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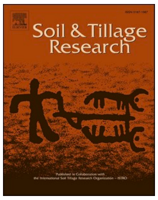

Soil quality assessment to compare tillage systems in Cukurova Plain, Turkey

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ABSTRACT

Agricultural practices should be carefully monitored for long-term impacts on soil quality to avoid further deterioration in ecosystem services provided by soils. The aim of this study was to evaluate and compare the effects of two conventional (CT), three reduced (RT) and two no-till (NT) tillage practices on soil quality of a clayey soil in a ten-year experiment using Soil Management Assessment Framework (SMAF). The field experiment was established in 2006 with six tillage methods, and winter wheat (*Triticum aestivum* L.), soybean (*Glycine max.* L.) – grain corn (*Zea mays* L.) crop rotation. The NT plots were divided into two parts, i.e., half of them were plowed with a moldboard plow during November 2015, and this practice was defined as strategic tillage (ST), while the remaining half was left undisturbed (NT). Disturbed and undisturbed soil samples were collected at three depths (0–10, 10–20 and 20–30 cm) from experimental plots in 2016. Fourteen soil quality indicators, including physical, chemical and biochemical properties were determined to assess soil quality. Soil productivity, water relations (WR), resistance and resilience (RR), and physical stability and support (PSS) functions defined in SMAF were calculated. The RR and PSS function scores were significantly higher at 0–10 cm depth under conservational tillage methods (RT and NT) compared to CT methods. Low nutrient content, compaction, aggregate size and stability values in 10–30 cm depth decreased the functioning potential. The RR function at 0–10 cm depth in NT method was 103 % and 72 % higher than CT-1 and CT-2, respectively. All soil functions under RT and NT methods decreased with depth. The ST significantly increased PSS and WR functions in all sampling depths and overall soil quality in 10–20 and 20–30 cm depths compared to long-term NT method. The comparison of soil functions and overall soil quality indices helped to identify the effects of different tillage practices on functional potential of the soil. Furthermore, soil quality assessment using soil functions provides an overview to distinguish the pros and cons of tillage practices on sustainability of the crop production.

1. Introduction

Soils perform several functions concurrently, and soil forming factors, physical, chemical and biological soil characteristics determine the extent of functionality for each function (Schulte et al., 2014). Productivity is a well-known function of soils, defined as the capacity of a soil to supply plant nutrients and water for supporting plant growth to provide food, fiber and fuel for living organisms (Sanden et al., 2019). Maintaining fiber and food production ability of agricultural lands for increasing global population pose severe threats to some of the soil functions and delivery of related ecosystem services (Barão et al., 2019). Sustainability in agricultural production is even more important for Turkey due to rapid population growth and massive migrations from eastern and southern countries. In addition, farmers unconsciously continue traditional practices, i.e., conventional tillage, stubble burning, flood irrigation etc. in agricultural activities (Korucu et al., 2009). Consequently, soil problems such as nutrient deficiencies, salinity, compaction and decline in organic matter content are seriously threatening the sustainability of soil quality and agricultural production in the country (Günal et al., 2015).

Tillage is the most common agricultural practice used to create a suitable environment for seed germination by promoting soil warming

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and water evaporation (Nunes et al., 2018) and managing weed populations. However, long-term intensive conventional tillage by moldboard plow decreases aggregate stability (Crittenden et al., 2015), increases compaction (de Moraes et al., 2016) and impairs biological properties of soils (Acar et al., 2018; Crittenden and de Goede, 2016; Karlen and Rice, 2015). In contrast, conservation practices such as reduced and no-till may increase production in the long run; however, these are highly recommended to conserve and improve the functioning ability of soils rather than increasing yield (Busari et al., 2015). Therefore, agricultural management decisions should not only focus on improving the supply of individual soil functions such as productivity or nutrient cycling, but also consider other important soil functions, including water purification, cycling and storage, climate regulation and carbon sequestration, soil biodiversity, resistance and resilience, physical stability and support (Adhikari and Hartemink, 2016; Andrews et al., 2004). Agricultural practices adopted for conservative purposes have to be monitored to evaluate their long-term effects on soil quality and the practices reducing soil quality should be relinquished. Farmers mostly focus on measurements of soil pH, electrical conductivity, nitrogen, phosphorus, potassium and sometimes zinc and iron to evaluate fertility status of their soils, which might be useful to increase crop yield. But, focusing only on chemical soil indicators may easily overlook other constraints related to physical and biological properties of soils (Nunes et al., 2019). Soil quality is not only related to the plant nutrient status of soils but also to the productivity and sustainability of agroecosystems, resilience to water deficiency and extreme rainfall, and conservation of soil and water (Moebius-Clune et al., 2016). Therefore, a comprehensive soil quality assessment is needed to describe the functioning ability of soils by integrating soil chemical, physical and biological components, which are highly sensitive to management decisions of land users (Karlen et al., 1997).

The importance of soil quality has been emphasized in many studies; however, discussion on selection of relevant soil properties and interpretation of measurements is continuing due to complexity and site-specificity of soils (Bünemann et al., 2018). The variable nature of soils due to genetic and anthropogenic factors (Trangmar et al., 1986) prevents the creation of a standard dataset for assessment of soils in different climatic and environmental conditions. Dynamic soil properties such as organic matter content and bulk density will vary greatly in soils formed under different climates, topography and parent materials or in soils under different agricultural practices. Therefore, the identification of a set of sensitive soil attributes, which have significant influence on soil functions and considered as soil quality indicators, is the main target of soil quality assessments (Bünemann et al., 2018). During the last two decades, soil quality assessment tools including Comprehensive Assessment of Soil Health (Moebius-Clune et al., 2016) and Soil Management Assessment Framework (SMAF) were developed (Andrews et al., 2004) to determine if the soil quality improved, being sustained, or degraded based on current land use and management practices (Karlen et al., 2019). The SMAF has been successfully applied in different agro-ecological regions of the world to assess the changes in soil quality due to land use change or adaptation of a new agricultural practice (Cherubin et al., 2017; Gura and Mnkeni, 2019; Karlen et al., 2013; Mbuthia et al., 2015). Non-linear scoring curves are used to integrate site-specific information with the physical, chemical and biological soil properties to assess soil quality (Karlen et al., 2019).

The Çukurova Plain is the second largest agricultural production land in the Mediterranean behind the Nile delta and produces most of the food and fiber demand of Turkey. Double cropping of winter wheat and summer corn or soybean are the main production pattern in the plain. Celik et al. (2019) evaluated the impact of tillage systems on soil physical attributes under winter wheat and summer corn or soybean rotation applied in the same study area. However, the effects of long-term conservational and conventional tillage methods on soil functions and overall soil quality have not been documented in the region. In this study, combination of some of biological, physical and chemical soil quality indicators have been used to better compare and monitor the performance of the soil under different tillage practices. The main purpose of this study was to evaluate and quantify the impacts of long-term conservation and conventional tillage practices used in wheat-corn-soybean rotation on soil quality to determine the most beneficial tillage practice improving the ability of a clayey soil to function and maintain the production potential. Measured, scored, and computed SQI values were used to evaluate tillage intensity and are expected to provide a general comparison of soil tillage methods. Nine years of conventional tillage systems under continuous crop rotation are expected to have more detrimental, while conservative practices more beneficial impacts on soil quality. Strategic tillage which is used to control weeds, remove soil compaction, incorporate crop residues accumulated on the soil surface, reduce stratification of C, nutrients and soil acidity under long term no-till (Blanco-Canqui and Wortmann, 2020) is expected to improve quality of soils under nine-year no-till system. In addition, careful examination of function scores and individual indicators may help to identify practices limiting the productivity under wheat-corn-soybean rotation systems under similar environmental conditions.

2. Materials and methods

2.1. Study area, experimental design and tillage practices

The experiment was set up in October 2006 at the Agricultural Experimental Station of Çukurova University (37°00′54″ N, 35°21′27″ E, 32 m a.s.l) in Adana province, Turkey. The climate of the study area is Csa (hot dry-summer) according to the Köppen-Geiger classification with a mean annual temperature of 19.2 °C, precipitation is 639 mm, ~75 % of which falls during winter and spring (from November to May) and the annual potential evapotranspiration is 1557 mm. The soil was classified as fine, smectitic, active, mesic Typic Haploxerert according to Soil Taxonomy (2014) and as Haplic Vertisol according to World Reference Base (WRB, I.W.G., 2015). The soil has a clay texture (50 % clay, 32 % silt and 18 % sand) formed over old terraces of Seyhan River. The mean pH, electrical conductivity and calcium carbonate were 7.82, 0.15 dS m^{-1}, and 244 g kg^{-1}, respectively at 0−30 cm soil depth (Celik et al., 2011).

The tillage practices comprised of two conventional (CT-1 and CT-2), three reduced (RT-1, RT-2 and RT-3) and two no-till (NT and ST) systems. The tillage plots were 12-m wide and 40-m long (480 m^2) for CT-1, CT-2, RT-1, RT-2 and RT-3. The experiment was initiated in 2006 with six tillage systems, half of which were no-till (NT) plots (240 m^2) were cultivated to mitigate compaction with moldboard plow only once in November 2015 to create strategic tillage (ST). The experimental layout was randomized complete block design for all seven tillage methods with three replications. In order to prevent interactions among treatments and to facilitate maneuver of soil tilling machines, a 4-m buffer zone was left around every plot in the experimental field.

In the CT-1 system, the soil was tilled to 30−33 cm depth using a tractor mounted moldboard plow and crop residues were returned and buried in the arable layer. In the CT-2 system, the crop residues were burned prior to the soil tillage and surface soil turned over with a moldboard plow for seedbed preparation of wheat. In CT-2, the soil was subsoiled to a depth of 30−35 cm by a subsoiling chisel, with its adjustable wings being set by intervals of 60 cm distance between their terminal tines. The residues were retained evenly on the soil surface as mulch under RT and NT systems. The details on tillage and other equipment used for crop production have been provided in Celik et al. (2019).

The crop rotation of winter wheat (*Triticum aestivum* L.), soybean (*Glycine max.* L.) – grain maize (*Zea mays* L.) is typical for the region, which was applied in all systems from the beginning of the experiment. Corn and soybean were rotated on alternate years. In order to control weeds, a non-selective herbicide (500 g ha^{-1} Glyphosate) was used in

Table 1
The protocols and references for laboratory analysis of soil quality indicators used in the study.

