KSÜ Tarım ve Doğa Derg 27 (6), 1443-1458, 2024
KSU J. Agric Nat 27 (6), 1443-1458, 2024
https://doi.org/10.18016/ksutarimdoga.vi.1428787

Sustaining Soil Biological Activity: The Role of Extended Reduced and No-Tillage Techniques

Murat GENCER[1]✉, Mustafa GÖK[2], İsmail ÇELİK[3]
[1,2,3]Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Çukurova University, Adana, Türkiye.
[1]https://orcid.org/0000-0002-5779-5073, [2]https://orcid.org/0000-0003-2868-2720, [3]https://orcid.org/0000-0002-8650-2639
✉: mgencer@cu.edu.tr

ABSTRACT

Soil management techniques can have varying effects on various soil properties. This study investigated the impact of various tillage techniques on soil properties for 14 years. The experiment was conducted at the Çukurova University Research Station, located in a region with a dominant Mediterranean climate. The research aimed to assess the changes in soil organic matter (SOM) content, soil respiration (SR), dehydrogenase enzyme activity (DHA), and soil temperature (ST) under seven different long-term tillage practices. The results revealed significant increases ($p \leq 0.05$) in SOM (17-115%), SR (19-37%), and DHA (63-142%), under conservation tillage compared to conventional tillage practices. Additionally, conventional tillage with stubble burned consistently had the lowest values across all measured properties. Seasons variations also significantly ($p \leq 0.05$) affected the observed values. These findings suggest that conventional tillage practices have a negative effect on the analyzed biological activities, with stubble burning further exacerbating this impact. Further research exploring the long-term effects of different tillage practices under varying crop rotations and soil conditions can contribute to the sustainable development of agricultural production in the region.

Soil Science

Research Article

Article History
Received : 31.01.2024
Accepted : 14.06.2024

Keywords
Tillage
Mediterranean conditions
Dehydrogenase enzyme activity
Organic matter
Soil respiration

Toprak Biyolojik Aktivitesinin Sürdürülmesi: Genişletilmiş Azaltılmış ve Sıfır Toprak İşlemenin Rolü

ÖZET

Toprak yönetimi tekniklerinin çeşitli toprak özellikleri üzerinde farklı etkileri olabilir. Bu çalışmada 14 yıl boyunca çeşitli toprak işleme tekniklerinin toprak özelliklerine etkisi araştırılmıştır. Deney, Akdeniz ikliminin hâkim olduğu bir bölgede yer alan Çukurova Üniversitesi Araştırma İstasyonu'nda gerçekleştirilmiştir. Araştırma, uzun süreli yedi farklı toprak işleme uygulaması altında toprağın organik madde (SOM) içeriği, toprak solunumu (SR), dehidrogenaz enzim aktivitesi (DHA) ve toprak sıcaklığındaki (ST) değişiklikleri değerlendirmeyi amaçlamıştır. Sonuçlar, geleneksel toprak işleme uygulamalarıyla karşılaştırıldığında koruyucu toprak işleme altında SOM (%17-115), SR (%19-37) ve DHA'da (%63-142) önemli artışlar ($p \leq 0.05$) göstermiştir. Ek olarak, anızları yakılmış geleneksel toprak işleme, ölçülen tüm parametrelerde en düşük değerleri göstermiştir. Mevsim değişimleri de incelenen parametreleri önemli ölçüde ($p \leq 0.05$) etkilemiştir. Bu bulgular, geleneksel toprak işleme uygulamalarının incelenen biyolojik aktiviteler üzerinde olumsuz bir etkiye sahip olduğunu ve anız yakmanın bu etkiyi daha da artırdığını göstermektedir. Farklı toprak işleme tekniklerinin uzun vadeli etkilerini çeşitli bitki rotasyonları ve toprak koşulları altında araştırmak, bölgedeki tarımsal üretimin sürdürülebilir gelişimine katkıda bulunabilir.

Toprak Bilimi

Araştırma Makalesi

Makale Tarihçesi
Geliş Tarihi : 31.01.2024
Kabul Tarihi : 14.06.2024

Anahtar Kelimeler
Toprak işleme
Akdeniz iklim koşulları
Dehidrogenaz enzim aktivitesi
Organik madde
Toprak solunumu

To Cite: Gencer, M., Gök, M., & Çelik İ., (2024). Sustaining Soil Biological Activity: The Role of Extended Reduced and No-Tillage Techniques. KSU J. Agric Nat *27*(6), 1442-1457. DOI: 10.18016/ksutarimdoga.vi.1428787.

Atıf İçin: Gencer, M., Gök, M., & Çelik İ., (2024). Toprak Biyolojik Aktivitesinin Sürdürülmesi: Genişletilmiş Azaltılmış ve Sıfır Toprak İşlemenin Rolü *KSÜ Tarım ve Doğa Derg 27* (7), 1442-1457. DOI: 10.18016/ksutarimdoga.vi.1428787.

INTRODUCTION

Soil organic matter (SOM) influences soil fertility by altering the physical, chemical, and biological aspects of the soil through different pathways. Elevated SOM content reduces soil bulk density (Zhang & Peng, 2021), boosts cation exchange capacity (Yost & Hartemink, 2019), and increases microbial diversity (Tian et al., 2018). Soil organic matter acts as a source of nutrients for microorganisms and enhances soil structure (Gök & Coskan, 2002). Therefore, maintaining high SOM content is crucial, not only for soil health but also because SOM is the largest global carbon pool (Wani et al., 2022). Each practice, particularly tillage, is linked to global warming and climate change (Bilen et al., 2010).

Tillage is defined as the process of loosening, crumbling, and mixing soil thoroughly with a tool at a specific depth for purposes such as seedbed preparation and weed management (Bilim & Korucu, 2016; Celik et al., 2017), and incorporating plant residues into the soil (Zhang & Peng, 2021). Tillage significantly impacts soil physical, chemical, and biological properties. Sustaining these attributes is essential for sustainable agriculture and soil management practices. Soil health refers to the ability of a particular soil type to function as a living system within an ecosystem, supporting plant and animal life, maintaining air and water quality, and contributing to human well-being (Doran & Parkin, 1997; Alkorta et al., 2003). Reduced and no-tillage practices, known as conservation tillage, are recognized as some of the most beneficial approaches for soil health. In conventional tillage systems, plows cultivate the top 30 cm of soil thoroughly. In contrast, reduced tillage approaches leave at least 30% of the soil surface covered with crop residue to reduce water and wind erosion. No-tillage, on the other hand, involves direct seeding into existing crop residue without any prior plowing (Köller, 2003). Conservation tillage is a well-established land management technique that continuous to be refined and studied for optimal soil benefits (Tang et al., 2020).

Annually two crops are harvested in the Çukurova Region, one of Turkey's most fertile plains, and consecutive tillage is used for each crop. The microbial populations in the surface soil are negatively affected by frequent tillage applications, which also continuously degrade the soil structure (Mirzavand et al., 2022). Tillage damages aggregates generated in the surface soil over time, and also microorganism habitats are destroyed (Celik et al., 2011). Consequently, the tillage has an impact on several nutrient cycles in the soil.

Existing studies demonstrated that changes in microbial activity might be positive, negative, or neutral as a result of soil tillage applications. The direction and severity of these effects are also closely influenced by the intensity and duration of the tillage applications. For instance, tillage may have a positive or negative impact on the soil system in the short term, but due to the long-term structural degradation of the soil, this impact may be neutral or negative (Das et al., 2014).

Soil organic matter in the soil directly influences the physical, chemical, and biological characteristics resulting in improvement of soil productivity (Li et al., 2021). While aggregates are maintained in no-tillage, they are broken down and exposed to microbial decomposition in standard tillage techniques, which stimulates the mineralization of SOM (Chen et al., 2009; Wang et al., 2020). Aside from being the primary SOM input, stubble supports SOM by promoting aggregate formation and soil stabilization (Pu et al., 2019). Furthermore, the stubble covers the soil surface and reduces temperature rise by reflecting sunlight (Salem et al., 2015). Soil temperature may rise (Bogužas et al., 2018) or fall (Hou & Li, 2019) due to tillage techniques, which that temperature fluctuations influence the biological activity of soil (Muñoz-Romero et al., 2015).

Biological properties are sensitive indicators reflecting the impact of frequently used agricultural practices. They can warn of structural changes in the soil (Futa et al., 2021; Mirzavand et al., 2022). Therefore, many researchers recommended determining soil biological properties due to their rapid response and high sensitivity (Mikanová et al., 2009). Among soil biological parameters, soil respiration, or CO_2 formation indicates the presence of active microorganisms (Mijangos et al., 2006). Dehydrogenase enzyme activity (DHA) is another indicator of overall microbial performance (Gajda & Przewloka, 2012). While some researchers (Akbolat et al., 2009; Moraru & Rusu, 2012) reported increased microbial activity with higher tillage intensity, long-term studies generally indicate the opposite trend (Li et al., 2021; Wang et al., 2022). For example, Moraru & Rusu (2012) reported the lowest soil respiration in no-tillage applications after three years of different tillage practices, whereas Celik et al. (2011) found the lowest value in conventional tillage. In contrast, studies by Cooper et al. (2020) and Nath et al. (2021) observed higher soil respiration in no-tillage treatments after 5 and 7 years of tillage practices, respectively.

