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Determining the effects of the forest stand age on the soil quality index in afforested areas: A case study in the Palandöken mountains

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Abstract: Afforestation is an essential strategy for erosion control. The objective of this study was to determine the soil quality index (SQI) in established afforested areas of different ages for erosion control in Erzurum, Turkey. Three afforested areas were selected as plots considering their establishment periods: + 40 years old ($AA_{>40}$), 10–40 years old ($AA_{10–40}$), and less than 10 years old ($AA_{<10}$). Forty soil samples were taken in each plot area over the 0–15 and 15–30 cm depths. The soil samples were analysed for the texture, mean weight diameter, aggregate stability, pH, electrical conductivity, total nitrogen, total carbon, and total sulfur contents. These properties were used as the soil quality indicators, whereby the analytic hierarchy process (AHP) and principal component analysis (PCA) were used to establish their relative importance for describing the soil quality. The indicators were scored using the linear score functions of "more is better" and "optimum value". For determining the SQI, the additive method (SQI_A), the weighted method with AHP (SQI_{AHP}), and the weighted method with PCA (SQI_{PCA}) were used. The SQI scores of the plots showed statistically significant differences. In all three methods, the highest SQI value was obtained from the $AA_{>40}$ plots.

Keywords: analytic hierarchy process (AHP); principal component analysis (PCA); degradation; ecosystem; forest

Since soil erosion can result in reduced soil productivity due to changes to the soil chemical and biological environment, accelerating the loss of nutrients, suppressing or eliminating the soil biota, reducing the soil pore space and soil sealing (Krasilnikov et al. 2016), the impacts of soil erosion are seen as key concerns for the sustainable management of the soil (Porto et al. 2009). Degradation resulting from erosion strongly affects the efficiency of ecosystem functions and services (Sutton et al. 2016; Cerretelli et al. 2018).

Afforestation is widely used for the restoration of ecosystem functions in degraded lands prone (or vulnerable) to erosion (Qi et al. 2009; Zhao et al. 2018; Zethof et al. 2019). The role of forestry has long been recognised as a protective measure of soil erosion by stabilising the topsoil, enriching the soil with organic matter and bringing about a favourable moisture regime for the complex environment (Siyag 2013). In many studies, it was determined that afforestation with both single and mixed tree species improves the soil's physical (Chen et al. 2016; Zhao et al. 2018), chemical (Chen et al. 2016; Li et al. 2018) and biological (Liu et al. 2018a) properties.

Soil quality is the capacity of a soil to function and promote plant and animal productivity, maintain or

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enhance the water and air quality, and support human health and habitation (Karlen et al. 1997). The soil quality index is a quantitative assessment concept and is widely used in the evaluation of agricultural production areas (Qi et al. 2009; Rodríguez et al. 2016; Vasu et al. 2016). Maintaining and promoting soil quality is a fundamental requirement to ensure ecosystem sustainability (Delelegn et al. 2017). Therefore, the soil quality index has recently been used in the evaluation of ecosystem components (Mukhopadhyay et al. 2016; Chaves et al. 2017; Liu et al. 2018b).

The soil's physical, chemical and biological properties are combined to develop a soil quality index. The most important problem overlooked in calculations using multiple parameters is that the effects of the used parameters are considered equal. In studies where the quality index value is determined, the randomness and uncertainty in the weight determination process must be eliminated (Guo et al. 2020). In this study, an analytic hierarchy process (AHP) and a principal component analysis (PCA) were used to determine the weight of each indicator. AHP and PCA have been used by researchers to weigh the parameters in soil quality index studies (Turan et al. 2019; Guo et al. 2020).

The Palandöken Mountains, located in the southern part of the Erzurum province, are downstream urban area. The mountains also have important potential for animal husbandry. Manmade forests, dominated by *Pinus sylvestris* L., and grasslands are the main landscape types in this area. The forest cover has increased since 1967 when afforestation was implemented for erosion control and many semi-arid rangelands were converted to *Pinus sylvestris* L. forest stands. Erzurum city is located about 35 km from the closest forest, so it cannot benefit from the very important contributions that forests provide to urban settlements. While the Palandöken afforested areas undertake basic functions such as soil protection and erosion prevention, they also provide ecosystem services such as preventing flood hazards after irregular rainfalls, hosting wildlife, preventing air pollution, filtering harmful particles in the air, increasing air quality, minimising evaporation by reducing the temperature of the area in the summer, providing carbon storage, contributing to the visual quality of the Palandöken ski resort and creating an environment for recreational activities. Thus, they significantly eliminate the disadvantage of the city centre being away from the forests. Due to these features, the Palandöken afforested area, which is a special ecosystem, were chosen as the study area. Although afforestation has been applied for a long time, there is less knowledge about the effects of the afforestation on the soil properties in these ecosystems. Thus, this study was carried out to examine the effects of the different afforestation periods on the soil properties, soil quality index and carbon-nitrogen storage using different weighting approaches.

