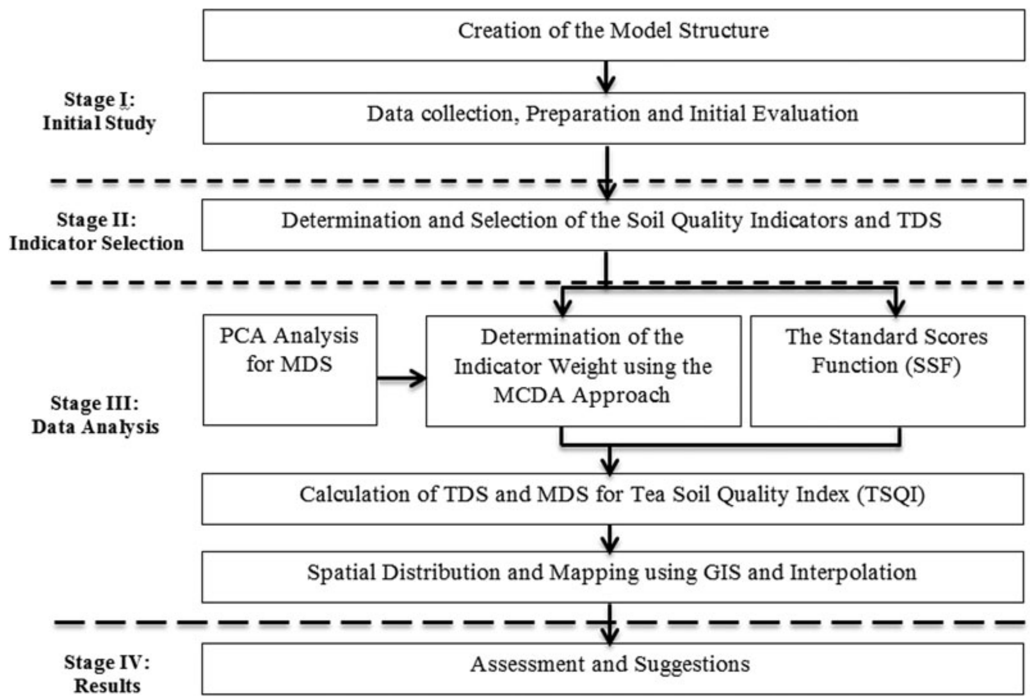

Fig. 3. Modelling architecture designed for the tea soil quality index (TDS: total data set; PCA: principal components analysis; MSD: minimum data set; MCDA: multi criteria decision analysis; SSF: standard scores function; TSQI: tea soil quality index; GIS: geographical information system).

case, negative SSF is used to indicate a lower parameter for better soil quality (less is better-LB). Besides, the parameters that are positively related to soil quality are determined by the optimum SSF scoring formula (Armenise *et al.*, 2013). Here, it was considered as the positive and negative scoring function for parameters presented in Table 2.

While performing an agricultural soil quality analysis for plants, it is appropriate to approach the problem as a multi-criteria evaluation or a multi-criteria decision-making problem. When determining the soil quality status of the land for the tea plant, we used 35 soil and land quality criteria and evaluated them in a hierarchical order in four main groups: physical, chemical, productivity and biological. The AHP was applied both in determining the weight of the main factors and the weight of their sub-criteria. Below is the hierarchical order of these parameters.

If the values of the soil for the determined criteria and their relative importance levels are known, using the weighted linear combination (WLC) method to analyse the soil quality classes is appropriate. WLC is also known as simple additive weighting (SAW), weighted sum, weighted linear average or weighted overlay (Malczewski and Rinner, 2015). This method is based on the weighted average, and an index is created by summing the contributions of each criterion. Using WLC, soil quality for the tea plant is calculated using the formula below.

$$\mathrm{TSQI} = \sum_{k=1}^{l} w_k \times a_{ik}$$

where TSQI is the soil quality index of sample i for tea cultivation, w_k is the degree of importance of criterion k, a_{ik} is the standard value of sample i under criterion k, and l is the total number of criteria (Elalfy *et al.*, 2010). Given the frequency distribution of the index values and statistical information, we deemed it appropriate to show each tea total dataset soil quality index ($\mathrm{TSQI_{TDS}}$) and tea minimum dataset soil quality index ($\mathrm{TSQI_{MDS}}$) in 5 classifications according to the Natural Breaks Jenks method (Jenks, 1967). This method is used when the data are not distributed evenly and there are large differences between the values, requiring classifications (Özkan *et al.*, 2020).

Principal components analysis and creating spatial distribution maps

The purpose of principal components analysis (PCA) is data reduction and interpretation (Johnson and Wichern, 2007). It reduces many variables to a smaller group without losing information and increases the power of interpretation. PCA is a linear analysis. Algebraically, the principal components are expressed as a linear combination of random variables ($x1, x2, \ldots, xp$), where p is the number of variables; geometrically, linear combinations reveal a new coordinate system by rotating the original axes. These new axes represent the aspects of the highest variability (Johnson and Wichern, 2007). The rotation is applied after the components are revealed by PCA. The aim of this rotation is to ensure a better interpretation of the structure by the factors. Whichever method is used to reveal the factor or the components, a good dataset yields similar results. In case of obvious correlations, different rotation methods tend to produce similar results.

We applied a PCA to the data to create the minimum dataset from the selected indicators for determining soil quality for tea cultivation. When determining the parameters that can be included in the minimum dataset, we took into account the component loads determined by PCA, correlation weight sums and correlation analysis methods. We compared the soil quality index values for both the total dataset and the minimum dataset using the T test (Alpar, 2017). The descriptive statistics of the

Table 2. Standard scoring functions (SSF) and selected parameters for soil indicators

