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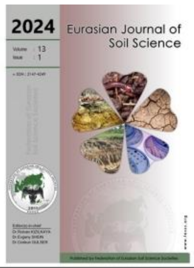

Impact of tillage and crop rotations on soil organic matter content in Northern Kazakhstan's chernozem soils: A 10-year study (2011-2021)

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Abstract

This extensive 10-year study conducted in Northern Kazakhstan investigates the intricate relationship between soil management techniques, crop rotations, and soil organic matter (SOM) content in Chernozem soils, an essential agricultural resource in the region. The experiments were established at the Karabalyk Agricultural Experimental Station, characterized by a arid continental climate. The study systematically examined the impact of two primary soil management techniques, conventional tillage (CT) and no-tillage (NT), in combination with various crop rotations. The crop rotations tested included grain-fallow rotations, fruit-exchange crop rotations, and an eight-field fruit-exchange crop rotation. The results provide valuable insights into the sustainable management of Chernozem soils in arid conditions, underscoring the role of crop rotation strategies in preserving SOM content. The findings reveal that among the crop rotations tested, the eight-field fruit-exchange crop rotation exhibited the most favorable outcomes for SOM preservation. This rotation helped maintain relatively stable SOM levels over the 10-year study period, contributing to soil health and fertility. In the context of the region's arid climate, the choice of soil management technique (CT or NT) had a limited impact on SOM content. The stability of SOM levels across diverse crop rotations and years highlights the dominant influence of crop management practices in this distinctive agricultural environment. This research serves as a valuable reference for tailored approaches to ensure soil health and organic matter preservation in the unique conditions of Northern Kazakhstan. It promotes the adoption of diversified crop rotations, with particular emphasis on the effectiveness of the eight-field fruit-exchange crop rotation, as a powerful strategy to mitigate organic matter loss, enhance soil quality, and optimize soil fertility in arid agricultural landscapes. The insights gained from this study are vital for sustainable land management in the region and underscore the importance of region-specific, holistic investigations to guide effective agricultural practices. The findings offer a solid foundation for the development of strategies that address soil health and safeguard the integrity of essential soil resources in these unique environments. The study conducted at the Karabalyk Agricultural Experimental Station in Northern Kazakhstan between 2011 and 2021 provides critical insights into the relationship between soil management techniques, crop rotations, and SOM content in Chernozem soils. The research suggests that diversified crop rotations, particularly the eight-field fruit-exchange crop rotation, represent a promising approach for mitigating organic matter loss and enhancing soil quality in arid regions.

Keywords: Chernozem soils, soil organic matter, soil management techniques, crop rotations, tillage.

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Introduction

Soil, an indispensable natural resource, serves as the lifeblood of agricultural production, food security, and environmental equilibrium, particularly in regions characterized by arable landscapes like Kazakhstan. In such areas, the preservation of soil fertility and the sustainable management of this vital resource stand as pivotal drivers for agricultural advancement (Saparov, 2014). Central to the concept of soil fertility is the soil organic matter (SOM) content, a fundamental determinant of crop productivity and soil quality (Kızılkaya and Hepşen Türkey, 2014; Gülser et al., 2015; İslamzade et al., 2023).

Traditional agricultural practices, while undeniably essential for food production, often carry the unintended consequences of water scarcity, soil erosion, and a reduction in soil fertility (Montgomery, 2007; Quinton et al., 2010). Recognizing these challenges, there has been a significant shift towards the adoption of conservation agriculture, an approach aimed at enhancing the sustainability of agroecosystems (Farooq et al., 2011; Zhang et al., 2016). Conservation agriculture introduces diversity into the cultivation landscape, favoring crop rotation over the continuous cultivation of a single crop species. This approach contributes to the conservation of soil organic carbon (West and Post, 2002; Tiemann et al., 2015). Furthermore, conservation tillage practices, defined by the retention of at least 30% of soil surface cover through crop residues, mitigate physical disturbances to the soil structure and can aid in the restoration of soil fertility (Madejon et al., 2009; Liu et al., 2014).