MATERIAL AND METHODS

Study area. The study areas were in the afforested sites in the Palandöken Mountains (Figure 1). The areas are situated approximately 10 km south of Erzurum province, in north-eastern Turkey. The region is identified as having a semi-arid and continental climate, according to the long-term period (1929–2019), the mean annual temperature is 5.7 °C and the mean annual precipitation is 431.4 mm (General Directorate of Meteorology 2020). The slope of the study area is 20–25% with elevations ranging from 2 000 to 2 200 m a.s.l. The site characteristics of the study area are given in Table 1. The main

Table 1. Geographic and topographic characteristics as well as the main rock, soil class, and vegetation cover of the afforested areas: fewer than a 10 year-old afforested area ($AA_{<10}$), a 10–40 year-old afforested area ($AA_{10–40}$), and more than a 40 year-old afforested area ($AA_{>40}$)

	$AA_{<10}$	$AA_{10–40}$	$AA_{>40}$
Coordinates	37S 698 153E, 4 416 892N	37S 696 268E, 4 415 820N	37S 694 746E, 4 415 017N
Elevation	2 250–2 270	2 180–2 200	2 200–2 220
Slope (%)	19–25	25–30	25–30
Aspect	northwest	north	north
Main rock	andesite	andesite	andesite
WRB soil taxonomy	Haplic Kastanozem	Haplic Kastanozem	Haplic Kastanozem
Vegetation	*Pinus sylvestris*	*Pinus sylvestris*	*Pinus sylvestris*

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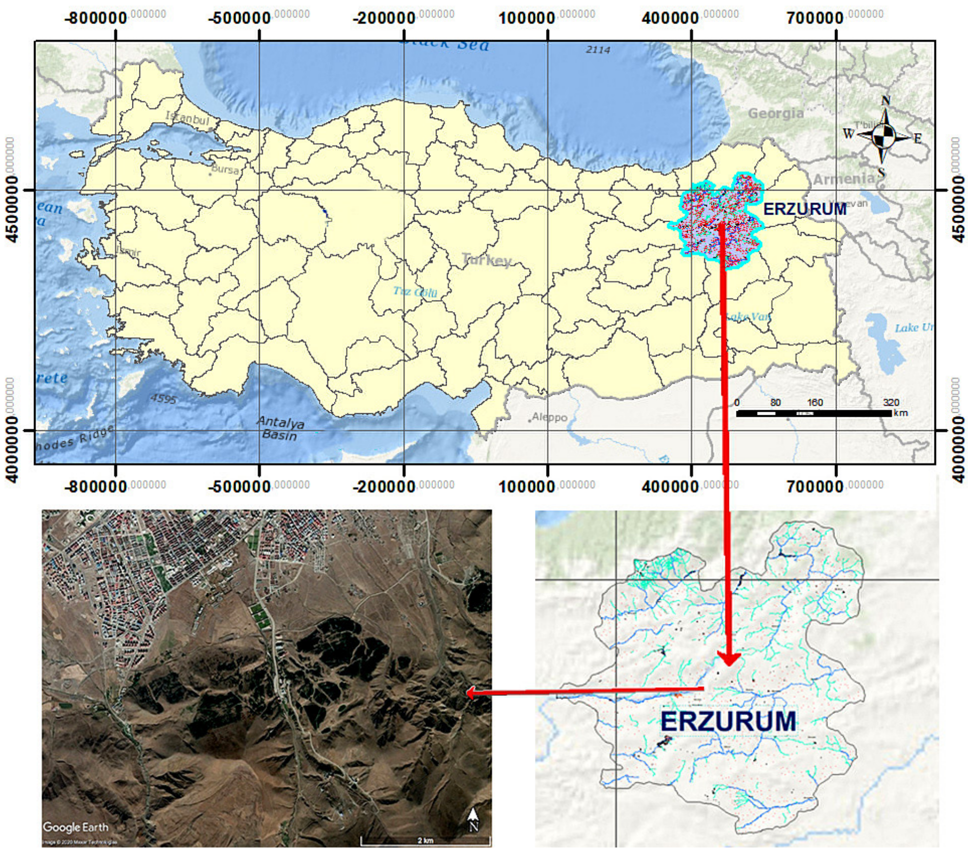

Figure 1. Location maps of the study area

parent material is andesite (Akbas et al. 2011) and the native vegetation is rangeland composed of *Astragalus eriocephalus* Wild, *Bromus tectorum* L., *Bromus tomentellus* Boiss., *Festuca ovina* L., and *Thymus* sp. (Çomaklı et al. 2012). Some rangelands have been converted into forests, dominated by *Pinus sylvestris* L., since 1967.

Sampling pattern and analyses. Three plots were selected considering the afforestation dates in the study area, the first site is under 10 years old (site $AA_{<10}$), the second site is 10–40 years old ($AA_{10–40}$), and the third site is over 40 years old ($AA_{>40}$). $AA_{<10}$ refers to the afforestation activities that started in 2010 and continue today. In $AA_{10–40}$, the afforestation started in the 1970 s and was completed in the early 2000 s. The exact records of the $AA_{>40}$ afforested stand date back to 1967. In addition, replacement planting was carried out in these afforested areas in different periods. Within each plot, with an area of approximately 3 ha, twenty soil samples were collected randomly at each depth (0–15 and 15–30 cm). The soil samples were taken with an auger after removing the litter.

The soil samples were air-dried and passed through a 2 mm sieve. The hydrometer method was used to determine the particle size distribution (Gee & Bauder 1986). The aggregate stability (AS) of the 1–2 mm aggregate size was determined with the Yoder wet-sieving method with a 0.25 mm mesh size (Kemper & Rosenau 1986). The aggregation rate was calculated by Equation (1) using the weight of the sand obtained in the aggregate stability analysis.

$$AR = [(SW - SaW)/SW] \quad (1)$$

where:

AR – aggregation rate (%);

SW – sample weight that was used in the aggregate stability;

SaW – the sand weight that was determined by the aggregate stability analysis.

