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Influence of Conventional and Minimum Tillage on Soil Aggregate Size Distribution and Aggregate-Associated Enzyme Activities in a Semi-Arid Region of Türkiye

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Abstract

Tillage practices influence soil structure and biological activity in semi-arid agroecosystems. This study aimed to determine how conventional tillage, minimum tillage for 5 years, and minimum tillage for 10 years affect soil aggregate size distribution and soil enzyme activities in a semi-arid region, and whether long-term reduction in tillage intensity improves soil structural and biological properties. Soil samples were collected from the 0–30 cm layer with three replicates under each tillage system. Soil texture, organic matter, pH, and electrical conductivity were determined, and aggregate size distribution was assessed using the dry-sieving method. Catalase, urease, and alkaline phosphatase activities were measured in different aggregate-size fractions. Results showed that tillage systems significantly affected both soil aggregate size distribution and enzyme activities ($p < 0.05$). Conventional tillage increased the proportion of macroaggregates (0.425–2.00 mm), whereas minimum tillage, particularly after 10 years, significantly increased the proportion of microaggregates (0.02–0.425 mm). Enzyme activities were significantly higher under minimum tillage than under conventional, with the highest catalase (69.62 ml O_2 3 min^{-1} g $soil^{-1}$), urease (5.81 µg N g $soil^{-1}$ h^{-1}), and alkaline phosphatase activities (53.94 µg p-nitrophenol g $soil^{-1}$ h^{-1}) recorded in the 10-year minimum tillage. Enzyme activities also varied significantly among aggregate-size classes. Findings demonstrate that long-term minimum tillage promotes the formation of microaggregates and enhances enzymatic activity, thereby improving soil structure, biological functioning, and overall soil quality. The study highlights reduced tillage as an effective and sustainable soil management strategy for semi-arid agricultural systems.

Keywords: Macroaggregates, microaggregates, conservation agriculture, soil enzymes, dryland farming.

INTRODUCTION

Soil is one of the most important natural resources on earth and plays a vital role in sustaining life. Since the beginning of human history, soil has been an indispensable element of agricultural production. From the past to the present, soil has been under intensive agricultural production in order to obtain more products from a unit area. However, intensive agriculture

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has caused degradation in soil properties. As a result of the degradation in soil properties, conservation soil management practices have begun to be used in agricultural production.

Tillage is one of the soil management practices that has been applied since the past. Conventional tillage used in the past and today, has some negative effects on soils such as disrupts soil aggregates, increases soil and water loss, as well as nutrient leaching, thus making the productivity of agricultural systems unsustainable (Huang et al., 2018; Liu et al., 2022a). As a result of the negative effects on soil properties in conventional tillage, conservation tillage methods have begun to be used in agricultural production. Conservation tillage methods include no-tillage, minimum (reduced) tillage (Blanco and Lal, 2008). Minimum tillage, one of the conservation tillage practices, has important benefits such as reducing surface runoff and soil erosion, improving soil structure and increasing soil aggregate stability (Blanco-Canqui and Ruis, 2018; Jia et al., 2020; Liu et al., 2022b).

Soil aggregates come together in different sizes and shapes with different binders to form the soil structure. Soil aggregates play different roles in preserving and providing soil organic matter, soil carbon or nutrients with different aggregate sizes. According to their aggregate sizes, they can be divided into microaggregates (< 0.25 mm) and macroaggregates (> 0.25 mm) (Six et al., 2004; Devine et al., 2014). It has been reported that some soil properties such as organic carbon, nutrients and enzymes change depending on the size of soil aggregates (Zhang et al., 2012; Wei et al., 2014; Wang et al., 2020; Liu et al., 2021; Erdel, 2022b; Liu et al., 2022b). Among agricultural practices, tillage has an effect on soil aggregates by affecting the size distribution and stability of soil aggregates (Tisdall and Oades, 1982; Hernandez-Hernandez and Lopez-Hernandez, 2002).

Soil enzymes play an important role in biological and biochemical processes, including the mineralization of organic matter and the recycling of macronutrients and micronutrients (Saha et al., 2008). Soil enzymes are very sensitive to changes in soil properties caused by soil management practices such as tillage, therefore they serve as good indicators in the soil (Roldan et al., 2005). Some researchers have reported that soil enzyme activities change with tillage practices (Erdel, 2022a; Erdel and Şimşek, 2023).