Land management practices can significantly influence soil quality over time (Van Eerd et al., 2014). To investigate this effect, we conducted a long-term (14-year) field experiment in a Mediterranean climate, examining how different tillage practices affect soil biological properties. Soil samples were collected and analyzed for soil organic carbon (SOC) content, soil respiration, and DHA, which serves as a marker of microbial activity. In this study, we hypothesized that: 1) Reduced tillage enhances SOM and biological activity: Less intensity tillage over time allows for greater accumulation of SOM, a key energy source of microbes, This, in turn, is expected to support higher soil respiration and DHA activity. 2) Stubble burning detriments soil biology: Burning crop residue removes potential organic matter input and disrupts microbial communities, leading to lower biological activity, 3) Reduced and conservation tillage moderate soil temperature: Leaving plant residues on the surface regulates soil temperature by reflecting sunlight, potentially influencing biological properties. By analyzing these factors, this study aims to quantify the long-term impacts of tillage practices on soil biology in a Mediterranean region. The findings will contribute to the development of sustainable soil management strategies that promote healthy biological activity.

MATERIALS and METHOD

Research Site, Experimental Design, and Tillage Practices

The long-term experiment was conducted at the Research Station of Çukurova University in Adana, Turkey in 2006, with different tillage practices implemented. The is located at 37°00'54.0" N 35°21'27.0" E, with an elevation of 32 meters above sea level (Figure 1). With a Mediterranean climate, the experimental area experiences monthly temperatures of 9.4 (the lowest), 19.1 (average) and 28.6 °C (the highest) Precipitation follows a similar pattern, with July receiving the least (9.8 mm) and December the most (127.3 mm for a total annual precipitation of 671 mm (AMS, 2021). According to the World Reference Base, the soil in the research area is categorized as Haplic Vertisol. The soil developed on the former Seyhan River terraces and contains 49% clay, 33% silt, and 18% sand (clay texture) (Group, 2014). According to the analyses performed on the soil sample (0-30 cm) at the beginning of the experiment, pH, EC, $CaCO_3$ and SOM were 7.82, 0.15 dS m^{-1} 24.4%, and 1.51%, respectively (Celik et al., 2011).

The experiment was arranged in a randomized complete block design with three replicates to evaluate the long-term effects of seven tillage practices. These practices included: two conventional tillage treatments (CT-1 and CT-2), three reduced tillage treatments (RT-1, RT-2, and RT-3), and two no-till treatments (NT and newly added ST) (Table 1). Initially, the experiment consisted of 18 plots, each measuring 40 x 12 m (480 m^2). Six soil tillage practices were applied from 2006 to 2015 (9 years). In 2015, half of the NT plots (240 m^2) were tilled once with a plow to a depth of 30-33 cm, creating a new strategic tillage (ST) treatment while maintaining no-till characteristics on the other half. This increased the total number of plots to 21. A disc harrow was used throughout this process to break up the large clods and level the soil surface after tillage events (Table 1). A 4-meter space was left between plots to minimize treatment interference.

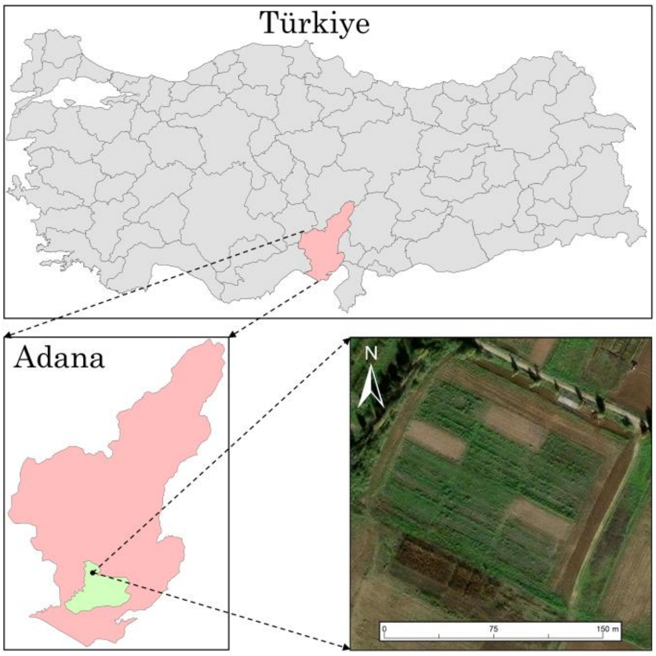

Figure 1. Location of the study area
Şekil 1. Çalışma alanının konumu

Wheat (*Triticum aestivum* L.) - corn (*Zea mays* L.) or soybean (*Glycine max* L.) -alternatively- rotation was followed throughout the 14-year long-term experiment. Plots with wheat (*Triticum aestivum* L.)

were examined for the objected parameters (Soil organic matter, soil respiration, dehydrogenase enzyme activity, soil temperature) in 2020. Glyphosate (500 g ha^{-1}) was applied as a non-selective herbicide on RT-3, NT, and ST plots for weed control two weeks before sowing the wheat. Duration of the inspected year of the long-term experiment, the plots were fertilized considering the results of soil analysis, with 260 kg ha^{-1} di-ammonium phosphate (46.8 kg N ha^{-1}; 119.6 kg P_2O_5 ha^{-1}) before planting. At the tillering and bolting stages, 150 kg ha^{-1} urea (69 kg N ha^{-1}) and 180 kg ha^{-1} calcium ammonium nitrate (46.8 kg N ha^{-1}) were applied, respectively.

Table 1. Summary of tillage methods and equipment used in the long-term experiment
Çizelge 1. Denemede kullanılan toprak işleme yöntemleri ve ekipmanlar

Tillage Methods	Soil Tillage for Winter Wheat	Soil Tillage for Second Crop Maize and Soybean
Conventional tillage with stubbles (CT-1)	▪ Stover chopping of second crop ▪ Moldboard plow ▪ Disc harrow (2 passes) ▪ Float (2 passes) ▪ Drill	▪ Stubble chopping of wheat ▪ Heavy tandem disc harrow ▪ Disc harrow (2 passes) ▪ Float (2 passes) ▪ Planter
Conventional tillage with stubbles burned (CT-2)	▪ Stover burning of second crop ▪ Moldboard plow ▪ Disc harrow (2 passes) ▪ Float (2 passes) ▪ Drill	▪ Stubble burning of wheat ▪ Chisel plow ▪ Disc harrow (2 passes) ▪ Float (2 passes) ▪ Planter
Heavy disc harrow reduced tillage (RT-1)	▪ Stover chopping of second crop ▪ Heavy tandem disc harrow (2 passes) ▪ Float (2 passes) ▪ Drill	▪ Stubble chopping of wheat ▪ Rotary tiller ▪ Float (2 passes) ▪ Planter
Reduced tillage with a rototiller (RT-2)	▪ Stover chopping of second crop ▪ Rotary tiller ▪ Float (2 passes) ▪ Drill	▪ Stubble chopping of wheat ▪ Rotary tiller ▪ Float (2 passes) ▪ Planter
Reduced tillage with a rototiller and no-tillage (RT-3)	▪ Stover chopping of second crop ▪ Heavy tandem disc harrow ▪ Float (2 passes) ▪ Drill	▪ Stubble chopping of wheat ▪ Herbicide treatment ▪ No-till planter
No-till or zero tillage (NT)	▪ Stover chopping of second crop ▪ Herbicide treatment ▪ No-till drill	▪ Stubble chopping of wheat ▪ Herbicide treatment ▪ No-till planter
Strategic tillage (ST)*	▪ Stover chopping of second crop ▪ Herbicide treatment ▪ No-till drill	▪ Stubble chopping of wheat ▪ Herbicide treatment ▪ No-till planter

*This treatment continued as NT from 2006 until November 2015. Afterwards, it was tilled with moldboard plow only once in November 2015 and then, the same operations as in NT were implemented.

Soil Sampling and Analysis

The basic physical and chemical properties of the soil were determined at a depth of 0 – 20 cm before the wheat sowing (November 02, 2020). Similarly, to monitor biological parameters throughout the wheat vegetation, samples were collected at depths from 0-20 cm. Soil samples were collected by using a soil auger at frequent intervals from the beginning of the experiment, the sampling interval was extended by time (11 to 35 d). The first sample was made just after wheat planting (November 19, 2020) and the last sample was made just before wheat harvest (May 26, 2021). Due to the fertilizer application stimulating several features of the soil, after every single fertilization application, more frequent samplings were done. Each treatment including replicates was represented for one composite soil sample which was prepared by homogenized soil samples taken in 3 different representative sampling points of each plot. To prevent changes in the soil biological properties of the soil, samples were transferred to the laboratory within one hour. On each sampling day, CO_2 formation and DHA were determined. Carbon dioxide production was determined according to Öhlinger (1996a) in which 100 g of fresh soil equivalent to dry soil was weighed and incubated for 24 h at 30 °C. Emitted CO_2 from the soil within 24 hours was collected by barium hydroxide, and soil respiration was determined by titrating the residual barium hydroxide with 0.05 M HCl. The DHA was evaluated at 10 g of dry soil equivalent to fresh soil according to Öhlinger (1996b) in which TTC (2,3,5-Triphenyltetrazolium chloride) was added to soil, incubated at 30 °C for 24 h. Emerged TPF (triphenyl formazan) was extracted by acetone and the TPF concentration of filtrate was measured by spectrophotometer at a wavelength of 546 nm. Soil temperatures were recorded on each sampling day by TP101 digital temperature sensor. The organic matter content of the soil was determined in the first sampling only (November 19, 2020) using chromate oxidation as described by (Kandeler, 1996).