Parameters	FT	L	U	SSF Equation[a]
Erodibility ratio	LB	13.6	95.6	$f(x) = \begin{cases} 0.1 & x \le L \\ 1 - 0.9 \times \frac{x-L}{U-L} + 0.1 & L \le x \le U \\ 1 & x \ge U \end{cases}$
Dispersion ratio	LB	5.90	86.2	
Crust Formation	LB	1.77	38.2	
Permanent wilting point	LB	4.90	22.3	
Hydraulic conductivity	LB	2.90	121.6	
Slope	LB	2.00	45.0	
Sand	LB	41.7	79.8	
Silt	LB	13.2	29.2	
Electrical conductivity	LB	36.3	732.1	
Exchangeable sodium	LB	0.03	3.30	
Hydrogen ion content	LB	6.00	81.0	
Metabolic quotient (qCO_2)	LB	0.01	0.20	
Calcium carbonate ($CaCO_3$)	MB	0.21	1.99	$f(x) = \begin{cases} 0.1 & x \le L \\ 0.9 \times \frac{x-L}{U-L} + 0.1 & L \le x \le U \\ 1 & x \ge U \end{cases}$
Clay	MB	4.82	36.2	
Aggregate stability	MB	11.0	86.1	
Structure stability index	MB	3.80	47.0	
Field capacity	MB	12.0	35.0	
Available water capacity	MB	7.00	21.0	
Depth	MB	20.0	90.0	
Organic matter	MB	0.50	11.3	
Available phosphorus	MB	2.86	82.1	
Total nitrogen	MB	0.04	1.27	
Exchangeable calcium	MB	0.10	32.9	
Exchangeable potassium	MB	0.02	9.08	
Exchangeable magnesium	MB	0.13	14.3	
Available iron	MB	2.89	163.3	
Available copper	MB	0.10	2.08	
Available zinc	MB	0.13	3.53	
Available manganese	MB	0.89	47.5	
Cation exchange capacity	MB	15.1	82.8	
Microbial biomass (Cmic)	MB	0.31	9.56	
Basal respiration	MB	0.02	51.5	
Microbial biomass carbon	MB	1.00	33.0	
Cmic/Corg	MB	0.31	9.56	
pH	MB	3.20	5.98	

FT, function type; MB, more is better; LB, low is better; OR, optimal range; SSF, standard scoring function.
[a]In these three equations, x is the monitoring value of the indicator, f(x) is the score of indicators ranged between 0.1 and 1, and L and U are the lower and the upper threshold value, respectively.

soils were determined by PCA using the IBM SPSS 23 package software. Also, the relationship between the total dataset and the minimum dataset was statistically revealed by a Taylor diagram. The images were created using the libraries 'chron,' 'lattice,' 'ggplot2,' 'plotrix,' and 'graphics' on the 'R' software. The Taylor diagram evaluates the similarity, correlations, centripetal root mean squares and the magnitudes of variation between two datasets (Taylor, 2001). We evaluated different interpolation models of soil quality indices for both the total and minimum datasets (Inverse distance weighting-IDW, Radial basis functions, Kriging). We created distribution maps for the fittest model using the ArcGIS 10.5v software. We also used the method that gave the lowest root mean square error (RMSE) when selecting the fittest distribution model. RMSE was calculated by the following

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equation:

$$\mathrm{RMSE}=\sqrt{\frac{\sum(z_{i^*}-z_i)^2}{n}}$$

where; Z_i is the estimated point value, Z_{i^*} is the measured point value, and n is the number of samples.

Results

Physical-chemical, productivity and biological properties of soils

To determine their quality indices, we examined 35 physical, chemical, productivity and biological properties in 102 soil samples in a micro-catchment for tea cultivation. Table 3 gives the basic descriptive statistics of these properties. 13 of these properties were physical quality indicators of tea cultivation soils. The soils were often medium to coarse-textured, their sand ratios ranged from 41.7 to 79.8% and clay ratios ranged from 4.8 to 36.2%. This change in the structure also affected the bulk density (BD) and hydraulic conductivity (HC), and these factors have 1.3 gr/cm^3 and 5.2 cm/h mean values within the area. Clay and organic matter contents are important factors that affect water retention in the soil. The field capacity of the soils ranged from 12.0 to 34.6% and available water-holding capacity ranged from 6.6 to 20.6%.

Most of the lands in the micro-catchment had slopes, and the tea gardens were located on these lands. Also, because the micro-catchment had very high precipitation, the sensitivity of the soils to replacement was increased. In this context, we investigated the erosion susceptibility factors of some soils. Erosion ratio (ER) ranged from 13.7 to 95.7% and clay ratio (CR) ranged from 4.82 to 36.2%. Besides, the soils had average aggregate stability (AS) of 57.5%, dispersion ratio (DR) of 34.8% and structural stability index (SSI) of 25.1%. Considering the skewness coefficients of these parameters, silt, ER, DR, SSI, HC, BD, FC and PWP showed normal distribution, but the other properties showed non-normal distribution. Among the properties with non-normal distribution, sand, CR and AS were negatively skewed, while the others were positively skewed (right). Many researchers accept the coefficient of variation (CV) as an important indicator for changes in soil properties (Dengiz *et al.*, 2020; Şenol *et al.*, 2020; Karaca *et al.*, 2021) and classify it as low (<15%), moderate (15–35%) or high (>35%) based on the value (Wilding, 1985; Mulla and McBratney, 2000). Accordingly, in our study area, sand, ER, AS, DR, SSI and HC had high variability; silt, FC and PWP had moderate variability; the other soil properties had low variability.

We selected 12 parameters as chemical quality indicators. The micro-catchment soils ranged between strongly acid and slightly acid reactions, with an average pH of 3.9. There was no salinity problem in the soils, and EC ranged from 0.04 to 0.7 dS/m. The lime content was quite low at an average of 1.4%. The dominant cation was the hydrogen ion, with an average of 41.8 cmolc/kg, as the soil mostly had a mild to strongly acid reaction. The total basic cation contents ranged from 0.7 to 40.8 cmolc/kg, and the base saturation ranged from 1.7 to 83.9%. Also, the skewness coefficients and the CEC showed normal distribution, while the other properties showed non-normal distribution. In the study area, CEC, total basic cation, base saturation, and H ion had high variability and all the other soil properties showed low variability. Considering the macro and micronutrient properties, total nitrogen (TN) ranged from 0.04 to 1.27% and available phosphorus (AvP) ranged from 2.8 to 82.1 mg/kg. Among available micronutrients, average AvCu, AvZn, AvFe and AvMn contents were 0.3, 0.5, 35.2 and 8.7 mg/kg, respectively. The skewness coefficients of the properties showed non-normal distribution. AvP, AvFe and ExMn had high variability, and all the other soil properties showed low variability.

Today, there are numerous methods and approaches for determining microorganisms and their activities in a micro-habitat (Karaca *et al.*, 2021). Table 3 shows the descriptive statistics of the four indicators considered for the biological soil quality properties. Soil respiration (CO_2) ranged from 0.02 to 1.8 and averaged 0.5. MBC showed significant variability, as in soil respiration, ranging from 1.1 to 32.6 mgC/g dry soil. The average metabolic quotient (qCO_2) was 0.01, and the average Cmic/Corg was 4.6. Besides, the soils showed non-normal distribution, and all were positively skewed (right). In terms of coefficient of variability, MBC and Cmic/Corg showed moderate variability, while all the other soil properties showed low variability.