Despite the extensive body of research examining the effects of tillage practices on soil aggregation and enzyme activities, studies investigating the combined responses of soil aggregate size distribution and aggregate-associated enzyme activities remain relatively limited. Previous research has demonstrated that tillage can alter both soil structure and biological functioning; however, the extent to which these responses vary among aggregate-size fractions under different durations of minimum tillage is still not fully understood. This knowledge gap is particularly relevant in semi-arid soils, where low organic matter content and climatic constraints strongly influence soil physical and biological processes. In eastern Türkiye, where semi-arid conditions and intensive agricultural practices increase the risk of soil degradation, information on the interactions between soil aggregation and enzyme activities under long-term minimum tillage is scarce. Therefore, evaluating minimum tillage systems of different durations (5 and 10 years) provides an opportunity to assess both medium- and long-term effects of reduced soil disturbance on soil structural and biological properties. The novelty of the present study lies in the simultaneous assessment of soil aggregate size distribution and aggregate-associated enzyme activities under different durations of minimum tillage in a semi-arid agroecosystem of Türkiye.

The aim of the study is to evaluate the effects of conventional tillage and minimum tillage systems implemented for 5 and 10 years on (i) soil aggregate size distribution, (ii) soil enzyme activities (catalase, urease, and alkaline phosphatase), (iii) enzyme activity patterns within different aggregate-size fractions, and (iv) the relationships between soil aggregation and enzyme activities in a semi-arid region of Türkiye.

It was hypothesized that long-term minimum tillage would promote the formation of microaggregates and enhance soil enzyme activities compared with conventional tillage, reflecting improvements in soil aggregates and biological functioning.

MATERIAL AND METHODS

Study site

The experiment was designed in Igdır University Agricultural Research and Application Center, Turkey. The region has hot summers and mild winters due to its microclimatic conditions. The highest rainfall in the region falls in May and the lowest falls in August. In the region, the annual average rainfall is 260.3 mm, and the evaporation is 1094.9 mm. January is the coldest month is and July is the warmest (data of Turkish State Meteorological Service, 2025) and the elevation of the region is 850 m, the slope is 0-2%. According to the WRB system, soil is identified as a Calcaric Pantofluvic Fluvisol (Loamic, Aric, Densic; Simsek et al., 2019). Some soil properties are shown in Table 1.

Table 1. Results of some soil properties.

Tillage	Soil properties			
	Texture	SOM%	EC, µmhos cm^{-1}	pH
Conventional tillage	Clay loam	1.1±0.2	210±12	9.1±0.7
Minimum tillage (5 years)	Clay loam	1.25±0.3	158±41	9.01±0.5
Minimum tillage (10 years)	Clay loam	1.35±0.1	190±45	9.04±0.2

* SOM: soil organic matter; EC: electrical conductivity; pH: soil pH.

Experimental design

The study included three tillage systems: conventional tillage, minimum tillage for 5 years, and minimum tillage for 10 years. The experimental design was arranged in a completely randomized design (CRD) with three replications for each tillage system. Each treatment was represented by independent field plots. Each replication represented a separate field unit under the respective tillage system. A total of nine experimental units (3 tillage systems × 3 replicates) were included in the study. Within each unit, composite soil samples were taken to minimize spatial variability.

Soil sampling and analysis

Disturbed soil samples were collected randomly at all different tillage lands with three replicates at the depth of 0-30 cm soil layer for soil analysis in 2023.

Soil texture, organic matter, soil pH and electrical conductivity were determined in disturbed soil samples with three replicates. Soil texture, soil organic matter, pH and electrical conductivity was determined according to Gee and Bauder (1986), Walkley and Black (1934), McLean (1982) and Rhoades (1983), respectively.

Soil enzyme analyses were performed on fresh soil samples without air-drying. Immediately after aggregate separation, the samples were preserved under appropriate conditions (stored at +4°C.) and analyzed to avoid potential alterations in enzymatic activity associated with drying.