Statistical Analysis

Data gathered from 21 randomized plots was subjected to a one-way analysis of variance (ANOVA) using the IBM SPSS Statistics program. Duncan's test was also used to compare differences between the means. Additionally, the Pearson correlation test was used to assess the correlations between the parameters. The Origin 2021 software was used to represent statistical findings.

RESULTS and DISCUSSION

The Effect of Long-Term Different Tillage Practices on Soil Organic Matter Content

The effects of various long-term tillage techniques on SOM content were statistically significant ($p \leq 0.001$) after 14 years (Figure 2). The SOM content of the soils ranged from 1.57 to 3.38%, with NT application yielding the greatest value whereas the lowest value was obtained from CT-2 application. The lowest SOM content in conservation tillage practice was 17% higher than the highest value observed in conventional tillage treatment. Additionally, the highest SOM content was found in the conservation soil cultivation application (NT) as 115% more SOM than that of the CT-2 which is the conventional soil tillage application with the lowest SOM content. These findings show that 14 years of tillage methods boosted the soil's SOM contents by 17 to 115%.

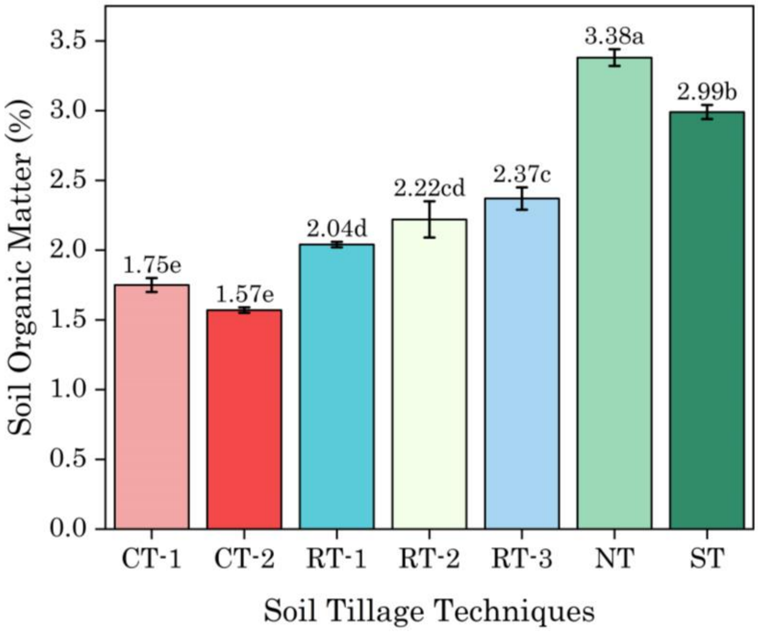

Figure 2. The effect of long-term different tillage practices on the soil organic matter content (%). Values are the average of samples from three plots. Means shown with the same letter are not statistically significant according to the Duncan test ($p \leq 0.001$). CT-1: Conventional tillage with wheat stubble incorporated, CT-2: Conventional tillage with burned-off stubble, RT-1: Heavy disc harrow reduced tillage, RT-2: Reduced tillage with a rototiller, RT-3: Reduced tillage with a rototiller and no-tillage practice combination, NT: Direct seeding without tillage, ST: Strategic tillage.

Şekil 2. Uzun süreli farklı toprak işleme uygulamalarının toprağın organik madde içeriğine etkisi (%). Değerler üç parselden alınan örneklerin ortalamasıdır. Aynı harfle gösterilen ortalamalar Duncan testine göre istatistiksel olarak anlamlı değildir ($p \leq 0.001$). CT-1: Anızlı geleneksel toprak işleme, CT-2: Anızı yakılmış geleneksel işleme, RT-1: Ağır diskli tırmıklı azaltılmış toprak işleme, RT-2: Rototillerli azaltılmış toprak işleme, RT-3: Ağır diskli tırmıklı azaltılmış ve sıfır toprak işleme kombinasyonu, NT: Doğrudan ekimli sıfır toprak işleme, ST: Stratejik sıfır toprak işleme.

Conventional tillage operations overturn the soil at depths ranging from 0 to 25 cm, producing soil deterioration as well as stimulating organic carbon mineralization (Wang et al., 2020). While 170 to 1000 kg ha^{-1} of organic carbon disappears every year in conventional tillage practices, no-tillage practices even result in SOM accumulation in the soil (Valkama et al., 2020). Similar to the results obtained in other studies, SOM increased as a result of reducing tillage intensity. While stubble management alone provided an 11% increase in SOM, without tillage practices increased this difference to 115%. Stubble contributes to the soil as a carbon source, and conservation tillage encourages their accumulation. Supporting this finding, Li et al. (2021) reported increased organic carbon contents in the soil because of conservative tillage and no-till practice, based on the existing 264 studies in the literature dealing with the effects of tillage practices on organic carbon. A distinction in conservative tillage techniques was also noted, and a 7.4% increase in organic carbon content was found in the no-till treatment compared to the reduced tillage application. This was attributed to less soil degradation and/or the addition of stubble resulting in the elevation of microbial biomass. According to Chen et al. (2009), no-tillage results in surface soil with 34% more SOM than conventional tillage. Several researchers reported that conventional soil cultivation is disturbing soil aggregates that are exposed to microbial decomposition leading to loss of SOM. Wang et al. (2020) reported that the organic carbon content in the surface soil increased significantly in both reduced and no-till applications compared to conventional tillage treatments. This difference resulted in more organic carbon accumulation with no-till application as well as the addition of plant residues. Similar results were also observed in the ST treatments, which were formed by dividing the NT plot and cultivated once, after 9 years after the beginning of the experiment in 2015 (Figure 2). Even single tillage on ST stimulated mineralization, therefore, a considerable decrease in the SOM of soil was observed compared to the NT. Similar to the existing literature, this study revealed that the management of stubble in the soil was found to alter the SOM content of the soil. The lowest SOM content was determined in CT-2, which is the only tillage method in the stubble is burned. Soil organic matter content was found to be 11% higher in CT-1 than in CT-2, which uses typical tillage techniques with the main variation being stubble management, although the difference was not statistically significant (Figure 2). The stubble, which is a potential source of organic materials, is removed from the soil by burning due to easy soil cultivation. However, Gök & Coskan (2002) stated that organic compounds with a high C/N ratio such as stubble can be considered as an important source of soil SOM content. Plant residues physically preserve SOM by providing aggregate formation and stabilization in the soil, in addition to being the primary source of SOM inputs (Pu et al., 2019). Furthermore, stubble promotes the establishment of a fluctuating carbon pool (Chen et al., 2009). Similar findings have been frequently reported by researchers focusing on stubble residue incorporation and the organic carbon content of soil (Gök & Coskan, 2002; Wang et al., 2020). Pu et al. (2019) reported higher SOM accumulation in surface soil in case of stubble addition. Stubble is the primary source of SOM, hence organic carbon levels increase through convenient stubble management. On the other hand, soil cultivation seems to be more effective for SOM pools in which SOM content was increased in no-tillage application compared to conventional practices independent of stubble management. This phenomenon is possibly associated with less degradation of soil and suppression of mineralization. Increased mineralization is also reported due to the increased contact of SOM that is conservation in soil aggregates with microorganisms.

The Effect of Long-Term Different Tillage Practices on Soil Respiration

The determined soil respiration values are presented in Table 2. The findings revealed that both different tillage techniques and sampling days had statistically significant ($p=0.024$ and $p \leq 0.001$, respectively) effects on soil respiration. Considering the sampling day averages, the highest mean value was observed at ST as 36.5 µg CO_2-C g_dry_soil^{-1} 24h^{-1} whereas the lowest mean was obtained in CT-2 with 26.8 µg CO_2-C g_dry_soil^{-1} 24h^{-1}. Based on these findings, the conventional tillage application (CT-2), has a 36% lower soil respiration rate than the ST applications, representing lower soil biological activity as a function of conventional tillage systems. Sampling day averages showed great variability among the mean values, the highest CO_2 formation was achieved on May 26, 2021, as 67.4 µg CO_2-C g_dry_soil^{-1} 24h^{-1} whereas the lowest value was on November 19, 2020, with 17.2 µg CO_2-C g_dry_soil^{-1} 24h^{-1}. Based on these data, CO_2 formation on May 26, 2021, is %292 greater than that of the sampling day of November 19, 2020. The temporal fluctuation of CO_2 output across the wheat vegetation appears to be mostly influenced by soil temperature. Soil respiration increased consistently around 172% and 168% following the sample period ending on February 24, 2021, depending on the temperature rise. The relationship between soil respiration and soil temperature is similar considering the data recorded between the dates of February 24, 2021, to May 26, 2021 (Tables 2 and 4).

Soil respiration after fertilization increased during the tillering period, while the increase in respiration was not statistically significant ($p=0.146$). The first sampling following fertilization during the bolting period showed an increase in soil respiration, but it is unclear whether this increase was due to fertilization or climate.

