Effects of Tillage Practices on Soil Water Infiltration, Organic Carbon Content, and Soil Structure: Postprint

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Abstract

To elucidate the mechanisms of different tillage methods on soil profile structure and water infiltration processes, intact soil columns (0–100 cm) and ring knife samples at 0–10 cm, 10–20 cm, ···, 90–100 cm, as well as intact and mixed soil samples were collected from a long-term field experiment with tillage treatments (conventional tillage, no-till, and subsoiling). Laboratory simulation experiments were conducted to determine the soil infiltration process and saturated hydraulic conductivity in the 0–100 cm soil layer, and the soil organic carbon content, soil structural characteristics, and their interrelationships across different soil layers were analyzed. The results showed that: the time required for water supplied from the top of the soil column (constant head) to completely infiltrate to the bottom was: conventional tillage > no-till > subsoiling; the soil infiltration rate and cumulative infiltration in the soil column were: subsoiling > no-till > conventional tillage; and the cumulative evaporation from the soil column was: conventional tillage > no-till > subsoiling. Saturated hydraulic conductivity exhibited the following patterns: in the 0–10 cm and 50–60 cm layers, no-till > subsoiling > conventional tillage; in the 20–50 cm and 60–100 cm layers, subsoiling > no-till > conventional tillage. With increasing soil depth, the content of >0.25 mm water-stable aggregates and soil organic carbon content both showed a trend of initially increasing (at 10–20 cm) and then decreasing. In the 0–40 cm and 80–100 cm soil layers, the subsoiling treatment had the highest content of >0.25 mm water-stable aggregates. In soil layers above 60 cm, soil organic carbon content followed the order: no-till > subsoiling > conventional tillage, whereas below 60 cm, soil organic carbon decreased significantly to values below 4 $g \cdot kg^{-1}$, and in layers below 70 cm, conventional tillage > no-till > subsoiling. In summary, tillage practices can alter soil organic carbon content, improve soil structure, and promote soil water storage and moisture conservation; subsoiling was more conducive to localized water infiltration, while no-till was more beneficial for enhancing organic carbon and water storage, with its effective depth in the 0-60 cm soil layer.

Full Text

Effect of Tillage Method on Soil Water Infiltration, Organic Carbon Content and Structure*

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Abstract: Long-term tillage practices can substantially influence soil profile physical properties. Subsoiling and no-tillage, for instance, can increase soil organic matter content, improve soil structure, enhance structural stability, and consequently ameliorate the soil moisture environment. Furthermore, rotational systems of no-tillage and subsoiling can significantly improve soil water storage. However, most previous studies have focused on no-tillage with mulching, subsoiling with mulching, or rotational practices of no-tillage and subsoiling, typically examining only the plowed layer. The effects of long-term subsoiling or no-tillage without mulching on soil physical properties, infiltration processes, organic carbon distribution, and soil structure—particularly in deeper soil layers—remain poorly documented. This study investigated the effects of long-term no-tillage, subsoiling, and conventional tillage (all without mulching) on soil profile structure and water infiltration processes.

Undisturbed soil columns (0-100 cm) and samples from 0-10 cm, 10-20 cm, ⋯ , 90-100 cm layers—including ring-cut undisturbed soil samples and mixed soil samples—were collected from a long-term field experiment to determine soil infiltration processes, saturated hydraulic conductivity, soil organic carbon content, and soil structure. Results showed that conventional tillage required the longest time for water to infiltrate from the surface to the bottom of the soil column. The order of both infiltration rate and cumulative infiltration was: subsoiling > no-tillage > conventional tillage. Cumulative evaporation from the soil columns followed the reverse order: conventional tillage > no-tillage > subsoiling. Saturated hydraulic conductivity in the 0-10 cm and 50-60 cm layers was highest under no-tillage, followed by subsoiling and conventional tillage, whereas in the 20-50 cm and 60-100 cm layers, the order was subsoiling > no-tillage > conventional tillage. With increasing soil depth, the content of >0.25 mm water-stable aggregates and soil organic carbon initially increased (in the 10-20 cm layer) then gradually decreased. Subsoiling produced the highest >0.25 mm water-stable aggregate content in the 0-40 cm and 80-100 cm layers. In the 0-60 cm layer, soil organic carbon content followed the order: no-tillage > subsoiling

> conventional tillage, while below 60 cm, organic carbon content was below 4.0 $g \cdot kg^{-1}$ and followed the order: conventional tillage > no-tillage > subsoiling below 70 cm. These findings demonstrate that appropriate tillage practices can improve soil organic carbon content and soil structure, thereby promoting soil water conservation. Subsoiling was more conducive to water infiltration, while no-tillage was more beneficial for organic carbon accumulation and water storage, particularly within the 0–60 cm soil layer.

