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Evaluating Soil Quality: A Comparative Study of Contrasting Soils Using Geospatial and Analytical Methods in Çukurova Region, Turkey

M. Acar^{a,*} (ORCID: 0000-0002-9971-4470), I. Celik^a (ORCID: 0000-0002-8650-2639),
M. Budak^b (ORCID: 0000-0001-5715-1246), and N. Acir^c (ORCID: 0000-0001-7591-0496)

^a Department of Soil Science and Plant Nutrition, Cukurova University, Adana, 01250 Turkey

^b Department of Soil Science and Plant Nutrition, Siirt University, Siirt, 56100 Turkey

^c Department of Soil Science and Plant Nutrition, Kirsehir Ahi Evran University, Kirsehir, 40100 Turkey

*e-mail: macar@cu.edu.tr

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Abstract—Three different soils—Chromic Vertisol, Pantofluvic Calcaric Fluvisol and Gleyic Solonchak—were selected for investigating soil quality in the Çukurova region of southern Turkey. Soil samples were collected from 49 main points within a study area of 1.5 × 1.5 km and their physical, chemical and biological properties were determined. Indicators were selected based on expert opinions for the soil quality index (SQI) assessment, scored using the Soil Management Assessment Framework (SMAF), and weighted using the Fuzzy-Analytical Hierarchy Process (FAHP). The weighted scores were integrated into a comparative SQI. Soil physical indicators contributed 56.7% of all the indicators including aggregate stability, bulk density and available water content were found as the most significant factors. Soil chemical indicators contributed 35.6% including soil pH, phosphorus and potassium as the most important factors. The SQI for the soils were significantly different ($p < 0.05$). Pantofluvic Calcaric Fluvisol, Chromic Vertisol and Gleyic Solonchak SQI were 74.9, 69.5 and 67.1% respectively. Pantofluvic Calcaric Fluvisol SQI was due to reduced soil disturbances, avoidance of plant residues and stubble burning, increased soil organic matter (SOM), and more informed use of fertilizer. Chromic Vertisol, Pantofluvic Calcaric Fluvisol and Gleyic Solonchak have consistently shown reduced productivity due to intensive mechanized agriculture, necessitating the assessment of their SQI.

Keywords: soil management assessment framework, fuzzy-analytical hierarchy process, soil mapping

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INTRODUCTION

Soil degradation has increased more than ever in the XXth century. It has been closely linked with anthropogenic activities and has affected between 24 and 33% of the Earth's surface [52]. The Mediterranean region, in addition to African soils [52], has been identified as highly susceptible to soil degradation due to the intrinsic properties of Mediterranean soils [37]. Reduction or loss of soil quality (SQ) is a form of degradation, caused by both natural and anthropogenic activities. Increase in alternative land use type aside from arable farming and the need to increase and sustain productivity from the available land are the main threats to agricultural lands [37], requiring the adoption of intensive agriculture and the use of agrochemicals and fertilizers to achieve higher yields [44]. This issue is further exacerbated by the total removal of plant residues, especially through stubble burning, a long-term common practice in the Cukurova region of Adana, Turkey [21]. Additionally, intensive agricultural activities, including over-fertilization and fre-

quent moldboard plowing [1], have been carried out in the plain for many years.

Degradation of soil quality negatively affects ecosystem functions, which ultimately reduces agricultural productivity and sustainability. This degradation manifests in several ways: soil physical properties, such as compaction from increased bulk density, reduced soil aggregate stability, and altered soil moisture characteristics [21, 27]; soil chemical properties, such as low and high soil pH, soil salinity [65, 91], heavy metal concentration [57], and nutrient imbalances [52]; and soil biological properties, such as low soil organic matter content, reduced microbial biomass, and decreased enzymatic activities [4]. Loss of inherent ecosystem functions can affect agroecosystem output. These functions prevent soil erosion, soil compaction, high soil pH and electrical conductivity (EC), and pollution of groundwater and nearby water bodies. The loss of these ecosystem functions reduces soil water storage and the adsorption of plant nutrients, affects plant rooting depth [26], increases soil surface runoff, and

diminishes soil-forming and quality-enhancing processes. Consequently, higher agricultural inputs are required to sustain production, leading to an increase in the price of agricultural products.

Protection and conservation are required to maintain and improve the arable land [3]. Inadequate soil monitoring can lead to a loss or reduction in soil quality [37]. Assessing the SQI is necessary to measure the impact of anthropogenic activities [21]. Plowing, irrigation, fertilization, and monocropping have been reported to affect the soil quality index [28]. The effects of different agronomic practices vary and are further influenced by intrinsic soil properties [83], necessitating the monitoring of soil degradation through SQI. Soil degradation can potentially be detected by monitoring declining SQI, helping decision-makers to be aware of the state of their lands and when intervention is required [12].

Soil quality can mainly be assessed indirectly, as the processes involved are interrelated at complex levels across soil physical, chemical, and biological aspects [3, 21]. The Soil Management Assessment Framework (SMAF) method, which basically comprises of indicators that are sensitive to soil management practices, [7] has recently gained acceptance as an alternative to existing methods for estimating soil quality at the micro-field scale [3, 21, 77] and at the soil order level for crops like sugarcane [56].

The Cukurova Plain in Adana is arguably one of the most important agricultural regions in the Mediterranean, producing household foods, animal feeds, and industrial materials. The productivity, sustainability, and quality of goods are highly dependent on soil quality and the factors affecting it. Examining soil quality at the field level in relation to the effects of soil tillage, fertilization, and other practices has been extensively researched [4, 21, 28, 33, 39, 66]. Some studies have focused on the soil order level [15, 18, 56], while very few have considered limitations in Analytical Hierarchy Process (AHP) [30] or used alternative methods for minimum data set selection [43, 86]. In order to study the level of degradation and assess the soil quality index at the lowest soil classification levels, three soil which accounts for the 41% of all the soil in the Çukurova Plain in Adana were selected. The variation in intrinsic and extrinsic factors present at the soil order level is minimal at the soil classification level, making comparison across different soil orders challenging. This research aims to initiate comparisons of different land use types on the selected soils of a major agriculture production area in response to long-term agricultural activities with the intention of identifying soil management practices that are ecologically sustainable for this ecosystem.

OBJECTS AND METHODS

Study area. The Cukurova region of southern Turkey was selected for this study. The soil characteristics

of this region make it highly suitable for intensive agricultural production [20]. The Chromic Vertisol, Pantofluvic Calcaric Fluvisol and Gleyic Solonchak [74] were chosen from the region based on their use in agricultural production. Also, these soils are classified as Chromic Haploxerert, Typic Xerofluvent and Vertic Halaquept, respectively, according to USDA [92]. These soils have distinct physiographic units and different properties. The criteria utilized for selecting the soil included distribution within the region, percentage of clay content and clay type (smectite) [35], irrigation-induced salinity, and poor drainage [22, 23, 35, 71], as well as adopted tillage and stubble burning practices [2, 27]. These soils account for 41% of the region. An area of 225 ha was mapped from each soil for the study (Fig. 1). The coordinates for the soil are as follows: for Chromic Vertisol, 4081 768 to 4083 268 N and 709 876 to 711 376 E (WGS-84, UTM Zone 36-S; 9–12 m above sea level); for Pantofluvic Calcaric Fluvisol, 4080 540 to 4082 040 N and 714 440 to 715 940 E (WGS-84, UTM Zone 36-S; 10–12 m above sea level); and for Gleyic Solonchak, 4068 650 to 4065 150 N and 714 660 to 716 160 E (WGS-84, UTM Zone 36-S; 3–5 m above sea level).