Properties	Indicators	Units	Protocols	References
Physical	AS	%	Wet sieving method	Kemper and Rosenau (1986)
	BD	g cm^{-3}	Core method	Blake and Hartge (1986)
	PR	MPa	Digital Penetrologger	Eijkelkamp Penetrologger 06.15. SA (ASAE, 1994)
	WFPS		Ratio of volumetric soil water content to total soil porosity	Linn and Doran (1984)
	AWC	%	Gravimetric method	Klute (1986)
	MWD	mm	Wet sieving method	Kemper and Rosenau (1986)
Chemical	pH		Saturated soil paste	Rhoades et al. (1999)
	EC	dS m^{-1}	Saturated soil paste	Rhoades et al. (1999)
	Lime	%	Scheiber's calcimeter method	Kacar (1994)
	SAR		Saturated soil paste	Soil Survey Staff (1996)
	P	mg kg^{-1}	Sodium bicarbonate Olsen method	Olsen (1954)
	K	mg kg^{-1}	Ammonium acetate extraction	Thomas (1982)
	SOC	%	Removing inorganic carbon from total carbon.	Tabatabai (1994)
Biological	PMN	mg kg^{-1}	Removing mineral nitrogen from total nitrogen.	Fabig et al. (1978) and Tabatabai (1994)
	MBC	mg kg^{-1}	Fumigation-incubation method	Horwath and Paul (1994)

AS: Aggregate stability; BD: Bulk density; PR: Penetration resistance; WFPS: Water filled pore space; AWC: Available water content; MWD: Mean weight diameter; EC: Electrical conductivity; SAR: Sodium adsorption ratio; P: Phosphorus; K: Potassium; SOC: Soil organic carbon; PMN: Potential mineralizable nitrogen; MBC: Microbial biomass carbon.

the RT-3, NT and ST systems two weeks prior to sowing. All tillage systems had the same mineral fertilizer application rate, i.e., 172 kg N ha^{-1} and 55 kg P_2O_5 ha^{-1} for wheat, 250 kg N ha^{-1} and 60 kg P_2O_5 ha^{-1} for corn and 120 kg N ha^{-1} and 40 kg P_2O_5 ha^{-1} for soybean. The wheat was sown in the first week of November at a seeding rate of 580–600 plants per m^{-2} and harvested in the first week of June. The corn and soybean at seeding rates of 8.4 and 23.6 plants per m^{2} were sown in the third week of June and harvested in the second week of October. Corn and soybean were sprinkler-irrigated once in every 13-day (total of 5–6 times) during the growing period, and no irrigation was applied to wheat crop. An average of 600−640 mm irrigation water was applied during the growing period of corn, and 540−570 mm irrigation water was applied for soybean.

2.2. Soil sampling and analyses

Disturbed and undisturbed soil samples were collected from three different locations in each tillage system from 0 to 10, 10 to 20 and 20 to 30 cm depths after soybean harvest in November 2016. Soil samples, except for undisturbed cores were air dried, crushed with a wood roller and sieved through a 2 mm mesh for analysis. The list of soil indicators, laboratory or field methods to determine the values and related references are summarized in Table 1. Penetration resistance (PR) was determined to a depth of 30 cm in field by a hand-pushed electronic cone penetrometer (Eijkelkamp Penetrologger 06.15.SA) following ASAE standard procedures (ASAE, 1994), using a cone with 1 cm^{2} base area, 60° included angle and 80 cm driving shaft. The readings were recorded at 10 mm intervals.

2.3. Soil quality assessment

Soil quality indices (SQI) under different tillage methods were determined using the Soil management Assessment Framework (SMAF) described by Andrews et al. (2004). In this study, four functions namely productivity, resistance and resilience (RR), physical stability and support (PSS) and water relations (WR) were defined in the soil quality assessment.

Representative minimum datasets (MDS), including physical, chemical and biological indicators were carefully chosen by experts to define soil functions. Expert opinions reflected the knowledge of researchers who have been working in the region where the experiment was established. When deciding about the indicators, the experts took the study area characteristics such as climate, rainfall and soil characteristics in the experimental field.

A total of fifteen soil quality indicators containing a variety of physical, chemical and biochemical properties, which have direct impact on soil quality were used to define soil functions. In this study, available P and K concentrations, plant available water capacity (AWC), penetration resistance (PR), potentially mineralizable N (PMN), microbial biomass carbon (MBC) and soil pH were considered as important indicators in fulfilling the productivity function of Arık soils and included in MDS. The P and K concentrations and pH value are commonly used indicators to assess the nutrient availability of soils (Cherubin et al., 2017). The MBC and PMN were only determined for 0−10 cm depth; thus, two separate productivity functions (productivity-1 and productivity-2) were calculated to enable better comparisons among soil depths. Seven indicators, including MBC, PMN, pH, P, K, AWC and PR were taken into account in the calculation of the productivity-2 function score of the surface layer. Whereas, soil pH, P, K, AWC and PR were used to define the productivity-1 functions of subsurface layers. In the productivity-1 function score, indicators of soil pH, AWC, PR, P and K were used for all three depths, since MBC and PMN scores were not determined for the subsurface layers.

The RR function is the ability of soil to resist the changes and to retain the vital functions after human induced or natural disturbances (Andrews et al., 2004). Water can easily infiltrate and move downward in physically resilient soils, which also retain and supply water in dry periods (Nouri et al., 2019). Therefore, MDS for RR function included soil organic carbon, PR and mean weight diameter (MWD). The PSS function is related to the physical structure and strength of soil against wind and water erosion (Andrews et al., 2004). The MDS for PSS function comprised of aggregate stability, bulk density, PR and pH. The WR function deals with water movement, partitioning and storage of water in soil (Andrews et al., 2004). Bulk density of soils is the most commonly used physical indicator and the importance of bulk density for functional ability of soils has been reported in the literature (Cherubin et al., 2017; Zornoza et al., 2015). The MDS for WR included bulk density, PR, AWC, water-filled pore space, pH, electrical conductivity, and sodium adsorption ratio.

The indicator values have different units; therefore, standard scoring functions of the SMAF were used to transform the values of soil properties to indicator values (Andrews et al., 2004; Stott et al., 2010; Wienhold et al., 2009). Since scoring curves for PR are not included in the current SMAF, curves created by Cornell University (USA) researchers and incorporated into the Cornell Soil Health Assessment (Moebius-Clune et al., 2016) were used to transform the PR values into the indicator scores. Non-linear scoring methods (Liebig et al., 2001) were used to normalize the values between 0 and 1.0 except mean weight diameter that was normalized using a linear scoring curve. Indicator score of 1.0 indicates the highest potential for an indicator in that particular soil, crop rotation and tillage system. Non-linear scoring curves of SMAF were developed by considering the factors that influence the performance of the indicators such as particle size distribution, climate of the study area, slope and laboratory method etc. (Andrews et al., 2004; Wienhold et al., 2009). Both non-linear and linear functions

Table 2

Mean values of chemical soil quality indicators under different tillage methods.

Tillage Methods	pH	Electrical Conductivity (dS m^{-1})	Sodium Adsorption Ratio	Phosphorus (mg kg^{-1})	Potassium (mg kg^{-1})	Organic Carbon (%)
0–10 cm						
CT-1	7.40[#]±0.00 ab[&]*	0.65 ± 0.02 a ns	0.28 ± 0.01 ab ns	6.40 ± 0.60 ab**	284 ± 16.10 bc ns	0.84 ± 0.04 c ns
CT-2	7.43 ± 0.02 a*	0.62 ± 0.02 ab ns	0.30 ± 0.02 a ns	4.78 ± 0.75 b**	299 ± 8.91 bc ns	0.78 ± 0.05 c ns
RT-1	7.35 ± 0.02 b ns	0.64 ± 0.03 ab ns	0.29 ± 0.01 ab ns	8.07 ± 0.91 a**	324 ± 19.96 ab**	1.26 ± 0.02 ab **
RT-2	7.40 ± 0.03 ab ns	0.56 ± 0.03 bc ns	0.29 ± 0.01 a ns	7.68 ± 0.93 a**	261 ± 16.75 c**	1.35 ± 0.05 ab **
RT-3	7.35 ± 0.02 b ns	0.53 ± 0.04 c ns	0.21 ± 0.03 c ns	4.33 ± 0.62 b ns	371 ± 32.41 a**	1.38 ± 0.03 a **
NT	7.33 ± 0.03 b ns	0.66 ± 0.01 a*	0.23 ± 0.03 bc ns	5.10 ± 0.41 b**	281 ± 21.08 bc**	1.35 ± 0.04 ab **
ST	7.38 ± 0.02 ab ns	0.65 ± 0.01 a ns	0.26 ± 0.01 abc ns	4.45 ± 0.15 b**	273 ± 10.57 bc*	1.23 ± 0.05 b **
ANOVA	0.038	0.004	0.024	0.001	0.005	0.000
10–20 cm						
CT-1	7.33 ± 0.02 ab	0.65 ± 0.0 ab	0.29 ± 0.02 a	2.88 ± 0.23 ab	274 ± 14.46 ab	0.79 ± 0.05 bc
CT-2	7.33 ± 0.03 ab	0.64 ± 0.02 ab	0.30 ± 0.01 a	2.63 ± 0.26 ab	289 ± 14.87 a	0.75 ± 0.04 bc
RT-1	7.38 ± 0.02 a	0.57 ± 0.05 c	0.32 ± 0.01 a	2.70 ± 0.35 ab	258 ± 12.60 ab	0.71 ± 0.05 c
RT-2	7.37 ± 0.02 a	0.58 ± 0.02 bc	0.31 ± 0.01 a	2.07 ± 0.07 ab	206 ± 10.19 c	0.80 ± 0.05 bc
RT-3	7.38 ± 0.02 a	0.61 ± 0.03 abc	0.26 ± 0.04 ab	3.53 ± 1.01 a	211 ± 6.31 c	0.88 ± 0.06 b
NT	7.40 ± 0.03 a	0.56 ± 0.02 c	0.20 ± 0.04 b	1.92 ± 0.36 b	217 ± 8.48 c	0.80 ± 0.03 bc
ST	7.28 ± 0.03 b	0.68 ± 0.02 a	0.28 ± 0.04 ab	2.69 ± 0.35 ab	250 ± 10.63 b	1.13 ± 0.04 a
ANOVA	0.027	0.009	0.075	0.279	0.000	0.000
20–30 cm						
CT-1	7.30 ± 0.04 a	0.63 ± 0.02 ab	0.27 ± 0.01 abc	2.40 ± 0.27 ab	261 ± 14.27 ab	0.76 ± 0.06 b
CT-2	7.35 ± 0.00 a	0.67 ± 0.02 a	0.29 ± 0.01 ab	1.98 ± 0.12 bc	268 ± 13.71 a	0.75 ± 0.05 b
RT-1	7.37 ± 0.03 a	0.61 ± 0.02 ab	0.32 ± 0.02 a	1.24 ± 0.12 d	234 ± 9.13 bc	0.68 ± 0.05 b
RT-2	7.42 ± 0.03 a	0.56 ± 0.03 b	0.29 ± 0.02 ab	1.68 ± 0.15 cd	187 ± 5.08 d	0.70 ± 0.03 b
RT-3	7.33 ± 0.10 a	0.61 ± 0.03 ab	0.22 ± 0.02 bc	2.69 ± 0.24 a	216 ± 7.78 c	0.75 ± 0.04 b
NT	7.38 ± 0.05 a	0.64 ± 0.04 ab	0.25 ± 0.04 abc	1.60 ± 0.06 cd	211 ± 5.80 cd	0.73 ± 0.03 b
ST	7.28 ± 0.04 a	0.69 ± 0.03 a	0.20 ± 0.03 c	1.63 ± 0.18 cd	226 ± 8.94 c	0.95 ± 0.03 a
ANOVA	0.530	0.048	0.025	0.000	0.000	0.002
Tillage (T)	0.176	0.000	0.000	0.013	0.000	0.000
Depth (D)	0.221	0.467	0.299	0.000	0.000	0.000
T x D	0.202	0.084	0.600	0.000	0.000	0.000