Creating a minimum dataset

To ensure sustainability in tea cultivation soils and determine the soil quality index, one of the most important steps is to select the most appropriate soil indicators. In this study, we evaluated 35 factors in a total dataset (TDS) to best represent the physical, chemical, biological, productivity and erosion susceptibility properties of soils. We used the PCA to generate this minimum dataset (Doran *et al.*, 1994; Qi *et al.*, 2009; Nabiollahi *et al.*, 2017). Before creating the minimum dataset, we performed a normality test on the dataset. We applied square root transformation on the non-normally distributed parameters: clay, OM, CF, AWC, MBC, pH, AvP, basal respiration, CEC and ExK. We also applied logarithmic transformation on the parameters of EC, TN, AvCu, AvZn, AvFe, Mn, qCO2, ExCa and ExNa. This way, the dataset was approximated to normal distribution. Then, we performed a factor analysis. According to the results, we accepted the groups with eigenvalues equal to or greater than 1 as factors, taking the critical factor load as 0.5 (Wander and Bollero, 1999; Andrews *et al.*, 2002). For each factor, we defined variables with high factor loadings as the most representative indicators, considering that the factors had absolute values at 10% of the highest factor load (Andrews *et al.*, 2002; Sharma *et al.*, 2005; Govaerts *et al.*, 2006; Nabiollahi *et al.*, 2017).

According to our findings, 79.6% of the total variation was explained by these factors (Table 3). After the Varimax transformation, sand had the highest load for factor F1, CF had the highest load for F2 and ExCa and ExMg had the highest load for F3. When multiple indicators have the highest load under a single factor, the correlation coefficient is checked for the minimum dataset (Andrews *et al.*, 2002). Well-correlated variables are considered redundant and only one is considered for the minimum dataset. If there is no correlation, both indicators are selected for a single factor. Accordingly, we chose ExCa with the highest load for F3. Regarding the remaining factors, AvP had the highest load for F4, EO for F5, CEC for F6, depth for F7, AvFe for F8 and MBS for F9 (Table 4).

Soil quality indices for total and minimum datasets with weighting

According to Doran and Jones (1996), to begin a TSQI calculation, soil quality indicators are first defined as soil formation

Table 3. Descriptive statistics of some physical-chemical and biological properties of soil sample

Descriptive Statistic	Mean	S.D.	CV (%)	Variance	Min.	Max.	Skewness	Kurtosis
Physical parameters								
Silt (%)	20.4	3.43	15.9	11.7	13.2	29.1	0.36	0.02
Sand (%)	64.8	8.23	38.1	67.7	41.6	79.7	−0.55	0.17
Clay (%)	14.7	6.63	31.4	44.0	4.82	36.2	0.85	0.52
Erodibility ratio	51.9	20.4	81.9	419.1	13.6	95.6	0.11	−0.76
Clay ratio	85.2	6.63	31.4	44.0	63.7	95.1	−0.85	0.52
Aggregate stability (%)	57.5	13.6	74.9	186.0	11.0	86.0	−0.68	0.75
Dispersion ratio (%)	34.8	14.8	80.2	219.0	5.92	86.1	0.41	0.52
Structure stability index (%)	25.1	9.17	43.2	84.2	3.79	47.0	0.00	−0.66
Hydraulic conductivity (cm/h)	5.16	26.7	118.6	713.7	2.89	121.5	0.27	−0.61
Bulk density (g/cm^3)	1.31	0.13	0.56	0.01	1.02	1.58	−0.17	−0.92
Field capacity (%)	23.7	5.78	22.6	33.4	12.0	34.6	−0.26	−0.59
Permanent wilting point (%)	12.6	4.07	17.4	16.6	4.90	22.3	0.03	−0.41
Available water capacity (%)	11.0	2.20	14.0	4.85	6.60	20.6	0.57	2.42
Chemical parameters								
pH (1:2.5w/v)	3.97	0.51	2.78	0.26	3.20	5.98	1.39	2.38
Electrical conductivity (dS/m)	0.11	0.08	0.70	0.00	0.04	0.73	4.22	27.3
Organic matter (%)	2.87	1.36	6.26	1.87	0.27	6.53	0.54	−0.19
Calcium carbonate ($CaCO_3$; %)	1.37	0.39	1.78	0.15	0.21	1.99	−0.52	−0.23
Cation exchange capacity (cmolc/kg)	47.6	12.6	67.8	160.8	15.1	82.9	−0.13	−0.31
Hydrogen ion content (cmolc/kg)	41.8	15.0	74.8	227.4	5.71	80.5	−0.20	−0.53
Total basic cation	5.82	7.72	40.2	59.7	0.66	40.8	2.81	8.10
Base saturation (%)	13.2	17.1	82.2	95.3	1.74	17.9	2.45	5.71
Soil nutrient elements								
Exchangeable calcium (cmolc/kg)	2.62	5.42	32.8	29.4	0.10	32.9	3.41	12.8
Exchangeable magnesium (cmolc/kg)	1.60	2.55	14.2	6.53	0.13	14.3	2.95	8.99
Exchangeable sodium (cmolc/kg)	0.39	0.35	3.29	0.13	0.03	3.32	6.05	45.6
Exchangeable potassium (cmolc/kg)	1.19	1.13	9.05	1.28	0.03	9.08	3.81	23.1
Total nitrogen (%)	0.28	0.20	1.23	0.04	0.04	1.27	1.59	4.39
Available phosphorus (mg/kg)	31.1	21.0	79.2	444.4	2.86	82.1	0.54	−0.99
Available copper (mg/kg)	0.35	0.28	1.98	0.08	0.10	2.08	3.62	17.3
Available zinc (mg/kg)	0.54	0.52	3.39	0.27	0.14	3.53	3.97	19.7
Available iron (mg/kg)	35.2	26.3	160.4	696.3	2.90	163.3	1.49	4.05
Available manganese (mg/kg)	8.72	7.89	46.7	62.38	0.90	47.6	2.30	6.97
Biological parameters								
Basal respiration	0.50	0.36	1.82	0.13	0.02	1.84	1.38	2.36
Microbial biomass carbon	11.6	7.98	31.4	63.8	1.11	32.5	0.74	−0.44
Cmic/Corg	4.60	3.29	16.5	10.8	0.21	16.7	1.39	2.39
Metabolic quotient (qCO_2)	0.01	0.02	0.15	0.00	0.00	0.15	2.97	10.3

S.D., standard deviation, CV, coefficient of variation.