Aggregate size distribution was determined using the dry sieving method with six sieves (2, 1, 0.85, 0.425, 0.106, and 0.02 mm; Cammeraat and Imeson, 1998). Although six sieves were used, soil aggregates were subsequently grouped into five size fractions by combining adjacent sieve classes: 2.00–1.00 mm, 1.00–0.850 mm, 0.850–0.425 mm, 0.425–0.106 mm, and 0.106–0.02 mm. Soil samples (500 g) were air-dried at room temperature (20 °C) and shaken for 5 min at 50 Hz using a horizontal shaker (Retsch AS 200 basic, Haan, Germany). Each fraction was weighed to determine its proportional distribution.

Soil enzyme activities were determined for each aggregate size fraction using standard colorimetric and gasometric methods. Catalase activity was measured according to Beck (1971) based on the decomposition rate of hydrogen peroxide and expressed as ml O_2 released per g soil per 3 min. Urease activity was determined following Hoffmann and Teicher (1961) by measuring ammonium released from urea hydrolysis and expressed as µg N g^{-1} soil h^{-1}. Alkaline phosphatase activity was analyzed according to Hofmann and Hoffmann (1966) using p-nitrophenyl phosphate as substrate, and results were expressed as µg p-nitrophenol g^{-1} soil h^{-1}.

All enzyme analyses were performed on soil samples from each aggregate size fraction under standardized laboratory conditions. Measurements were conducted in three replicates for each treatment and aggregate class.

Statistical analysis

The data were analyzed using SPSS statistical software (SPSS Inc., USA). One-way analyses of variance (ANOVA) were applied separately for each tillage system (conventional tillage, minimum tillage for 5 years, and minimum tillage for 10 years) to evaluate their effects on each soil aggregate size distribution and soil enzyme activities. In addition, separate one-way ANOVAs were conducted within each aggregate size fraction to compare the effects of the different tillage systems. In the statistical model, the independent variable was tillage system, while the dependent variables included soil aggregate size distribution and enzyme activities (catalase, urease, and alkaline phosphatase). In addition, soil aggregate size classes were analyzed as a second factor when evaluating enzyme activities within aggregate fractions. When significant differences were detected ($p < 0.05$), means were separated using Duncan's multiple range test. Correlation analysis between soil aggregate size distribution and enzyme activities was performed using R statistical software.

RESULTS AND DISCUSSION

Aggregate size distribution

The distribution of aggregate sizes is shown in Table 2. Tillage intensity significantly affected soil aggregate distributions. This difference was observed across all aggregate size fractions. Among the soil tillage practices, the highest values in aggregate sizes of 1.00-0.850 and 0.850-0.425 mm were observed in conventional tillage while the lowest were in minimum till (10 years). However, for aggregate sizes of 0.425-0.106 mm and 0.106-0.02 mm, the highest values were observed in minimum till (10 years) and the lowest values in conventional tillage (Table 2). The results indicated that increasing tillage intensity increased the proportion of macroaggregates (1–0.425 mm), while reduced tillage promoted the formation of microaggregates (0.425–0.106 mm).

Contrary to the expectation that intensive tillage promotes larger aggregates, the present results indicate that conventional tillage was associated with a higher proportion of macro-aggregate-sized fractions. This apparent pattern should be interpreted in the context of temporary aggregation effects created immediately after mechanical disturbance, where fragmented soil particles can appear as larger unstable aggregates. However, these structures are generally weakly bound and more susceptible to breakdown, leading to a dominance of less stable aggregate fractions over time. In contrast, reduced tillage systems enhance the formation of stable micro-aggregates through the preservation of soil organic matter and reduced disruption of fungal hyphal networks and microbial binding agents, consistent with established aggregate turnover theory (Tisdall & Oades, 1982; Six et al., 2004).

When the tillage applications were evaluated, the highest proportion in conventional and minimum tillage (5 years) was found at 0.850-0.425 mm and the lowest was found at 0.106-0.02 mm aggregate size. However, the result is different in minimum tillage (10 years), the highest proportion was found at 0.425-0.106 mm and the lowest at 1.00-0.850 mm aggregate size (Figure 1).

Piazza et al. (2020) reported that minimum tillage increased micro aggregates, minimum tillage demonstrates a greater potential to improve soil structure through the stabilization of aggregates (Six et al., 2000a, 2004). Other researchers also determined that comparing no-tillage (NT) to conventional ploughing demonstrated a significant increase in microaggregates and a corresponding decrease in macroaggregates, highlighting the disruptive effect of tillage on soil structure (Six et al., 2000b; Mikha et al., 2013; Sheehy et al., 2015).