Table 2. The effect of long-term different tillage practices on soil respiration ($\mu g\ CO_2\text{-}C\ g\_dry\_soil^{-1}\ 24h^{-1}$)

Çizelge 2. Uzun süreli farklı toprak işleme uygulamalarının toprak solunumuna etkisi ($\mu g\ CO_2\text{-}C\ g\_dry\_soil^{-1}\ 24h^{-1}$)

Soil Tillage Techniques[1]	Sampling Date																							
	19.11.2020[6]				30.11.2020				11.12.2020				31.12.2020				13.01.2021				26.01.2021[7]			
	$p \leq 0.001$				$p \leq 0.001$				$p \leq 0.001$				$p \leq 0.001$				$p=0.029$				$p=0.007$			
CT-1	11.7[2]	±0.8[3]	d[4]	F[5]	23.2	±1.2	b	DE	17.1	±0.3	c	EF	30.7	±0.0	c	C	22.4	±1.5	a	DE	17.8	±1.5	c	EF
CT-2	8.1	±0.8	e	F	23.8	±0.9	b	D	19.2	±1.4	c	E	24.8	±0.6	d	D	18.0	±0.4	b	E	24.6	±1.1	ab	D
RT-1	16.8	±1.0	c	F	30.7	±0.5	a	DE	32.5	±1.9	a	CD	34.8	±0.4	ab	CD	24.9	±2.1	a	E	23.8	±2.3	b	E
RT-2	16.9	±0.4	c	E	20.5	±0.5	b	E	23.6	±0.8	b	E	24.3	±0.6	d	E	24.4	±1.6	a	E	23.0	±2.1	bc	E
RT-3	24.5	±0.2	a	D	28.7	±2.3	a	CD	24.0	±0.7	b	D	34.0	±0.2	b	C	25.5	±1.3	a	D	28.1	±0.6	ab	CD
NT	19.8	±0.7	bc	G	31.8	±1.0	a	EF	25.9	±1.3	b	E-G	33.2	±2.5	bc	DE	24.1	±1.5	a	FG	24.8	±2.0	ab	FG
ST	22.4	±1.8	ab	F	28.3	±2.5	a	DE	25.7	±0.7	b	D-F	37.4	±0.3	a	C	24.1	±0.5	a	EF	30.2	±2.3	a	D
Mean		17.2	F			26.7	E			24.0	E			31.3	D			23.3	E			24.6	E	

Soil Tillage Techniques	Sampling Date																								Mean	
	8.02.2021				24.02.2021				31.03.2021[8]				16.04.2021				03.05.2021				26.05.2021					
	$p \leq 0.001$				$p \leq 0.001$				$p=0.014$				$p \leq 0.001$				$p=0.028$				$p \leq 0.001$				$p=0.024$	
CT-1	18.4	±0.6	e	E	22.9	±2.2	c	DE	41.6	±3.9	ab	B	27.7	±0.7	b	CD	47.2	±1.4	bc	AB	52.3	±4.3	d	A	27.7	bc
CT-2	27.9	±1.9	bc	CD	17.9	±0.8	d	E	31.4	±0.9	c	C	27.5	±1.3	b	CD	43.9	±3.2	c	B	54.9	±1.1	cd	A	26.8	c
RT-1	28.3	±2.5	bc	DE	25.0	±1.4	a-c	E	39.3	±2.7	bc	C	28.1	±2.2	b	DE	53.1	±1.1	a-c	B	67.4	±5.1	b	A	33.7	a-c
RT-2	21.4	±0.7	de	E	24.1	±1.5	bc	E	40.2	±2.9	bc	C	32.5	±1.2	b	D	59.7	±3.7	a	B	86.3	±5.2	a	A	33.1	a-c
RT-3	34.4	±0.8	a	C	24.8	±1.4	a-c	D	50.6	±3.2	a	B	30.1	±1.8	b	CD	50.4	±4.5	a-c	B	82.1	±1.7	a	A	36.4	a
NT	23.9	±1.0	cd	FG	28.9	±0.9	ab	EF	43.9	±3.4	ab	C	39.7	±2.4	a	CD	56.3	±5.2	ab	B	65.4	±4.0	bc	A	34.8	ab
ST	29.2	±1.7	b	DE	29.6	±1.6	a	DE	43.1	±2.1	ab	B	44.8	±3.7	a	B	59.6	±1.4	a	A	63.3	±0.5	b-d	A	36.5	a
Mean		26.2	E			24.8	E			41.5	C			32.9	D			52.9	B			67.4	A			

Means shown with the same letter are not statistically significant according to Duncan's test. The ANOVA value is $p \leq 0.001$ for sampling dates and is shown in the table for comparisons between treatments.

[1]: CT-1: Conventional tillage with wheat stubble incorporated, CT-2: Conventional tillage with burned-off stubble, RT-1: Heavy disc harrow reduced tillage, RT-2: Reduced tillage with a rototiller, RT-3: Reduced tillage with a rototiller and no-tillage practice combination, NT: Direct seeding without tillage, ST: Strategic tillage. [2]: It is the average of the samples in three plots. [3]: It is the standard error of the means. [4]: Lowercase letters give statistical comparisons among treatments. [5]: Uppercase letters give statistical comparison among sampling dates. [6]: It is the sampling performed after pre-planting fertilization. [7]: It is the first sampling performed after fertilization during the tillering period. [8]: It is the first sampling performed after fertilization during the bolting period.

No-tillage and reduced tillage strategies improve the soil's organic matter content by undergoing less physical degradation of SOM than typical tillage techniques (Das et al., 2019) by encouraging biological activity. Previously, Çelik et al. (2021) have taken soil samples from the same long-term experiment, and they reported higher organic carbon content in the surface soil than in conventional tillage on the same soil layer. Similarly, Li et al. (2021) reported that the conservation tillage practices increase SOM content and lead promotion to the of microbial activity with this enhancement (Mirzavand et al., 2022). The findings of the SOM analysis conducted in this study area during the sampling date of November 19, 2020, revealed a pattern that was similar to the findings of the study with soil respiration indicated above. Figure 3 shows the correlation between soil respiration and SOM, which was found to be a positive correlation ($r=0.182$; $p<0.01$). According to the results acquired, during the sample dated November 19, 2020, both soil respiration and SOM content were determined as the lowest in CT-2 among tillage methods, followed by CT-1, RT-1, and RT-2. Although the highest CO_2 production was measured in RT-3 and ST-applied plots, the highest SOM content was obtained in ST applications. While RT-3 and ST applications produced the highest CO_2 formation, NT applications provided the highest SOM content. This could be attributed to tillage applied soon before the sampling date on November 19, 2020. In the RT-3 application, however, unlike the NT and ST applications, processing with both a heavy disc harrow and a tiller may have resulted in an increase in CO_2 emission from the soil. When soil respiration during the sampling time is considered, the highest CO_2 production was recorded in RT-3, and the lowest CO_2 production was observed in CT-2 application. When CO_2 generation was compared between these two tillage techniques, RT-3 produced nearly three times more soil respiration than CT-2. This is the date with the largest inter-application variation among all sampling dates. This can be explained by the fact that the aggregates that degrade after soil tillage applications (Celik et al., 2011) boost CO_2 emissions (Fiedler et al., 2016). Therefore, a lowering tendency on CO_2 production is expected after the tillage practice. Table 2 shows that the CO_2 output differs, which grew between soil tillage applications as the aggregates broke down, reduced throughout the sampling date of November 30, 2020, which was conducted 11 days after the initial sampling. Similar results were reported by Buragienė et al. (2019) and Zhang et al. (2021). All tillage methods were found to be significantly greater than other sampling intervals on May 26, 2021, when soil respiration was at its peak. The increased soil temperature is responsible for the highest values seen in tillage practices during this date (Table 4 and Figure 3). In addition, the increase in plant root growth from wheat planting to harvest, as well as the associated root exudate, may have enhanced CO_2 flow by promoting microbial activity. Consistent with these findings, a study by Bilen et al. (2010), the highest soil respiration was observed during the harvest period and stated that this was due to increases in root growth and microbial activity.

Furthermore, the dry climate during the sampling time of May 26, 2021, the lack of irrigation in the wheat growth, and the low seasonal soil moisture content may have reduced the rise in soil respiration during this date. Another study found that as temperatures decreased, SOM in the soil remained steady, resulting in little CO_2 emission, which was consistent with the findings in this study (Moreno et al., 2021). Under ideal temperature and humidity conditions, according to Gök et al. (1999), microbial activity increased in soil. The increase in soil temperature causes an increase in microbial activity and promotes the decomposition of SOM, which enhances soil heterotrophic respiration (Zhang et al., 2021). Furthermore, fertilizer had no obvious influence on soil respiration.

Soil respiration was strongly influenced ($p=0.024$) by the management of stubble which is another soil management practice, studied. When the average of the sampling dates is taken into consideration, CT-2, which is the only application of the tillage methods in which the stubble is burned, has the lowest CO_2 output. The amount of soil respiration was decreased due to the microbial community in the surface soil being adversely impacted by rising temperature. Destruction of the stubble which is the main carbon source was also responsible for lower CO_2 formation. Regarding the issue, Shakoor et al. (2021) stated that stubble supports heterotrophic respiration by providing ready-to-use C and N substrates for the microbial population. By leaving the stubble in the soil and reducing tillage density, Mirzavand et al. (2022) found that SOM increased, enhancing the diversity of microbial biomass and promoting CO_2 formation. When the average of the sample dates of the other six tillage techniques, in which the stubble is incorporated into the soil or left on the surface, is examined, there were no significant differences in soil respiration (Table 2). The temporal fluctuation of CO_2 production across the wheat vegetation appears to be mostly influenced by soil temperature. Particularly, based on the sampling dates soil respiration followed a proportionate path with temperature after the samples were taken on February 24, 2021. The association between soil respiration and soil temperature was comparable when taking into account the average of tillage techniques in the sample dated February 24, 2021, and May 26, 2021, and these values rose by 172% and 169%, respectively. Similar findings are obtained when research on the issue is evaluated (Du et al., 2021; Zhang et al., 2021). Additionally, a positive correlation (r=0.758) between soil respiration and soil temperature was determined (Figure 3). Furthermore, fertilizer had no obvious influence on soil respiration.