CT-1: Conventional tillage with residue incorporated, CT-2: Conventional tillage with residues burned, RT-1: Reduced tillage with heavy tandem disc harrow, RT-2: Reduced tillage with rotary tiller, RT-3: Reduced tillage with heavy tandem disc harrow fallowed by no tillage for the second crop, NT: No tillage, direct planting, ST: Strategic tillage, #: Mean value for three replicates, ±: Standard error of the mean, **&**: Differences in the same column are presented with the same letters (Duncan, $P \leq 0.05$). Changes with depth obtained in Duncan test **: Significant at $P < 0.01$, *: $P < 0.05$; ns: Not significant.

in normalization of indicator values were created using "more is better" (such as organic carbon), "less is better" (such as bulk density), and "mid-point optimum" (such as plant available P) approaches (Hussain et al., 1999).

After scoring the indicators, the function scores were calculated using the arithmetic mean of the indicator scores selected for each of the soil functions (Eq. 1).

$$SFI = \left(\frac{\sum_{i=1}^{n} Si}{n}\right) \tag{1}$$

In the equation, SFI is the soil function index, Si is the indicator score, and n is the number of indicators integrated in the function index.

Three different soil quality indices (SQI) were generated and values were presented as SQI-1, SQI-2 and SQI-3. The SQI-1 was calculated by the arithmetic mean of all indicator scores which is known as simple additive method. In SQI-2 and SQI-3, the weights of 0.25 were given for each of productivity, RR, PSS and WR functions, respectively. The given weights were multiplied by each function score and the obtained values were summed to obtain a general soil quality index (Eq. 2). The second method is known as weighted additive. The difference between SQI-2 and SQI-3 was related to the use of MBC and PMN in calculation of productivity function in surface soils. The soil function and SQI values were rated between 0 and 100 by multiplying the calculated values by 100. The soil quality score of 100 means that the soil can fulfill its potential at 100 %, and 80 means functioning at 80 % of its genetic performance (Hammac et al., 2016).

$$SQI = \sum_{i=1}^{n} (wiSFI) \tag{2}$$

where, SFI is the soil functioning index, wi is the respective weight for each soil function.

2.4. *Statistical analysis*

The impact (significance) of tillage methods on soil quality indicators, soil functions and SQI values was assessed by two-way variance analysis (ANOVA). Duncan's multiple range test at 95 % probability was used as post-hoc where ANOVA indicated significant differences. All of the data were analyzed on IBM SPSS statistical package (version 21.0, SPSS Inc., Chicago, IL), and the figures were created using Microsoft Excel.

3. Results and discussion

3.1. *Soil characteristics*

Soil pH ranged in a quite narrow range (from 7.28 to 7.43); thus, individual or interactive effects of tillage systems and depth on pH were non-significant (Table 2). The ANOVA indicated significant effect of tillage systems on EC and SAR values, though the effects of depth and tillage by depth interaction were non-significant. Despite the significance of tillage effect on EC and SAR, values of both indicators were within the safe margins, which do not pose any harm to the soil functioning (Rhoades and Loveday, 1990). Individual and interactive effects of tillage systems and depths significantly changed the plant available P and K concentrations. The changes of P and K concentrations with depth were in accordance with those reports that long-term NT system caused stratification of plant nutrients (Nunes et al., 2019; Robbins and Voss, 1991; Zuber et al., 2017). Different from other studies, concentrations of P and K were significantly decreased with the increasing depth, not only in NT, but also in all RT and CT systems. Plant available P concentrations in 0–10 cm depth was either moderate or low for all tillage systems, but it was much lower in 10–20 and 20–30 cm depths compared to 0–10 cm depth and may be limiting the crop yield in all tillage systems.

Table 3
Mean values of physical soil quality indicators under different tillage methods (Çelik et al., 2019).

Tillage Methods	Aggregate Stability (%)	Bulk Density (g cm^{-3})	Penetration Resistance (MPa)	Water Filled Pore Space	Available Water Content (Volumetric, %)	Mean Weight Diameter (mm)
0–10 cm						
CT-1	21.18[#]±1.99 d[&*]	1.32 ± 0.02 ab ns	1.77 ± 0.10 c ns	0.57 ± 0.01 cd **	7.73 ± 0.89 bc *	0.18 ± 0.02 f ns
CT-2	18.43 ± 1.03 d**	1.23 ± 0.02 cd**	1.29 ± 0.11 d **	0.52 ± 0.01 d**	7.44 ± 0.49 bc**	0.15 ± 0.01 f *
RT-1	27.92 ± 0.99 d**	1.26 ± 0.04 bc**	1.61 ± 0.12 c *	0.60 ± 0.01 bc**	9.89 ± 0.62 a**	0.25 ± 0.01 e **
RT-2	35.92 ± 0.83 c**	1.29 ± 0.02 abc**	1.85 ± 0.11 bc**	0.62 ± 0.02 b**	8.30 ± 0.92 abc**	0.40 ± 0.00 d **
RT-3	42.21 ± 0.81 b**	1.28 ± 0.03 abc*	2.15 ± 0.13 ab ns	0.65 ± 0.01 ab**	9.43 ± 0.39 ab**	0.50 ± 0.01 c **
NT	50.61 ± 0.27 a**	1.36 ± 0.02 a ns	2.18 ± 0.10 a **	0.68 ± 0.03 a ns	9.35 ± 0.78 ab ns	0.69 ± 0.02 a **
ST	51.36 ± 0.18 a**	1.17 ± 0.02 d **	1.73 ± 0.10 c ns	0.52 ± 0.02 d **	6.96 ± 0.32 c**	0.64 ± 0.02 b **
ANOVA	0.000	0.001	0.000	0.000	0.023	0.000
10–20 cm						
CT-1	24.63 ± 2.07 e	1.38 ± 0.04 a	1.97 ± 0.09 cd	0.74 ± 0.02 ab	10.06 ± 0.88 a	0.22 ± 0.02 e
CT-2	21.78 ± 0.74 e	1.35 ± 0.01 a	2.03 ± 0.15 cd	0.67 ± 0.01 c	10.46 ± 0.17 a	0.19 ± 0.01 e
RT-1	32.27 ± 0.64 d	1.38 ± 0.03 a	2.17 ± 0.14 bc	0.74 ± 0.01 a	8.94 ± 0.75 ab	0.30 ± 0.01 d
RT-2	38.33 ± 1.15 c	1.44 ± 0.02 a	2.43 ± 0.11 ab	0.69 ± 0.01 c	5.19 ± 0.13 c	0.37 ± 0.01 c
RT-3	45.31 ± 1.06 b	1.38 ± 0.03 a	2.47 ± 0.12 ab	0.71 ± 0.01 bc	7.96 ± 0.29 b	0.52 ± 0.01 b
NT	40.79 ± 0.34 c	1.42 ± 0.03 a	2.62 ± 0.09 a	0.70 ± 0.01 c	8.20 ± 0.28 b	0.41 ± 0.01 c
ST	55.66 ± 0.17 a	1.26 ± 0.03 b	1.79 ± 0.11 d	0.58 ± 0.01 d	6.40 ± 0.50 c	0.73 ± 0.02 a
ANOVA	0.000	0.005	0.000	0.000	0.000	0.000
20–30 cm						
CT-1	30.56 ± 1.89 c	1.38 ± 0.03 ab	2.08 ± 0.14 bc	0.72 ± 0.03 b	10.78 ± 0.35 b	0.24 ± 0.02 d
CT-2	23.49 ± 1.15 d	1.39 ± 0.03 ab	1.94 ± 0.14 c	0.68 ± 0.01 b	8.84 ± 0.37 c	0.18 ± 0.00 e
RT-1	30.14 ± 0.36 c	1.45 ± 0.01 a	2.04 ± 0.09 bc	0.83 ± 0.02 a	12.59 ± 0.36 a	0.30 ± 0.01 c
RT-2	32.50 ± 0.71 c	1.45 ± 0.01 a	2.37 ± 0.10 ab	0.72 ± 0.01 b	6.18 ± 0.17 e	0.30 ± 0.01 c
RT-3	37.33 ± 1.09 b	1.39 ± 0.03 ab	2.61 ± 0.14 a	0.71 ± 0.01 b	7.54 ± 0.42 d	0.37 ± 0.01 b
NT	30.78 ± 0.50 c	1.45 ± 0.04 a	2.64 ± 0.09 a	0.72 ± 0.02 b	7.02 ± 0.67 de	0.28 ± 0.01 c
ST	50.15 ± 0.21 a	1.32 ± 0.04 b	1.93 ± 0.13 c	0.69 ± 0.03 b	10.15 ± 0.45 b	0.57 ± 0.01 a
ANOVA	0.000	0.012	0.000	0.000	0.000	0.000
Tillage (T)	0.000	0.000	0.000	0.000	0.000	0.000
Depth (D)	0.000	0.000	0.000	0.000	0.014	0.000
T x D	0.000	0.686	0.357	0.000	0.000	0.000

CT-1: Conventional tillage with residue incorporated, CT-2: Conventional tillage with residues burned, RT-1: Reduced tillage with heavy tandem disc harrow, RT-2: Reduced tillage with rotary tiller, RT-3: Reduced tillage with heavy tandem disc harrow fallowed by no tillage for the second crop, NT: No tillage, direct planting, ST: Strategic tillage, #: Mean value for three replicates, ±: Standard error of the mean, **&**: Differences in the same column are presented with the same letters (Duncan, $P \leq 0.05$). Changes with depth obtained in Duncan test **: Significant at $P < 0.01$, *: $P < 0.05$; ns: Not significant.