The study area is under Mediterranean climate, characterized by hot, dry summers and rainy, mild winters. The long-term meteorological data for the region are summarized as follows: the mean annual temperature is 19.2 °C, total annual evapotranspiration is 1557 mm, and total annual rainfall is 639 mm [8]. Rainfall primarily occurs in the winter and spring. Soil temperature and moisture regimes indicate that they are thermic and xeric. The most common soil is classified as Chromic Vertisol (Aric, Pelocrustic, Ochric) [74]. These Vertisols, formed on alluvial deposits of old river terraces, have a clay texture, and a slope of less than 1°, with a 24% distribution (56 083 ha) [35]. In the sampling area, soil texture distribution of sand, silt, and clay in 0–20 cm soil depth ranging from 1.5–17.4, 31.5–39.9, and 47.5–62.4%, average values of 8.3, 38.5 and 53.2%, respectively and a carbonate content ranging between 10.02–20.68%, with an average of 14.83% [2]. The type and percentage of clay, cation exchange capacity (CEC), and water holding capacity contribute to the soil's high natural productivity. However, the clay content also causes preferential flow, leading to the transport of fertilizers and other agricultural inputs to the groundwater table. The second most commonly found soil is classified as Pantofluvic Calcaric Fluvisol (Loamic, Ochric), with a 13% distribution (30 190 ha). The soil is formed on young river terraces, and has silty loam and clay loam textures [35]. In the sampling area, soil texture distribution of sand, silt and clay in 0–20 cm soil depth ranging from 10.2–43.5, 30.8–63.4, and 20.9–41.7%, with averages of 25.2, 48.2 and 26.6%, respectively. The carbonate content ranges between 5.61–20.98%, with an average of 12.10% [2]. The 7th most common soil is classified as Gleyic Solonchak (Clayic, Chloridic,

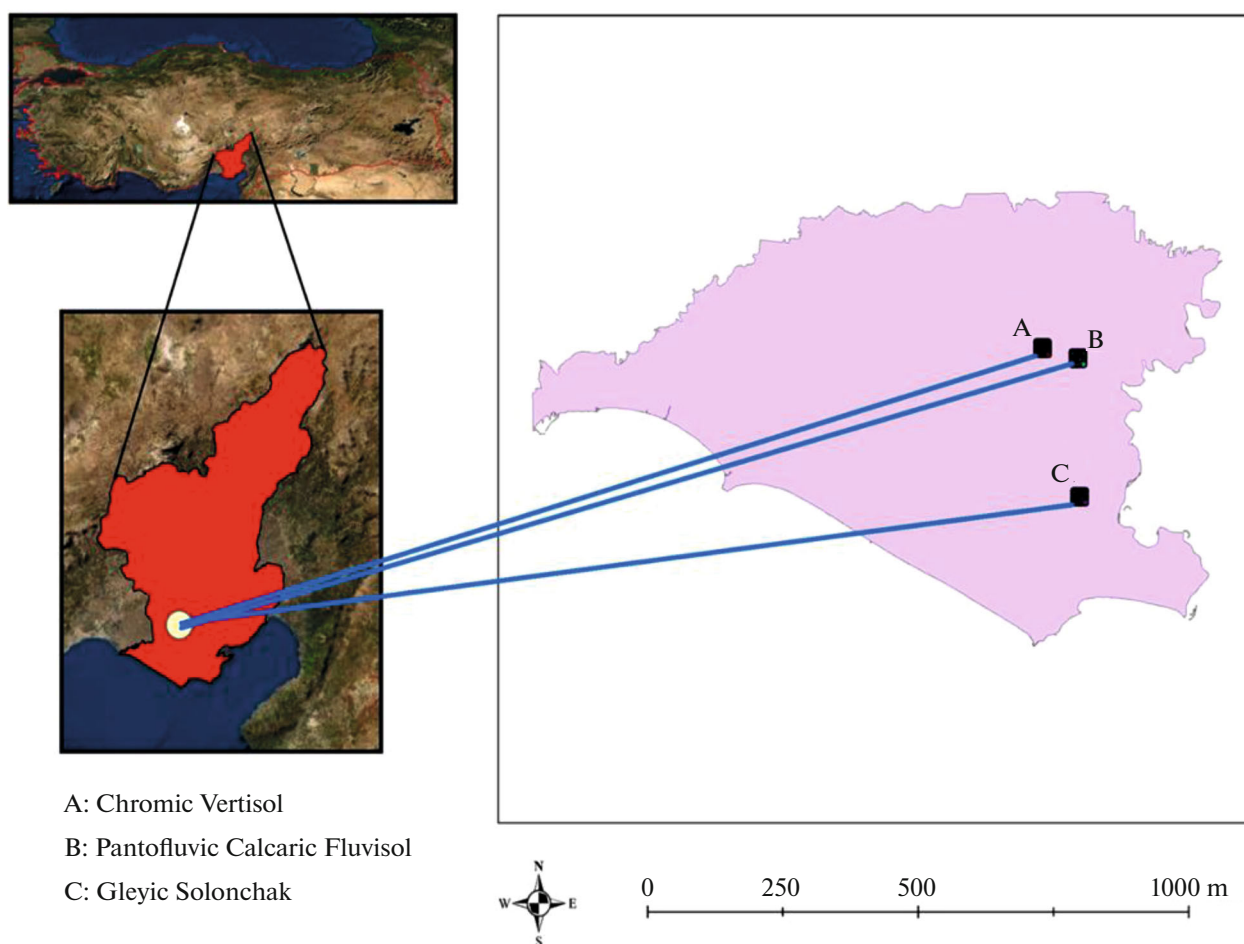


Fig. 1. Study area.

Ochric, Vertic) which has 4% distribution (9791 ha) is formed on alluvial deposits at the base of delta depressions. Poor drainage and proximity to the sea make the soil mostly saline, with high salinity levels [35]. In the sampling area, the soil texture distribution of sand, silt and clay in 0–20 cm soil depth ranges from 2.3–11.5, 24.8–39.9, and 50.4–69.7% with average values of 5.6, 35.0, and 59.4%, respectively and the carbonate content ranges between 12.16–20.72%, with an average of 16.25% [2]. All the soils are formed on delta sediments [61].

A large part of the study area has been used for intensive agricultural production for over 50 years due to the favorable climate and availability of irrigation facilities. The prevalent land use types in Chromic Vertisol are mainly arable lands; however, horticultural lands are also present. Due to the medium soil texture of Calcaric Fulvisol, this soil is predominantly used for horticultural purposes. On the other hand, Gleyic Solonchak, aside from a few horticultural lands, is primarily used as arable land. Two crops are grown per year in arable lands [20]. However, due to the closeness of Gleyic Solonchak to the Mediterranean Sea, which results in high water table, only a sin-

gle crop can be grown within a year. Winter crops include wheat, onions, and potatoes, while summer crops include cotton, corn, soybean, and peanuts. Some crops are grown in rotation, with wheat + corn and wheat + soybean being the preferred combinations. Pre-tilling of arable lands involves stubble burning followed by conventional tillage with a moldboard plow [20]. Due to limited or no soil analysis, high amounts of chemical fertilizers, especially nitrogen fertilizers, are used during agricultural production [42]. Two forms of irrigation are used: sprinkler and flood irrigation. Flood irrigation is widely adopted in the south, while sprinkler irrigation is more common in the other areas. In horticultural lands, drip irrigation is often used for various citrus species (orange, tangerine, lemon, golden top). In the land, citrus fruits are especially prominent. Horticultural land owners, with substantial investments, seek technical support from agricultural engineers compared to arable land owners. Thus, soil analysis-based fertilizer application is carried out as needed, and soil is tilled while pruned residues are removed.