The total carbon (TC), total nitrogen (TN) and total sulfur (TS) contents of the soils were identified using an elemental analysis device (Vario MACRO cube CHNS elemental analyser; Elementar, Langenselbold, Germany). The pH and EC values of

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the soils were measured in a 1 : 2.5 soil : water suspension (Conklin 2013). To determine the mean weight diameter (MWD), the air-dried soil samples were sieved manually on a column of five sieves: 2, 0.850, 0.500, 0.250, 0.180, 0.150 mm, resulting in the collection of six aggregate size fractions: 2–0.850, 0.850–0.500, 0.500–0.250, 0.250–0.180, 0.180–0.150, and 0–0.150 mm and the weight percentage of each aggregate-size fraction was calculated. Lastly, Equation (2) was used to calculation the MWD (Van Bavel 1950).

$$\text{MWD} = \sum\nolimits^{n}_{i=1} x_i y_i \qquad (2)$$

where:

y_i – the proportion of each size class by weight concerning the total sample;

x_i – the mean diameter of the size classes (mm).

Statistical analyses. Descriptive statistics, including the averages, standard deviation, minimum and maximum values, and the coefficient of variation were determined for all the studied soil properties. The Shapiro-Wilk W test was used to determine whether the soil properties fit the normal distribution. Moreover, an analysis of variance (ANOVA) was applied in determining the differences between the afforested areas and the soil layers in terms of the soil properties. Post-hoc comparisons were made using Tukey's test. The statistical analyses were performed with JMP statistical software (Ver. 5.0 ; SAS Institute Inc., Cary, USA).

Soil quality index (SQI) evaluation methods. The soil quality index (SQI) was used for a comprehensive comparison of the effect of the afforestation on the soil properties. The additive soil quality index (SCI_A) method, the weighted additive soil quality index using the AHP (SQI_{AHP}) method, and the weighted additive soil quality index using the principal component analysis (SQI_{PCA}) method were used for the SQI calculation. To calculate the SQI, the steps of selecting the indicators, weighting indicators, and scoring indicators were followed (Karlen et al. 1997). The soil properties that differed significantly along with the afforestation periods were selected as the indicators such as the clay, silt and sand content, mean weight diameter (MWD), pH, electrical conductivity (EC), aggregate stability (AS), aggregation rate (AR), TC, TN, and TS.

Two different weighting methods were used for the AHP and the PCA. A pairwise comparison matrix was created to determine the weights of the indicators according to the AHP methodology. In the weighting with the AHP method, the indicators were ranked on a scale from 1 to 9 following the fundamental scale presented by Saaty (2008). After the experts agreed on the ranking to determine the weight of the indicators for the SQI, each indicator was scored with the next parameter using the utilisation of the preference scale (Table 2) as suggested by Saaty (1980) and a pairwise comparison matrix was created (Table 3) (Saaty 1980, 2004). In the expert opinion process, the opinions of ten agronomists and faculty members working in the Department of Soil Science and Plant Nutrition in the Agriculture Faculties were received. In the case of differences in the scores in the Pairwise comparisons, the average scores were used. The consistency ratio of the pairwise comparison judgments was calculated as

Table 2. The fundamental scale for the pairwise comparison

Intensity of importance	Definition	Explanation
1	equal importance	two activities contribute equally to the objective
3	weak importance of one over another	experience and judgment slightly favour one activity over another
5	essential or strong importance	experience and judgment strongly favour one activity over another
7	demonstrated importance	an activity is strongly favoured, and its dominance demonstrated in practice
9	absolute importance	the evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	intermediate values between the two adjacent judgments	when compromise is needed
Reciprocals	if activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	

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Table 3. Pairwise matrix evaluation of the nine soil quality index parameters using the analytic hierarchy process priority and weight of the parameters calculated by using a matrix (the detailed calculation method can be accessed from the Electronic Supplementary Material 1 (ESM 1)

	Clay	Silt	Sand	MWD	AS	AR	EC	TN	TC	Weight
Clay	1	4	2	1/2	1/4	1/3	3	1/6	1/5	0.051
Silt	1/4	1	1/3	1/5	1/7	1/6	1/2	1/9	1/8	0.018
Sand	1/2	3	1	1/3	1/5	1/4	2	1/7	1/6	0.035
MWD	2	5	3	1	1/3	1/2	4	1/5	1/4	0.074
AS	4	7	5	3	1	2	6	1/3	1/2	0.155
AR	3	6	4	2	1/2	1	5	1/4	1/3	0.108
EC	1/3	2	1/2	1/4	1/6	1/5	1	1/8	1/7	0.025
TN	6	9	7	5	3	4	8	1	2	0.312
TC	5	8	6	4	2	3	7	1/2	1	0.222

MWD – mean weight diameter; AR – aggregation rate; AS – aggregate stability; EC – electrical conductivity; TN – total nitrogen; TC – total carbon; maximum eigenvalue (λmax)= 9.40; n = 9; consistency index (CI) = (λmax–n)/(n–1) = 0.0509; random index (RI) = 1.45; consistency ratio (CR) = CI/RI = 0.035

0.035, which was below 0.10 and indicates that the judgment matrix had satisfactory consistency and could be used without any adjustment (Xu 2004). In the weighting the using principal component analysis (PCA), after the VARIMAX rotation, principal components with eigenvalues > 1 were generated, and the weight of each parameter was calculated by the communality value of each parameter (Table 4) using Equation (3) (Johnson & Wichern 2002).

$$\text{Weight} = C_p/C_t \quad (3)$$

where:
C_p – communality value of the parameter;
C_t – total communality value.

A 0–1 scale was used for scoring in the AHP method. A 30–35% range of clay content, silt content, and sand content were given a value of 1, while the values below and above this range were scored linearly lower. Other indicators were scored considering the minimum and maximum values in the dataset. The minimum value was 0.1 and the maximum value was 1, while the remaining values were scaled linearly (Table 5).

The indicators were scored with the linear score functions, such as "more is better" "optimal range" and "less is better" for SQI_{PCA} (Qi et al. 2009; Zheng et al. 2015). The "optimum value" function was used for the clay content, silt content, and sand content, where the value of 1 was given for the range of 30–35%. The score increased to the optimum range (30–35%) and decreased after this point. The "more is better" function was applied to the MWD, AS, AR, TN, and TC; the "less is better" function was applied to the EC (Table 6). The score values corresponding to the measurement values of the indicators are given in Figure 2.