Table 4
Potential mineralizable nitrogen (PMN) and microbial biomass carbon (MBC) concentration and indicator scores under different tillage methods.

Tillage Systems	PMN (mg kg^{-1})	MBC (mg kg^{-1})
0–10 cm		
CT-1	84.23[#]±5.49[†] bc[&]	170 ± 9.45 d
CT-2	71.44 ± 3.25 c	154 ± 12.00 d
RT-1	85.16 ± 3.70 bc	228 ± 4.22 c
RT-2	96.99 ± 6.01 ab	261 ± 9.11 b
RT-3	99.06 ± 2.95 ab	283 ± 10.65 b
NT	107.43 ± 7.33 a	335 ± 11.72 a
ST	81.06 ± 3.78 c	214 ± 9.19 c
ANOVA	0.000	0.000

Tillage Systems	PMN (score)	MBC (score)
0–10 cm		
CT-1	0.60 ± 0.04 bc	0.80[#]±0.04[†] b[&]
CT-2	0.51 ± 0.02 c	0.70 ± 0.06 c
RT-1	0.61 ± 0.03 bc	0.96 ± 0.00 a
RT-2	0.70 ± 0.04 ab	0.98 ± 0.00 a
RT-3	0.71 ± 0.02 ab	0.99 ± 0.00 a
NT	0.77 ± 0.05 a	1.00 ± 0.00 a
ST	0.58 ± 0.03 c	0.94 ± 0.01 a
ANOVA	0.000	0.000

#: Averages of the three soil samples from replicates, †: Standard error of mean values, **&**: The differences between the means in the same column are shown in separate letters (Duncan, $P \leq 0.05$). CT-1: Conventional tillage with residue incorporated, CT-2: Conventional tillage with residues burned, RT-1: Reduced tillage with heavy tandem disc harrow, RT-2: Reduced tillage with rotary tiller, RT-3: Reduced tillage with heavy tandem disc harrow fallowed by no tillage for the second crop, NT: No tillage, direct planting, ST: Strategic tillage.

Tillage had a significant impact on organic carbon content, which significantly increased in RT and NT systems. The difference on organic carbon among tillage systems were more prominent in the surface layer (0–10 cm) in which C concentration in NT method was higher than CT-1 and CT-2 methods at a rate of 61 % and 73 % (Table 2).

Mean values of physical soil quality indicators for different tillage methods are given in Table 3. The effects of tillage systems on physical soil indicators are previously discussed and data have been presented in Celik et al. (2019); thus, briefly presented herein. Rather, the discussion will focus on four soil functions and general soil quality, both expressing the effects of combining several soil indicators, including soil physical properties.

Tillage systems caused significant variation in all bio-chemical soil properties investigated. The increase in soil OC is related to C input and output equilibrium (Zibilske et al., 2002). Burning of residues and frequent deep tillage in conventional tillage (CT-1 and CT-2) resulted in the lowest potential mineralizable nitrogen (PMN) and microbial biomass carbon (MBC) contents in the surface layer. Similarly, Karlen et al. (2013) attributed lower values of OC, MBC and PMN in the surface layer to burying of crop residues below the soil surface by moldboard plow. In contrast to CT systems, the highest PMN and MBC values were obtained under the NT system where residues were neither burned nor buried to the subsurface layer. The MBC and PMN contents in NT soils were increased by 1.97 and 1.28 times compared with those in CT-1 soils (Table 4). The results suggested that a considerable amount of C has been returned to the atmosphere due to the intensive tillage practices. One-time tillage or ST of NT plots using moldboard plow caused 36.1 % decrease in MBC of soils. Conventional tillage with removal of residues led to the lowest MBC content. The MBC content of soils decreased with the increased magnitude of soil disturbances. The MBC under different tillage systems showed the following order; NT > RT-3 > RT-2 > RT-1 >

Table 5
Mean scores of chemical soil quality indicators under different tillage methods.

Tillage Methods	pH	Electrical Conductivity	Sodium Adsorption Ratio	Phosphorus	Potassium	Organic Carbon
0−10 cm						
CT-1	0.63[#]±0.00 ab[&]*	1.00 ± 0.00 a ns	0.98 ± 0.00 a ns	0.88 ± 0.03 ab**	1.00 ± 0.00 a ns	0.49 ± 0.04 b ns
CT-2	0.61 ± 0.01 b*	1.00 ± 0.00 a ns	0.98 ± 0.00 a ns	0.72 ± 0.08 c**	1.00 ± 0.00 a ns	0.42 ± 0.05 b ns
RT-1	0.66 ± 0.01 a ns	1.00 ± 0.00 a ns	0.95 ± 0.03 ab ns	0.94 ± 0.02 a**	1.00 ± 0.00 a ns	0.87 ± 0.01 a**
RT-2	0.63 ± 0.01 ab ns	1.00 ± 0.00 a ns	0.92 ± 0.04 ab ns	0.92 ± 0.02 a**	1.00 ± 0.00 a ns	0.90 ± 0.02 a**
RT-3	0.66 ± 0.01 a ns	1.00 ± 0.00 a ns	0.89 ± 0.04 b ns	0.68 ± 0.09 c ns	1.00 ± 0.00 a ns	0.92 ± 0.01 a**
NT	0.67 ± 0.02 a ns	1.00 ± 0.00 a ns	0.98 ± 0.00 a ns	0.80 ± 0.04 abc**	1.00 ± 0.00 a ns	0.90 ± 0.01 a**
ST	0.64 ± 0.01 ab ns	1.00 ± 0.00 a ns	0.98 ± 0.00 a ns	0.75 ± 0.02 bc**	1.00 ± 0.00 a ns	0.84 ± 0.03 a**
ANOVA	0.038	Ns	0.060	0.003	Ns	0.000
10−20 cm						
CT-1	0.67 ± 0.01 ab	1.00 ± 0.00 a	0.98 ± 0.00 a	0.45 ± 0.06 a	1.00 ± 0.00 a	0.43 ± 0.05 bc
CT-2	0.67 ± 0.02 ab	1.00 ± 0.00 a	0.98 ± 0.00 a	0.38 ± 0.07 a	1.00 ± 0.00 a	0.39 ± 0.05 bc
RT-1	0.64 ± 0.01 b	1.00 ± 0.00 a	0.92 ± 0.04 a	0.39 ± 0.08 a	1.00 ± 0.00 a	0.36 ± 0.04 c
RT-2	0.65 ± 0.01 b	1.00 ± 0.00 a	0.95 ± 0.03 a	0.23 ± 0.02 a	0.99 ± 0.01 a	0.45 ± 0.06 bc
RT-3	0.64 ± 0.01 b	1.00 ± 0.00 a	0.98 ± 0.00 a	0.46 ± 0.16 a	1.00 ± 0.00 a	0.53 ± 0.06 b
NT	0.63 ± 0.01 b	1.00 ± 0.00 a	0.92 ± 0.04 a	0.20 ± 0.09 a	1.00 ± 0.00 a	0.45 ± 0.04 bc
ST	0.69 ± 0.02 a	1.00 ± 0.00 a	0.98 ± 0.00 a	0.39 ± 0.09 a	1.00 ± 0.00 a	0.77 ± 0.03 a
ANOVA	0.027	Ns	0.219	0.311	0.299	0.000
20−30 cm						
CT-1	0.68 ± 0.02 a	1.00 ± 0.00 a	0.98 ± 0.00 a	0.33 ± 0.07 ab	1.00 ± 0.00 a	0.40 ± 0.06 b
CT-2	0.66 ± 0.01 a	1.00 ± 0.00 a	0.98 ± 0.00 a	0.21 ± 0.03 bc	1.00 ± 0.00 a	0.39 ± 0.05 b
RT-1	0.65 ± 0.02 a	1.00 ± 0.00 a	0.95 ± 0.03 a	0.07 ± 0.02 d	1.00 ± 0.00 a	0.33 ± 0.05 b
RT-2	0.62 ± 0.02 a	1.00 ± 0.00 a	0.92 ± 0.04 a	0.15 ± 0.03 cd	0.98 ± 0.01 b	0.34 ± 0.04 b
RT-3	0.66 ± 0.05 a	1.00 ± 0.00 a	0.92 ± 0.04 a	0.40 ± 0.06 a	1.00 ± 0.00 a	0.39 ± 0.04 b
NT	0.64 ± 0.02 a	1.00 ± 0.00 a	0.95 ± 0.03 a	0.12 ± 0.01 cd	1.00 ± 0.00 a	0.37 ± 0.03 b
ST	0.69 ± 0.02 a	1.00 ± 0.00 a	0.99 ± 0.00 a	0.14 ± 0.04 cd	1.00 ± 0.00 a	0.62 ± 0.03 a
ANOVA	0.504	ns	0.370	0.000	0.000	0.001
Tillage (T)	0.162	ns	0.013	0.027	0.000	0.000
Depth (D)	0.227	ns	0.960	0.000	0.047	0.000
T x D	0.178	ns	0.481	0.001	0.001	0.000

CT-1: Conventional tillage with residue incorporated, CT-2: Conventional tillage with residues burned, RT-1: Reduced tillage with heavy tandem disc harrow, RT-2: Reduced tillage with rotary tiller, RT-3: Reduced tillage with heavy tandem disc harrow fallowed by no tillage for the second crop, NT: No tillage, direct planting, ST: Strategic tillage, #: Mean value for three replicates, ±: Standard error of the mean, &: Differences in the same column are presented with the same letters (Duncan, $P \leq 0.05$). Changes with depth obtained in Duncan test **: Significant at $P < 0.01$, *: $P < 0.05$; ns: Not significant.

Table 6
Variation of productivity function under different tillage systems.