processes and properties that are sensitive to variability due to natural or artificial indicators. So, soil quality indicators can be divided into two categories: natural and dynamic. Examples of natural indicators are grain size distribution or mineral composition, and an example of dynamic indicators includes soil conditions resulting from the current agro-technology. Wienhold *et al.* (2004) suggested that dynamic indicators are used to evaluate how soil management decisions affect soil

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Table 4. Results of principal component analyses of potential soil quality parameters

	Factors								
Principal Components	F1	F2	F3	F4	F5	F6	F7	F8	F9
Eigenvalue	8.98	5.17	3.40	1.84	1.66	1.50	1.38	1.17	1.11
Percent	27.2	15.6	10.3	5.59	5.03	4.57	4.20	3.55	3.38
Cumulative percent	27.2	42.9	53.2	58.8	63.8	68.4	72.6	76.1	79.5
Eigenvalues									
Depth	0.29	−0.00	0.04	−0.01	0.01	0.09	**0.77**	0.00	0.11
Silt	0.67	0.09	0.08	0.06	−0.26	−0.15	0.03	0.05	0.30
Sand	**−0.92**	0.17	−0.13	−0.08	−0.18	−0.06	−0.12	−0.08	−0.01
Clay	0.79	−0.24	0.15	0.09	0.37	0.18	0.15	0.06	−0.13
Organic matter	0.24	0.86	0.19	0.03	0.00	0.24	0.04	−0.11	0.02
Crust Formation	−0.13	**0.91**	0.12	0.00	−0.07	0.17	−0.02	−0.12	0.01
Hydraulic conductivity	−0.64	0.56	−0.08	−0.07	−0.34	−0.12	−0.11	−0.05	0.11
Aggregate stability	−0.06	0.75	0.03	−0.12	0.31	0.06	0.04	0.17	0.08
Dispersion ratio	−0.23	−0.43	−0.18	−0.02	−0.66	−0.03	−0.33	−0.09	−0.17
Structure stability index	0.60	0.26	0.07	0.04	0.53	−0.03	0.22	0.13	0.11
Erodibility ratio	−0.28	0.06	−0.05	−0.17	**−0.76**	0.04	0.15	0.05	0.06
Bulk density	−0.24	−0.88	−0.20	−0.05	0.16	−0.09	−0.03	0.12	−0.04
Field capacity	0.86	0.25	0.24	0.09	0.164	0.16	0.12	−0.01	−0.06
Permanent wilting point	0.81	0.15	0.21	0.09	0.29	0.21	0.16	0.01	−0.12
Available water capacity	0.77	0.38	0.25	0.07	−0.09	0.04	0.03	−0.06	0.04
Microbial biomass carbon	−0.07	0.58	−0.47	0.05	0.00	−0.09	−0.13	−0.06	**0.48**
pH	0.25	0.22	0.82	0.22	0.01	0.06	0.03	−0.10	0.09
Electrical conductivity	0.15	0.32	0.66	0.25	0.11	−0.24	0.11	0.00	0.04
Calcium carbonate ($CaCO_3$)	−0.03	−0.09	−0.17	−0.11	−0.03	−0.19	−0.05	0.06	−0.73
Available phosphorus	0.18	0.09	0.12	**0.75**	0.05	0.09	0.00	−0.07	0.29
Total nitrogen	0.08	0.56	−0.00	0.13	0.33	0.04	−0.09	−0.13	0.00
Available copper	0.13	−0.05	0.44	−0.22	−0.01	0.21	−0.26	0.59	−0.01
Available zinc	−0.18	−0.34	0.21	−0.51	0.01	0.12	−0.30	0.07	−0.13
Available iron	0.06	0.46	0.08	0.34	0.01	−0.02	0.10	**−0.67**	−0.05
Available manganese	0.12	−0.03	−0.15	0.37	0.03	−0.11	0.01	0.77	−0.15
Metabolic quotient (qCO_2)	0.24	−0.17	0.28	−0.10	0.08	0.00	0.70	−0.10	−0.11
Basal respiration	−0.27	−0.06	−0.67	−0.00	−0.01	−0.25	−0.18	−0.03	0.46
Cation exchange capacity	0.12	0.21	0.01	0.15	−0.00	**0.90**	0.03	0.01	0.04
Exchangeable calcium	−0.07	0.00	**−0.85**	0.17	−0.03	−0.14	0.05	−0.00	−0.10
Exchangeable magnesium	−0.23	−0.07	−0.85	0.17	−0.07	−0.09	−0.03	0.02	−0.08
Exchangeable sodium	−0.06	0.13	−0.31	0.25	−0.09	−0.04	0.48	−0.11	−0.04
Exchangeable potassium	0.05	−0.15	−0.08	0.75	0.16	0.15	−0.05	0.10	−0.10
Hydrogen ion content	0.21	0.25	0.38	0.01	0.01	0.78	0.03	−0.01	0.17

The factor loadings in bold are considered highly weighted.

properties. The 35 soil quality indicators we used here made it possible to reflect the main effects of agricultural practices and the soil properties of the tea plant. We assigned weights to each soil sample after the following procedures. First, we applied one of the most frequently used MCDA methods, the AHP technique, to determine the eigenvector values. In this step, the consistency ratio was set to 0.1. Table 5 shows the contribution weights of soil indicators to T- SQI estimated by AHP. In the hierarchy, B1

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Table 5. Contribution weight of soil parameters to soil quality calculated by the AHP

Hierarchy A						
	Hierarchy B					Wi
	(B1)	(B2)	(B3)	(B4)	(B5)	
Hierarchy C	Physical	Chemical	Nutrient Element	Biological	Erodibility	
Indicators	0.3452	0.1806	0.0772	0.1241	0.2729	Combine weight Σ Bi × Ci
Sand (%)	0.0484					0.0167
Clay (%)	0.2561					0.0884
Silt (%)	0.0700					0.0242
Depth (cm)	0.2079					0.0718
Field capacity (%)	0.1485					0.0513
Available water capacity (%)	0.1102					0.0380
Hydraulic conductivity (cm/h)	0.0768					0.0265
Bulk density g/cm^3	0.0430					0.0148
Permanent wilting point (%)	0.0390					0.0135
pH		0.2702				0.0488
Electrical conductivity (dS/m)		0.0539				0.0097
Organic matter (%)		0.3939				0.0711
Calcium carbonate ($CaCO_3$; %)		0.1052				0.0190
Cation exchange capacity (cmol/kg)		0.1769				0.0319
Total nitrogen (%)			0.2153			0.0166
Available phosphorus (mg/kg)			0.1889			0.0146
Exchangeable potassium (cmol/kg)			0.1482			0.0114
Exchangeable calcium (cmol/kg)			0.1189			0.0092
Exchangeable magnesium (cmol/kg)			0.0960			0.0074
Exchangeable sodium (cmol/kg)			0.0218			0.0017
Available iron (mg/kg)			0.0719			0.0056
Available copper (mg/kg)			0.0369			0.0028
Available zinc (mg/kg)			0.0567			0.0044
Available manganese (mg/kg)			0.0453			0.0035
Microbial biomass carbon				0.3400		0.0422
Basal respiration				0.3094		0.0384
Cmin/Corg				0.2297		0.0285
Metabolic quotient (qCO_2)				0.1210		0.0150
Crust Formation					0.1131	0.0309
Dispersion ratio					0.1400	0.0382
Erodibility ratio					0.2738	0.0747
Aggregate stability					0.3849	0.1050
Structure stability index					0.0881	0.0240
	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