The soil quality index was calculated at every sample point using Equation (4) for SQI_{AHP} and SQI_{PCA}.

$$SQI = \sum^{n}_{i=1}(a_i b_i) \quad (4)$$

where:
a_i – the weight of the i^{th} parameter;
bi – the score of the i^{th} parameter.

Table 4. Communality values of the parameters using a principal component analysis (PCA) and the weight of the parameters calculated by using communality values (the detailed calculation method can be accessed from ESM 2)

Parameters	Communality	Weight
Clay	0.750	0.132
Silt	0.180	0.032
Sand	0.783	0.138
MWD	0.644	0.113
AS	0.413	0.073
AR	0.737	0.129
EC	0.553	0.097
TN	0.792	0.139
TC	0.841	0.148
Total	5,695	1

MWD – mean weight diameter; AR – aggregation rate; AS – aggregate stability; EC – electrical conductivity; TN – total nitrogen; TC – total carbon

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Table 5. Scores of the sub-criteria determined with the expert opinion in the analytic hierarchy process (AHP) method

Indicators	Sub-criteria	Score	Indicators	Sub-criteria	Score
Clay content (%)	< 10	0.1	AR (%)	0–20	0.2
	10–15	0.3		20–40	0.4
	15–20	0.4		40–60	0.6
	20–25	0.5		60–80	0.8
	25–30	0.7		80–100	1.0
	35–40	0.9	AS (%)	< 50	0.1
	40–45	0.7		50–60	0.3
	45–50	0.3		60–70	0.5
	> 50	0.1		70–80	0.7
Silt content (%)	< 10	0.1		80–90	0.9
	10–15	0.3		90–100	1
	15–20	0.4	EC	0–100	1
	20–25	0.5		10–200	0.9
	25–30	0.7		200–300	0.7
	30–35	1		300–400	0.5
	35–40	0.9		400–500	0.3
	40–45	0.7		500–600	0.1
	45–50	0.3	TN (%)	0–0.15	0.1
	> 50	0.1		0.15–0.30	0.3
Sand content (%)	< 10	0.1		0.30–0.45	0.5
	10–15	0.3		0.45–0.60	0.7
	15–20	0.4		0.75–0.90	1
	20–25	0.5	TC (%)	0–2.00	0.2
	25–30	0.7		2.00–4.00	0.4
	30–35	1		4.00–6.00	0.6
	35–40	0.9		6.00–8.00	0.8
	40–45	0.7		8.00–10.00	1
	> 50	0.1			
MWD (mm)	< 0.125	0.1			
	0.125–0.250	0.3			
	0.25–0.50	0.5			
	0.50–0.75	0.7			
	0.75–1.00	0.9			
	> 1.00	1			

MWD – mean weight diameter; AR – aggregation rate; AS – aggregate stability; EC – electrical conductivity; TN – total nitrogen; TC – total carbon

RESULTS AND DISCUSSION

Soil's physical and chemical parameters. The descriptive statistical results of the soil properties including the minimum, maximum, mean, standard deviation and coefficient of variation are given in Table 7.

Since there was no significant difference between the sampling layers in terms of the soil properties, the analysis results of both layers were merged and evaluated together (Table 8). The means and standard deviations of the soil's physical properties were used as indicators of the soil quality, and Tukey's post-hoc groups are presented in Table 9. All the physical properties were statistically different in the afforested zones. AA_{10-40} had the highest clay content, $AA_{<10}$ had the highest silt content, and $AA_{>40}$ had the highest

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Table 6. Indicators and function types used to calculate the soil quality index with the principal component analysis method

Indicator	Function type	x_1	r_1	r_2	x_2	Equation
MWD (mm)	more is better	0.44			1.09	$f(x) = \frac{(x - x_1)}{(x_2 - x_1)}$
AS (%)		60.11			96.34	
AR (%)		27.50			95.50	
TC (%)		2.15			9.47	
TN (%)		0.28			0.80	
Clay (%)	optimal range	2.83	30	35	76.17	$f(x) = \frac{(x - x_1)}{(r_1 - x_1)}$; $x_1 < x < x_2$
Sand (%)		2.83	30	35	76.17	$f(x) = 1$; $r_1 < x < r_2$
Silt (%)		2.83	30	35	76.17	$f(x) = \frac{(x - r_2)}{(x_2 - r_2)}$; $r_2 < x < x_2$
EC (mS/m)	less is better	42			562	$f(x) = 1 - \frac{(x - x_1)}{(x_2 - x_1)}$

MWD – mean weight diameter; AS – aggregate stability; AR – aggregation rate; TC – total carbon; TN – total nitrogen; EC – electrical conductivity; x – the measured value of the indicator; x_1, x_2 – the minimum and maximum values of the indicator, respectively; r_1, r_2 – the lower and the upper values of the optimal range, respectively