Although no-tillage techniques decrease CO_2 output in the short term, long-term effects may vary. While short-term studies show low CO_2 formation owing to the preservation of SOM from tillage methods (Akbolat et al., 2009), long-term studies show an increase in the accumulated SOM pool and microbial population, which promotes increased soil respiration (Mirzavand et al., 2022).

The Effect of Long-Term Different Tillage Practices on Dehydrogenase Enzyme Activity

Determined DHA values are presented in Table 3. Similar to CO_2 production results (Table 2), DHA was influenced by both soil tillage practice and sampling interval significantly ($p \leq 0.001$ and $p \leq 0.001$, respectively). Based on the mean values, the highest value was determined in NT treatment as 84.8 µg TPF g_dry_soil^{-1} 24h^{-1}. The CT-2 application yielded the lowest mean with 35.1 g TPF g_dry_soil^{-1} 24 h^{-1}. According to these findings, DHA activity in NT was 142% higher than in CT-2 treatment. As mentioned earlier, sampling day was also significant on DHA activity in which the highest value was achieved on February 8, 2021, with 113.4 µg TPF g_dry_soil^{-1} 24 h^{-1}. The lowest mean value was observed on November 30, 2020, as 28.4 µg TPF g_dry_soil^{-1} 24 h^{-1}. The observed DHA activity on February 8, 2021, was 299% higher than the value obtained on November 30, 2020. This difference was probably due to temperature changes.

The DHA levels significantly increased in samples collected after fertilization during tillering, followed by a significant decrease in samples from the bolting period. However, the conflicting results cast doubt on fertilization being the direct cause. The conventional tillage application CT-2 had the lowest average DHA value when the average of the sample intervals across the wheat plant vegetation was analyzed. This value was followed by CT-1, and the difference between them was found to be statistically insignificant. Both no-tillage and reduced tillage practices demonstrated higher DHA than conventional tillage practices, and there were no statistically significant differences between no-tillage and reduced tillage treatments according to the results of these various tillage practices ongoing for 14 years. In research carried out in the same long-term experiment where several tillage techniques were used over three years, similar results were attained by Celik et al. (2011). In this study, the lowest DHA was found in the conventional tillage methods CT-2 and CT-1, whereas the highest DHA was found in NT and RT-3, which are no-tillage and reduced tillage techniques. It was shown that there was a statistically significant difference between conventional tillage techniques ($p<0.05$). Furthermore, Gajda & Przewloka (2012) reported that direct sowing and reduced tillage treatments produce 18-28% and 13-17% more DHA activity, respectively, than conventional tillage due to lowering the usage of plows. On the other hand, Moreno et al. (2021) reported that biological activity increased by creating favorable temperature and humidity conditions in no-tillage applications compared to traditional tillage.

Soil organic matter content is enhanced by reduced tillage practices and stubble incorporation (Gök & Coskan, 2002; Wang et al., 2020); therefore, suitable habitat for microbial activity appears (Kumar et al., 2021) leading to higher DHA activity. Furthermore, because the majority of microorganisms in the soil are chemoorganotrophic, using organic carbon as an energy and substrate source promotes enzyme activity in the soil (Nugis et al., 2016). The correlation analysis performed in this study revealed a positive correlation (r=0.428) between DHA and SOM (Figure 3). Existing literature points out an increase in DHA activity with a decrease in tillage density (Nath et al., 2021; Saurabh et al., 2021). According to Mikanová et al. (2009), the use of conservation tillage causes SOM to build on the soil surface, and the accumulated SOM serves as a source of energy and a substrate for the soil biota, increasing the activity of enzymes.

Among the soil cultivation techniques, CT-2, which involves burning the stubble, was found to have the lowest statistical group average throughout several sample dates, making it the soil cultivation technique with the lowest date average. The two conventional tillage techniques, CT-1 and CT-2, with their sole distinction being how stubble is managed, had the lowest results. Within CT-1 and CT-2, CT-1 has 15% more DHA than CT-2, which is still a significant difference. The primary reason for this is that stubble, which is a rich source of carbon and energy for soil microflora, has a favorable effect on soil microbial activity (Mrunalini et al., 2021). According to Das et al. (2019), incorporation of the stubble into the soil enhanced the physical characteristics of the soil increased the SOM content, and hence encouraged microbial activity.

DHA rose over the first six sample dates, peaked on February 8, 2021, and then fluctuated throughout the rest of the experiment. During this time, fertilization did not affect DHA levels. All tillage techniques appear to follow a similar trend (Table 3). The lowest DHA was measured on November 30, 2020. The low DHA at this date is probably related to both the low soil temperature (Table 4) and the damage to the microbiota due to the recent tillage. Wolinska & Stepniewska (2011) stated that DHA shows strong fluctuations depending on the seasons.

Table 3. The effect of long-term different tillage practices on dehydrogenase enzyme activity (µg TPF g_dry_soil^{-1} 24h^{-1})

Çizelge 3. Uzun süreli farklı toprak işleme uygulamalarının dehidrogenaz enzim aktivitesi üzerine etkisi (µg TPF g_dry_soil^{-1} 24h^{-1})

Soil Tillage Techniques[1]	Sampling Date					
	19.11.2020[6]	30.11.2020	11.12.2020	31.12.2020	13.01.2021	26.01.2021[7]
	p≤0.001	p≤0.001	p≤0.001	p≤0.001	p≤0.001	p≤0.001
CT-1	21.0[2] ±0.3[3] d[4] E[5]	15.8 ±1.2 c EF	33.3 ±1.4 c D	35.2 ±2.8 d D	36.8 ±0.9 d D	50.2 ±0.7 d BC
CT-2	17.7 ±0.5 e G	18.6 ±1.7 bc G	20.4 ±0.7 d FG	23.8 ±0.2 e E-G	29.7 ±2.1 e E	39.7 ±0.4 d CD
RT-1	30.4 ±1.2 c F	36.2 ±2.3 a EF	34.3 ±2.0 c F	47.6 ±0.7 c DE	54.7 ±1.7 c D	105.1 ±3.4 b B
RT-2	34.7 ±0.7 b FG	22.7 ±1.0 b G	33.4 ±1.8 c FG	71.0 ±3.0 ab DE	61.2 ±1.6 b E	133.3 ±7.0 a A
RT-3	32.5 ±0.9 bc F	36.4 ±0.3 a F	39.2 ±2.5 bc F	76.7 ±3.7 a D	60.7 ±0.5 b E	92.5 ±3.5 bc BC
NT	44.5 ±0.1 a GH	37.6 ±3.0 a H	47.5 ±1.4 a F-H	71.9 ±1.8 ab E	63.4 ±0.8 b EF	106.8 ±11.9 b CD
ST	43.5 ±1.9 a H	31.9 ±2.6 a I	41.9 ±3.1 ab H	67.3 ±1.4 b FG	74.5 ±1.0 a EF	86.3 ±0.6 c CD
Mean	32.0 E	28.4 E	35.7 E	56.2 D	54.4 D	87.7 B

Soil Tillage Techniques	Sampling Date						Mean
	8.02.2021	24.02.2021	31.03.2021[8]	16.04.2021	03.05.2021	26.05.2021	
	p≤0.001	p≤0.001	p≤0.001	p≤0.001	p≤0.001	p≤0.001	p≤0.001
CT-1	58.7 ±5.0 d A	48.6 ±3.2 d C	17.3 ±0.7 d E	60.4 ±3.6 c A	51.4 ±1.1 c BC	56.5 ±2.1 c AB	40.4 c
CT-2	68.0 ±4.7 d A	39.7 ±4.4 d CD	27.9 ±1.2 c EF	49.5 ±4.8 c B	47.5 ±4.0 c BC	38.4 ±1.2 d D	35.1 c
RT-1	122.9 ±8.0 bc A	79.6 ±8.1 c C	33.2 ±2.1 c F	89.1 ±3.6 b C	76.4 ±2.7 b C	80.6 ±5.6 ab C	65.8 b
RT-2	142.3 ±9.1 ab A	90.7 ±3.7 bc BC	42.4 ±1.1 b F	104.0 ±7.8 ab B	79.7 ±4.0 ab CD	94.9 ±4.0 a B	75.8 ab
RT-3	136.3 ±8.6 a-c A	80.7 ±1.8 c CD	56.2 ±4.2 a E	101.1 ±7.9 ab B	83.7 ±2.8 ab CD	88.6 ±8.5 a B-D	73.7 ab
NT	151.5 ±4.7 a A	133.7 ±8.8 a B	60.0 ±4.8 a E-G	118.7 ±8.7 a BC	90.0 ±4.1 a D	92.1 ±4.2 a D	84.8 a
ST	114.2 ±6.9 c A	101.8 ±1.7 b B	58.4 ±3.7 a G	91.8 ±2.7 b C	80.0 ±3.4 ab DE	71.5 ±2.8 b EF	71.9 ab
Mean	113.4 A	82.1 BC	42.2 DE	87.8 B	72.7 C	74.6 BC	

Means shown with the same letter are not statistically significant according to Duncan's test. The ANOVA value is p≤0.001 for sampling dates and is shown in the table for comparisons between treatments.