Table 2. Effect of tillage systems on the weight distribution (%) of soil aggregate size fractions.

Soil	Aggregate size classes (mm)				
	2.00-1.00	1.00-0.850	0.850-0.425	0.425-0.106	0.106-0.02
Conventional till	32.10±0.88Ab	10.29±0.84Ac	48.53±0.62Aa	9.44±0.12Cc	0.35±0.16Bd
Minimum till (5 years)	20.65±0.73Bc	7.47±0.19Bd	49.32±0.73Aa	23.08±0.48Bb	0.06±0.07Be
Minimum till (10 years)	13.31±0.73Cc	4.79±0.21Ce	29.43±0.68Bb	44.77±0.64Aa	7.78±0.22Ad

* Lowercase letters were used for horizontal evaluations, and uppercase letters for vertical evaluations. Differences between means were tested at $p<0.05$ significance level.

Xian-Qing et al. (2013) detected that macroaggregates (>0.25 mm) were reduced with conventioanl tillage. This is likely due to the mechanical disruption of macroaggregates caused by frequent tillage operations (Chen et al., 2007).

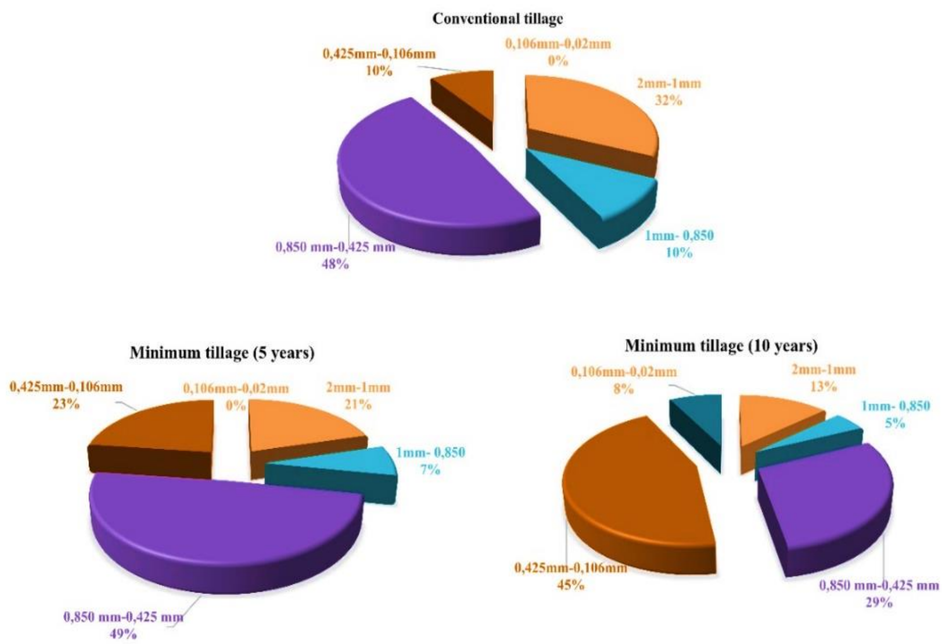

Figure 1. Effect of different tillage systems (conventional tillage and minimum tillage for 5 and 10 years) on soil aggregate size distribution

Catalase activity

Results showed that statistically significant differences were determined in catalase activity according to both tillage method and aggregate size distribution, however, no significant relationship was found between the aggregate size distribution and catalase activity (Table 3, Figure 5). According to the statistical analysis, the highest activity was determined at 0.425-0.106 mm aggregate size for both conventional and minimum tillage (5 years). But in minimum tillage (10 years), the highest activity was found at 0.850-0.425 mm (Figure 2). Consistent with the results, Erdel (2022) determined that the highest catalase activity was at 0.850-0.425 mm aggregate size. When the soil tillage systems were evaluated, the highest activity (69.62 ml O_2 3 min $^{-1}$ g soil $^{-1}$) was detected in minimum tillage (10 years). Kabiri et al. (2016) reported that tillage affected soil catalase activity but they also detected that the change in catalase activity was depending on sampling year. Besides, Jin et al. (2009) found higher catalase activity in reduced tillage.

Table 3. Catalase activity (ml O_2 3 min^{-1} g $soil^{-1}$) in different soil aggregate size fractions under tillage systems.