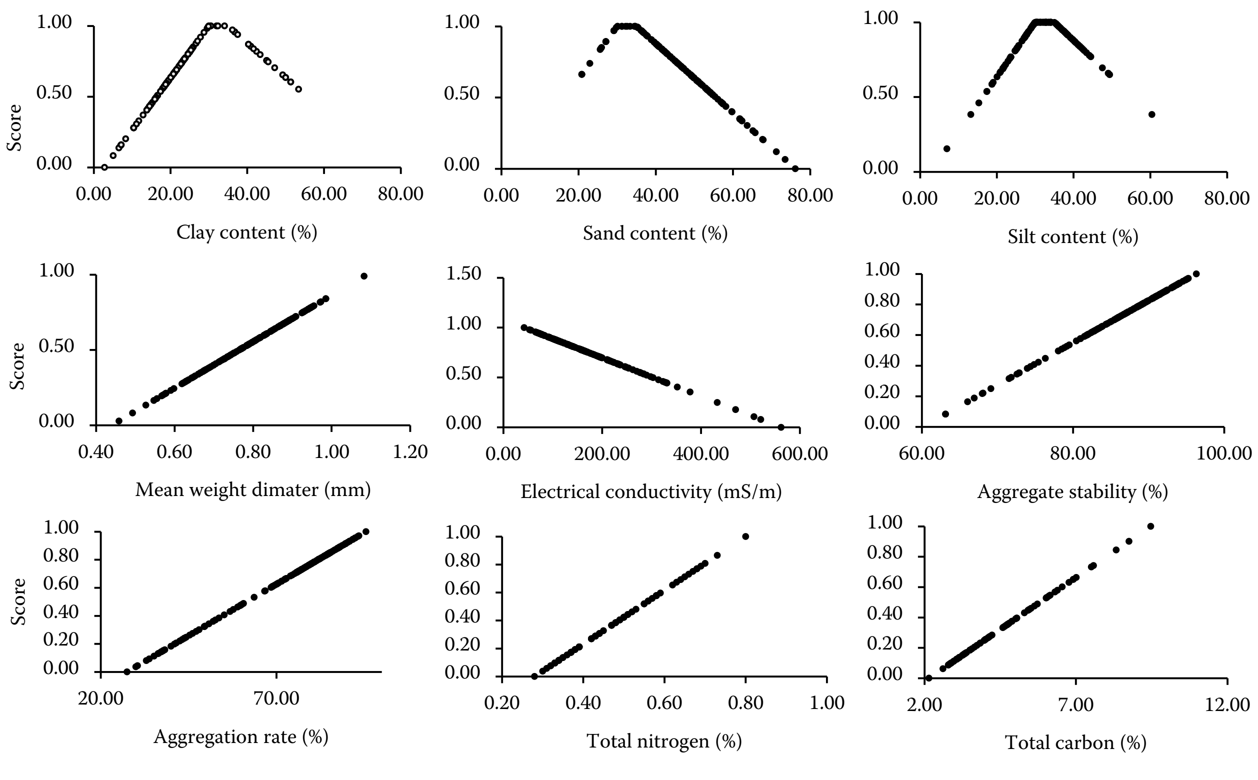

Figure 2. Score values calculated for the indicators using the more is better, optimal range and less is better linear functions

sand content. The mean weight diameter (MWD) increased from 0.63 mm in $AA_{<10}$ to 0.82 mm in $AA_{10–40}$ and 0.86 mm in $AA_{>40}$, while the aggregate stability (AS) and aggregation rate (AR) increased in the following order, respectively: 46.60% ($AA_{<10}$), 80.44% ($AA_{10–40}$), 80.45% ($AA_{>40}$) and 80.83% ($AA_{<10}$), 86.76% ($AA_{10–40}$), and 90.09% ($AA_{>40}$). The electrical conductivity (EC) also increased from 97.98 in $AA_{<10}$ to 189.48 in AA_{10-40} and 226.53 in $AA_{>40}$.

The chemical properties such as the TN, and TC, TS, and pH are summarised in Table 10. As the differences between the afforested stands in terms of

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Table 7. Descriptive statistics of the soil properties

Soil properties	Minimum	Maximum	Mean	SD	*CV*
Clay (%)	2.83	56.25	24.08	10.41	43.23
Sand (%)	16.67	76.17	45.57	11.07	24.29
Silt (%)	2.08	60.42	30.72	7.91	25.75
MWD (mm)	0.44	1.09	0.78	0.12	15.38
AR (%)	20.33	96.33	72.69	17.78	24.46
AS (%)	60.11	96.34	86.35	6.87	7.96
pH	6.40	8.77	7.82	0.38	4.86
EC (mS/m)	42	623	175.32	93.01	53.05
TN (%)	0.22	0.80	0.46	0.12	26.09
TC (%)	2.07	9.47	4.45	1.43	32.13
TS (%)	0.04	0.12	0.06	0.02	25.44

MWD – mean weight diameter; AR – aggregation rate; AS – aggregate stability; EC – electrical conductivity; TN – total nitrogen; TC – total carbon; TS – total sulfur; SD – standard deviation; *CV* – coefficient of variation

Table 8. Effect of the soil layers on the clay content, silt content, sand content, mean weight diameter (MWD), aggregation rate (AR), aggregate stability (AS), pH, electrical conductivity (EC), total nitrogen (TN), total carbon (TC), and total sulfur (TS) in the soil samples from the afforested sites

Soil properties	Soil layers (cm)		*F* value	Soil properties	Soil layers (cm)		*F* value
	0–10	10–20			0–10	10–20	
Clay content (%)	23.4	23.5		pH	7.78	7.84	1.14^{ns}
Silt content (%)	31.6	31.1	0.200^{ns}	EC (mS/m)	189.75	161.98	3.76^{ns}
Sand content (%)	45.0	45.4	0.040^{ns}	TN (%)	0.48	0.45	1.47^{ns}
MWD (mm)	0.76	0.79	3.670^{ns}	TC (%)	4.80	4.35	1.64^{ns}
AR (%)	72.35	71.61	0.07^{ns}	TS (%)	0.058^{B}	0.065^{A}	4.28*
AS (%)	85.12	87.09	3.100^{ns}				

The different letters denote statistically significant differences ($P \leq 0.05$), and ns denotes no statistically significant differences between the layers using Tukey's post-hoc test