Keywords: Conventional tillage; Subsoiling; No-tillage; Soil water infiltration; Soil organic carbon; Soil structure

Introduction

Soil tillage measures such as no-tillage, subsoiling, and surface soil operations can improve soil structure [1-2], reduce soil erosion on sloping dryland, enhance soil microbial activity, and mitigate crop drought stress [3]. Simultaneously, these practices can improve soil fertility [4] and porosity, reduce bulk density, and promote crop growth [5]. Straw return combined with no-tillage can increase aeration pores in the surface soil, reduce ineffective pores, improve soil structure, enhance water-holding capacity, and increase the soil water reservoir [6]. Minimum or no-tillage is beneficial for rainfall acceptance and water storage, promoting improvements in crop yield and water use efficiency [7-9]. No-tillage with straw mulching can effectively maintain soil profile moisture content, reduce soil evaporation [10], and increase saturated hydraulic conductivity [11]. Yu Tongyan et al. [12] demonstrated that although no-tillage is not conducive to water infiltration, it can effectively conserve soil moisture. Yang Yonghui et al. [13] found that two consecutive years of no-tillage improved soil structure, reduced bulk density, and improved soil pore conditions. Subsoiling can break up the plow pan, improve soil pores, promote water storage and moisture conservation, and facilitate crop root utilization of deep soil water [14], while significantly increasing the content of >0.25 mm water-stable aggregates and effectively improving soil water storage capacity [15]. Subsoiling with ground cover can improve soil aggregate structure and enhance soil profile moisture conditions [16]. Rotation of no-tillage and subsoiling can significantly increase soil water storage [17-18].

Previous studies have predominantly focused on no-tillage with mulching, subsoiling with mulching, or rotational practices, with investigation depths typically limited to above the plow pan. The effects of long-term subsoiling or no-tillage without mulching on soil profile physical characteristics, infiltration processes, and organic carbon distribution patterns, particularly in deep soil layers, have rarely been reported and require further investigation to elucidate the mechanisms of action of long-term subsoiling and no-tillage.

This study examined soil structure, water infiltration and evaporation characteristics, organic carbon distribution, and their interrelationships in the 0–100 cm soil layer under long-term subsoiling and no-tillage conditions, providing a scientific basis for understanding the improvement of soil profile physical characteristics and the underlying mechanisms of long-term subsoiling and no-tillage in wheat (*Triticum aestivum*)-maize (*Zea mays*) rotation systems.

1.1 Study Area Overview

The experiment was conducted at the Yuzhou Experimental Base in Henan Province (113°03 -113°39 E, 33°59 -34°24 N, elevation 116.1 m), with a mean annual precipitation of 674.9 mm, of which over 60% occurs in summer. The soil type is cinnamon soil. The research area is flat terrain. The plow layer soil contained 12.3 $g \cdot kg^{-1}$ organic matter, 0.80 $g \cdot kg^{-1}$ total nitrogen, 47.82 $mg \cdot kg^{-1}$ hydrolyzable nitrogen, 6.66 $mg \cdot kg^{-1}$ available phosphorus, and 114.8 $mg \cdot kg^{-1}$ available potassium. The study area is a wheat-maize rotation zone. The soil mechanical composition was: sand particles (2-0.02 mm) 59.1%, silt particles (0.02-0.002 mm) 22.5%, and clay particles (<0.002 mm) 18.4%.

1.2 Experimental Design

The long-term field experiment was initiated in mid-October 2006 during wheat sowing, with tillage practices implemented annually at wheat planting; maize was always sown under no-tillage. Three treatments were established: conventional tillage (tillage depth 15 cm), no-tillage, and subsoiling (depth 30 cm). No straw return was applied in the experimental plots. A compound fertilizer N25P15K15 was applied as a basal dressing at wheat sowing. For conventional tillage and subsoiling, fertilizer was uniformly spread before tillage; for no-tillage, fertilizer was applied at points after wheat and maize sowing.

On October 12, 2014, after maize harvest, undisturbed soil columns (0-100 cm) were collected from the center of each of the three replicate plots per treatment using an undisturbed soil column sampler to determine soil infiltration processes. Specifically, a plexiglass tube was placed in the sampler and driven vertically into the soil with a hammer until reaching 110 cm depth, then the sampler was extracted and the plexiglass tube removed from the bottom. Simultaneously, a soil profile was excavated adjacent to the column sampling location, and samples were collected by layer (0-10 cm, 10-20 cm, ···, 90-100 cm) as ring-cut samples (for saturated hydraulic conductivity), undisturbed soil (for aggregate structure), and mixed soil samples (for soil organic carbon content). Three replicates per treatment were collected for laboratory analysis.