Tillage Methods	Productvity-1* (%)			Productivity-2** (%)
	0−10 cm	10−20 cm	20−30 cm	0−10 cm
CT-1	59.4[#] ± 1.50 bc[&] ns	56.3 ± 2.48 a	54.0 ± 2.18 a	62.5 ± 0.77 c ns
CT-2	61.4 ± 2.14 ab *	55.1 ± 2.32 ab	50.8 ± 2.66 ab	61.2 ± 1.45 c *
RT-1	65.4 ± 1.87 a **	51.2 ± 2.53 ab	49.0 ± 0.98 ab	69.2 ± 1.65 a **
RT-2	60.2 ± 1.63 bc **	41.5 ± 0.96 d	40.2 ± 1.34 c	67.0 ± 1.14 ab **
RT-3	55.8 ± 1.50 c *	48.7 ± 2.56 bc	46.9 ± 2.83 b	64.1 ± 0.98 bc *
NT	57.5 ± 0.96 bc**	42.5 ± 1.47 cd	39.7 ± 0.52 c	66.3 ± 1.12 ab **
ST	57.4 ± 1.09 bc ns	55.3 ± 3.29 ab	52.1 ± 2.35 ab	62.7 ± 0.61 c ns
ANOVA	0.003	0.000	0.000	0.000
Tillage (T)	0.000			0.000
Depth (D)	0.000			0.000
T x D	0.000			0.000

*Procutivity-1: MBC and PMN have not been included into the calculations. **Productivity-2: MBC and PMN have been included into the calculations. CT-1: Conventional tillage with residue incorporated, CT-2: Conventional tillage with residues burned, RT-1: Reduced tillage with heavy tandem disc harrow, RT-2: Reduced tillage with rotary tiller, RT-3: Reduced tillage with heavy tandem disc harrow fallowed by no tillage for the second crop, NT: No tillage, direct planting, ST: Strategic tillage, #: Mean value for three replicates, ±: Standard error of the mean, &: Differences in the same column are presented with the same letters (Duncan, $P \leq 0.05$). Changes with depth obtained in Duncan test **: Significant at $P < 0.01$, *: $P < 0.05$; ns: Not significant.

ST > CT-1 > CT-2. Similar to MBC, ST led to a significant decrease in PMN content compared to NT plots (Table 4).

3.2. *Soil quality assessments*

3.2.1. *Productivity function of soil*

Mean values of soil chemical indicator scores and productivity function scores for different tillage methods are given in Tables 5 and 6. Productivity function score indicates the effects of carefully chosen, appropriate soil indicators on quantity, quality, and stability of producing economically important plants (Andrews et al., 2004). Biological soil quality indicators, i.e., MBC and PMN included in the productivity function dataset were analyzed only for surface soil samples; therefore, two productivity function scores were calculated and presented as productivity-1 and productivity-2. The ANOVA indicated significant effects ($P < 0.01$) of tillage and depth and tillage × depth interaction on productivity function (Table 6). The productivity-1 function scores in 0−10 cm depth under RT-1 (65.4 %) were significantly higher than other tillage systems (except CT-2). The productivity-2 function of soil in 0−10 cm under RT-1 method (69.2 %) was significantly higher than CT and similar to NT methods. In contrast to our results on low productivity function under NT method, several authors (Busari et al., 2015; Nunes et al., 2018) reported significant improvement in soil quality under continuous NT, which has been a widely used practice of conservation agriculture.

The low P concentrations in surface and subsurface soils reduced the productivity function under all tillage systems (Tables 2 and 6). The mean MBC indicator score decreased from 1.00 in NT to 0.94 in the ST method (Table 4), though the difference was non-significant. In contrast, PMN indicator score in NT significantly decreased from 0.77 to 0.58 in ST, due to lower PMN concentration under ST (81.6 mg kg^{-1}) compared to PMN (107.43 mg kg^{-1}) in NT system (Table 4). The MBC and PMN

Table 7
Mean scores of physical soil quality indicators under different tillage methods.

Tillage Methods	Aggregate Stability	Bulk Density	Available Water Content	Water Filled Pore Space	Penetration Resistance	Mean Weight Diameter
0−10 cm						
CT-1	0.42[#]±0.05 e[&]*	0.44 ± 0.03 cd ns	0.27 ± 0.05 b ns	0.95 ± 0.00 a**	0.18 ± 0.04 bc ns	0.22 ± 0.02 f ns
CT-2	0.35 ± 0.03 e**	0.60 ± 0.05 b**	0.29 ± 0.04 ab**	0.94 ± 0.00 a**	0.44 ± 0.07 a ns	0.19 ± 0.01 f *
RT-1	0.59 ± 0.02 d**	0.56 ± 0.08 bc**	0.42 ± 0.05 a ns	0.94 ± 0.00 a**	0.26 ± 0.06 b ns	0.31 ± 0.01 e **
RT-2	0.75 ± 0.02 c**	0.49 ± 0.03 bcd**	0.31 ± 0.05 ab**	0.91 ± 0.02 a**	0.15 ± 0.05 bc ns	0.49 ± 0.01 d **
RT-3	0.85 ± 0.01 b**	0.50 ± 0.04 bcd*	0.38 ± 0.03 ab**	0.89 ± 0.01 a**	0.07 ± 0.02 c ns	0.61 ± 0.01 c **
NT	0.98 ± 0.01 a**	0.40 ± 0.03 d ns	0.35 ± 0.04 ab*	0.82 ± 0.05 b ns	0.06 ± 0.02 c ns	0.85 ± 0.02 b **
ST	1.00 ± 0.00 a ns	0.74 ± 0.05 a**	0.28 ± 0.02 b**	0.94 ± 0.00 a**	0.20 ± 0.04 bc ns	0.77 ± 0.03 a **
ANOVA	0.000	0.020	0.067	0.000	0.054	0.000
10−20 cm						
CT-1	0.51 ± 0.05 e	0.38 ± 0.04 b	0.38 ± 0.06 a	0.73 ± 0.04 c	0.33 ± 0.07 ab	0.27 ± 0.03 e
CT-2	0.44 ± 0.02 f	0.39 ± 0.01 b	0.40 ± 0.01 a	0.87 ± 0.02 b	0.30 ± 0.10 ab	0.23 ± 0.01 e
RT-1	0.68 ± 0.01 d	0.37 ± 0.03 b	0.32 ± 0.04 ab	0.72 ± 0.03 c	0.22 ± 0.08 bc	0.36 ± 0.01 d
RT-2	0.79 ± 0.02 c	0.31 ± 0.02 b	0.12 ± 0.01 d	0.82 ± 0.01 b	0.08 ± 0.04 c	0.45 ± 0.01 c
RT-3	0.89 ± 0.01 b	0.37 ± 0.03 b	0.26 ± 0.02 bc	0.80 ± 0.02 b	0.08 ± 0.04 c	0.64 ± 0.01 b
NT	0.83 ± 0.01 bc	0.33 ± 0.02 b	0.26 ± 0.01 bc	0.82 ± 0.02 b	0.03 ± 0.02 c	0.50 ± 0.01 c
ST	1.00 ± 0.00 a	0.54 ± 0.06 a	0.22 ± 0.03 c	0.94 ± 0.00 a	0.47 ± 0.10 a	0.89 ± 0.02 a
ANOVA	0.000	0.148	0.000	0.004	0.072	0.000
20−30 cm						
CT-1	0.64 ± 0.04 c	0.37 ± 0.03 b	0.41 ± 0.03 a	0.76 ± 0.06 a	0.28 ± 0.10 ab	0.29 ± 0.02 d
CT-2	0.48 ± 0.03 d	0.36 ± 0.03 b	0.31 ± 0.02 b	0.84 ± 0.02 a	0.36 ± 0.11 a	0.22 ± 0.01 e
RT-1	0.64 ± 0.01 c	0.30 ± 0.01 b	0.47 ± 0.02 a	0.50 ± 0.04 b	0.27 ± 0.06 ab	0.36 ± 0.01 c
RT-2	0.69 ± 0.01 c	0.30 ± 0.01 b	0.16 ± 0.01 d	0.76 ± 0.03 a	0.10 ± 0.04 bc	0.36 ± 0.01 c
RT-3	0.77 ± 0.02 b	0.36 ± 0.03 b	0.24 ± 0.03 c	0.80 ± 0.02 a	0.05 ± 0.03 c	0.46 ± 0.01 b
NT	0.65 ± 0.01 c	0.32 ± 0.03 b	0.20 ± 0.03 cd	0.77 ± 0.04 a	0.03 ± 0.01 c	0.35 ± 0.01 c
ST	0.98 ± 0.01 a	0.46 ± 0.05 a	0.40 ± 0.02 a	0.82 ± 0.05 a	0.38 ± 0.09 a	0.70 ± 0.02 a
ANOVA	0.005	0.005	0.005	0.267	0.001	0.000
Tillage (T)	0.000	0.000	0.000	0.000	0.000	0.000
Depth (D)	0.003	0.000	0.026	0.000	0.828	0.000
T x D	0.000	0.192	0.000	0.000	0.217	0.000

CT-1: Conventional tillage with residue incorporated, CT-2: Conventional tillage with residues burned, RT-1: Reduced tillage with heavy tandem disc harrow, RT-2: Reduced tillage with rotary tiller, RT-3: Reduced tillage with heavy tandem disc harrow fallowed by no tillage for the second crop, NT: No tillage, direct planting, ST: Strategic tillage, #: Mean value for three replicates, ±: Standard error of the mean, **&**: Differences in the same column are presented with the same letters (Duncan, $P \leq 0.05$). Changes with depth obtained in Duncan test **: Significant at $P < 0.01$, *: $P < 0.05$; ns: Not significant.

scores were lower under ST compared to NT; however, higher PR score (0.20) or lower PR value (1.73 MPa) in ST due to disruption of surface compaction by tillage prevented a significant change in the productivity function under ST compared to NT (Tables 3, 6 and 7). In contrast, deep tillage removed subsurface compaction as indicated by lower PR values (1.79 and 1.93 MPa for 10−20 and 20−30 cm) and indicator scores (0.47 and 0.38 for 10−20 and 20−30 cm); therefore, productivity function scores in the ST system at 10−20 and 20−30 cm depths were significantly higher than productivity scores under the NT system (Table 6).