Soil sampling and analyses. The study area was 1.5×1.5 km across all soils (Fig. 2). The land was

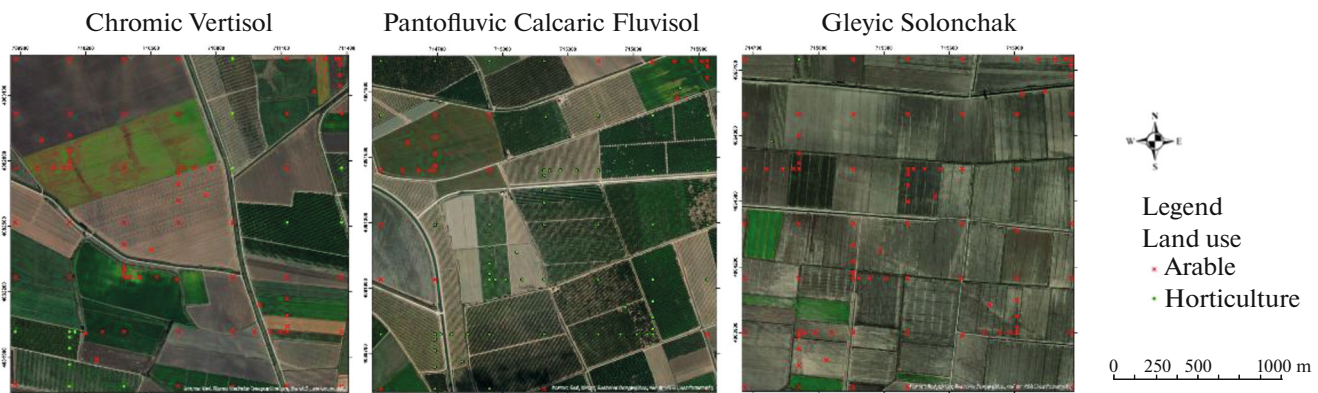


Fig. 2. Sampling point.

divided into square grids of 250×250 m for soil sampling. Soil samples were collected from 49 main points, located near the center of each grid. For more accurate prediction of soil properties at distances less than 250 m, intermediate sampling lines (transects) were placed between the corner points of six grids. On these lines, a total of 36 soil samples were collected at 25, 75, and 150 m distances in the north-south (NS) and east-west (EW) directions, and at 175 m in the northeast (NE) and northwest (NW) directions. In total, 42 intermediate sampling points along transects were added, resulting in 91 soil samples. Soils were sampled at a depth of 20 cm, which is consistent with several land use studies [84, 86]. Depending on the analysis method and purpose, 3 disturbed and 3 undisturbed soil samples were collected from each point. All collected samples were carefully transported to the laboratory. Soil sampling was conducted in September 2018. For physical, chemical, and biological analyses of the soils, preliminary preparations such as root removal and coarse particle sieving were performed. The list of analytical protocols carried out on the soils is presented in Table S1, with all analyses performed in triplicate.

Soil quality assessment. The four steps required for determining Soil Quality Index (SQI) are: (i) selection of indicators, (ii) scoring the selected indicators using the Soil Management Assessment Framework (SMAF), (iii) determining indicator weights using the Fuzzy-Analytical Hierarchy Process (FAHP), and (iv) integrating the weighted indicator scores into a comparative SQI [39]. Based on expert recommendations, soil indicators and factors affecting them, such as climate and land use, were carefully selected.

Soil physical properties can impact many ecosystem services crucial for sustaining life, such as food, feed, fiber and fuel production. Main soil physical properties such as aggregate stability (AS), bulk density (BD), available water content (AWC), and water-filled pore space (WFPS) were used for the assessment of soil quality [18, 21, 26, 33].

Nutrient availability and root growth are of essential necessity to soil fertility, which is impacted by soil

pH, electrical conductivity (EC), phosphorus (P), and potassium (K) [21, 39, 48]. Intensive agriculture encourages heavy use of nitrogenous fertilizers to maintain productivity in the study area [42]. Prolonged and intensive fertilizers use can lead to the accumulation of anions and cations, which may negatively alter soil salinity and EC, as soil pH affects the availability of supplied plant nutrients [91].

Organic carbon (OC) influences all soil properties and moderates their interactions. The importance of OC to soil includes improving soil structure [65], enhancing microbial activity [50], sustaining and improving soil functions and quality [21], and increasing crop productivity. Therefore, OC is a crucial SQI indicator [4, 13, 24]. Additionally, microbial biomass carbon (MBC) and basal respiration (BGEA), which depend on organic carbon [11], are also used as additional indicators due to their sensitivity to changes in soil quality [12].

Selected indicators were converted to unitless scores by using non-linear scoring curves with SMAF based on soil taxonomy [92]. There are 13 scoring curves for indicators based on soil type, texture, climate, mineralogy, sampling season, etc. [7]. The factors were categorized in a SMAF spreadsheet. Indicators such as AS, AWC, K, OC, MBC, and BGEA were scored with the “more is better” curve; BD was scored with the “less is better” curve; and WFPS, EC, pH, and P indicators were scored with the “mid-point is optimum” curve in SMAF.

All the indicators were grouped into three sub-criteria in the third step: physical, chemical, and biological (Fig. 3). The scored indicators within these groups and the groups themselves in the Soil Quality Index (SQI) were weighted using the Fuzzy-Analytical Hierarchy Process (FAHP). The Analytical Hierarchy Process (AHP) is a multi-criteria decision-making method that considers the opinions of a group or individual when evaluating qualitative and quantitative variables together [70]. Despite its use in solving real-world problems [29], one of its major limitations is the inability to fully address the complexity and non-

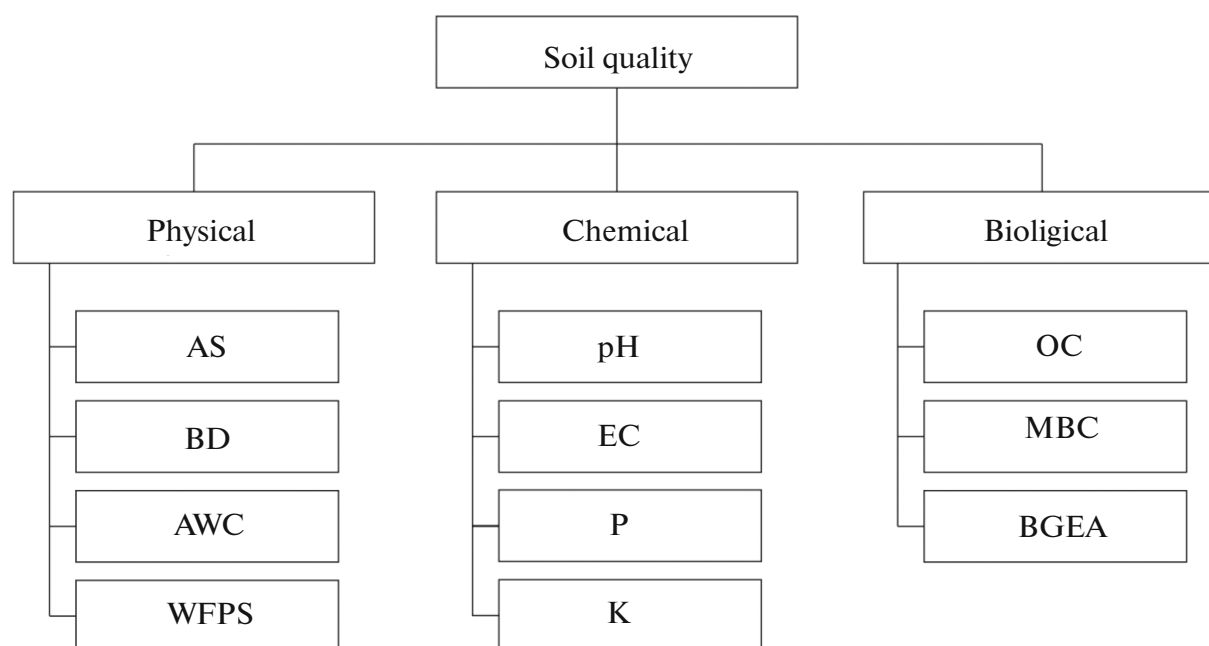


Fig. 3. Sub-criteria in soil quality.