[1]: CT-1: Conventional tillage with wheat stubble incorporated, CT-2: Conventional tillage with burned-off stubble, RT-1: Heavy disc harrow reduced tillage, RT-2: Reduced tillage with a rototiller, RT-3: Reduced tillage with a rototiller and no-tillage practice combination, NT: Direct seeding without tillage, ST: Strategic tillage. [2]: It is the average of the samples in three plots. [3]: It is the standard error of the means. [4]: Lowercase letters give statistical comparisons among treatments. [5]: Uppercase letters give statistical comparison among sampling dates. [6]: It is the sampling performed after pre-planting fertilization. [7]: It is the first sampling performed after fertilization during the tillering period. [8]: It is the first sampling performed after fertilization during the bolting period.

In a study by Piotrowska & Długosz (2012), higher DHA was detected in April compared to August, and this situation increased with the growth of the wheat plant in April, polysaccharides, organic acids, etc. associated with the increase such as substrates. In addition, in the same study, it was stated that the highest DHA was observed in spring and the lowest in winter months in humid and slightly arid areas.

The maximum mean DHA throughout the wheat vegetation was obtained on February 8, 2021. When the DHA values among the applications were compared, the no-tillage application had the highest value, followed by the RT-2, RT-3, and ST applications. There was no statistically significant difference between these treatments. The lowest values were obtained from CT-1 and CT-2, which are conventional tillage methods.

The Effect of Long-Term Different Tillage Practices on Soil Temperature

Recorded soil temperature data are presented in Table 4. The soil temperature ranged from 7.9 to 25.1 °C, and the sampling days had a statistically significant ($p \leq 0.001$) effect on soil temperature. While the RT-3 application received the greatest value of 25.1 °C on the last sampling day before the harvest, the lowest value recorded from the CT-2 application was 7.9 °C on January 26, 2021. Based on the mean values, the temperature difference between the lowest and the highest value was 0.7 °C the lowest value was 13.5 °C in CT-2, and the highest value was 14.2 in RT-3. Although there was a 5% difference between the two practices those were not found to be statistically significant. Considering the averages of soil tillage practices on the sampling days, the highest average was 24.4 °C on the last sampling date on May 26, 2021; the lowest average was obtained on the sampling day on January 26, 2021, with 8.1 °C. These significant ($p \leq 0.001$) differences showed that the soil temperature on May 26, 2021 was 201%, higher than the sampling day on January 26, 2021. An increase in soil temperature was associated with elevated air temperature due to seasonal changes.

Soil temperature appeared to fluctuate in response to air temperature changes across different sampling times (data not included). However, these fluctuations were independent of tillage techniques employed, as no statistical differences were observed. This finding aligns with some previous research. For instance, Hou & Li (2019) reported no statistically significant impact of tillage practices on soil temperature. Their study also noted a trend of higher soil temperatures in no-tillage treatments compared to conventional tillage, no statistical difference was determined by Bogužas et al. (2018) between tillage practices in two of the six different measurement dates. In one measurement date, higher soil temperature was obtained in conventional tillage application compared to no-tillage. It has been stated that the reason for this situation is due to the faster drying and warming of the disturbed soil. According to Muñoz-Romero et al. (2015), both conventional and no-tillage treatments resulted in a comparable pattern of soil temperature. However, the findings revealed that at all measurement dates, conventional tillage operations had higher soil temperatures than no-tillage approaches, while the difference was not statistically significant. The soil absorbs more heat and has lesser thermal conductivity under traditional tillage than it does with no tillage, according to the study. Salem et al. (2015) in a related study, conventional tillage produced the greatest soil temperature. Researchers have shown that no-tillage methods result in increased soil moisture contents, and wet soils get warmer or cooler more slowly. Additionally, it was claimed that when no-tillage is used, more residues are left behind in the soil, and these residues reflect sunlight to prevent soil temperatures from rising.

Correlations Between Soil Properties

Pearson correlation test revealed that there was a statistically significant ($p \leq 0.01$) positive correlation between SOM content and soil respiration ($r = 0.182$) as well as SOM content and DHA ($r = 0.428$); however, no correlation was observed between SOM and soil temperature (Figure 3). A positive correlation was determined between soil respiration and both DHA ($r=0.240$) and soil temperature ($p \leq 0.01$). There was no statistically significant correlation between DHA and soil temperature.

CONCLUSION

Tillage techniques had impacts on the examined parameters in all sampling days, although the first sample date following the tillage practices showed the greatest variations. The lowest soil respiration and dehydrogenase enzyme activity were determined because of stubble burning. In the initial measurement dates, increasing tillage methods had a considerable impact on the biological characteristics of the soil, but this influence subsided in the last stages of wheat growth.

On the other hand, dehydrogenase enzyme activity and soil respiration decreased because of the intensifying soil tillage. Moreover, burning stubble had a detrimental effect on soil respiration and DHA activity as an essential biological indicator of the soil. Observed parameters revealed that the largest variability between sampling dates was due to air/soil temperature. Along with the rise in soil temperature, increases in microbial activity were observed.

Table 4. The effect of long-term different tillage practices on soil temperature (°C)

Çizelge 4. Uzun süreli farklı toprak işleme uygulamalarının toprak sıcaklığına etkisi (°C)

Soil Tillage Techniques[1]	Sampling Date					
	19.11.2020	**30.11.2020**	**11.12.2020**	**31.12.2020**	**13.01.2021**	**26.01.2021**
	p=0.316	p=0.467	p=0.763	p=0.833	p=0.843	p=0.616
CT-1	15.0[2] ±0.2[3] a[4] C[5]	11.0 ±0.4 a G	12.6 ±0.3 a F	9.1 ±0.7 a H	12.3 ±0.2 a F	8.0 ±0.1 a I
CT-2	14.9 ±0.2 a C	10.9 ±0.3 a F	12.4 ±0.2 a E	9.1 ±0.4 a G	12.4 ±0.1 a E	7.9 ±0.0 a H
RT-1	14.5 ±0.1 a C	10.7 ±0.4 a E	12.6 ±0.2 a D	9.0 ±0.5 a F	12.3 ±0.1 a D	8.1 ±0.1 a G
RT-2	16.0 ±0.8 a C	11.3 ±0.2 a G	12.8 ±0.2 a EF	9.7 ±0.4 a H	12.4 ±0.1 a GF	8.1 ±0.0 a I
RT-3	16.3 ±0.7 a C	11.4 ±0.4 a G	12.9 ±0.1 a F	9.8 ±0.4 a H	12.4 ±0.0 a F	8.2 ±0.1 a I
NT	15.9 ±0.8 a C	11.6 ±0.4 a G	12.8 ±0.2 a EF	9.7 ±0.4 a H	12.4 ±0.0 a FG	8.2 ±0.0 a I
ST	15.9 ±0.8 a C	11.6 ±0.4 a G	12.7 ±0.3 a E-G	9.6 ±0.7 a H	12.3 ±0.1 a FG	8.1 ±0.1 a I
Mean	15.5 C	11.2 H	12.7 FG	9.4 I	12.4 G	8.1 J

Soil Tillage Techniques	Sampling Date						Mean
	08.02.2021	**24.02.2021**	**31.03.2021**	**16.04.2021**	**03.05.2021**	**26.05.2021**	
	p=0.032	p=0.144	p=0.456	p=0.532	p=0.954	p=0.126	p=0.997
CT-1	12.8 ±0.1 b EF	9.0 ±0.2 ab H	14.3 ±0.5 a CD	13.8 ±0.2 a DE	21.8 ±0.1 a B	24.3 ±0.3 ab A	13.7 a
CT-2	12.8 ±0.1 b E	8.7 ±0.1 b GH	13.7 ±0.4 a D	13.7 ±0.3 a D	22.0 ±0.4 a B	23.7 ±0.0 b A	13.5 a
RT-1	13.0 ±0.2 b D	9.0 ±0.2 ab F	13.9 ±0.2 a C	14.1 ±0.3 a C	22.1 ±0.3 a B	24.1 ±0.3 ab A	13.6 a
RT-2	13.1 ±0.1 ab EF	9.2 ±0.2 a HI	14.9 ±0.9 a CD	14.1 ±0.4 a DE	22.0 ±0.4 a B	25.0 ±0.7 a A	14.1 a
RT-3	13.3 ±0.0 a EF	9.3 ±0.1 a H	15.1 ±0.5 a D	14.2 ±0.1 a DE	22.3 ±0.4 a B	25.1 ±0.3 a A	14.2 a
NT	13.0 ±0.1 b EF	9.2 ±0.1 a H	14.6 ±0.5 a D	13.8 ±0.1 a DE	21.9 ±0.4 a B	24.5 ±0.1 ab A	14.0 a
ST	13.0 ±0.1 b EF	9.1 ±0.1 ab HI	14.4 ±0.3 a D	13.7 ±0.1 a DE	22.1 ±0.2 a B	24.3 ±0.3 ab A	13.9 a
Mean	13.0 F	9.1 I	14.4 D	13.9 E	22.0 B	24.4 A	

Means shown with the same letter are not statistically significant according to Duncan's test. The ANOVA value is $p \leq 0.001$ for sampling dates and shown in the table for comparisons between treatments.

[1]: CT-1: Conventional tillage with wheat stubble incorporated, CT-2: Conventional tillage with burned-off stubble, RT-1: Heavy disc harrow reduced tillage, RT-2: Reduced tillage with a rototiller, RT-3: Reduced tillage with a rototiller and no-tillage practice combination, NT: Direct seeding without tillage, ST: Strategic tillage. [2]: It is the average of the samples in three plots. [3]: It is the standard error of the means. [4]: Lowercase letters give statistical comparison among treatments. [5]: Uppercase letters give statistical comparison among sampling dates.