The benefits of NT and RT methods on productivity function were restricted to the surface layer. The productivity function was significantly reduced under all tillage systems with depth. Decrease in the productivity function at 10−20 cm relative to 0−10 cm depth was 22 %, 31 % and 26 % in RT-1, RT-2 and NT, respectively. Productivity function scores of CT-1, CT-2, RT-1 and ST in 20−30 cm depth were similar to each other. The lowest productivity functions at 20−30 cm depth was obtained for NT (39.7 %) followed by RT-2 (40.2 %), RT-3 (46.9 %) and RT-1 (49.0 %), while the highest productivity function was in CT-1 (54.0 %) and ST (52.1) systems (Table 6). The higher organic carbon content under NT and RT methods was restricted to 0−10 cm depth. Therefore, decrease in productivity function at 10−20 and 20−30 cm depths compared to 0−10 cm depth is related to the lower OC and very low available P concentrations and scores (Tables 2 and 5). Souza et al. (2018) reported similar trend in organic carbon of soils after nine years of NT system and indicated that soils under NT had similar soil organic carbon content in comparison with CT methods.

3.2.2. *Resilience and resistance function of soil*

Soil resilience contributes to agroecosystem resilience and has significant impact on other soil functions such as recycling and retaining water, carbon and nutrients, filtering of pollutants and biodiversity (Blanco-Canqui and Francis, 2016). Since tillage is the main disturbing agricultural practice, determining the best tillage practice improving the resilience and resistance (RR) function is vital to sustain soil functions. Tillage systems, depth and tillage × depth interaction had a significant effect on the RR function of the soil (Table 8). The highest RR function in all sampling depths was obtained under ST methods. The lowest RR functions were calculated for CT-1 (29.6 %) in 0−10 cm, CT-2 (30.8 %) in 10−20 cm and NT (24.6 %) in 20−30 cm depth (Table 8). The RR function was not changed with depth in CT methods, while significant decrease was recorded in RT and NT methods. The decrease in RR function for the NT system from 0−10 cm to 20−30 cm depth was 59 %, while it was only 7% for the ST method (Table 8). Souza et al. (2018) also reported restricted improvements of soil physical characteristics under 9 years NT methods due to higher BD, increased micro and decreased macro porosity. The RR function in 0−10 cm depth under NT and ST was similar; however, RR function in 10−20 cm depth under ST was significantly higher than RR function under NT (Table 8). The increase in RR function at 10−20 cm depth relative to NT is mainly related to higher MWD in ST (0.73 mm) than NT (0.41 mm) (Table 3). Tillage with moldboard plow incorporated stable and large aggregates along with organic matter accumulated on soil surface to the tillage depth. Therefore, RR function in 10−20 cm (71.3 %) and 20−30 cm (56.3 %) under ST was much higher than PR function calculated for NT (32.5 % and 24.6 %, respectively) (Table 8).

Impact of cultivation and burning of crop residues on RR function was more evident in the surface layer when comparing NT with CT-1 and CT-2 methods (Appendix A). The RR function at 0−10 cm depth in NT was 103 % and 72 % higher than CT-1 and CT-2 methods, respectively. Soil aggregates with high MWD score (0.85) under NT were more resistant to disintegration compared to the soil aggregates observed in CT-1 (MWD score, 0.22) and CT-2 (MWD score, 0.19) methods (Table 7). These findings are similar to those of Karlen et al. (1994) who reported

Table 8
Resistance and resilience, physical stability and support and water relations function scores.

Tillage Methods	0–10 cm	10–20 cm	20–30 cm
Resistance and Resilience (%)			
CT-1	29.6[#] ±1.98 c[&] ns	34.4 ± 2.05 bc	32.6 ± 4.39 b
CT-2	35.1 ± 3.16 c ns	30.8 ± 3.92 c	32.4 ± 3.34 b
RT-1	48.0 ± 1.76 b **	31.1 ± 1.97 c	31.9 ± 3.56 b
RT-2	51.4 ± 1.74 b **	32.9 ± 3.03 bc	26.6 ± 1.91 b
RT-3	53.3 ± 0.88 b **	41.6 ± 3.09 b	29.9 ± 1.89 b
NT	60.2 ± 0.97 a **	32.5 ± 1.45 bc	24.6 ± 0.70 b
ST	60.4 ± 2.31 a *	71.3 ± 4.09 a	56.3 ± 3.36 a
ANOVA	0.000	0.000	0.000
Tillage (T) 0.000 Depth (D), 0.000 T x D 0.000			
Physical Stability and Support (%)			
CT-1	41.8[#] ± 2.73 c[&] ns	46.9 ± 1.90 b	49.2 ± 2.58 b
CT-2	50.2 ± 1.89 b ns	44.8 ± 2.34 b	46.5 ± 2.05 bc
RT-1	51.7 ± 3.43 b ns	47.7 ± 2.64 b	46.3 ± 1.48 bc
RT-2	50.5 ± 1.27 b **	45.8 ± 1.28 b	42.6 ± 0.91 c
RT-3	52.1 ± 1.68 b ns	49.4 ± 1.42 b	46.0 ± 1.81 bc
NT	52.6 ± 1.00 b **	45.6 ± 1.00 b	40.8 ± 1.12 c
ST	64.4 ± 0.67 a ns	67.5 ± 3.01 a	62.7 ± 3.04 a
ANOVA	0.000	0.000	0.000
Tillage (T) 0.000 Depth (D) 0.001 T x D 0.004			
Water Relations (%)			
CT-1	63.6[#] ± 1.52 b[&] ns	63.6 ± 2.18 bc	64.0 ± 0.85 a
CT-2	69.5 ± 1.85 a ns	65.8 ± 1.49 ab	64.5 ± 1.23 a
RT-1	68.4 ± 2.40 a **	59.7 ± 2.12 cd	59.0 ± 1.02 b
RT-2	63.0 ± 1.29 b **	56.2 ± 1.02 d	55.1 ± 1.23 b
RT-3	62.8 ± 1.44 b *	59.0 ± 1.19 cd	57.6 ± 1.22 b
NT	61.1 ± 0.78 b **	57.1 ± 0.61 d	55.8 ± 0.99 b
ST	68.2 ± 0.48 a ns	69.1 ± 1.78 a	67.6 ± 2.29 a
ANOVA	0.001	0.000	0.000

CT-1: Conventional tillage with residue incorporated, CT-2: Conventional tillage with residues burned, RT-1: Reduced tillage with heavy tandem disc harrow, RT-2: Reduced tillage with rotary tiller, RT-3: Reduced tillage with heavy tandem disc harrow fallowed by no tillage for the second crop, NT: No tillage, direct planting, ST: Strategic tillage, #: Mean value for three replicates, ±: Standard error of the mean, &: Differences in the same column are presented with the same letters (Duncan, $P \leq 0.05$). Changes with depth obtained in Duncan test **: Significant at $P < 0.01$, *: $P < 0.05$; ns: Not significant.
Tillage (T) 0.000 Depth (D) 0.000 T × D 0.046.

significantly more stable soil aggregates in the upper 5 cm surface for double residue treatment than for maintaining and removal treatments. Higher aggregate stability in NT treatment compared to the chisel and plow treatments was attributed the high carbon available for supporting fungal activity and binding surface soil aggregates. Wang et al. (2010) also indicated that maintaining crop residues in NT provided a food source and favored fungal community, which had a significantly beneficial effect on the formation of large and resistant macro-aggregates.

3.2.3. Physical stability and support function of soil

Tillage type clearly affected physical stability and support (PSS) function of soils in the wheat-soybean-corn rotation, and ST improved the PSS of soils (Table 8). The effects of tillage type, soil depth and the interaction among tillage × depth had significant impact on PSS of soils. The PSS functions in 10–20 cm and 20–30 cm depths under CT-1 and in 10–20 cm under ST were higher relative to the surface layer, while the PSS function decreased with depth in all other tillage methods. The PSS function scores with depth differed significantly ($P < 0.01$) in RT-2 and NT, while in the other five methods depth remained non-significant.

The subsurface layers under RT and NT methods tended to reveal a high degree of compaction indicated by low penetration resistance (PR), bulk density (BD) and water filled pore space (WFPS) indicator scores (Table 7 and Appendix B). In RT-2 and NT methods, PSS function in 10–20 cm and 20–30 cm depths decreased by 9.3 and 13.3 %, and 15.6 and 22.4 %, respectively, compared to 0–10 cm depth. The highest level of PSS function in the first 10 cm depth was found in ST (64.4 %), while PSS function in CT-1 (41.8 %) was rather inadequate compared to other tillage methods (Table 8). The underlying cause of very low PSS function was lower aggregate stability due to extensive tillage practices. In many studies, BD and PR values under NT system were reported higher due to repeated machine traffic compared to conventional tillage practices (Gao et al., 2016; Leão et al., 2006; Tormena et al., 2017). High BD and PR that restrict root and water penetration, have been alleviated by one-time deep tillage by chisel (Tormena et al., 2017). Similarly, soil tillage with a moldboard plowing after a period of nine years (from 2006 to 2015) of wheat-soybean-corn rotation under NT improved PSS function of soils by 22.4 %, 48.0 % and 53.7 % for 0–10 cm, 10–20 cm and 20–30 cm depths, respectively (Table 8). The indicator scores of BD and PR in ST method significantly increased compared to NT (Table 7). The reduction in soil compaction improved the potential of soil to physical stability and support. Soils under ST system had high organic matter content and aggregate stability because they have been under NT for nine years. Therefore, despite being deep tilled by a plow as in CT's, the PSS potential in ST was considerably higher compared to CT-1 and CT-2.

Increased BD or decreased porosity of surface layers have been reported from long-term NT or RT where rototiller or disc harrow were used to mix the soil. Deep tillage has been recommended to diminish sub-surface soil compaction, improve soil quality and consequently increase crop yield (Tian et al., 2016). Deep tillage of clayey soils, which have been used under NT for nine years removed the surface compaction and distributed the stable aggregates in surface horizon to plow depth. The results reported from all over the world on the use of deep tillage for long-term NT sites support our findings. Deep tillage of soils under conservational practices for long-term was effective in breaking the compacted subsurface layer, reducing BD at a rate of 11.8 % and increasing total porosity (Liangpeng et al., 2015). The highest PSS function score for subsurface (10–20 cm) soils was obtained with ST (67.5 %) as in the first 10 cm and the lowest PSS values were recorded under CT-2 (44.8 %), NT (45.6 %) and RT-2 (45.8 %) (Table 8). The PSS scores obtained of 10–20 cm depth in all tillage methods except ST were statistically similar. The disturbance and mixing of stable aggregates in soil surface homogenized the plow depth in ST treated soils with regard to PSS function. The mean AS indicator score under NT at 10–20 cm was 0.83, while the mean AS score was 1.0 for soils under ST (Table 7).