Table 9. Effect of the afforestation times on the clay content, silt content, sand content, mean weight diameter (MWD), aggregation rate (AR), aggregate stability (AS), and electrical conductivity (EC) in the soil samples from the afforested sites

Afforested zones	Clay content (%)	Silt content (%)	Sand content (%)	Texture class
$AA_{<10}$	19.48 ± 7.98^{B}	32.77 ± 5.56^{A}	47.75 ± 9.42^{A}	loam
$AA_{10–40}$	27.68 ± 10.45^{A}	32.56 ± 8.86^{A}	40.67 ± 10.77^{B}	clay loam
$AA_{>40}$	19.57 ± 6.49^{B}	27.54 ± 5.07^{B}	52.89 ± 7.77^{A}	sandy loam
F value	16.37**	7.26**	22.28**	
	MWD (mm)	AS (%)	AR (%)	EC (dS/m)
$AA_{<10}$	0.63 ± 0.07^{B}	80.83 ± 8.38^{C}	46.60 ± 12.28^{B}	97.98^{C}
$AA_{10–40}$	0.82 ± 0.09^{A}	86.76 ± 6.24^{B}	80.44 ± 8.25^{A}	189.48^{B}
$AA_{>40}$	0.86 ± 0.07^{A}	90.09 ± 3.39^{A}	80.45 ± 6.54^{A}	226.53^{A}
F value	96.25**	22.30**	208.58**	29.19**

The different letters denote statistically significant differences at a level of 0.01 among the afforested zones using Tukey's post-hoc test

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Table 10. Effect of the afforestation times on the pH, total nitrogen (TN), total carbon (TC), and total sulfur (TS) in soil samples from afforested sites

	pH	TN (%)	TC (%)	TS (%)
$AA_{<10}$	7.84 ± 0.46	0.442 ± 0.129^{B}	3.99 ± 1.39^{B}	0.062 ± 0.01
$AA_{10–40}$	7.84 ± 0.32	0.447 ± 0.096^{B}	4.32 ± 1.22^{B}	0.059 ± 0.02
$AA_{>40}$	7.72 ± 0.41	0.532 ± 0.140^{A}	5.68 ± 1.89^{A}	0.065 ± 0.02
F value	1.397^{ns}	4.129*	7.98**	1.049ns

The different capital and small letters denote statistically significant differences at a level of 0.01 and 0.05, respectively, and ns denotes no statistically significant differences among the afforested zones using Tukey's post-hoc test

the soil reaction (pH) and TS were not statistically significant, they were not used for the soil quality parameters. The TN and TC of $AA_{>40}$, $AA_{10–40}$ and $AA_{<10}$ was 0.532%, 0.447%, 0.442% and 5.68%, 4.32%, 3.99%, respectively. The differences in the afforested zones in terms of the TN and TC were statistically significant.

The effect of the land management on the particle size distribution of the soils is not possible to determine in a short time. Therefore, the reason for the change in the grain size distribution may be the erosion-deposition processes rather than the afforestation. It is well known that the structural stability and total carbon, as well as the total nitrogen are closely related to the organic matter content in the soil (Pritchett 1980; Jensen et al. 2020). The important part of the organic matter in the forests consists of the leaves, cones, bark, and branches of the trees. It is expected that the organic matter content is relatively high in an area covered with trees for a longer period and, accordingly, the structural stability and nutrients are better than that during a shorter period (Wang et al. 2021). In this study, the afforestation time in $AA_{>40}$ tended to produce more leaf and root systems in the soil due to the longer duration of the soil being covered with trees, which may be the main reason for the differences in the MWD, AR, AS, TN and TC along with the afforestation periods.

Indicator weights. The highest weight was calculated for the TC (0.232) and the lowest for the silt content (0.022) in the AHP method. According to these results, the TC was the most effective parameter, and the silt content was evaluated as the least effective parameter for the soil quality index value. In similar studies, it was stated that the organic matter content has the highest weight coefficient than any other property, and the silt content has the lowest weight coefficient (Karaca et al. 2021; Zhao et al. 2021). Like the AHP, the highest weight was obtained from the TC (0.151) and the lowest from the silt content (0.033) in the PCA method. In general, the weight values obtained from the AHP and PCA methods were different. The PCA evaluated the particle size distribution as a more important indicator than the AHP. Meanwhile, the experts and PCA evaluated the TN and TC as the most important indicators, and the silt content as the least important indicator affecting the SQI (Figure 3). Previously, studies showed that the weighting values differed between the AHP and factor analysis methods (Qi et al. 2009; Liu et al. 2018b). The consistency of the weighting values can only be tested in the AHP method. For this reason, this should be considered in selecting the method.

Soil quality index. Since the soil quality index did not differ between the soil layers (*F*: 0.148; $P > 0.05$), the samples taken from all the depths were used for

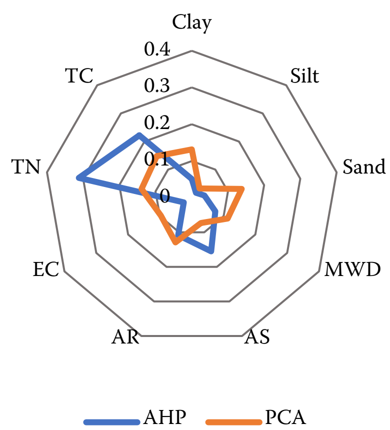

Figure 3. Weighting values of the indicators obtained from the AHP and PCA

AHP – analytic hierarchical process; PCA – principal component analysis; MWD – mean weight diameter; AS – aggregate stability; AR – aggregation rate; EC – electrical conductivity; TN – total nitrogen; TC – total carbon

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the evaluation of the areas with all the methods. As a result of the evaluation, it was determined that the additive SQI (SQI_A) values increased due to the age of the afforested sites. The lowest SQI_A score (0.527) was observed in $AA_{<10}$, the youngest afforested area, and gradually increased in $AA_{10–40}$ (0.633), and reached the highest value (0.635) in the oldest afforested area ($AA_{>40}$) (Figure 4A). The difference in the afforested areas was found to be statistically significant. The ANOVA test showed that the differences between the SQI_A of the plots were statistically significant (Figure 4A). The MWD and AR are the limiting indicators for $AA_{<10}$, also the TN and AR are the limiting indicators for both $AA_{<10}$ and $AA_{10–40}$ (Figure 4B).