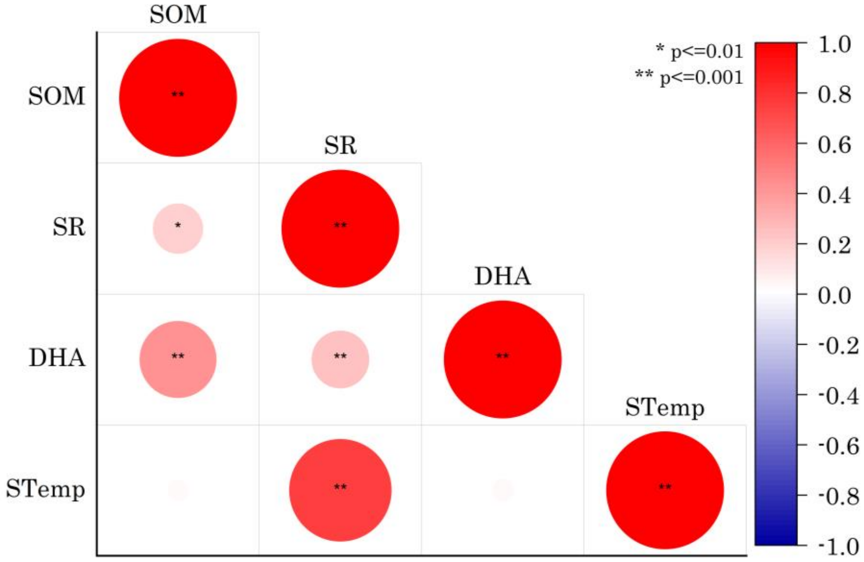

Figure 3. Pearson correlation test between soil organic matter (SOM), soil respiration (SR), dehydrogenase enzyme activity (DHA), and soil temperature (STemp)

Şekil 3. Toprak organik maddesi (SOM), toprak solunumu (SR), dehidrogenaz enzim aktivitesi (DHA) ve toprak sıcaklığı (STemp) arasındaki Pearson korelasyon testi

Consequently, conservation tillage practices are the most ideal tillage practices in terms of the biological qualities of the soil when all the above findings are assessed together. Therefore, further research is required in which physical, chemical, and biological properties are evaluated together to find out the impact of long-term different soil tillage practices in terms of sustainable and ecological agriculture. The sustainability of agricultural production in the area will also be improved by deep looking into the long-term consequences of various tillage systems under various plant rotations as well as in various climate and soil conditions.

THANKS

This paper was derived from a master thesis with a similar title and was funded by Çukurova University Scientific Research Projects [FYL-2021-13511]. We would like to thank Prof. Dr. Ali COŞKAN for his language support for the article. We also thank Prof. Dr. Hayriye İBRİKÇİ for reviewing the paper. We would also like to thank the anonymous reviewers who contributed to our article with their valuable suggestions.

Contribution Rate Statement Summary of Researchers

The authors declare that they have contributed equally to the article.

Conflict of Interest Statement

The authors of the article declare that there is no conflict of interest between them.

REFERENCES

Akbolat, D., Evrendilek, F., Coskan, A., & Ekinci, K. (2009). Quantifying soil respiration in response to short-term tillage practices: a case study in southern Turkey. *Acta Agriculturae Scandinavica Section B-Soil and Plant Science*, *59*(1), 50-56. https://doi.org/10.1080/09064710701833202

Alkorta, I., Aizpurua, A., Riga, P., Albizu, I., Amézaga, I., & Garbisu, C. (2003). Soil enzyme activities as biological indicators of soil health. *Reviews on environmental health*, *18*(1), 65-73.

AMS. (2021). *General Directorate of State Meteorology Affairs, Adana Meteorology Station (AMS)* https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?m=ADANA

Bilen, S., Çelik, A., & Altikat, S. (2010). Effects of strip and full-width tillage on soil carbon IV oxide-carbon (CO-C) fluxes and on bacterial and fungal populations in sunflower. *African Journal of Biotechnology*, *9*(38), 6312-6319.

Bilim, H., & Korucu, T. (2016). Antepfıstığında Toprak İşleme Yöntemlerinin Yabancı Ot Yoğunluğu ve Ürün Verimine Etkisi. *KSÜ Doğa Bilimleri Dergisi*, *19*(1), 32-36.

Bogužas, V., Sinkevičienė, A., Romaneckas, K., Steponavičienė, V., Skinulienė, L., & Butkevičienė, L. M. (2018). The impact of tillage intensity and meteorological conditions on soil temperature, moisture content, and CO 2 efflux in maize and spring barley cultivation. *Zemdirbyste-Agriculture*, *105*(4), 1-10.

Buragienė, S., Šarauskis, E., Romaneckas, K., Adamavičienė, A., Kriaučiūnienė, Z., Avižienytė, D., Marozas, V., & Naujokienė, V. (2019). Relationship between CO2 emissions and soil properties of differently tilled soils. *Science of the Total Environment*, *662*, 786-795.

Celik, I., Barut, Z. B., Ortas, I., Gok, M., Demirbas, A., Tulun, Y., & Akpinar, C. (2011). Impacts of different tillage practices on some soil microbiological properties and crop yield under semi-arid Mediterranean conditions. *International Journal of Plant Production*, *5*(3), 237-254.

Celik, I., Günal, H., Acar, M., Gök, M., Barut, Z. B., & Pamiralan, H. (2017). Long-term tillage and residue management effect on soil compaction and nitrate leaching in a Typic Haploxerert soil. *International Journal of Plant Production*, *11*(1), 131-149.

Çelik, I., Günal, H., Acir, N., Barut, Z. B., & Budak, M. (2021). Soil quality assessment to compare tillage systems in Cukurova Plain, Turkey. *Soil & Tillage Research*, *208*, 104892. https://doi.org/10.1016/j.still.2020.104892

Chen, H. Q., Hou, R. X., Gong, Y. S., Li, H. W., Fan, M. S., & Kuzyakov, Y. (2009). Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China. *Soil & Tillage Research*, *106*(1), 85-94. https://doi.org/10.1016/j.still.2009.09.009

Cooper, R. J., Hama-Aziz, Z. Q., Hiscock, K. M., Lovett, A. A., Vrain, E., Dugdale, S. J., Sünnenberg, G., Dockerty, T., Hovesen, P., & Noble, L. (2020). Conservation tillage and soil health: Lessons from a 5-year UK farm trial (2013-2018). *Soil & Tillage Research*, *202*, 104648. https://doi.org/10.1016/j.still.2020.104648

Das, A., Lal, R., Patel, D. P., Idapuganti, R. G., Layek, J., Ngachan, S. V., Ghosh, P. K., Bordoloi, J., & Kumar, M. (2014). Effects of tillage and biomass on soil quality and productivity of lowland rice cultivation by small scale farmers in North Eastern India. *Soil & Tillage Research*, *143*, 50-58. https://doi.org/10.1016/j.still.2014.05.012

Das, A., Layek, J., Ramkrushna, G. I., Rangappa, K., Lal, R., Ghosh, P. K., Choudhury, B. U., Mandal, S., Ngangom, B., Dey, U., & Prakash, N. (2019). Effects of tillage and rice residue management practices on lentil root architecture, productivity and soil properties in India's Lower Himalayas. *Soil & Tillage Research*, *194*, 104313. https://doi.org/10.1016/j.still.2019.104313

Doran, J. W., & Parkin, T. B. (1997). Quantitative indicators of soil quality: a minimum data set. *Methods for assessing soil quality*, *49*, 25-37.

Du, K., Li, F., Qiao, Y., Leng, P., Li, Z., Ge, J., & Yang, G. (2021). Influence of no-tillage and precipitation pulse on continuous soil respiration of summer maize affected by soil water in the North China Plain. *Sci Total Environ*, *766*, 144384. https://doi.org/10.1016/j.scitotenv.2020.144384

Fiedler, S. R., Leinweber, P., Jurasinski, G., Eckhardt, K. U., & Glatzel, S. (2016). Tillage-induced short-term soil organic matter turnover and respiration. *Soil*, *2*(3), 475-486. https://doi.org/10.5194/soil-2-475-2016

Futa, B., Kraska, P., Andruszczak, S., Gierasimiuk, P., & Jaroszuk-Sierocinska, M. (2021). Impact of Subsurface Application of Compound Mineral Fertilizer on Soil Enzymatic Activity under Reduced Tillage. *Agronomy-Basel*, *11*(11), 2213. https://doi.org/10.3390/agronomy11112213

Gajda, A. M., & Przewloka, B. (2012). Soil biological activity as affected by tillage intensity. *International Agrophysics*, *26*(1), 15-23. https://doi.org/10.2478/v10247-012-0003-0

Gök, M., & Coskan, A. (2002). *Sürdürülebilir ve organik tarımda biyolojik gübreleme* GAP I. Tarım Kongresi, Ankara.

Gök, M., Coskan, A., Onaç, I., Sağlamtimur, T., Tansı, V., Karip, B., & İnal, İ. (1999). Organik Gübrelemenin Toprakta N-Mineralizasyonuna, Denitrifikasyonla Azot Kaybına ve Mikrobiyel Aktiviteye Etkisi. *GAP I. Tarım Kongresi Bildiri Kitabı*, *2*, 971-978.