The PSS function at 20–30 cm was similar to 10–20 cm depth. The PSS function at 20–30 cm depth relative to surface layer was only increased in CT-1, while it was lower under all other tillage methods compared to the soil surface. The highest PSS function score was obtained with ST (62.7 %) and the lowest score with NT (40.8 %). Increased compaction in both NT and RT resulted in lower BD and PR scores (Table 7), which caused a significant reduction in PSS score (Table 8). On the contrary, higher AS, BD and PR scores in ST (Table 7) compared to other methods contributed to the increase in PSS potential of soils (Table 8).

3.2.4. Water relation function of soil

The yield of winter wheat in the Mediterranean region mainly depends on the available moisture stored in the soil profile and no irrigation water is applied during the vegetation period. Therefore, improving water relation (WR) function has a great importance in sustaining productivity. Tillage and surface cover significantly influence moisture stored in the soil profile and evaporation (Acar et al., 2017; De Vita et al., 2007). The results suggested that tillage practices and depth had a strong influence ($P < 0.01$) on WR functions. The interaction of tillage and depth had a relatively small effect ($P = 0.046$) on WR functions (Table 8). The WR function of soils under CT-1, CT-2 and ST, where the soil was tilled by reversing with a plow at a 30–33 cm depth did not significantly change with depth. However, considerable decrease occurred with depth relative to 0–10 cm under RT and NT methods. The highest decrease in WR functions was noted under RT-1 and RT-2 at the rates of 12.7 % and 10.8 % in 10–20 cm and 13.7 % and 12.5 % in 20–30 cm depth, respectively (Table 8).

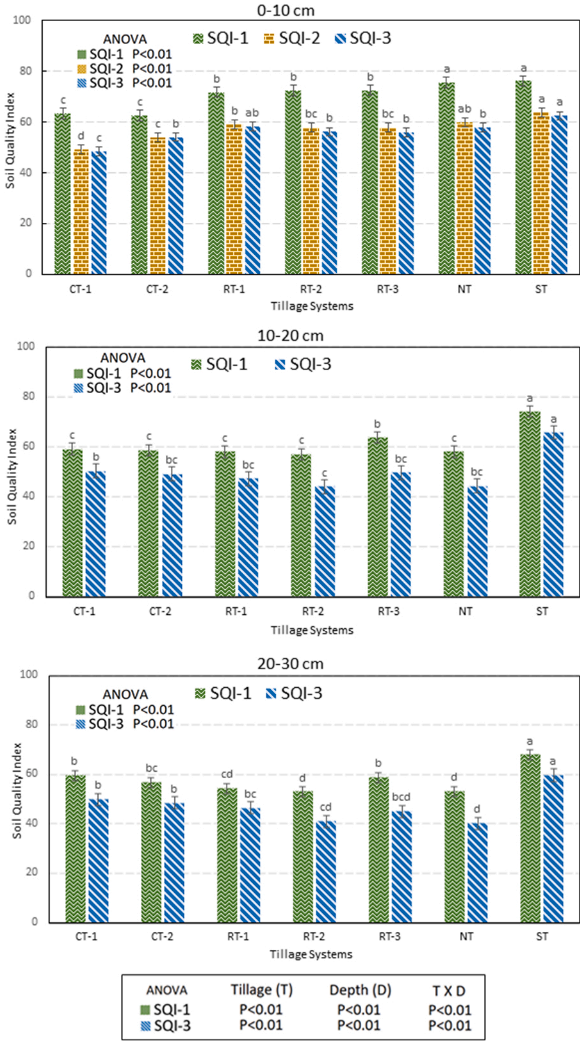

Fig. 1. Variation of soil quality indices under different tillage systems. SQI-1 and SQI-2: MBC and PMN have been included into the calculations. SQI-3: MBC and PMN have not been included into the calculations. CT-1: Conventional tillage with residue incorporated, CT-2: Conventional tillage with residues burned, RT-1: Reduced tillage with heavy tandem disc harrow, RT-2: Reduced tillage with rotary tiller, RT-3: Reduced tillage with heavy tandem disc harrow fallowed by no tillage for the second crop, NT: No tillage, direct planting, ST: Strategic tillage.

The highest WR function in the first 10 cm depth was observed in CT-2 (69.5 %), RT-1 (68.4 %) and ST (68.2 %), while the lowest WR functions, in contrast to the expectations, occurred under CT-1 (63.6 %), RT-2 (63.0 %), RT-3 (62.8 %), and NT (61.1 %) methods (Table 8). Since the organic carbon content at 0−10 cm depth in RT-3 (1.38 %) and NT (1.35 %) was relatively higher (Table 2), WR function of the soils under RT-3 and NT was expected to be higher than other tillage practices. However, contrary to the expectations, results suggested that high organic matter content did not contribute enough to the improvement of WR functions in clayey textured Arik soils. The findings reported by Minasny and McBratney (2018) indicated that increase in organic matter content has only a small effect on plant available water capacity, which is larger in sandy soils and the least in clayey soils. However, ST at 30−33 cm depth with moldboard plow significantly improved WR function under NT. Higher WR function under ST can be attributed to the disturbance of the compacted layers at surface and subsurface layers in NT, which increased mesoporosity, which supports water retention, of the tilled layer as indicated by lower BD and PR values (Table 3), which increased their indicator scores (Table 7). Further research is needed to determine the duration of the benefits obtained by the ST in the NT system. Studies conducted to determine the changes in soil physical properties after ST in NT system are very few. Botta et al. (2012) indicated that the benefits of ST on BD lasted less than 12 months after ST in a long term NT, while, the persistence of improvement in PR, macro porosity and total porosity was longer than 24 months. The researchers attributed the increase in BD to the reconsolidation of soil by the rearrangement of soil particles and aggregates and to the pressure applied by the traffic of agricultural machinery and equipment. In contrast to the findings of Botta et al. (2012), Lamandé and Schjønning (2011) and Dang et al. (2018) reported that the persistence of ST in BD decrease was longer than 24 months.

Mean BD score in NT at 0−10 cm increased from 0.40 to 0.74 in ST, at 10 to 20 cm from 0.33 to 0.54 and at 20 to 30 cm from 0.32 to 0.46. Similarly, PR indicator scores increased from 0.06 to 0.20, from 0.03 to 0.47, and from 0.03 to 0.38, at 0 to 10 cm, 10 to 20 cm and 20 to 30 cm depths, respectively (Table 7). Tormena et al. (2017) also reported that BD was reduced from 1.55 g cm^{-3} to 1.45 g cm^{-3} by the use of a chisel plough on a field under NT for long time, which significantly increased water holding capacity of the soil.

The compaction interferes with hydraulic conductivity; thus, constrains plant water availability, diffusion of air and heat (Nunes et al., 2019). The WR function scores under ST, CT-1 and CT-2 were higher relative to RTs and NT due to soil compaction indicated by low BD and PR indicator scores (Table 7). The highest WR function score at 10−20 cm depth was obtained in ST (69.1 %), CT-2 (65.8 %) and CT-1 (63.6 %), while the lowest values were observed in RT-2 (56.2 %) and NT (57.1 %) (Table 8). Application of ST in NT led to a non-significant reduction in plant available water capacity of soils (Table 7). However, BD, WFPS and PR indicator scores used to define WR functions were significantly increased in soils under ST compared to NT (Table 8). The increase in indicator scores with ST led to 21 % increase in WR function of soils at 10−20 cm depth compared to NT.

The change in WR function at 20−30 cm was quite similar to 10−20 cm depth. The highest WR function scores at 20−30 cm depth were obtained by ST (67.6 %), CT-2 (64.5 %) and CT-1 (64.0 %), while the lowest scores were observed under RT-2 (55.1 %), NT (55.8 %), RT-3 (57.6 %) and RT-1 (59.0 %) (Table 8). The WR function in all layers within the first 30 cm under ST was higher than all other tillage methods. The results clearly demonstrated the benefits of ST in remediating the problems occurred in time by the adaptation of RT as well as NT method.

3.2.5. *Soil quality assessment of tillage methods*

Soil tillage methods, soil depth and tillage × depth interaction significantly ($P < 0.01$) affected SQI values (Fig. 1). Differences in tillage methods and residue management for the last ten years caused a significant change in functioning capacity of the same soil under the same climatic conditions. Hammac et al. (2016) also stated that dynamic factors, i.e., management decisions such as crop selection and tillage along with climate and soil type significantly affected soil quality.

The SQI values indicated that the highest functioning potential in all three sampling depths can be obtained by ST in NT soils. The lowest SQI values for 0−10 cm depth were found with CT-2 (62.6 %) in SQI-1, with CT-1 (49.4 %) in SQI-2 and with CT-1 (48.6 %) in SQI-3 (Fig. 1). Harvest residues are important sources of soil organic matter content, whereas, the impacts of residue removal on soil properties and crop yield are highly site and crop specific (Blanco-Canqui and Lal, 2009; Cherubin et al., 2018). The results clearly suggested that burning the crop residues, which have a critical role in sustaining the soil functions, decreased the overall soil quality in CT-2. Similar to our findings, Blanco-Canqui and Lal (2009) indicated that large decrease in crop residue adversely affected the soil organic matter content which is important to improve structure and water retention capacity of soils, reduce soil erosion, and increase soil fertility and productivity. The removal of organic matter in CT systems increases the use of mineral fertilizers, due to the negative impact on nutrient cycling and

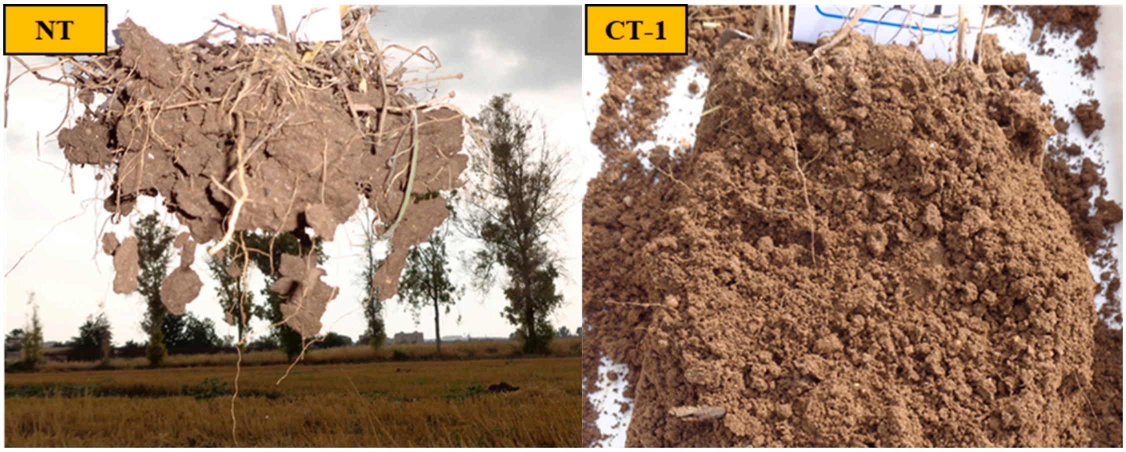

Fig. A1. Effects of organic matter and crop residue on resistance to degradation. CT-1: Conventional tillage with residue incorporated, NT: No tillage, direct planting.