The calculated SQI_{AHP} scores across the plots were 0.618, 0.686 and 0.732 for $AA_{<10}$, $AA_{10–40}$ and $AA_{>40}$, respectively (Figure 5A). The lowest SQI_{AHP} was calculated in the youngest afforested area ($AA_{<10}$), and the values increased gradually until they reached the highest value in the $AA_{>40}$. The results of the ANOVA showed that the differences in the SQI_{AHP} values across the afforested areas were statistically significant. The lower SQI_{AHP} score of $AA_{<10}$ was caused by a lower AR (Figure 5B).

The results showed that the SQI_{PCA} in the $AA_{>40}$ (0.600) and $AA_{10–40}$ (0.598) plots were significantly

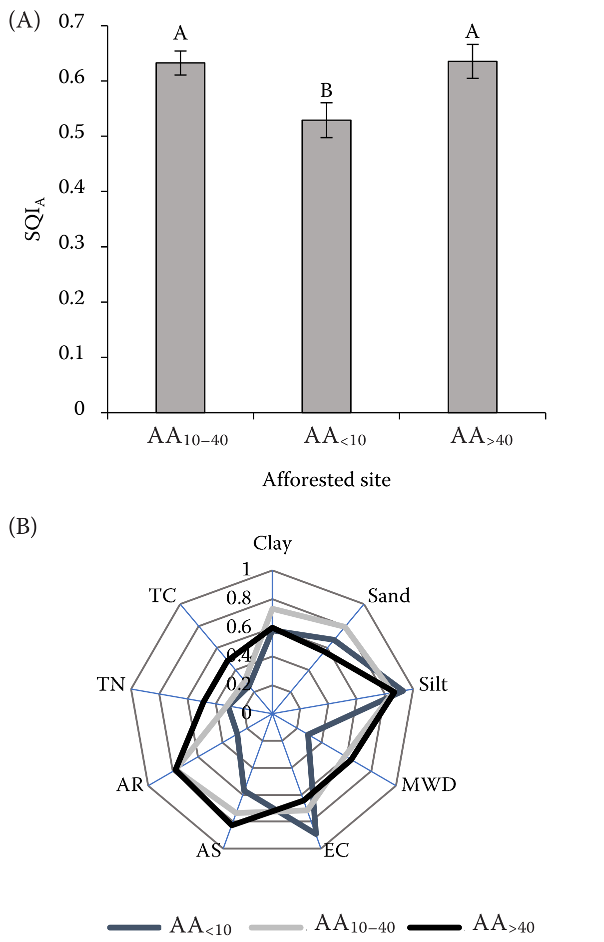

Figure 4. Effect of the afforestation times on the soil quality index with the additive method (SQI_A)

The different capital letters denote statistically significant differences at a level of 0.01 according to Tukey's post-hoc test (A); the radar plot indicates the limiting indicators of SQI_A in the afforested areas (B)

MWD – mean weight diameter; EC – electrical conductivity; AS – aggregate stability; AR – aggregation rate; TN – total nitrogen; TC – total carbon

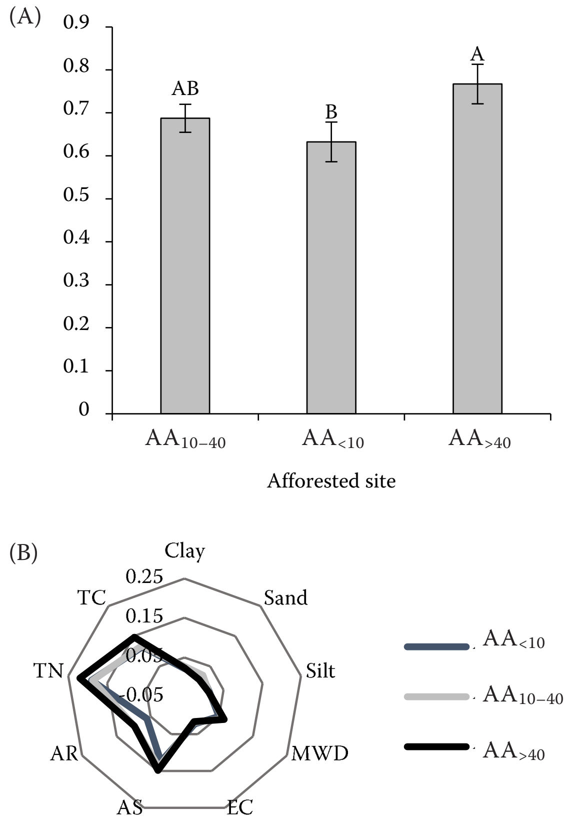

Figure 5. Effect of the afforestation times on the soil quality index with the analytical hierarchical process method (SQI_{AHP})

The different capital letters denote statistically significant differences at a level of 0.01 according to Tukey's post-hoc test (A); the radar plot indicates the limiting indicators of SQI_{AHP} in the afforested areas (B)

MWD – mean weight diameter; EC – electrical conductivity; AS – aggregate stability; AR – aggregation rate; TN – total nitrogen; TC – total carbon