Understanding the intricacies of how crop rotation and conservation tillage impact soil properties has been the subject of extensive field and incubation studies (Bünemann et al., 2004; Jacinthe and Lal, 2005; Madari et al., 2005; Salvo et al., 2010; Xu et al., 2013; Suleimenova et al., 2019; Ospanbayev et al., 2023). Collectively, these studies have presented a multifaceted view of the relationship between these practices and soil organic carbon. While some research indicates that conservation practices promote the accumulation of organic carbon in the surface layer of soil, primarily due to crop residue retention (Mazzoncini et al., 2016; VandenBygaart et al., 2010), others have reported less pronounced effects or no significant differences compared to conventional tillage and monoculture approaches (Angers et al., 1997; Barbera et al., 2012; Chatterjee et al., 2016; Sombrero and de Benito, 2010). Consequently, the dynamics of soil organic carbon content in response to crop rotation and various tillage practices remain intricate and warrant further exploration.

Ordinary chernozem soils, prevalent in regions like Kostanay, are distinguished by their naturally high SOM content, predominantly concentrated within the 60-80 cm horizon, where average SOM hovers around 7% (Saparov, 2014). Although these soils experience alterations due to anthropogenic activities, their fundamental classification generally remains intact. However, debates persist regarding whether prolonged human influence can engender substantial shifts in soil formation.

The sustained cultivation of crops over time, particularly within monoculture systems, has had a gradual and adverse effect on SOM content. Recent soil analyses conducted at the Karabalyk Agricultural Experimental Station tell a telling tale – by 2021, the SOM content had dwindled to 5.0-5.5%, marking a disconcerting loss exceeding 20% over half a century (Kabbozova-Saljnikov, 2004). These changes have driven the adoption of intensive mechanical soil treatments, aimed at controlling weeds, retaining moisture, and preserving nutrients. However, these very mechanical actions foster the mineralization of SOM in fallow fields (Kabbozova-Saljnikov, 2004). In recent years, the agricultural sector in northern Kazakhstan has witnessed the implementation of systemic measures aimed at adopting highly efficient no-tillage technology. This innovative approach to soil management, as introduced in the region, has played a pivotal role in mitigating soil erosion processes and bolstering grain crop yields (FAO, 2013; Saparov, 2014). Furthermore, various agricultural zones across the Republic of Kazakhstan have embraced the foundational principles of resource-conserving agriculture. This involves the implementation of mulch systems utilizing plant residues and, in some cases, a significant reduction or even the complete elimination of mechanical tillage. Consequently, the adoption of No-tillage technology has emerged as a linchpin in advancing the sustainability of dryland agriculture in the region. It achieves this by curbing erosion, enhancing soil quality, and augmenting the overall ecosystem services provided by the soil.

This study seeks to explore the ramifications of various tillage technologies, crop rotations, and precursors on SOM content in ordinary chernozem soils, particularly in the context of moderately arid steppe conditions. To this end, our research pursues several core objectives:

- Conduct a comprehensive comparative assessment of the influence of diverse tillage technologies on SOM content.

- Elucidate the distinctions in SOM preservation between grain fallow and fruit-exchange crop rotations, with a focus on the technological applications employed.
- Investigate the effects of continuous spring wheat cultivation on SOM content in contrast to crop rotations.
- Identify and recommend the most effective crop rotation strategies and processing technologies to mitigate SOM losses.

Furthermore, our research benefits from an extensive dataset collected at the Karabalyk Agricultural Experimental Station, spanning from 2011 to 2021 and encompassing the transition to a diversified eight-field fruit-exchange crop rotation. By comparing the long-term effects of zero technology with traditional practices, our study aims to make significant contributions to the ongoing discourse surrounding soil health and fertility preservation in Kazakhstan's agricultural landscape.