(physical indicators) had the highest value (0.35), while productivity (B3) had the lowest value (0.08). For each hierarchy (B1, B2, B3, B4 and B5), the highest indicator values were found for clay (0.26), OM (0.39), TN (0.22), basal respiration (0.34) and AS (0.39), respectively.

Secondly, we determined score values for all indicators according to their function on soil quality using a SSF approach, corresponding to a value between 0 and 1, meaning high and low function. We assigned an eigenvector value to each indicator and determined the scoring values. Finally, we determined the

Table 6. Interpolation models and RMSE values of $TSQI_{TDS}$ and $TSQI_{MDS}$

Interpolation	Semivariogram model	$TSQI_{TDS}$ RMSE	$TSQI_{MDS}$ RMSE
IDW	IDW-1	**0.0615**	0.0895
	IDW-2	0.0623	0.0886
	IDW-3	0.0642	0.0908
RBF	TPS	0.0738	0.1118
	CRS	0.0624	0.0885
	SWT	0.0622	**0.0884**
	Ordinary		
Kriging	Gaussian	0.0617	0.0896
	Exponential	0.0616	0.0896
	Spherical	0.0617	0.0890
	Simple		
	Gaussian	0.0616	0.0896
	Exponential	0.0624	0.0892
	Spherical	0.0619	0.0891
	Universal		
	Gaussian	0.0610	0.0896
	Exponential	0.0616	0.0890
	Spherical	0.0617	0.0891

Bold number shows the lowest RMSE values for each semivariogram.
RMSE, root mean squire error; IDW, invers distance weight; RBF, radial base function; TPS, thin plate spline; CRS, completely regularized spline; SWT, spline with tension; $TSQI_{TDS}$, tea soil quality index-total data set; $TSQI_{MDS}$, tea soil quality index-minimum data set.

TSQI value for each soil sample using the WLC technique. We then applied the same process to the indicators in the minimum dataset determined by PCA analysis [physical indicators: erosion ratio (ER), crust formation (CF), available phosphorus (AvP); productivity indicators: ExCa and AvFe ions; chemical indicator: cation exchange capacity (CEC); biological indicator: MBC.

To create a spatial distribution map for the soil quality indices of the tea cultivation soils in the micro-catchment, we determined the most suitable distribution models for the TSQI values of each point using different interpolation methods. The RMSE values for both the total and minimum data sets are shown in Table 6. Accordingly, the lowest RMSE was observed for the Invers Distance Weighting (IDW-1) model in the total dataset ($TSQI_{TDS}$) and the Spline with Tension (SWT) model of Radial Base Function (RBF) in the minimum dataset ($TSQI_{MDS}$).

The spatial and proportional distributions of the $TSQI_{TDS}$ and $TSQI_{MDS}$ indices and classes are shown in Table 7, and the maps are given in Fig. 4. Accordingly, the spatial distributions were quite similar between the $TSQI_{TDS}$ and $TSQI_{MDS}$ indices. Low and very low-class areas constituted 34.1% of the total area in $TSQI_{TDS}$ and 33.6% of the total area in $TSQI_{MDS}$. Very high and high-class areas constituted 56.2% of the total area in $TSQI_{TDS}$ and 55.3% of the total area in $TSQI_{MDS}$. Also, nearly 10% of the study area had moderate class soil quality.

Table 8 shows the descriptive statistics and T-test results for the soil quality indices obtained by assessing the two datasets. According to the total dataset with 35 indicators ($TSQI_{TDS}$), soil quality indices ranged from 0.3189 to 0.6443. 64.3% of the soil samples were very low and low class, and 49.0% were high and very high class. According to the minimum data set ($TSQI_{MDS}$), soil quality indices ranged from 0.3159 to 0.7257. 45.1% of the soils were very low and low class, and 39.2% were very high and high class. In both datasets, nearly 16% of the total area was moderate class. The T-test performed to determine the significance of the difference between the two datasets showed a P-value of zero. Also, considering the correlation between $TSQI_{TDS}$ and $TSQI_{MDS}$ by a Taylor diagram (Fig. 5), there was a statistically significant difference between the datasets, although the distribution maps showed a close pattern among the soil quality indices.

Discussion

Soil is the basis of all agricultural production. Therefore, the first condition to obtain the desired amount and quality of a product is to increase soil fertility and quality. One of the most important factors for increasing soil fertility is plant nutrients; however, protecting the chemical, physical and biological content of the soil should not be ignored. In terms of soil properties, the tea plant likes acidic soils and shows optimum growth in soils with a pH of 5.0 to 6.0 and low in active lime content. It is adversely affected by acid or alkaline changes in soil pH and when it falls below 4, a product with the desired yield and quality cannot be obtained (Saygın *et al.*, 2017). Physical and chemical properties that have been taken into consideration in the current study showed variability as a result of dynamic interactions among natural

Table 7. Spatial distribution of index values for $TSQI_{TDS}$ and $TSQI_{MDS}$ in the study area

	$TSQI_{TDS}$			$TSQI_{MDS}$		
		Area			Area	
Class	Index value	ha	%	Index value	ha	%
Very low	0.3189-0.4406	267.7	16.0	0.3159-0.4282	193.6	11.6
Low	0.4406-0.4701	302.4	18.1	0.4282-0.4893	367.2	22.0
Moderate	0.4701-0.5085	161.0	9.6	0.4893-0.5552	186.7	11.2
High	0.5085-0.5470	512.7	30.7	0.5552-0.6131	425.8	25.5
Very high	0.5470-0.6443	427.1	25.6	0.6131-0.7257	497.6	29.8
Total		1670.9	100.0	Total	1670.9	100.0

$TSQI_{TDS}$, Tea soil quality index-total data set; $TSQI_{MDS}$, tea soil quality index-minimum data set.