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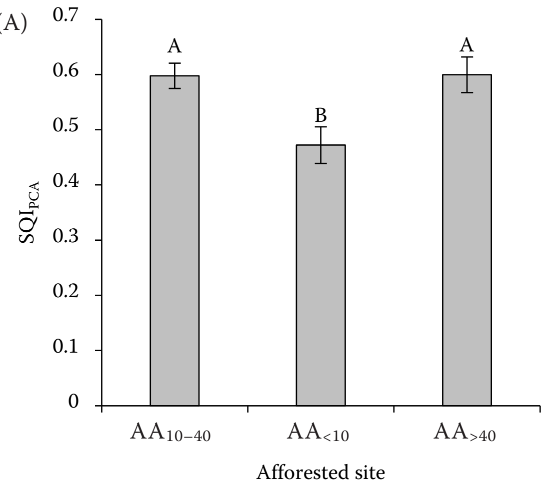
higher than $AA_{<10}$ (0.472) (Figure 6A). Like the SQI_A and the SQI_{AHP}, the SQI_{PCA} score increased gradually from the youngest to oldest afforested areas. The limiting indicators in this method were the MWD and AR (Figure 6B).

All the methods showed that the SQI gradually increased from the youngest afforested area to the oldest one. The shorter afforestation period caused the low TC, TN, and low structural parameters (MWD, AS, AR) in this study. The SQI increased gradually in the middle duration afforestation period ($AA_{10–40}$), where the soil quality is limited by the low TN and TC. The TN and TC are higher than $AA_{<10}$, but lower than $AA_{>40}$. The highest SQI was obtained in the oldest afforestation period ($AA_{>40}$), which was the first afforested area in the study. In these plots, the grain size distribution limited the SQI. However, the strongest effects of the TN, TC, AS, AR, and MWD on the SQI were obtained in these plots. The afforestation times caused an increase in the vegetation cover, root development, and the consequent soil organic matter accumulation (Wang et al. 2017, 2021). The higher soil organic matter increases the parameters TN, TC, AS, AR and MWD that affect the soil quality. Like our study results, it was reported by researchers that the physical, chemical, and biological properties of soils and the soil quality index increased over the time since the afforestation (Wang et al. 2017; Zhao et al. 2018; Zethof et al. 2019).

Comparison of methods. The variance analysis determined that the score obtained by the SQI_{AHP} method (0.680) was higher than the SQI_A (0.606) and SQI_{PCA} (0.565) (Figure 7). These differences were statistically significant (F = 34.39; P < 0.01). It is thought that the different scoring and weighting methods caused this difference. Previous studies reported that the SQI values were calculated in the following order: expert opinion > additive model > weighted model (Vasu et al. 2016; Nabiollahi et al. 2018; Turgut et al. 2021). The expert opinion used to weight the parameters in the AHP method is a useful methodology, but also subjective. However, the consistency of the weighting value can be tested

(A)



(B)

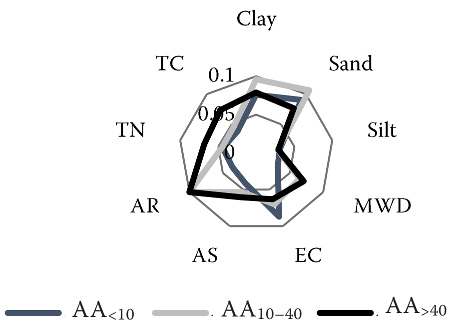


Figure 6. Effect of the afforestation times on the soil quality index with the principal component analysis method (SQI_{PCA})

The different capital letters denote statistically significant differences at a level of 0.01 according to Tukey's post-hoc test (A); the radar plot indicates the limiting indicators of SQI_A in the afforested areas (B)

MWD – mean weight diameter; EC – electrical conductivity; AS – aggregate stability; AR – aggregation rate; TN – total nitrogen; TC – total carbon

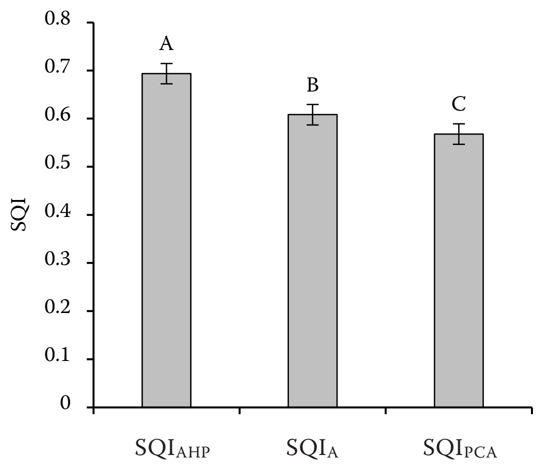


Figure 7. Comparison of the soil quality index calculated using the additive (SQI_A), analytic hierarchical process (SQI_{AHP}), and principal component analysis (SQI_{PCA}) methods with the ANOVA

The different capital letters denote statistically significant differences at a level of 0.01 according to Tukey's post-hoc test

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only in the AHP method. Turan et al. (2019) reported that the integration of type-2 fuzzy sets with AHP significantly contributed to the elimination of uncertainties in expert opinions. When the strength of the AHP is supported by type-2 fuzzy sets, this method was thought to be a safe and preferable way for the SQI calculations.

CONCLUSION

Three different methods (additive soil quality index, weighted soil quality index using AHP and weighted soil quality index using principal component analysis) were applied to determine the effects of the afforestation period on the SQI and they gave the same results. The soil quality index varied in the afforested areas and ranged from 0.505 to 0.680. The afforestation did not cause any differences between the topsoil and subsoil layers. However, the SQI gradually increased from the youngest afforested area to the moderate age and then to the oldest one.

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