numeric nature of pairwise comparisons [68]. Additionally, AHP struggles with handling uncertainty and indecision [32]. FAHP addresses these limitations by incorporating fuzzy logic into AHP. FAHP includes a triangular method proposed by van Laarhoven and Pedrycz [82], which was further refined for pairwise comparisons of triangular fuzzy numbers and has been adopted in many recent studies [46, 48]. While there are various approaches to fuzzy logic and AHP [17, 25, 32], the extent analysis method developed by Chang [25] was used in this study. The final FAHP results are presented in the following Eq. (1).

$$\mu M(x) = \begin{cases} \frac{x}{m-l} - \frac{l}{m-l}, & x \in [l, m], \\ \frac{x}{m-u} - \frac{u}{m-u}, & x \in [m, u], \\ 0, & \text{otherwise} \end{cases}, \quad (1)$$

where $l \leq m \leq u$, l and u are the lower and upper values of M respectively, and m being the modal value. l , m , and u constitute the triangular fuzzy number. M is the set of the defined elements. If all the triangular fuzzy numbers are equal ($l = m = u$), they are considered as a crisp number rather than a fuzzy number. After determining the relative importance levels of the indicators, the selected indicators were combined into an overall SQI using the following Eq. (2).

$$SQI = \sum_{i=1}^n W_i S_i, \quad (2)$$

SQI is the soil quality index, W is the weight of an indicator to FAHP and S is the indicator score.

Descriptive statistics and spatial variability of SQI.

Descriptive statistics were conducted to assess data integrity, and one-way analysis of variance (ANOVA) was used to evaluate the significance of the soils on the Soil Quality Index (SQI). Post-hoc analysis at a 95% probability level using Duncan's multiple range test was performed for significant variables. Data analysis was conducted using SPSS 21.0 statistical software (SPSS, Inc., Chicago, IL), while GS+ (version 7) was employed for experimental semivariogram modeling. The best-fit model for SQI was selected based on Residual Sum of Squares (RSS) and r^2 values of the semivariogram model. Models with the lowest residuals (RSS) and highest r^2 values were chosen [88]. The integrity of the spatial distribution map of SQI, including range, sill, nugget, and lag number, were estimated using semivariogram models. The kriging map of SQI was created using the geostatistical extension of ArcGIS 10.2. Grades were assigned following Gugino et al. [40] as very low (<40%), low (40–55%), medium (55–70%), high (70–85%), and very high (>85%).

RESULTS AND DISCUSSION

The physical, chemical, and biological properties of soils showed variability due to the dynamic interactions of different land uses and anthropogenic activities such as tillage, fertilization, and irrigation under long-term intensive agricultural production on the three soils. Descriptive statistics for soil properties and indicator scores used in the SQI calculation are provided in Table 1 and Table 2, respectively.

Table 1. Physical, chemical and biological soil properties

Parameter	BD	AS	AWC	WFPS	pH	EC	P	K	OC	MBC	BGEA
	g cm ⁻³	%				dS m ⁻¹	mg kg ⁻¹			%	mg kg ⁻¹
Chromic Vertisol											
Min	1.05	25.5	2.29	0.50	7.48	0.41	2.4	199	0.63	59	32
Max	1.46	76.2	18.58	0.79	8.16	2.51	59.8	497	1.68	147	313
Mean	1.27	53.8	11.12	0.60	7.87	0.74	12.4	317	1.10	84	87
Std. D.	0.07	11.3	3.63	0.06	0.11	0.34	7.8	66	0.19	19	64
CV	5.7	20.9	32.7	10.3	1.4	45.2	63.3	20.9	17.6	22.4	73.4
Skewness	0.23	-0.57	-0.24	0.75	-0.74	3.05	3.37	0.94	0.24	1.29	2.37
Pantofluvic Calcaric Fluvisol											
Min	1.13	5.5	7.12	0.47	6.97	0.42	3.0	147	0.41	25	21
Max	1.54	62.4	25.02	0.79	7.73	3.89	49.5	513	2.25	166	317
Mean	1.34	22.8	14.16	0.63	7.37	0.85	19.0	304	0.99	89.1	118
Std. D.	0.09	11.6	3.37	0.09	0.15	0.57	10.7	79	0.38	34	85
CV	6.5	50.8	23.8	13.9	2.0	66.7	56.1	25.9	38.1	38.5	72.0
Skewness	-0.20	0.78	0.46	0.36	0.20	3.05	0.71	0.31	1.09	0.36	0.90
Gleyic Solonchak											
Min	1.14	10.4	2.90	0.53	7.26	0.49	7.0	278	0.58	21	14
Max	1.36	68.5	17.26	0.79	8.27	3.93	38.2	474	1.38	80	131
Mean	1.26	38.7	10.72	0.65	7.84	1.02	16.2	354	0.95	42	50
Std. D.	0.05	12.0	2.77	0.06	0.22	0.74	5.1	36	0.18	13	16
CV	4.0	31.0	25.8	9.3	2.8	72.1	31.2	10.1	18.9	32.1	31.6
Skewness	-0.38	-0.26	0.13	0.36	-0.47	2.27	1.08	0.16	0.09	0.77	1.46

Soil physical indicators. The bulk densities for the Chromic Vertisol and Pantofluvic Calcaric Fluvisol had wider variation in contrast to Gleyic Solonchak soil with a narrower, their bulk average bulk density varied between 1.26 and 1.34 g cm⁻³ with Chromic Vertisol and Gleyic Solonchak having the least while Pantofluvic Calcaric Fluvisol had the highest bulk density. Variations in land use and soil texture may have affected the bulk density in the research area. The SMAF scores variations followed a similar trend to the BD range values. The average SMAF scores for the soils varied between 0.53–0.65. Chromic Vertisol and Gleyic Solonchak having the least BD SMAF scores while Pantofluvic Calcaric Fluvisol had the highest. Chromic Vertisol and Gleyic Solonchak, being the most common soils in arable lands due to their high clay content, exhibited the lowest average bulk density scores. In contrast, Pantofluvic Calcaric Fluvisol, commonly used for horticultural crops, had higher scores due to its well-balanced soil texture. Zero tillage and reduced tillage systems initially resulted in higher bulk density compared to conventional tillage, but temporal changes reduced these differences [14]. Zero and reduced tillage, which do not disturb the soil in Pantofluvic Calcaric Fluvisol, may have caused higher bulk density SMAF scores compared to other soils.

The soil was initially used for intense mechanized arable cropping, and later converted to as needed minimum mechanized system horticulture for citrus trees and depending on the year of conversion can affect the gradual return of their bulk density to untilled condition. High soil compaction observed in arable fields is attributed to frequent soil tillage with a moldboard plow and a reduction in soil organic carbon (SOC). The decrease in SOM and the increase in soil compaction are linked to continuous agronomic activities and heavy farm equipment [89]. These results indicate that long-term continuous agronomic activities reduced SOM and bulk density SMAF scores, attributing this to the negative effects of compaction.