1.3 Measurement Items and Methods

1) Soil saturated hydraulic conductivity was determined using the constant head method [19]. Water-stable aggregates were measured using the wet sieving method (Vinov method) [20]. Soil organic carbon was analyzed using the modified external heating potassium dichromate oxidation method [21].

2) Soil infiltration process measurement. Undisturbed soil columns collected from the field (110 cm length, 20 cm diameter, 1 cm wall thickness) were brought indoors and allowed to equilibrate until the soil water content reached approximately 8%-10% (Table 1) before conducting infiltration observations. Prior to observation, each column was weighed to record its initial weight. Graduated coordinate paper with 1 mm precision was affixed parallel to the column length on the side of the transparent plexiglass column, with depth markings from top to bottom. A Mariotte bottle supplied water at a constant head from above the column (with 10 cm headspace left at the top to accommodate water supply). The Mariotte bottle height was adjusted to maintain a water layer thickness of approximately 5 cm above the column. Timing began when water supply commenced, and the water infiltration front distance was observed along the column profile. Three sets of data were recorded per column (three vertical coordinate paper strips affixed at equal intervals around the column circumference, with the average calculated as the observation value, minimum scale 1 mm), yielding nine sets of data per treatment (three columns) for averaging. Initially, the infiltration distance was recorded every minute, simultaneously with the water level decline in the Mariotte bottle. When the infiltration front advanced slowly, the recording interval was extended. When water infiltrated to the column bottom, the outflow was measured. Water supply was stopped when outflow became constant (indicating column saturation, see Table 1), and the column bottom was sealed with tape to prevent water loss. After observation, cumulative infiltration and infiltration rate were calculated. The saturated column was weighed using an electronic balance with 1 g precision to obtain its total saturated weight. Cumulative evaporation was monitored by weighing the column every 1 d; water contents before and after the evaporation experiment are shown in Table 1.

The soil column infiltration rate was calculated as follows:

$$V = \frac{Q_n}{t_n \times S} \times 10 \times 60$$

where: V is the infiltration rate ($\mathrm{mm \cdot h^{-1}}$); Qn is the volume of water entering the soil column from the Mariotte bottle at the nth measurement (mL, i.e., $\mathrm{cm^3}$); tn is the time interval between measurements (min); S is the cross-sectional area of the column ($\mathrm{cm^2}$); 10 is the conversion factor from cm to mm; and 60 converts the infiltration rate unit from $\mathrm{mm \cdot min^{-1}}$ to $\mathrm{mm \cdot h^{-1}}$.

1.4 Data Processing

All reported values are arithmetic means of three replicates, and data were processed using Microsoft Excel and SPSS software.

Results and Discussion

2.1.1 Water Movement Pattern Analysis

Different tillage measures produced distinct water movement patterns in the soil profile (Fig. 1 [Figure 1: see original paper]). Due to the low initial water content of the soil columns in all three treatments (Table 1), water infiltration was relatively rapid, reaching 35 cm depth within a short period under all three tillage methods, with the subsoiling treatment being the fastest. Thereafter, the infiltration wetting front slowed significantly, with marked differences among treatments ($P<0.01$). Conventional tillage required substantially more time to reach equivalent depths. Subsoiling maintained relatively rapid water movement, infiltrating to the column bottom in less than 3 h; no-tillage required twice as long as subsoiling, while conventional tillage exceeded 24 h. These results indicate that subsoiling breaks up the plow pan, making the soil profile more permeable (as evidenced by linear movement curves) and facilitating local water infiltration. Conventional tillage, constrained by the plow pan, showed significantly reduced infiltration capacity. Although no-tillage was also affected by the plow pan, its improved surface soil structure resulted in greater infiltration capacity than conventional tillage.

2.1.2 Cumulative Infiltration Analysis

Initial infiltration rates were similar across tillage treatments, but differences increased progressively over time (Fig. 2 [Figure 2: see original paper]), reaching highly significant levels ($P<0.01$). The subsoiling treatment columns reached saturation within 3 h of water application. Conventional tillage required substantially longer to achieve saturated water content, and its cumulative infiltration was lower than other treatments throughout. At any given time, cumulative infiltration followed the order: subsoiling > no-tillage > conventional tillage ($P<0.01$). These results demonstrate that subsoiling significantly increases soil water storage capacity, with no-tillage also showing notable improvement in water storage, increasing by 27.3% and 22.8% compared with conventional tillage, respectively.