Material and Methods

Experimental Site

The study was conducted at the Karabalyk Agricultural Experimental Station which is situated in the Karabalyk region, Kazakhstan (53°50´N, 62°05´E). The experimental site is characterized by typical chernozem soils in a region with a high-water table, with a humus horizon thickness ranging from 40 to 60 cm. The soil is characterized by high base saturation (95-98%), primarily dominated by Ca^{2+} (29.7 meq 100 g^{-1}) in the soil exchange complex, low Na^{+} content (0.22 meq 100 g^{-1}), resulting in low swelling and good sediment absorption properties. The soil's pH in aqueous extract is near neutral (6.6-7.0). The nutrient content in the arable layer is as follows: total nitrogen (N) - 0.28-0.32%, total phosphorus (P) - 0.11-0.15%, and total potassium (K) - 1.8-2.8%.

Figure 1. Location of the experimental site at the Karabalyk Agricultural Experimental Station, Kazakhstan

The climate of the experimental site is continental and dry with large daily and monthly fluctuation in air temperatures. Mean annual temperature is around 2,8°C and the average yearly precipitation was 340 mm. The locations of the evaluations were characterized by the continental climate (large daily and annual fluctuations in air temperature, characterized by cold winters and long hot summers), the air temperature reaches minimum values in January (-17,5^{0}C), and maximum values in July (20,6^{0}C).

Experimental Design:

This study was conducted at the "Karabalyk Agricultural Experimental Station". The rotations were set in a randomized complete block design in three replicates with all phases of each rotation present every year. Plot size was 55 × 6 m. The experiment followed a split-plot design with four replications, considering two main factors: tillage practices (Tillage) and crop rotations. Three tillage practices were examined: (i) Conventional Tillage (CT), which involved deep plowing followed by clod fragmentation, (ii) No-till (NT), where all mechanical treatments were excluded except for direct seeding after glyphosate application.

Crop Rotations;

- Grain-Fallow Crop Rotation (2011-2015)
- Fruit-Exchange Type Crop Rotation (2011-2015)
- Eight-Field Crop Rotation (Fruit-Exchange Type) (2016-2021)
- Eight-Field Crop Rotation (Fruit-Exchange Type) (2016-2021)

Agronomic Activities

Throughout the experimental period, various agronomic activities were meticulously conducted at the experimental site. These activities encompassed soil preparation, planting, cultivation, and harvesting, all performed in strict adherence to the designated tillage practices and crop rotations. The overarching objective was to establish and maintain conditions conducive to crop growth and data collection within the constraints of real-world agricultural practices. It is important to emphasize that no external organic matter inputs, aside from natural sources such as post-harvest crop residues, were introduced to the soils during the trial period. Furthermore, it should be noted that irrigation was exclusively reliant on natural precipitation and excluded any supplemental watering practices under controlled conditions. This comprehensive description ensures a clear understanding of the ecological and agronomic parameters governing the experimental setup.

Soil Sampling and SOM analyses

Soil samples were collected during specific time frames relevant to the study's objectives. Sampling involved collecting soil from the topsoil layer (0–20 cm depth) and was performed with three replicates. Soil organic carbon was determined using the wet oxidation method. Approximately 0.2 g of air-dried, 0.5 mm-sieved soil was oxidized with a solution of potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4), and the soil organic carbon content was determined titrimetrically (Walkley and Black, 1934).

Results and Discussion

Table 1 presents the SOM content based on different tillage practices in the grain-fallow crop rotation and continuous wheat monoculture for the years 2011 to 2015. Two tillage practices, Conventional Tillage (CT) and No-till (NT), were compared to evaluate their effects on SOM content. In the grain-fallow crop rotation, it is evident that both CT and NT resulted in similar SOM content across the years, with an average of around 5.0%. This indicates that the choice of tillage method had a limited impact on SOM in this specific rotation. It's important to note that there were no significant differences observed between CT and NT. In contrast, when considering continuous wheat monoculture, similar results were observed. The average SOM content remained around 5.0% for both CT and NT, indicating that neither tillage method had a substantial impact on SOM in this scenario.