Aggregate stability varied the highest in Chromic Vertisol, while Pantofluvic Calcaric Fluvisol and Gleyic Solonchak varied the least. The average AS mean value varied between 22.8–53.8% with Pantofluvic Calcaric Fluvisol having the least AS, Chromic Vertisol having the highest. The Aggregate stability SMAF average score varied between 0.71–0.94, Chromic Vertisol was 0.20 greater than the other two soils. Aggregate stability reflects the soil's structural ability to withstand external forces such as mechanical breakdown and the dispersive nature of water [34]. Different management practices may have affected aggregate

Table 2. SMAF scores of soil quality indicators

Parameter	BD	AS	AWC	WFPS	pH	EC	P	K	OC	MBC	BGEA
Chromic Vertisol											
Min	0.29	0.53	0.04	0.61	0.28	1.00	0.41	1.00	0.06	0.05	0.03
Max	0.96	1.00	0.78	0.95	0.88	1.00	1.00	1.00	0.32	0.14	0.99
Mean	0.53	0.94	0.47	0.91	0.68	1.00	0.97	1.00	0.14	0.07	0.19
Std. D.	0.13	0.11	0.18	0.06	0.18	0.00	0.07	0.00	0.05	0.02	0.25
CV	23.9	12.2	38.4	7.1	27.1	0.0	7.0	0.0	32.4	25.6	136.1
Skewness	0.60	-1.90	-0.52	-2.53	-0.98	-	-6.60	-	1.28	1.87	2.52
Pantofluvic Calcaric Fluvisol											
Min	0.28	0.34	0.20	0.55	0.55	0.64	0.50	0.80	0.14	0.11	0.06
Max	0.99	1.00	0.85	0.97	0.98	1.00	1.00	1.00	1.00	0.96	1.00
Mean	0.65	0.71	0.54	0.87	0.90	1.00	0.98	0.99	0.62	0.43	0.58
Std. D.	0.22	0.20	0.13	0.12	0.07	0.04	0.07	0.03	0.26	0.26	0.38
CV	34.5	27.8	24.3	13.3	7.5	3.7	7.6	3.1	41.4	61.5	64.8
Skewness	-0.08	-0.21	-0.35	-1.26	-3.52	-9.54	-4.94	-3.57	-0.14	0.68	-0.09
Gleyic Solonchak											
Min	0.37	0.01	0.05	0.60	0.26	0.63	0.93	1.00	0.05	0.06	0.02
Max	0.81	1.00	0.77	0.95	0.94	1.00	1.00	1.00	0.21	0.17	0.13
Mean	0.53	0.73	0.49	0.87	0.75	0.99	0.99	1.00	0.11	0.09	0.06
Std. D.	0.10	0.24	0.15	0.09	0.18	0.04	0.01	0.00	0.03	0.03	0.02
CV	18.7	32.9	30.3	9.9	23.4	4.1	1.3	0.0	30.6	29.7	44.1
Skewness	0.83	-1.06	-0.29	-1.26	-1.77	-8.44	-3.07	-	0.82	1.17	1.16

stability. Field observations indicated that Pantofluvic Calcaric Fluvisol, primarily planted with older horticultural crops, has tightly packed soils, which may explain the lower SMAF score obtained. SOM acts as a cementing agent in soil, enhancing aggregate structure [80]. Adding different organic manures to soils [65] and adopting reduced and zero tillage [27] improve SOM and have a synergistic effect on aggregate stability. Additionally, clay minerals enhance aggregate stability by binding soil particles [45]. The higher aggregate stability in Chromic Vertisol, where clay content is high, is attributed to higher SOC compared to the other soils, positively contributing to aggregate stability. However, Gleyic Solonchak, despite having high clay content, exhibited lower aggregate stability, likely due to the prevalent use of conventional tillage and the burning of harvest residues and plant stubbles. In contrast, conventional management practices were applied on Chromic Vertisol at lower intensity. The reduction in SOM is linked to conventional tillage practices, which break up organic matter within soil aggregates, leading to the decomposition of exposed SOM, and the lack of plant residue return to the soil. Long-term zero tillage and incorporation of stubble, rather than burning, improve SOM and aggregate stability [21, 75], suggesting that implementing such measures can positively impact soil quality characteristics across all soils.

The available water content (AWC) for all soils ranged within a within similar range and Pantofluvic Calcaric Fluvisol had 0.2% more AWC compared to the other soil. The SMAF score also followed a similar trend. Pantofluvic Calcaric Fluvisol was 0.07 greater than other average SMAF scores. Compacted soils and those with high bulk density SMAF scores generally have low available water content SMAF scores. Soil compaction affects available water content by reducing pore spaces and restricting root growth, which impacts overall soil quality [73]. The Chromic Vertisol and Gleyic Solonchak, due to their high clay content, showed similar available water contents and lower values compared to Pantofluvic Calcaric Fluvisol, which has a more balanced soil texture. While SOC levels were similar across all soils, SOC may have influenced available water content in Pantofluvic Calcaric Fluvisol due to a lower clay content. A meta-analysis study showed that organic matter directly impacts available water content, with sandy and silt soils responding to changes in SOM, while clay soils remained relatively unchanged [59]. Therefore, the 62% OC SMAF score for Pantofluvic Calcaric Fluvisol positively contributed to the improvement of available water content. This is due to the role of SOM in soil physical properties such as bulk density, porosity, and aggregate stability, which affects available water content [53].

The water-filled pore space (WFPS) for Chromic Vertisol, Pantofluvic Calcaric Fluvisol and Gleyic Solonchak were within similar range of 0.47–0.79. Pantofluvic Calcaric Fluvisol and Gleyic Solonchak had slightly higher average than Chromic Vertisol. The WFPS SMAF score ranges for the soils ranged between 0.55–0.97, Chromic Vertisol had a slightly higher SMAF average (0.04) above other soils. WFPS is a critical factor influencing microbial activity [55]. Optimal level for microbial activity was reported to be 60% water-filled pore space [55, 81] and air-filled pore space may be negatively affected above this level. All examined soils were within this optimal range. Agronomic activities across all soils suggests that WFPS is not a limiting factor and falls within the range necessary for microbial activity.

Soil chemical indicators. The pH ranges for Chromic Vertisol and Gleyic Solonchak varied within a wider range while Pantofluvic Calcaric Fluvisol within a wider range. The Chromic Vertisol and Gleyic Solonchak are slightly alkaline, while the Pantofluvic Calcaric Fluvisol ranges from neutral to slightly alkaline. There was little variation in soil pH across the Çukurova region, with pH values being relatively similar [35]. Land use may have affected the soil pH SMAF scores, with Pantofluvic Calcaric Fluvisol, primarily used for horticultural crops, showing higher SMAF scores. The higher soil pH SMAF scores for the soil, ranging from 0.55 to 0.98 with an average of 0.90, suggest that problems with nutrient uptake will be minimal compared to other soils with lower SMAF scores. In areas with lower soil pH SMAF scores in Pantofluvic Calcaric Fluvisol and Gleyic Solonchak, soil mineral nutrients may be negatively influenced, potentially limiting plant nutrient uptake. The parent material of the study area has a high calcium carbonate content [35]. Soils with high carbonate deposition in the rooting zone exhibited low pH scores, likely limiting the uptake of beneficial soil nutrients such as phosphorus, iron and zinc [3]. This is due to the formation of slightly soluble CaPO_4 compounds from available phosphorus with calcium [54], which can reduce the availability of readily accessible plant nutrients.