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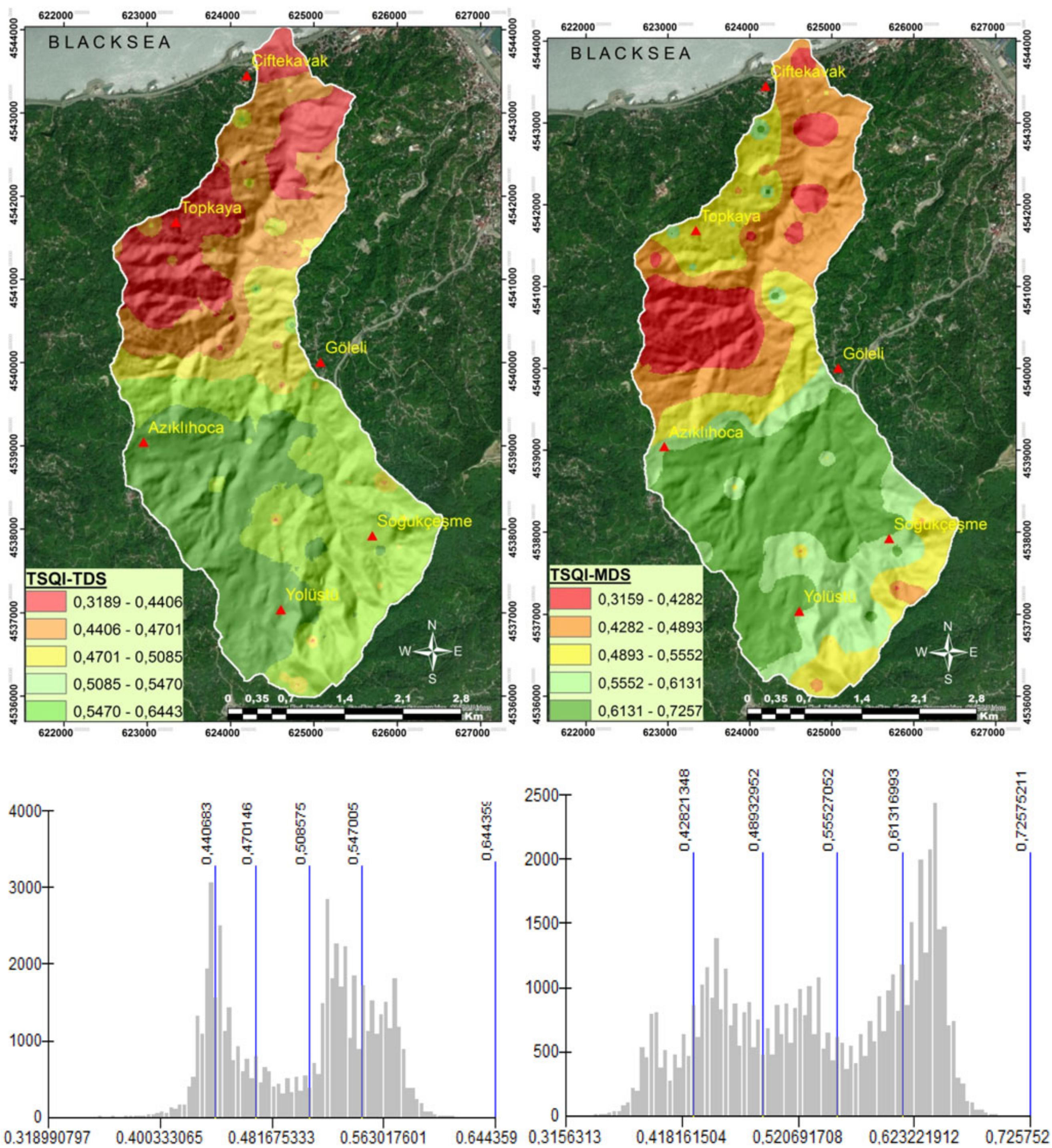

Fig. 4. Index values using natural breaks and spatial distribution maps of tea total dataset soil quality index ($TSQI_{TDS}$; left) and tea minimum dataset soil quality index ($TSQI_{MDS}$; right).

environmental factors (degree of soil development and leaching processing etc.) and human activities such as fertilization management. In the present study, soils were in the medium-fine and course texture group, and their texture classes were determined as sandy clay loam (SCL), loam (L), sandy loam (SL) and clay loam (CL). Mostly catchment soils have coarse texture therefore their FC and AWC values are low. Also, these findings are similar to those of a study conducted by Miháliková *et al.* (2016). Classification of studied soil properties was made according to Lindsay and Norvell (1978); FAO (1990); Arshad and Martin (2002); Borůvka *et al.* (2005); Hazelton and Murphy (2016). The values of pH in soil samples slightly ranged between from strong acid to moderately soil reaction, whereas electrical conductivity had low values called as ‘non-saline’ soils. In addition, $CaCO_3$ mean is less than 2% in all soil samples. Therefore, the $CaCO_3$ content of the study area soils was classified as ‘limeless’ and ‘low limey’, OM content varied from ‘low’ to ‘high’. In addition, micro nutrient elements were found in

Table 8. Results of T-test

	Minimum	Maximum	Mean	St.Dev	T-Value	*P*-Value
$TSQI_{TDS}$	0.31	0.64	0.51	0.08	−1.46	<0.001
$TSQI_{MDS}$	0.32	0.73	0.54	0.12		

$TSQI_{TDS}$, total data set of soil quality index for 35 indicators; $TSQI_{MDS}$, minimum data set of soil quality index for 9 indicators; St. Dev., standard deviation.