Table 1. SOM content based on different tillage practices in grain-fallow crop rotation and continuous wheat monoculture (2011 - 2015, %)

Year	Tillage	Crops of grain-fallow crop rotation				Average crop rotation	Monoculture of wheat
		Fallow	Wheat 1 after fallow	Wheat 2 after wheat	Wheat 3 after wheat		
2011	CT	4,8	5,2	5,2	5,2	5,1	5,0
	NT	5,0	5,2	5,0	5,0	5,1	5,0
2012	CT	5,0	5,4	5,4	5,3	5,3	5,0
	NT	5,1	5,4	5,2	5,2	5,2	5,0
2013	CT	4,7	5,1	5,1	5,1	5,0	4,9
	NT	4,9	5,1	4,9	4,9	5,0	4,9
2014	CT	4,8	5,4	5,2	5,3	5,2	4,9
	NT	5,1	5,4	5,1	5,1	5,2	4,9
2015	CT	4,7	5,2	5,1	5,1	5,1	5,0
	NT	5,0	5,2	5,0	5,0	5,0	5,0
Average	CT	4,8	5,3	5,2	5,2	5,1	5,0
	NT	5,0	5,3	5,0	5,0	5,1	5,0

Table 2 presents the SOM content based on different tillage practices in the fruit-exchange type crop rotation and continuous wheat monoculture for the years 2011 to 2015. The same tillage practices, CT and NT, were evaluated in this rotation. In the fruit-exchange type crop rotation, there was a slight variation in SOM content between CT and NT, with the average SOM content for CT being around 5.2% and for NT around 5.4%. These results suggest that NT may have a slightly positive effect on SOM content compared to CT in this specific rotation. For continuous wheat monoculture, the average SOM content for CT was around 5.0%, while for NT, it was also around 5.0%. These results indicate that, similar to the grain-fallow crop rotation, the choice of tillage method had minimal impact on SOM content in continuous wheat monoculture.

Table 3 presents the SOM content based on different tillage practices in the first section of the eight-field crop rotation in the fruit-exchange type and continuous wheat monoculture for the years 2016 to 2021. In this rotation, CT and NT were compared. For the first section of the eight-field crop rotation, both CT and NT resulted in similar SOM content, with an average of around 4.9%. This suggests that the choice of tillage method did not have a significant impact on SOM content in this section of the rotation. In the case of continuous wheat monoculture, the average SOM content for both CT and NT remained around 4.9%. Thus, as in previous cases, the choice of tillage method had limited effects on SOM content in continuous wheat monoculture.

Table 2. SOM content based on different tillage practices in fruit-exchange type crop rotation and continuous wheat monoculture (2011 - 2015, %)

Year	Tillage	Crop rotation crops of the fruit-exchange type				Average by crop rotation	Monoculture of wheat
		Pea	Wheat after peas	Oilseed flax after wheat	Wheat after oilseed flax		
2011	CT	5,1	5,4	5,4	5,2	5,3	5,0
	NT	5,4	5,4	5,2	5,2	5,3	5,0
2012	CT	5,2	5,4	5,4	5,3	5,3	5,0
	NT	5,5	5,4	5,3	5,2	5,4	5,0
2013	CT	5,4	5,6	5,5	5,3	5,5	4,9
	NT	5,7	5,5	5,4	5,6	5,6	4,9
2014	CT	5,2	5,4	5,4	5,3	5,3	4,9
	NT	5,5	5,4	5,3	5,2	5,3	4,9
2015	CT	5,1	5,4	5,4	5,2	5,3	5,0
	NT	5,4	5,4	5,2	5,2	5,3	5,0
Average	CT	5,2	5,4	5,4	5,3	5,3	5,0
	NT	5,5	5,4	5,3	5,3	5,4	5,0

Table 3. SOM content based on different tillage practices in the first section of the eight-field crop rotation in fruit-exchange type and continuous wheat monoculture (2016-2021, %)