availability in the soil (Cherubin et al., 2018). Therefore, the soils in the experimental field are performing far below than their genetic potentials under especially CT tillage practices investigated in wheat-soybean-corn rotation. The lower SQI values are associated with lower productivity, RR, PSS and WR functions. To understand the reason for this potential impairment, individual indicators used to calculate SQI scores need to be examined. The SQI scores reflect the impact from individual indicators that are thought to be effective in fulfilling the functions of the soil. Biological properties such as low PMN and MBC, chemical properties such as high pH and partially inadequate P concentration and physical properties such as high PR and BD and low WFPS, caused functioning potential of Arık soils between 50–60 %. The Arık soils may perform better if the relevant soil properties are examined and the necessary management practices are changed to improve these properties accordingly. For example, high PR, BD and correspondingly reduced WFPS problem encountered in NT seem to be partially resolved with ST. Three SQI scores calculated for ST were significantly higher than NT, which clearly show the effectiveness of the ST in sustaining the benefits of NT practices. In a comprehensive review on strategic tillage, Peixoto et al. (2020) indicated that the effect of ST on crop yield varies depending on the soil and crop type and also the environmental conditions of the experimental fields. Some studies reported no significant effect on crop yields, while yield increases were also observed in regions with water restrictions, and soils with low holding capacity. After two years of ST implementation in NT, Çelik et al. (2020) reported slightly lower wheat and corn yields and significantly higher soybean yield compared to the yields in NT system.

The highest functional potentials (SQI-1, 74.1 % and SQI-3 65.8 %) determined by both the arithmetic mean and the weights of the soil functions in 10−20 cm depth were obtained in soils under ST, while the lowest potential was found in soils under RT-2 (SQI-1 and SQI-3 were 57.1 % and 44.1 %, respectively). According to SQI-1, functioning potential of soils under all tillage methods decreased with increasing depth compared to 0−10 cm depth. This decrease in SQI-1 from 0−10 to 10−20 cm depth was 2.8 % under ST, CT-2 (6.2 %) and CT-1 (6.6 %) methods, while it was as high as 23.1 % in NT, 21.2 % in RT-2 and 19.1 in RT-1 methods (Fig. 1). Significant reductions of soil functioning capacity in RT and NT have been observed at subsurface relative to surface layers as the physical conditions deteriorated due to soil compaction, and nutrient concentrations reduced because of stratification effect. Büchi et al. (2017) also detected significant changes in soil properties and stratification in a soil profile 6 years after adaptation of NT in the west of Switzerland. The SQI values of 20−30 cm depth were similar to 10−20 cm depth. The lowest SQI values for 20−30 cm were obtained with RT-2 and NT (53 %) in the SQI-1, and NT and RT-2 (40 and 41 %) in the SQI-3, while the highest SQI values were recorded in ST (SQI-1, 68 % and SQI-3, 59.7 %) (Fig. 1). The implementation of ST in NT system helped in partial remediation of the problem, and increased the functional capacity of the soil. The SQI values for NT and ST methods in the surface layer were very similar to each other. Functioning potentials in 20−30 cm depth under NT were 21.7 % and 32.6 % lower than ST-based SQI-1 and SQI-3 values, respectively (Fig. 1). However, the positive effects of ST may not persist longer. The review carried out by Blanco-Canqui and Wortmann (2020) revealed that the benefits of ST are often small, inconsistent and of less than 24 months duration. Therefore, alternative conservation practices such as controlled traffic, cover crops and diversity in crop rotation to the strategic tillage were suggested to overcome the problems encountered in NT systems (Blanco-Canqui and Wortmann, 2020) in addition to strategic tillage.

Biological soil quality indicators are defined as the earliest respondents or biological processes that occur in the environment. Unlike organic carbon content of soils, microbial biomass or basal respiration can react to changes in the environment within a few days or months (Dilly et al., 2011). Therefore, biological quality indicators are very important in detecting early changes in soil quality. Soil quality assessment without biological properties lead to overestimation of soil quality in all tillage methods. Including MBC and PMN into SQI calculation significantly reduced SQI values and the highest difference was observed between SQI-1 and SQI-2 under CT-1 and the lowest was in ST (Fig. 1).

4. Conclusions

This study focused on the importance of incorporating soil chemical, physical and biological indicators into soil quality assessment for evaluating the impacts of long-term tillage practices on functioning ability of a clayey soil in Mediterranean region. The beneficial effects of reduced tillage and no-till methods was restricted to the surface layer due to low nutrient content, compaction and small aggregate size and stability at subsurface layers. The highest function scores were obtained at 0−10 cm depth for conservational tillage systems and the functional potentials of soils under reduced and no-till systems were significantly decreased with depth.

The results suggested that integration of soil functions into soil quality assessment helps to better evaluate the pros and cons of tillage practices. The disadvantages encountered in soils under long-term conservational tillage methods, especially in no-till, can be alleviated by strategic tillage, which would improve functional potential of soils. The resistance and resilience, physical stability and support, and water relation functions performed better when no-till plots were deep tilled after nine years. Finally, results concluded that no-till with strategic tillage is the best method to sustain the functions and overall quality of the soil under Mediterranean climate. However, further studies are needed to determine the frequency of strategic tillage operations to

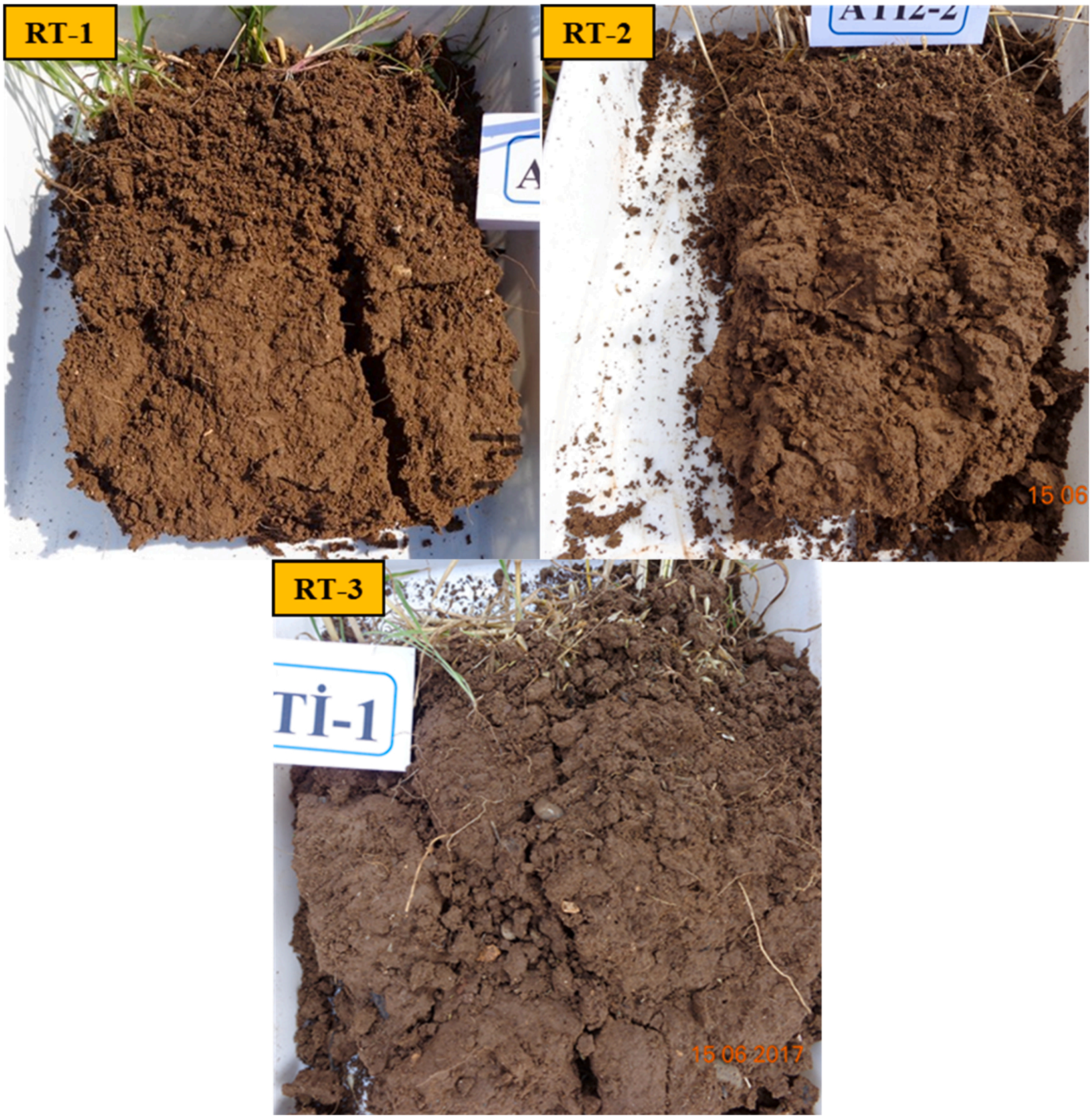

Fig. B1. Subsurface soil compactions at somehow shallow depth under reduced tillage systems. RT-1: Reduced tillage with heavy tandem disc harrow, RT-2: Reduced tillage with rotary tiller, RT-3: Reduced tillage with heavy tandem disc harrow fallowed by no tillage for the second crop.

prevent the loss of advantages gained in no-till system. In addition to the strategic tillage; alternative management practices such as controlled traffic, cover plants and diversity in crop rotation can also be suggested to maintain and sustain the benefits of no-till system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

See Fig. A1.

Appendix B

See Fig. B1.

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