Tillage system	Aggregate size classes (mm)					
	2.00-1.00	**1.00-0.850**	**0.850-0.425**	**0.425-0.106**	**0.106-0.02**	Means
Conventional till	53.20±0.95Aa	42.79±1.40Cc	48.33±1.78Cb	53.77±1.19Ca	32.84±1.58Bd	46.19±8.11B
Minimum till (5 years)	45.27±0.45Cc	52.07±1.62Bb	62.64±1.21Ba	63.47±1.67Ba	-*	44.69±24.19B
Minimum till (10 years)	47.53±0.62Be	71.80±0.68Ad	80.25±0.69Aa	73.18±0.81Ac	75.36±0.85Ab	69.62±11.83A

* Lowercase letters were used for horizontal evaluations, and uppercase letters for vertical evaluations. Differences between means were tested at $p<0.05$ significance level; Catalase activity analysis was not conducted for the corresponding aggregate size fraction because the available soil quantity was insufficient and the missing value was not treated as zero when calculating the treatment means.

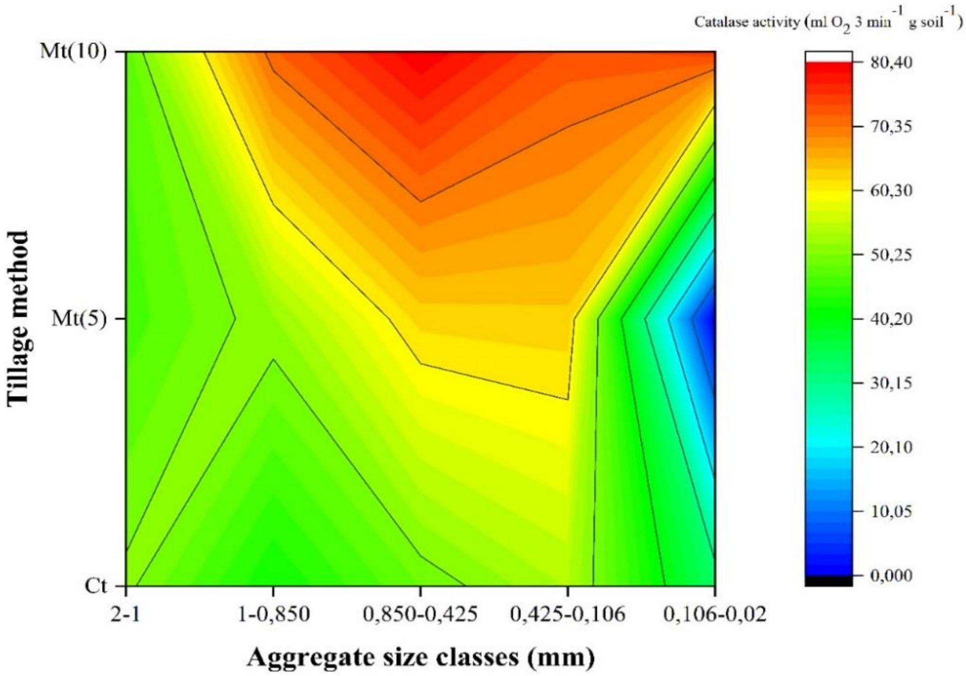

Figure 2. Effect of tillage systems on catalase activity across different soil aggregate size fractions (Ct, conventional tillage; Mt (5), minimum tillage 5 years; Mt (10), minimum tillage 10 years).

Urease activity

Soil urease activity varied significantly by both tillage systems and aggregate size classes (Table 4). However no significant relationship was found between the aggregate size distribution and urease activity (Figure 5). Among the soil tillage treatments, the highest urease activity was observed in minimum tillage (10 years), while the lowest activity was observed in conventional till (Figure 3). In agreement with the findings, Kabiri et al. (2016) and Mohammadi et al. (2013) reported that reduced tillage increased soil urease activity. When the aggregate size distributions were evaluated; the highest urease activity was observed in 0.850-0.425 mm for conventional and minimum tillage (5 years), 2.00-1.00 mm for minimum tillage (10 years). In line with the results, Erdel (2022) determined that the highest urease activity was at 0.850-0.425 mm aggregate size.