Hou, X. Q., & Li, R. (2019). Interactive effects of autumn tillage with mulching on soil temperature, productivity and water use efficiency of rainfed potato in loess plateau of China. *Agricultural Water Management*, *224*, 105747. https://doi.org/10.1016/j.agwat.2019.105747

IUSS. (2014). *World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps*.

Kandeler, E. (1996). *Organic matter by wet combustion*. Springer: Berlin. https://doi.org/10.1007/978-3-642-60966-4_29

Köller, K. (2003). Conservation tillage-technical, ecological and economic aspects. Conservation Tillage and Direct Seeding Workshop, İzmir,

Kumar, M., Mitra, S., Mazumdar, S. P., Majumdar, B., Saha, A. R., Singh, S. R., Pramanick, B., Gaber, A., Alsanie, W. F., & Hossain, A. (2021). Improvement of Soil Health and System Productivity through Crop Diversification and Residue Incorporation under Jute-Based Different Cropping Systems. *Agronomy-Basel*, *11*(8), 1622. https://doi.org/10.3390/agronomy11081622

Li, Y., Li, Z., Cui, S., Liang, G. P., & Zhang, Q. P. (2021). Microbial-derived carbon components are critical for enhancing soil organic carbon in no-tillage croplands: A global perspective. *Soil & Tillage Research*, *205*, 104758. https://doi.org/10.1016/j.still.2020.104758

Mijangos, I., Pérez, R., Albizu, I., & Garbisu, C. (2006). Effects of fertilization and tillage on soil biological parameters. *Enzyme and Microbial Technology*, *40*(1), 100-106. https://doi.org/10.1016/j.enzmictec.2005.10.043

Mikanová, O., Javurek, M., Simon, T., Friedlová, M., & Vach, M. (2009). The effect of tillage systems on some microbial characteristics. *Soil & Tillage Research*, *105*(1), 72-76. https://doi.org/10.1016/j.still.2009.05.010

Mirzavand, J., Asadi-Rahmani, H., & Moradi-Talebbeigi, R. (2022). Biological indicators of soil quality under conventional, reduced, and no-tillage systems. *Archives of Agronomy and Soil Science*, *68*(3), 311-324.

Moraru, P. I., & Rusu, T. (2012). Effect of tillage systems on soil moisture, soil temperature, soil respiration and production of wheat, maize and soybean crops. *Journal of Food Agriculture & Environment*, *10*(2), 445-448.

Moreno, M. V., Biganzoli, F., Casas, C., Manso, L., Moreira, E., & Silvestro, L. B. (2021). Changes in soil biological properties in different management and tillage systems in petrocalcic argiudoll. *Journal of the Saudi Society of Agricultural Sciences*, *20*(2), 75-80.

Mrunalini, K., Jayaraman, S., Srinivasa Rao, C., Praharaj, C., Singh, N., & Patra, A. (2021). Impact of Conservation Agriculture and Residue Management on Soil Properties, Crop Productivity Under Pulse-Based Cropping Systems in Central India. *Conservation Agriculture: A Sustainable Approach for Soil Health and Food Security: Conservation Agriculture for Sustainable Agriculture*, 117-137.

Muñoz-Romero, V., Lopez-Bellido, L., & Lopez-Bellido, R. J. (2015). Effect of tillage system on soil temperature in a rainfed Mediterranean Vertisol. *International Agrophysics*, *29*(4).

Nath, C. P., Kumar, N., Das, K., Hazra, K. K., Praharaj, C. S., & Singh, N. P. (2021). Impact of variable tillage based residue management and legume based cropping for seven years on enzymes activity, soil quality index and crop productivity in rice ecology. *Environmental and Sustainability Indicators*, *10*, 100107. https://doi.org/10.1016/j.indic.2021.100107

Nugis, E., Edesi, L., Tamm, K., Kadaja, J., Akk, E., Viil, P., & Ilumäe, E. (2016). Response of soil physical properties and dehydrogenase activity to contrasting tillage systems. *Zemdirbyste-Agriculture*, *103*(2), 123-128. https://doi.org/10.13080/z-a.2016.103.016

Öhlinger, R. (1996a). *Soil respiration by titration.* Springer: Berlin. https://doi.org/10.1007/978-3-642-60966-4_6

Öhlinger, R. (1996b). *Dehydrogenase activity with the substrate TTC.* Springer: Berlin. https://doi.org/10.1007/978-3-642-60966-4_15

Piotrowska, A., & Dlugosz, J. (2012). Spatio-temporal variability of microbial biomass content and activities related to some physicochemical properties of. *Geoderma*, *173*, 199-208. https://doi.org/10.1016/j.geoderma.2011.12.014

Pu, C., Kan, Z., Liu, P., Qi, J., Zhao, X., & Zhang, H. (2019). Residue management induced changes in soil organic carbon and total nitrogen under different tillage practices in the North China Plain. *Journal of Integrative Agriculture*, *18*(6), 1337-1347.

Salem, H. M., Valero, C., Muñoz, M. A., Rodríguez, M. G., & Silva, L. L. (2015). Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield. *Geoderma*, *237*, 60-70. https://doi.org/10.1016/j.geoderma.2014.08.014

Saurabh, K., Rao, K. K., Mishra, J. S., Kumar, R., Poonia, S. P., Samal, S. K., Roy, H. S., Dubey, A. K., Choubey, A. K., Mondal, S., Bhatt, B. P., Verma, M., & Malik, R. K. (2021). Influence of tillage based crop establishment and residue management practices on soil quality indices and yield sustainability in rice-wheat cropping system of Eastern Indo-Gangetic Plains. *Soil Tillage Res*, *206*, 104841. https://doi.org/10.1016/j.still.2020.104841

Shakoor, A., Shahbaz, M., Farooq, T. H., Sahar, N. E., Shahzad, S. M., Altaf, M. M., & Ashraf, M. (2021). A global meta-analysis of greenhouse gases emission and crop yield under no-tillage as compared to conventional tillage. *Sci Total Environ*, *750*, 142299. https://doi.org/10.1016/j.scitotenv.2020.142299

Tang, H., Li, C., Xiao, X., Tang, W., Cheng, K., Pan, X., Wang, K., & Li, W. (2020). Soil physical and chemical quality as influenced by soil tillage managements under double cropping rice system of southern China. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, *70*(1), 14-23.

Tian, J., He, N. P., Hale, L., Niu, S. L., Yu, G. R., Liu, Y., Blagodatskaya, E., Kuzyakov, Y., Gao, Q., & Zhou, J. Z. (2018). Soil organic matter availability and climate drive latitudinal patterns in bacterial diversity from tropical to cold temperate forests. *Functional Ecology*, *32*(1), 61-70. https://doi.org/10.1111/1365-2435.12952

Valkama, E., Kunypiyaeva, G., Zhapayev, R., Karabayev, M., Zhusupbekov, E., Perego, A., Schillaci, C., Sacco, D., Moretti, B., & Grignani, C. (2020). Can conservation agriculture increase soil carbon sequestration? A modelling approach. *Geoderma*, *369*, 114298.

Van Eerd, L. L., Congreves, K. A., Hayes, A., Verhallen, A., & Hooker, D. C. (2014). Long-term tillage and crop rotation effects on soil quality, organic carbon, and total nitrogen. *Canadian Journal of Soil Science*, *94*(3), 303-315.

Wang, H., Wang, S., Yu, Q., Zhang, Y., Wang, R., Li, J., & Wang, X. (2020). No tillage increases soil organic carbon storage and decreases carbon dioxide emission in the crop residue-returned farming system. *J Environ Manage*, *261*, 110261. https://doi.org/10.1016/j.jenvman.2020.110261

Wang, M. R., Dungait, J. A. J., Wei, X. M., Ge, T. D., Hou, R. X., Ouyang, Z., Zhang, F. S., & Tian, J.

(2022). Long-term warming increased microbial carbon use efficiency and turnover rate under conservation tillage system. *Soil Biology & Biochemistry*, *172*, 108770. https://doi.org/10.1016/j.soilbio.2022.108770

Wani, O. A., Kumar, S., Hussain, N., Wani, A. I. A., Subhash, B., Parvej, A., Rashid, M., Popescu, S. M., & Mansoor, S. (2022). Multi-scale processes influencing global carbon storage and land-carbon-climate nexus: A critical review. *Pedosphere*.

Wolinska, A., & Stepniewska, Z. (2011). Microorganisms abundance and dehydrogenase activity as a consequence of soil reoxidation process. *Research Signpost: Kerala, India*, 111-143.

Yost, J. L., & Hartemink, A. E. (2019). Soil organic carbon in sandy soils: A review. *Advances in Agronomy, 158*, 217-310. https://doi.org/10.1016/bs.agron.2019.07.004

Zhang, X. F., Xin, X. L., Yang, W. L., Ding, S. J., Ren, G. C., Li, M. R., & Zhu, A. N. (2021). Soil respiration and net carbon flux response to long-term reduced/no-tillage with and without residues in a wheat-maize cropping system. *Soil & Tillage Research*, *214*, 105182. https://doi.org/10.1016/j.still.2021.105182

Zhang, Z. B., & Peng, X. H. (2021). Bio-tillage: A new perspective for sustainable agriculture. *Soil & Tillage Research*, *206*, 104844. https://doi.org/10.1016/j.still.2020.104844

Zhang, Z., & Peng, X. (2021). Bio-tillage: A new perspective for sustainable agriculture. *Soil and Tillage Research*, *206*, 104844. https://doi.org/10.1016/j.still.2020.104844