Year	Tillage	Crops of the first section of the crop rotation of the fruit-exchange type				Average by section	Monoculture of wheat
		Fallow	Wheat after fallow	Pea after wheat	Wheat after pea		
2016	CT	4,9	5,0	5,4	5,3	5,2	5,0
	NT	4,9	5,4	5,6	5,4	5,3	5,0
2017	CT	4,8	4,9	5,3	5,2	5,1	4,9
	NT	4,8	5,3	5,5	5,3	5,2	4,9
2018	CT	5,0	5,1	5,5	5,4	5,3	4,9
	NT	5,0	5,5	5,7	5,5	5,4	4,9
2019	CT	5,1	5,0	5,4	5,3	5,2	4,8
	NT	5,1	5,4	5,6	5,4	5,4	4,8
2020	CT	5,0	5,1	5,5	5,4	5,3	4,9
	NT	5,0	5,5	5,7	5,5	5,4	4,9
2021	CT	4,9	5,0	5,4	5,3	5,2	5,0
	NT	4,9	5,4	5,6	5,4	5,3	5,0
Average	CT	5,0	5,0	5,4	5,3	5,2	4,9
	NT	5,0	5,4	5,6	5,4	5,4	4,9

Table 4 presents the SOM content based on different tillage practices in the second section of the eight-field crop rotation in the fruit-exchange type and continuous wheat monoculture for the years 2016 to 2021. In this section, CT and NT were compared. For the second section of the eight-field crop rotation, both CT and NT resulted in similar SOM content, with an average of around 4.9%. This indicates that the choice of tillage method did not have a significant impact on SOM content in this section of the rotation. In continuous wheat monoculture, the average SOM content for both CT and NT remained around 4.9%, suggesting that the choice of tillage method had limited effects on SOM content in this scenario.

In light of the results obtained in our study, it is evident that the choice of tillage method (CT or NT) had a limited impact on SOM content within various crop rotations and continuous wheat monoculture, as previously discussed. The SOM content remained relatively stable across the years and rotations, regardless of the specific tillage practice employed. These findings indicate that other factors, such as the selection of crop type and crop rotation, may exert a more substantial influence on SOM content within the studied agricultural landscape. However, it is noteworthy that these conclusions diverge from the outcomes of another research effort conducted in North Kazakhstan. In that study, prolonged agricultural land use was observed to lead to significant changes in chemical indicators. Over the course of a decade, the SOM content within ordinary chernozems exhibited a notable decrease. Specifically, in the arable horizon, the SOM content averaged around 5.5% after 10 years of agricultural use, reflecting a 33% reduction in the upper portion and a 23% decrease in the lower part of this horizon (Oshakbaeva, 2006). Moreover, the results of this prior investigation highlighted that over two decades of plowing ordinary chernozems, the humus content in the arable horizon experienced a slight decline, reaching 5.2%. This decline in humus content amounted to a 32% reduction when compared to virgin soils. In the upper section of the arable layer, humus content measured 5.6%, signifying a 32% reduction in comparison to the humus content of virgin soils. In the lower part of the arable horizon, humus content stood at 4.9%, with a 30% reduction relative to virgin lands (Oshakbaeva, 2006). The disparities between these two studies emphasize the complex and multifaceted nature of soil dynamics in agricultural systems. It is imperative to recognize that soil health and organic matter content are influenced by a myriad of interacting variables, including climatic conditions, agricultural practices, and specific regional characteristics. As such, while our study may suggest a limited impact of tillage practices on SOM content, the contrasting findings from the North Kazakhstan research underscore the necessity for region-specific and comprehensive investigations to guide sustainable land management practices. These insights further underscore the need for context-specific approaches in soil conservation and fertility preservation.

Table 4. SOM content based on different tillage practices in the second section of the eight-field crop rotation in fruit-exchange type and continuous wheat monoculture (2016-2021, %)