The electrical conductivity (EC) levels of Chromic Vertisol, varied within a narrow range compared to the wider range in Pantofluvic Calcaric Fluvisol and Gleyic Solonchak. Gleyic Solonchak was at least 0.28 dS m^{-1} higher than other soils. The EC of these soils was not above the recommended range for plant growth. Consequently, the Chromic Vertisol and Pantofluvic Calcaric Fluvisol SMAF scores of 1 further supported this observation. The SMAF scores for Gleyic Solonchak EC varied from 0.63 to 1, with an average of 0.99. Pantofluvic Calcaric Fluvisol, which is primarily utilized for horticultural crops, had a higher EC of 3.89 dS m^{-1} and a low SMAF score of 0.64, potentially negatively affecting plant productivity, especially for plants sensitive to high salinity. Ayers

and Westcot [9] reported that EC levels above 1.7 to 1.8 dS m^{-1} can affect the productivity of orchard trees such as grapefruit and lemon. The higher EC observed in the Gleyic Solonchak is primarily due to management practices. Some of these management practices include flood irrigation and the lack of a drainage system. Recent construction of drainage channels has alleviated the salinity problems, particularly at the soil surface. While crop productivity has not been severely impacted, flood irrigation may continue to hinder the productivity of the soil. The low aggregate stability of Gleyic Solonchak tends to create difficulties such as low permeability. In addition, during summer irrigation, the supplied water dries rapidly, potentially leading to capillary flow from below the groundwater table. Over several cycles, this may increase soil salinity beyond tolerable levels.

The Chromic Vertisol is mainly used for heavy mechanized arable farming, resulted in wider phosphorus content range but with the least P average content compared to the other soils. While Pantofluvic Calcaric Fluvisol varied slightly lesser than Chromic Vertisol, the highest P average content was measured for the soil, having 2.8 P mg kg^{-1} more than the other soils. The phosphorus content in the Gleyic Solonchak varied within a much narrower range, but had an average greater than Chromic Vertisol. Most soils had available soil phosphorus levels in the optimal range of 10.9 to 21.4 mg kg^{-1} for crop growth [10]. The SMAF scores for phosphorus were high and within similar ranges: Chromic Vertisol, Pantofluvic Calcaric Fluvisol and Gleyic Solonchak had scores above 0.95. There was spatial variation at some sampling points, with some showing soil phosphorus at optimal levels, while others exceeded this level, which can limit zinc availability [60] and reduce yield [38]. Excess phosphorus transported to nearby water bodies can cause eutrophication [63] and should be monitored due to its environmental impacts. The variation in soil phosphorus is partly due to the application of mineral fertilizers without considering residual soil phosphorus [42]. This highlights the need for soil-based tests for phosphorus application to increase efficiency, reduce fertilizer costs, and protect the environment.

Available potassium in the Chromic Vertisol, Pantofluvic Calcaric Fluvisol and Gleyic Solonchak varied within similar range of 147 to 513 mg kg^{-1} . The average K in Gleyic Solonchak was at least 37 mg kg^{-1} greater than in the other soils. The available potassium levels were within and above the recommended range [36], as most soils in Turkey are either rich in potassium or at sufficient levels for plant production [67]. Despite intensive agronomic activities, available potassium levels were sufficient for plant production. Therefore, the SMAF scores for available potassium in Chromic Vertisol, Pantofluvic Calcaric Fluvisol and Gleyic Solonchak was ~ 1.00 , indicating that potassium is not limiting plant growth or soil quality.

Soil biological indicators. Soil organic carbon (SOC) content ranges for the soils indicated that Gleyic Solonchak < Chromic Vertisol < Pantofluvic Calcaric Fluvisol and all varied with 0.41–2.25%. The Çukurova region, has a Mediterranean climate, heavily mechanized agricultural activities are carried out and has a low soil organic matter (SOM) [35]. Heavily mechanized agricultural activities typically lead to reduced SOM/OC [89]. The use of tillage equipment, such as moldboard plows that invert the topsoil, lead to the oxidation and reduction of sequestered soil OC in the Chromic Vertisol and Gleyic Solonchak. Increased aeration from breaking up soil clods accelerates the decomposition of SOM protected within soil aggregates [1]. Despite a ban on burning stubble and harvest residues, which have the potential to become SOM [20], this practice continues, contributing to low OC levels. Periodic plowing with conventional tillage equipment, such as moldboard plows, and the complete removal of plant residues significantly reduces OC [87, 90]. Additionally, the removal of tree prunings, which is one of the main sources of SOM in the Pantofluvic Calcaric Fluvisol (mainly used for horticultural crops), contributes to the low OC in the soil [2].

Chromic Vertisol and Gleyic Solonchak had the least OC SMAF scores ranging from 0.05 to 0.32. This indicates that they are generally poor in soil organic carbon (SOC). Reduced biodiversity from monocropping systems, such as the cultivation of wheat, maize, soybean and cotton and the use of conventional tillage systems like the moldboard plow, which disrupts soil aggregates and clods protecting SOM, along with the burning of harvest residues and stubble, all contribute to reduced carbon sequestration and overall OC. Previous studies have shown that conventional tillage systems in intensive agriculture accelerates the decomposition of sequestered SOM [1]. The Pantofluvic Calcaric Fluvisol, mainly planted with horticultural crops, had relatively higher OC SMAF scores ranges, and an average SMAF score 0.48 higher than the other soils. Soil texture and soil suborders were major factors influencing the OC SMAF scores, while climate, which is uniform across all soils, played a lesser role [7].

The suborders of soils significantly influenced their OC classification: Chromic Vertisol and Gleyic Solonchak were classified in the 2nd class with Xerert and Aquept suborders, respectively, while Pantofluvic Calcaric Fluvisol was in the 4th class under the Fluvent suborder [35]. The upper limit for OC SMAF scoring decreases as the OC class changes from 1 to 4. The correlation between OC and clay content influenced the OC SMAF classification, with soils high in clay having higher scores compared to those high in sand [7]. Despite relatively equal OC levels across all soils, Pantofluvic Calcaric Fluvisol had a higher OC SMAF scores due to its underlying subgroups. The higher sand content in Pantofluvic Calcaric Fluvisol results in lower OC compared to other soils, which require more organic matter to achieve similar changes.

The beta-glucosidase enzyme activity (BGEA) for Chromic Vertisol and Pantofluvic Calcaric Fluvisol had wider variation compared to the Gleyic Solonchak. The BGEA scores for Chromic Vertisol and Pantofluvic Calcaric Fluvisol had a wider SMAF score range compared to the narrower range in Gleyic Solonchak. The SMAF score averages indicated that Gleyic Solonchak < Chromic Vertisol < Pantofluvic Calcaric Fluvisol and The SMAF score of Pantofluvic Calcaric Fluvisol was 0.39 higher than the other soils. Similar to OC, BGEA was very low. BGEA is sensitive to residue management and serves as an indicator of SOC changes within soils [76]. Soils that are low in organic matter residues can limit BGEA since these residues provide energy for soil microorganisms that produce the enzymes. Intensive agricultural practices, prevalent across all soils, such as conventional tillage with moldboard plows, flood irrigation, and the removal and burning of harvest residues and stubble, severely degrade soil biological activities and influence BGEA [5, 58, 85].

The Microbial biomass carbon (MBC) results indicated that the range for Gleyic Solonchak < Chromic Vertisol < Pantofluvic Calcaric Fluvisol, their averages also followed a similar trend, Pantofluvic Calcaric Fluvisol with 89.1 mg kg⁻¹ had a higher MBC average compared to the other soils. The MBC SMAF scores range results showed that Chromic Vertisol < Gleyic Solonchak < Pantofluvic Calcaric Fluvisol. The average MBC SMAF scores for Chromic Vertisol and Gleyic Solonchak were quite low, while Pantofluvic Calcaric Fluvisol average SMAF score was at least 0.34 higher than other soils. Annual monocropping, prevalent in the Chromic Vertisol and Gleyic Solonchak, disrupts OM sequestration due to land preparation and harvesting, while horticultural gardens, where such practices are minimal and only periodic, show higher MBC and BGEA SMAF scores.