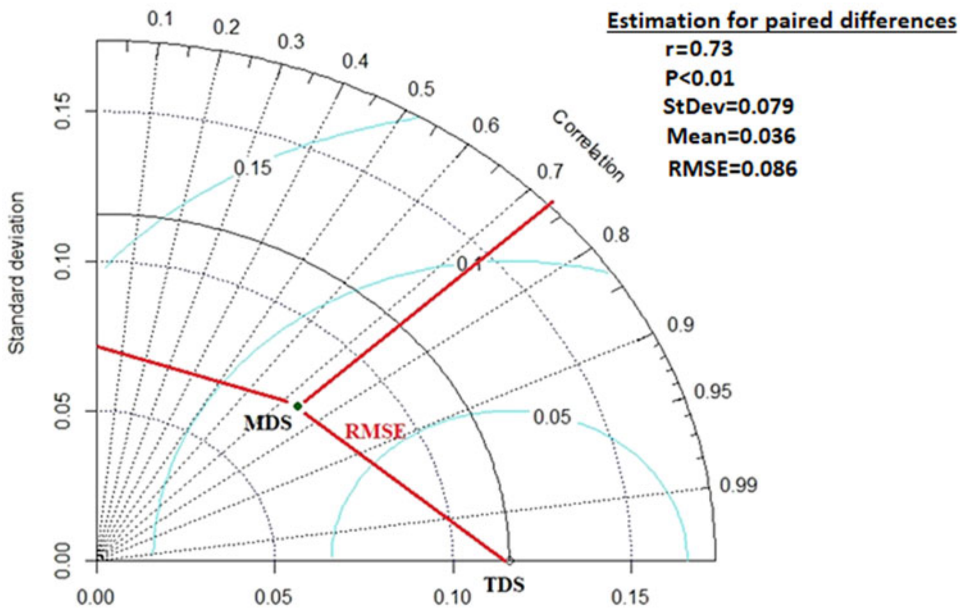

Fig. 5. Taylor diagram between total data set (TDS) and minimum data set (MDS).

sufficient amounts in some of the soil samples and their mean values. The pH of the soil solution maintained at acid condition showed high mobility of micro nutrient elements. Also, it could be attributed to the leaching of calcium carbonates at a very low concentration. Similar outcomes were reported in some few investigations such as Özyazıcı *et al.* (2013), Saygın *et al.* (2017), Bayraklı and Dengiz (2020) carried out in the Black Sea region. As for macronutrient element of samples, available P and exchangeable K showed high variation between minimum and maximum values. Also, N contents of the soils are 'low', 'sufficient' and 'high', respectively and phosphorus was determined as 'low', 'sufficient', 'high' and 'very high' in the soils, respectively. Moreover, various microbial response parameters like MBC, basal respiration and metabolic quotient are often used to evaluate soil organic matter stabilization, soil aggregation and soil quality and monitor soil formation (Rogers and Li, 1985). One of the most influential factors here is the activity of the microbial population for obtaining energy and nutrients like organic matter or organic carbon and N, P, K, Ca, Mg, etc. In the present study, MBC showed the highest variability in selected biological indicators.

To monitor soil quality status under long term cultivated tea farming, continuous monitoring of soil quality is crucial because it changes in response to environmental changes and human interventions. In addition, the tea field productivity is determined by soil fertility and management system, such as fertilization, land management, irrigation system and returning organic material from the crop residues after harvest to the field. Therefore, analysing soil quality status on tea areas in a micro-catchment of Rize province that applied the TSQI method as a viewpoint for decision-makers in soil quality and fertility management is necessary.

We investigated 35 bio-physical-chemical factors in told data set (TDS) to derive their quality indexes. It was also reported that using minimum data sets (MDS) to determine soil quality indicators gives the best results in terms of fewer costs, less workforce and higher data quality (Şenol *et al.*, 2020). Hence, we created a MDS to reduce data redundancy and identify the optimal indicators. Thus, nine bio-physical-chemical properties were determined for MDS (sand, CF, ExCa, AvP, EO, CEC, soil depth, AvFe and MBS). The parameters for MDS and TDS both need to be weighted.

With multiple characteristics and a heterogeneous system, closely related physical, chemical, mineralogical and pedological properties, as well as individual characteristics, the soil is a complex system and its management should include all these aspects. Otherwise, irreversible mistakes can be made (Ferman and Skapura, 1991). The efficient and sustainable use of soils is only possible by determining the limiting factors that affect productivity and the properties that affect sustainability using the appropriate methods. The traditional approach has been based on explaining or analysing certain properties and their fitness to various criteria using specific tools for each property and measuring the positive or negative dependent correlations between these properties. Even though fertilization programmes based on analysis were developed, this practice is not sufficient to maintain or improve plant productivity and production in its current form. Soil is a complex system with multiple variabilities. Evaluating the soil only in terms of nutrient content and ignoring other properties cannot ensure productivity or sustainability.

The AHP method, one of the widely used multi-criteria approaches, was considered for this operation's performance. The results explain why B1 (Physical) and B5 (Erodibility) had the highest values (Table 5). Soil texture is an unchangeable-hereditary property of soils. The amount and type of clay is a key soil property that affects the physical, chemical and even biological properties of soils. It has direct and indirect effects on the physical properties of soils like water-holding capacity, aggregate formation and permeability, as well as on their chemical properties like cation exchange capacity (Şenol *et al.*, 2020). Dengiz and Sarıoğlu (2013) also reported the amount and type of clay to be one of the main properties of soil quality criteria. Haghighi Fashi *et al.* (2017) highlighted that this parameter had significant effects on soil compaction indicators like penetration resistance and bulk density, moisture level at field capacity and available water for the plant.

Most of the tea gardens in our study area are located on steep slopes. Also, this area has over 2300 mm of precipitation annually. Therefore, it is potentially at high risk for erosion as the soil surface is unprotected, especially during tea planting or management (regeneration-renewal). Hence, aggregate stability, dispersion ratio and other erosion susceptibility parameters were determined. Dengiz *et al.* (2020) reported a similar situation for the Orta Çay micro-catchment where tea cultivation is performed, using similar parameters to determine the erosion susceptibility of the soils due to the slopes and the lost or weakened vegetation due to improper practices. Karaca *et al.* (2021) investigated the soil quality of pasture soils in a semi-arid ecosystem to determine erosion susceptibility due to overgrazing, especially in slopes. For this, the authors considered aggregate stability, dispersion ratio and crust formation as key indicators. Because, these factors have a more important role than other soil properties for plant growth, which is directly or indirectly affected by the risk of land degradation-desertification due to misapplications. Demirağ Turan *et al.* (2019) reported that intensive agricultural practices and improper land management, like overgrazing, particularly on slopes, were the main causes of soil degradation. The authors emphasized that such practices caused poor physical conditions: e.g., lower aggregate stability or erodibility factors like high dispersion ratio and crust formation, thus lowering resistance to erosion. Therefore, the physical soil quality indicator coded as B1 was detected the highest weighted value.