Table 4. Urease activity (µg N g soil^{-1} h^{-1}) in soil aggregate size fractions under conventional and minimum tillage systems.

Tillage system	Aggregate size classes (mm)					
	2.00-1.00	**1.00-0.850**	**0.850-0.425**	**0.425-0.106**	**0.106-0.02**	Means
Conventional till	3.02±0.01Cc	3.12±0.04Cb	3.36±0.05Ca	1.84±0.02Ce	1.92±0.03Bd	2.65±0.66C
Minimum till (5 years)	4.51±0.08Bd	5.97±0.10Ab	6.17±0.07Ba	5.18±0.07Ac	-*	4.36±2.34B
Minimum till (10 years)	8.44±0.06Aa	5.43±0.03Bc	8.34±0.04Ab	3.82±0.03Bd	3.03±0.06Ae	5.81±2.32A

* Lowercase letters were used for horizontal evaluations, and uppercase letters for vertical evaluations. Differences between means were tested at $p<0.05$ significance level; Urease activity analysis was not conducted for the corresponding aggregate size fraction because the available soil quantity was insufficient and the missing value was not treated as zero when calculating the treatment means.

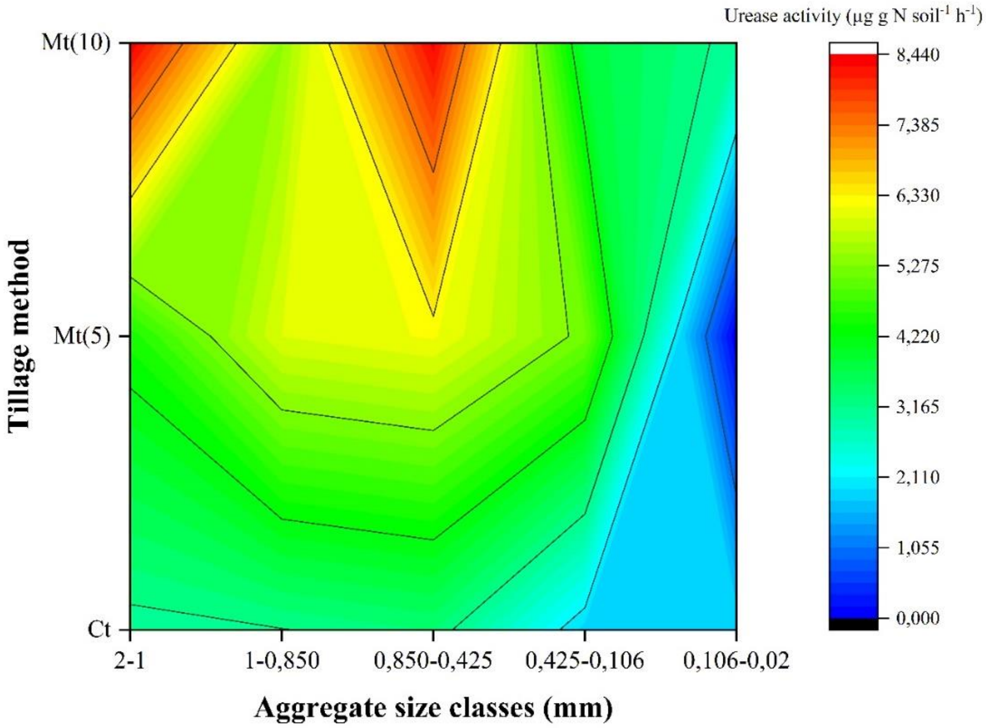

Figure 3. Variation in soil urease activity under conventional tillage and minimum tillage (5 and 10 years) across soil aggregate size classes (Ct, conventional tillage; Mt(5), minimum tillage 5 years; Mt(10), minimum tillage 10 years).

Phosphatase activity

Soil alkaline phosphatase activity affected significantly by tillage systems and varied significantly by soil aggregate size classes (Table 5). Moreover no significant relationship was found between the aggregate size distribution and alkaline phosphatase activity (Figure 5).