The soil physical, chemical and biological indicators gave peculiar insights into how the soil could be managed for increased potential. In the soil physical properties SMAF scores AS and WFPS indicated a high potential while BD and AWC calculated scores were just a little bit above average. The average BD score may be linked to compaction due to heavy farm mechanization [89], the possible solution to improving the BD score is to limit frequent soil tillage, and also increase the OC of all the soils as the SMAF scores for the soils except for Pantofluvic Calcaric Fluvisol was below 14%. Improvement in the SOM will cause a dilution effect in the soil, improving the BD. The AWC average SMAF score across the soils suggest that plant productivity potential may be limited. The factors affecting AWC are majorly BD, AS and WFPS, and OC, the average score of the AS and WFPS are very high while for the others between average and low. Decreasing the mass per volume of soil creates an avenue for more soil moisture retention in the soil [73], and increasing the OC can increase the water retention

Table 3. Weight values for physical, chemical, biological and soil quality calculated by the FAHP

Indicators	Soil Quality			Total
	Physical	Chemical	Biological	
AS	0.297			
BD	0.225			
AWC	0.382			
WFPS	0.096			
pH		0.382		
EC		0.096		
P		0.297		
K		0.225		
OC			0.449	
MBC			0.351	
BGEA			0.200	
Total	1.000	1.000	1.000	1.000

of the soil [53]. The soil chemical indicators show an above average SMAF scores, however further consideration can be given to the soil pH, this is necessary to further improve the ionic balance of the soils. An increase in SOC can improve the buffering capacity of the soil, liming and selective consideration to the types of fertilizer used can also be effective. The soil biological properties were generally low especially in Chromic Vertisol and Gleyic Solonchak, while in Pantofluvic Calcaric Fluvisol slightly above average. The heavy mechanization and agricultural inputs may lead to accelerated SOM decomposition [1, 87], this can be ameliorated by frequent manure and organic fertilizer application, restrictions on stover and stubble burning, reduced soil tillage and change to alternative land use types may all improve the SOC of all the soils. MBC and BGEA are both essential to ecological function and stability, while SOM may improve their potential across all the soils, other strategies can also be considered. Monocropping, heavy fertilizer application, pesticide and herbicides are especially detrimental to MBC, all of these should be minimized and possibly avoided where applicable. Switching to an alternative land use type would also be beneficial to, as horticulture had almost average SMAF scores for all soil biological properties compared to the low scores for arable cropping.

Indicator weights. The weight values of soil properties used for the assessment of soil quality were determined using the FAHP. First, soil quality indicators were hierarchically grouped into three main criteria. Pairwise comparisons for this study were conducted by experts using the triangular fuzzy conversion scale within the hierarchical structure. The pairwise comparison matrix was developed based on expert evaluations (Table S2). Subsequently, the indicator weights for the soil properties were determined according to FAHP (Table 3).

Eleven indicators were categorized into three main groups to assess SQI. Physical, chemical, and biological indicators of soil are defined as natural or inherent factors arising from soil formation and environmental conditions [43]. These indicators have been utilized by many researchers for SQI assessment [18, 39, 43, 66]. In this study, physical quality had the highest weight at 0.567, whereas biological quality had the lowest weight at 0.077. Among inherent quality components, soil physical indicators play a key role in soil-plant-water relations, soil conservation, productivity, and sustainability [41]. Additionally, soil physical quality significantly influences biological and chemical quality, as it forms the basis for the functioning of other aspects (Dexter, 2004). Therefore, soil physical quality received the highest weight in SQI evaluation.

The soil physical properties weights results indicate that $AWC > BD > AS > WFPS$. AWC is one of the most important soil properties for plant growth, carbon management, nutrient cycling, and controlling crop yield [59], and it affects the relative abundance of macro- and micro-flora and fauna in the soil. Furthermore, AWC becomes even more crucial considering the anticipated effects of climate change on water management. The results of this study align with findings from [3, 33, 43], which also identified AWC as having a high weight.

The influence of soil pH on soil chemical quality is reflected in its weight relative to other chemical properties. This is due to the effect of soil pH on chemical reactions and nutrient availability for plant growth [72] and its impact on the abundance of bacteria and fungi, which are primary decomposers of organic matter in soils.

The soil biological weights indicated that $OC > MBC > BGEA$. OC affects soil physical, chemical, and biological properties [33, 39] and is an important

Table 4. The descriptive statistics and the differences in the means of SQI (lowercase letters (*a*, *b*, and *c*) denote significant differences between soils according to Duncan's multiple range test)

Parameter	Min	Max	Mean	Std. D.	CV	Sensitivity	Skewness
Chromic Vertisol	57.1	84.5	69.5 _b	5.09	7.3	1.48	0.38
Pantofluvic Calcaric Fluvisol	61.5	89.4	74.9 _a	6.40	8.5	1.45	0.22
Gleyic Solonchak	50.9	78.4	67.1 _c	5.61	8.4	1.54	-0.52
ANOVA				0.000			

Table 5. Model parameters for the Chromic Vertisol, Pantofluvic Calcaric Fluvisol and Gleyic Solonchak

Soils	Model	Nugget	Sill	Spatial dependence, %	Range, A	Active lag distance	Lag class distance interval	r^2	RSS
		Co	Co + C						
Chromic Vertisol	Exponential	3.08	25.33	12.2	132.0	1000	115	0.632	10.6
Pantofluvic Calcaric Fluvisol	Exponential	0.1	37.21	0.3	136.2	410	43	0.898	45.8
Gleyic Solonchak	Spherical	17.13	36.55	46.9	487.5	420	35	0.836	74.9

indicator for aggregation and erosion, nutrient storage and provision, and overall soil fertility and quality improvement [43]. In this context, as in Demir [31] study, OC received a higher weight in soil biological quality compared to other biological indicators.

The weight values from each soil properties suggest that AS, BD and AWC are the most essential soil indicators for soil physical properties; pH, P and K are the most essential for chemical properties; and OC, MBC and BGEA for soil biological properties. At the soil properties levels these are to be accessed at interval to monitor soil quality levels.

Soil quality assessment and spatial variability of SQI.

The SQI range results indicates that Pantofluvic Calcaric Fluvisol > Chromic Vertisol > Gleyic Solonchak (Table 4). Furthermore, there was a significant difference among the soils. The mean SQI in the Pantofluvic Calcaric Fluvisol was at least 5.4% significantly higher than the other soils. Intrinsic soil properties, such as soil texture distribution and parent materials, affected the SQI of the soils [11]. However, different agronomic practices, such as changes from natural vegetation to intensive monoculture systems, could also have influenced the SQI of the soils [51]. The higher SQI in Pantofluvic Calcaric Fluvisol, mainly used as orchards, may have been caused by reduced soil disturbances from tillage, periodic planting, harvesting, and machine traffic associated with intensive agronomic practices. The agronomic practices, such as the burning of harvest residues and plant stubble, especially in Chromic Vertisol and Gleyic Solonchak, disrupt the carbon and nutrient cycles, reducing the SQI of the soils [4, 21]. Furthermore, flood irrigation further depletes the SQI of Gleyic Solonchak by increasing soil salinity and creating ion imbalances

within the soil. Conversely, all agronomic activities carried out on Pantofluvic Calcaric Fluvisol have maintained and improved the organic carbon level, contributing to the higher SQI compared to the other soils.