Within the B2 hierarchy (chemical), the OM content of soils has great importance and the highest value with its influence on biological and physiochemical soil properties (Table 5). This indicator is also involved in reducing erosion risks, storing and supplying nutrients, improving overall soil fertility and affecting cation exchange capacity. It can also be affected by soil and tea plant management practices. Alaboz *et al.* (2017) found that OM content was one of the most effective parameters for increasing aggregate formation, water-holding capacity, biological activity and productivity. Thus, it is well known that soil OM content is a significant indicator of both land productivity dynamics and terrestrial ecosystem functions. Another key chemical indicator within this hierarchy is soil reaction. The tea plant cannot grow well in strong acid conditions like pH<4 (Saygın *et al.*, 2017), but some soil samples have a lower reaction than 4. Also, management practices like adding lime, regulating pH and fertilization and eliminating insufficient macronutrients or micronutrients have been applied to meet the requirements of the tea plant. EC was chosen as an indicator here as in most studies, but since there was no salinity problem in the study area, it had the lowest weight value in the B2 hierarchy (0.0539). The B1 and B5 hierarchies are more stable properties and are related to formation, but the B2, B3 and B4 hierarchies include the dynamic properties of the soil and are constantly changing. In the B3 hierarchy, the macronutrients total nitrogen and available phosphorus had the highest weight values. The tea gardens in this study were from the Acrisol-Alisol large soil group, which commonly had low base saturation capacity, with pH values less than 5. So, nitrogen fertilizers like calcium ammonium nitrate should be used as nitrogen fertilizers to prevent further increase in acidity.

In the B4 hierarchy (biology), MBC had a weight of 0.3400. Soil microorganisms are important for soil organic matter dynamics and for maintaining the pool of nutrients in the plant. Therefore, microbial properties like microbial biomass and respiration ratio are often used as sensitive indicators of ecosystem responses to soil stress and exogenous disturbance. Parameters like the ratio of biomass C to organic C (Anderson and Domsch, 1989) and a metabolic fraction (qCO_2) (the ratio of respiration to biomass) (Anderson and Domsch, 1985) are useful when comparing different soil types because of increased soil organic ratio. The C content often increases microbial biomass C and respiratory ratio. Besides, the ratio of biomass C to organic C under steady-state conditions can be considered an indicator of C availability in soils (Insam and Domsch, 1988). qCO_2 can indicate the relative effectiveness of soil microbes in the use of C (Anderson and Domsch, 1993). A relatively low qCO_2 value indicates a certain amount of metabolized organic carbon and a lower proportion of exhaled carbon so that the larger carbon is assimilated into MBC cells. Moreover, Islam and Weil (2000) report that in case of low qCO_2, soil microorganisms wait for relatively labile carbon to exist and can allocate more resources for activities like the growth, degradation and recycling of plant nutrients, improving soil quality. Also, biological parameters are often used as indicators of microbial response to land degradation. Disturbed soils, rather than natural and undisturbed soils, are expected to display a relatively lower biomass C/organic C ratio and a higher qCO_2. According to our findings, all samples had low qCO_2 and high biomass C/organic C ratio, indicating that the micro-catchment was undisturbed.

After the consistency of the weighting process, we used a conventional scoring function approach to determine the score values for each indicator based on how well they relate to soil quality. Thus, weighted and scored values were combined using the WLC approach for each soil samples. In order to generate spatial distribution maps of $TSQI_{TDS}$ and $TSQI_{MDS}$ geostatistical approach were applied. After this process, it was realized that the spatial distribution of TSQI values were quite similar between the $TSQI_{TDS}$ and $TSQI_{MDS}$ indices. There was also a close pattern in the both maps. According to results, about one third of the total study area ($TSQI_{TDS}$ and $TSQI_{MDS}$) for has low and very low soil quality. These areas were mostly in the central and northern parts of the micro-catchment (Çifte Kavak and Topkaya). These areas had a strong acid reaction, coarse texture with very high sand content and low organic matter, resulting in low water-holding capacity, nutrient elements and poor biological activity, hence the low soil quality. Soils are a significant component of land management due to their decomposition of plant residues and their crucial role in the nutrient-water cycle (Karlen *et al.*, 2003). Therefore, organic waste applications (vermicompost, compost, barn manure, etc.) are suitable for increasing the organic matter levels in such areas with low quality. Many physical properties of soils are associated with texture, but some properties like bulk density and infiltration ratio can be affected by land and soil application systems (Bharati *et al*., 2002). On the other hand, more than half of the study area for $TSQI_{TDS}$ and $TSQI_{MDS}$ is in very high and high soil quality classes. These areas were mostly in the middle and south-southeast parts. Additionally, the soil quality was in the moderate range in almost 10% of the research area.

Conclusion

The present research analysed the soil quality index of tea cultivation soils in a micro-catchment with long term intensive tea cultivation in Rize in the Eastern Black Sea Region under humid ecosystems. We took 102 representative soil samples from the micro-catchment, ensuring a near- homogeneous distribution. Considering their effects on the tea plant, 35 indicators were grouped according to 5 main criteria (physical, chemical and biological properties, nutrition status and erodibility). We applied a PCA to the soil quality index to evaluate the physical, chemical, productivity and biological parameters and then to determine the most important ones. Because, PCA is a useful tool that saves time and costs with its sampling and analysis and ensures practical, economical and reliable results under similar ecological conditions, removing certain SQI data from the list of factors and determining the most influential ones. Besides, we used the analytical hierarchical process, an important MCDA approach, to determine the contribution rates of these indicators for tea cultivation soils. In the current study, the soil quality classes were calculated using the $TSQI_{TDS}$ and $TSQI_{MDS}$ approaches, and they showed statistical differences, though parallel spatial distributions. Over half of the soils in the study area had high to very high soil quality properties, and about one-third of the total area had low to very low soil quality. Low soil quality properties were particularly more common in the northern and north-western parts of the area, and soil quality tended to increase towards the south. Thus, in areas with low soil quality, some biophysical measures need to be taken to increase soil quality levels, such as creating an optimum growing environment for the tea plant by liming, applying an appropriate fertilization programme and increasing the soil's erosion resistance.

Consequentially, the following are this study's primary outcomes and strengths: (i) by combining SMCA, SSF, PCA, GIS and geostatistical approaches, the soil quality map for tea cultivation expanded the available planning possibilities, (ii) the study's facilitating the development thorough assistance for examining and evaluating soil quality for the production of tea, (iii) this present research will produce an important and practical strategic planning framework for humankind, land planning, agricultural land use planning and food security. Consideration and adoption of this strategy at the national level will result in notable enhancements in product efficiency and quality on the international market, (iv) this research can help farmers, tea growers and regional planners make better options and selection about where to plant tea and (v) The model developed in this study can be applied as a planning tool for tea cultivation in different study regions.

Furthermore, the soil quality assessment used here provides a useful decision- making approach to assist tea producers and decision-makers in evaluating soil fitness for the tea plant. In addition, socio-economic and cultural factors that allow for better decisions should also be considered when making final decisions.

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