Year	Tillage	Crops of the second section of the crop rotation of the fruit-exchange type				Average by crop rotation	Monoculture of wheat
		Oilseed flax	Wheat after flax	Lentils after wheat	Barley after lentils		
2016	CT	5,4	5,7	5,6	6,3	5,5	5,0
	NT	5,4	5,5	6,2	5,7	5,5	5,0
2017	CT	5,3	5,8	5,5	6,2	5,4	4,9
	NT	5,3	5,4	5,9	5,6	5,4	4,9
2018	CT	5,5	6,0	5,7	5,4	5,5	4,9
	NT	5,5	5,6	6,1	5,8	5,6	4,9
2019	CT	5,4	5,9	5,6	6,3	5,5	4,8
	NT	5,4	5,5	6,0	5,7	5,5	4,8
2020	CT	5,5	6,0	5,7	5,4	5,5	4,9
	NT	5,5	5,6	6,1	5,6	5,6	4,9
2021	CT	4,9	5,0	5,4	5,3	5,2	5,0
	NT	4,9	5,4	5,6	5,4	5,3	5,0
Average	CT	5,3	5,7	5,6	5,8	5,4	4,9
	NT	5,3	5,5	6,0	5,6	5,5	4,9

Previous studies have highlighted the multifaceted interplay between SOM dynamics, tillage practices, crop rotations, and regional conditions. These studies have consistently emphasized the significance of SOM for soil quality and crop productivity (Dick, 1983; Cambardella and Elliott, 1992; La1 et al., 1994; Angers et al., 1997; Suleimenova et al., 2019; Jaziri et al., 2022; Ospanbayev et al., 2023). Specifically, investigations comparing no-tillage (NT) to conventional tillage have often revealed an increase in SOM, favoring NT, especially in the surface soil layer down to the depth of plowing (20-30 cm in most cases). It's worth mentioning that the variation in C content in the surface soil layer is consistent with the outcomes of many studies, with fine-textured soils exhibiting higher C content regardless of tillage practice. Moreover, the long-term implications of tillage and crop rotation on SOC have been a subject of considerable interest. In a 36-year long-term experiment conducted in Canada, it was demonstrated that SOC was significantly higher for NT (2.73%) compared to CT (2.51) (Laamrani et al., 2020). Furthermore, the positive effects of crop rotations on physical, chemical, and biological soil properties have been attributed to higher SOC inputs and the diversity of plant residues returned to soils (Follett, 2001; Dimassi et al., 2013). The combination of NT and crop rotation has been shown to have the potential to further increase SOC and nitrogen content due to improved water use efficiency, particularly in semi-arid areas (Luo et al., 2010; Bahri et al., 2019).

Experimental site in the region's harsh continental climate, characterized by arid summers and frigid winters, suggests that the impact of soil processing and crop rotation on organic matter loss may be relatively minimal in the experimental site. However, it is essential to acknowledge the intricate interplay of diverse factors, including climatic conditions and the regional characteristics that contribute to soil dynamics and organic matter content. These findings underscore the necessity for region-specific and comprehensive investigations to guide sustainable land management practices. The combined insights from these studies underscore the importance of crop diversification and conservation agriculture adoption, particularly in ordinary chernozems in arid regions, to mitigate organic matter loss and enhance soil quality and fertility.

Conclusion

This study examined the complex relationship between soil management methods, crop rotations, and soil organic matter (SOM) content in the context of moderately arid steppe conditions in Kazakhstan, characterized by a arid continental climate. Through comprehensive analyses spanning multiple years and diverse crop rotations, several key findings emerged. The results suggest that the choice of soil management methods, whether conventional tillage (CT) or no-tillage (NT), had a limited impact on SOM content. Regardless of the specific tillage method employed, SOM content remained relatively stable over various years and rotations. The region's harsh continental climate, with arid summers and frigid winters, appeared to mitigate the effects of soil processing and crop rotations on organic matter loss. However, it is crucial to acknowledge the intricate interplay of diverse factors, including climatic conditions and regional characteristics that contribute to soil dynamics and organic matter content. This study's insights underscore the importance of region-specific and comprehensive research to guide sustainable land management practices. The combined findings from these studies emphasize the significance of crop diversification and the adoption of conservation agriculture, particularly in ordinary chernozems in arid regions. These practices can help mitigate organic matter loss, enhance soil quality, and improve soil fertility. In summary, the research conducted in Kazakhstan's arid steppe region highlights the need to consider local ecological conditions and agricultural practices when addressing soil health and fertility preservation. By doing so, we can develop context-specific approaches to ensure the sustainability of agricultural landscapes and maintain vital soil resources for future generations.

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