Table 5. Alkaline phosphatase activity (µg p-nitrophenol g soil^{-1} h^{-1}) in different soil aggregate size fractions under tillage treatments

Tillage system	Aggregate size classes (mm)					
	2.00-1.00	**1.00-0.850**	**0.850-0.425**	**0.425-0.106**	**0.106-0.02**	**Means**
Conventional till	37.36±2.79Cb	35.86±0.72Cb	35.84±0.41Cb	41.24±1.70Ba	25.01±0.45Bc	35.06±5.73B
Minimum till (5 years)	42.59±2.02Bb	38.93±1.17Bc	48.99±1.13Ba	48.40±0.77Aa	-*	35.78±18.94B

Minimum till (10 years)	56.93±0.50Ab	58.70±0.48Aa	55.27±1.02Ac	50.53±0.58Ad	48.27±0.57Ae	53.94±4.10A

* Lowercase letters were used for horizontal evaluations, and uppercase letters for vertical evaluations. Differences between means were tested at $p<0.05$ significance level; Alkaline phosphatase activity analysis was not conducted for the corresponding aggregate size fraction because the available soil quantity was insufficient and the missing value was not treated as zero when calculating the treatment means.

Among the tillage practices; the highest phosphatase activity was observed in minimum tillage (10 years), while the lowest activity was observed in conventional till (Figure 4). In agreement with the results, Kabiri et al. (2016) and Mohammadi et al. (2013) determined that reduced tillage increased soil alkaline phosphatase activity. When soil aggregate size distributions are assessed, the highest phosphatase activity was observed in 0.425-0.106 mm for conventional, in 0.850-0.425 mm for minimum tillage (5 years) and 1.00-0.850 mm for minimum tillage (10 years).

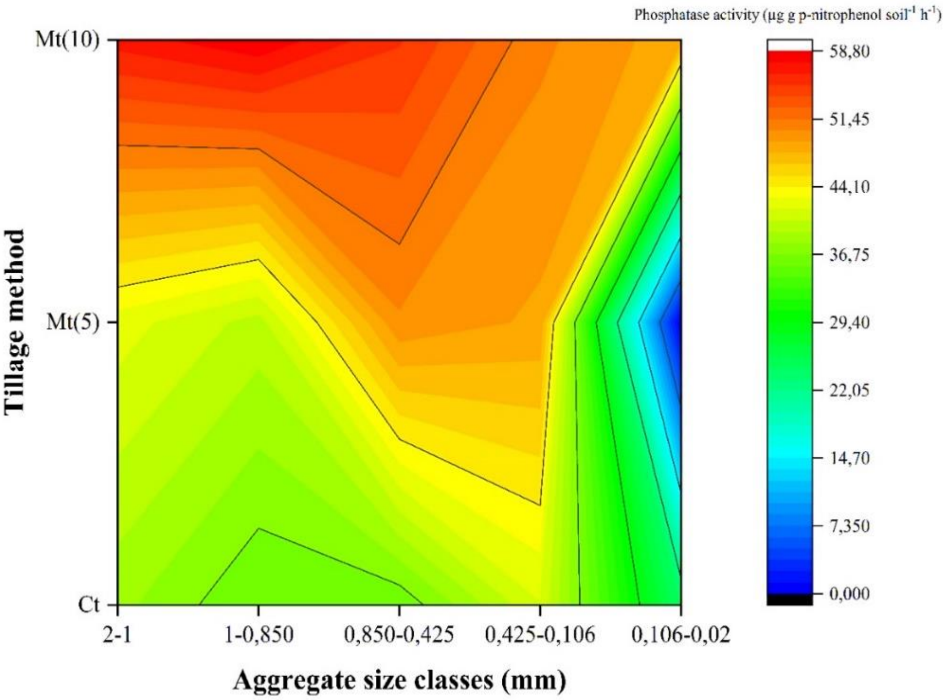

Figure 4. Effects of tillage systems on alkaline phosphatase activity in different soil aggregate size fractions (Ct, conventional tillage; Mt(5), minimum tillage 5 years; Mt(10), minimum tillage 10 years).