The best models fitting the different spatial structures of the Chromic Vertisol, Pantofluvic Calcaric Fluvisol and Gleyic Solonchak were identified using semi-variograms (Table 5). Exponential model describes the SQI in both the Chromic Vertisol and Pantofluvic Calcaric Fluvisol, while spherical model describes the SQI in the Gleyic Solonchak. The Chromic Vertisol and Pantofluvic Calcaric Fluvisol showed spatial dependence of 12.2 and 0.3%, respectively, indicating a strong spatial dependence, as both soils had spatial dependence values of less than 25%. In contrast, the Gleyic Solonchak, with a spatial dependence of 46.9%, showed moderate spatial dependence [19]. The moderate spatial variation in the Gleyic Solonchak was due to its intrinsic variability. Pantofluvic Calcaric Fluvisol had the least nugget effect, having a spatial continuity up to 136 m and Chromic Vertisol and Gleyic Solonchak due to a higher nugget effect of 3.08 and 17.13 have a range of 132 and 487.5 m, respectively.

The spatial variability of all the soils was above 50% (Fig. 4). The Chromic Vertisol SQI showed two levels: a mid-range of 57.1–70.0% and a high range of 70.0–84.5%. The Pantofluvic Calcaric Fluvisol had three levels: a mid-range of 61.5–70.0%, a high range of 70.0–85.0% and a very high range of 85.0–89.4%. The Gleyic Solonchak was classified into three ranges: a very low range of 50.9–55.0%, a mid-range of 55.0–70.0% and a high range of 70.0–78.4%.

Across the soil in Chromic Vertisol, most of the landmass had average SQI, while the remaining other part has high SQI. The high SQI values were concen-

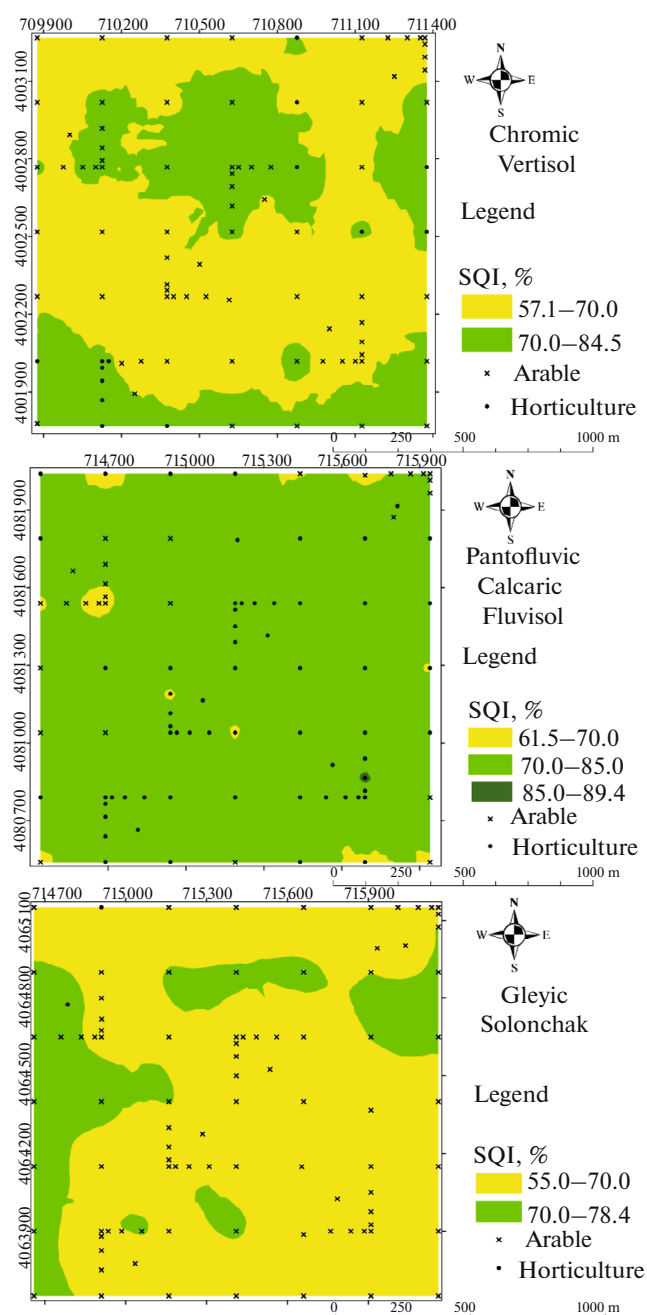


Fig. 4. Spatial variability of SQI.

trated in clusters to the south and north, where most horticultural fields are located, while low SQI values were found in areas occupied by arable fields. The Pantofluvic Calcaric Fluvisol majorly had a high SQI with very few average SQI and a spot of very high SQI. The patches of low SQI are located at the fringes to the north and south, while the very high SQI patches in the southeast of the sampling locations. According to the land-use type in Pantofluvic Calcaric Fluvisol, horticulture land use type was majorly found in areas with high and very high SQI, while very low arable

activities are carried out, this arable land use type mainly have average SQI. The Gleyic Solonchak had only a few patches with high SQI and generally showed low SQI values. Although two land use types are found in this soil, the major land use type is arable cropping with only a few sampling points for horticulture. Excluding the locations with horticultural activities, the remaining areas with higher SQI are mostly linked to reduced levels of intensive agronomic practices such as soil ploughing, high fertilizer application and frequent irrigation. Although both Chromic Vertisol and Gleyic Solonchak have similar land uses, lower SQI values were more prevalent in the Gleyic Solonchak. In contrast, higher SQI values were observed in the Chromic Vertisol, due to its horticultural gardens, which improved the overall SQI of the soil. Horticultural activities are prevalent in the Pantofluvic Calcaric Fluvisol, with only a few patches dedicated to arable farming. The presence of a few patches with very high SQI suggests that there may still be more potential for increasing the SQI of the soil to enhance productivity. Based on the land use types, horticulture land use majorly ranged between 70–85% with only a few greater than >85% and arable land use were between 55–70%. This suggests that while intrinsic soil genetic properties may influence SQI, the major factor influencing SQI was land use types.

CONCLUSIONS

The examination of soil quality at the lowest soil classification level enabled a better understanding of soil degradation and the probable solutions to proffer to them. SMAF and FAHP effectively detected changes resulting from various agronomic activities. Overall, the SQI of the Pantofluvic Calcaric Fluvisol was maintained, considering that horticultural lands generally have higher SQI compared to cultivated fields. SMAF results for the soils showed distinct variations in biological parameters, especially in organic carbon, microbial biomass carbon and beta-glucosidase activity.

The use of conventional tillage equipment exposes occluded soil organic carbon, a crucial mediator of physical, chemical and biological activities. This exposure is further exacerbated by practices such as plant residue and stubble burning, which negatively impact the SMAF scores of the Chromic Vertisol and Gleyic Solonchak. The intrinsic soil properties are factors in determining their use types: Chromic Vertisol and Gleyic Solonchak are allocated to arable fields, while Pantofluvic Calcaric Fluvisol is used for horticultural crops. However, both Chromic Vertisol and Gleyic Solonchak had SQI values below 70%, with Gleyic Solonchak having the lowest score. The SQI of Pantofluvic Calcaric Fluvisol (74.9%) indicates that conventional tillage and destructive agronomic activities, such as stubble burning, significantly impact soil quality and should be avoided. Sustainable agronomic practices such as reduced tillage and use of

and practices which returns organic materials to the soil should be adopted, and experts should be consulted to inform farmers about the negative effects of harmful practices. This will help in maintaining and improving the SQI of both soils.

SUPPLEMENTARY INFORMATION

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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