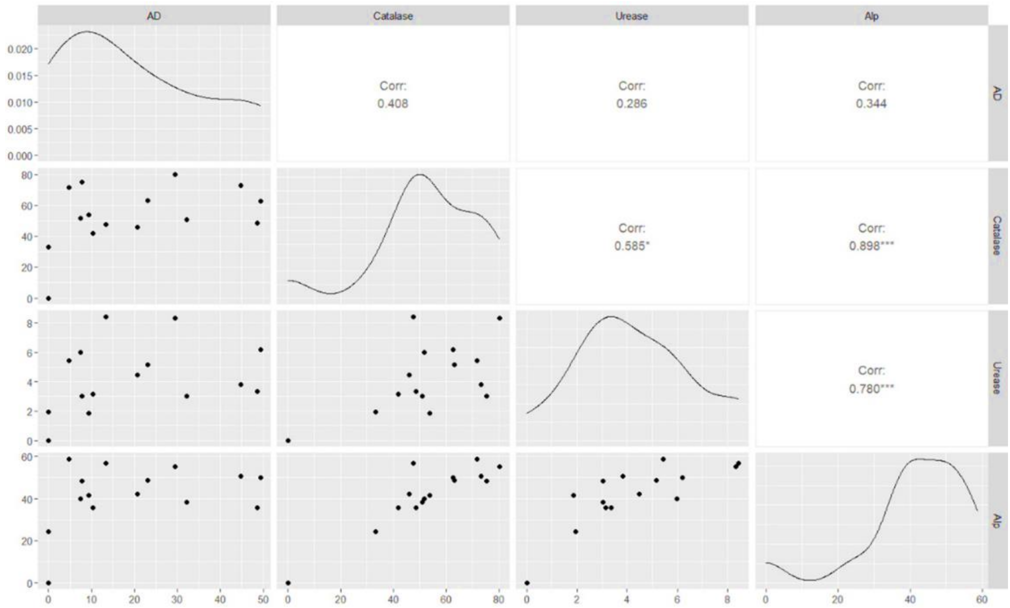

Figure 5. Correlation analysis between soil aggregate size distribution and alkaline phosphatase activity under different tillage systems (AD, aggregate size distribution; Alp, alkaline phosphatase activity).

The reduction in tillage intensity had a generally positive effect on all enzymes in the bulk soil, increasing their activities at both soil depths. Similarly, positive effects on soil enzymes due to reduced or no tillage have been widely reported (Lagomarsino et al., 2009; Nivelle et al., 2016; Zuber and Villamil, 2016). The higher enzyme activity under minimum tillage may be due to an increased presence of labile compounds through the decomposition of residues (Cotrufo et al., 2013; Nivelle et al., 2016). The highest enzyme activities in macroaggregates may be attributed to the macroaggregates, which contain higher levels of soil organic matter and organic carbon, as well as a greater return of organic carbon compared to microaggregates (Mendes et al., 1999; Oades, and Waters, 1991).

Although the present study demonstrated significant effects of tillage systems on soil aggregate size distribution and enzyme activities, the mechanisms underlying these responses were not directly investigated. Soil labile carbon fractions, particularly permanganate oxidizable carbon (POXC), are known to strongly influence microbial activity and soil enzyme production. Since POXC was not measured in the current study, its contribution to the observed changes in enzyme activities could not be evaluated. Future studies incorporating POXC and other soil carbon fractions would provide a more comprehensive understanding of the relationships among tillage practices, soil aggregation, carbon dynamics, and enzyme activities.

CONCLUSIONS

This study demonstrated that tillage systems significantly influence soil aggregate size distribution and soil enzyme activities in a semi-arid agroecosystem. Conventional tillage increased the proportion of macroaggregates, whereas long-term minimum tillage (10 years) enhanced the formation of microaggregates and significantly increased the activities of catalase, urease, and alkaline phosphatase. Enzyme activities were also strongly dependent on aggregate size fractions, indicating a close relationship between soil structural organization and biological activity. Overall, minimum tillage promoted higher soil biological activity compared to conventional tillage, with the greatest enzyme activities generally observed in finer aggregate fractions (0.106–1.00 mm). These findings suggest that reduced soil disturbance enhances both soil aggregates and biochemical functioning, thereby improving soil quality in semi-arid environments. This study has certain limitations, including its conduction at a single experimental site and over a limited sampling period, which may restrict the broader applicability of the results across different soil and climatic conditions. Additionally, only a limited set of soil enzyme activities were evaluated, while other microbial and functional soil quality indicators were not considered. Future research should focus on multi-site and long-term experiments to improve the generalizability of the findings. Further studies incorporating microbial community structure, soil carbon fractions, and greenhouse gas emissions would provide a more comprehensive understanding of the impacts of tillage systems on soil ecosystem functioning.

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