2.1.3 Infiltration Rate Analysis

Soil infiltration rate decreased gradually over time. Throughout the entire infiltration process, subsoiling maintained the highest rate, followed by no-tillage, with conventional tillage showing the lowest rate ($P<0.05$). Differences were particularly pronounced during the 0–2.0 h period ($P<0.01$) (Fig. 3 [Figure 3: see original paper]). As time progressed, the rate of decline in infiltration rate diminished for all treatments, eventually stabilizing at constant values, with subsoiling and no-tillage remaining significantly higher than conventional tillage ($P<0.05$).

2.2 Cumulative Evaporation Analysis

Cumulative soil evaporation increased progressively over time across all tillage treatments, with significant differences observed (Fig. 4 [Figure 4: see original paper]) ($P<0.01$). Although the saturated water content under conventional tillage was lower than other treatments (Table 1), its initial and subsequent evaporation rates remained significantly higher ($P<0.01$). No-tillage exhibited the lowest evaporation, significantly below other treatments ($P<0.01$), followed by subsoiling. These results indicate that subsoiling and no-tillage can effectively reduce ineffective soil evaporation.

2.3 Saturated Hydraulic Conductivity Analysis

As shown in Fig. 5 [Figure 5: see original paper], saturated hydraulic conductivity was lowest in the 20–30 cm layer and highest in the 10–20 cm layer (except for no-tillage), gradually stabilizing with increasing soil depth. In the 0–10 cm layer, saturated hydraulic conductivity followed the order: no-tillage > subsoiling > conventional tillage ($P<0.05$). In the 10–20 cm layer, subsoiling was significantly higher than other treatments ($P<0.05$), likely due to enhanced crop root and earthworm activity after subsoiling. In the 20–30 cm layer, differences among treatments were minor ($P>0.05$), though subsoiling maintained the highest saturated hydraulic conductivity. In the 30–40 cm layer, saturated hydraulic conductivity increased for all treatments, with subsoiling highest, followed by no-tillage and conventional tillage lowest ($P<0.05$). With further depth increase, saturated hydraulic conductivity stabilized across treatments; however, below 60 cm, no-tillage and conventional tillage showed relatively low saturated hydraulic conductivity, while subsoiling maintained higher values ($P<0.05$). These results demonstrate that long-term no-tillage and subsoiling improved soil profile hydraulic conductivity, particularly in layers above 20–30 cm, with subsoiling showing the most pronounced effects.

2.4 Soil Organic Carbon Distribution

Fig. 6 [Figure 6: see original paper] shows that soil organic carbon content was abundant in layers above 40 cm, particularly in the surface layer above 20 cm. The 40–70 cm layer served as a transition zone, while below 70 cm was a stable layer, with overall content decreasing with depth. In the 0–60 cm layer, no-tillage exhibited the highest organic carbon content, followed by subsoiling, with conventional tillage lowest. In the 70–100 cm layer, soil organic carbon varied moderately, with content ranging from 2–4 $g \cdot kg^{-1}$. In the 80–100 cm layer, conventional tillage showed higher organic carbon than no-tillage and subsoiling. These results indicate that long-term no-tillage and subsoiling promoted root growth and soil biological activity, improving soil organic carbon to a depth of 60 cm.

2.5 Water-Stable Aggregate Content Analysis

The content of >0.25 mm water-stable aggregates indicates soil structural stability. As shown in Fig. 7 [Figure 7: see original paper], with increasing soil depth, >0.25 mm water-stable aggregate content initially increased then decreased significantly. In the 0–10 cm and 10–20 cm layers, the content followed the order: subsoiling > no-tillage > conventional tillage ($P<0.05$). In the 0–40 cm and 80-100 cm layers, subsoiling produced the highest >0.25 mm water-stable aggregate content ($P<0.05$). Conventional tillage showed relatively high >0.25 mm water-stable aggregate content only in the 70–90 cm layer, with the lowest values in all other layers. These results demonstrate that different tillage measures improved soil aggregate structure and enhanced structural stability throughout the profile, particularly in layers above 60 cm.

2.6 Correlation Analysis

The relationships between >0.25 mm water-stable aggregate content and soil organic carbon content, between >0.25 mm water-stable aggregate content and saturated hydraulic conductivity, and between soil organic carbon content and saturated hydraulic conductivity all exhibited quadratic curve relationships (Fig. 8 [Figure 8: see original paper]), with correlations reaching highly significant levels ($P<0.01$). As soil organic carbon content increased, >0.25 mm water-stable aggregate content increased, while saturated hydraulic conductivity initially decreased then increased. When >0.25 mm water-stable aggregate content increased beyond a certain threshold (30% of total aggregates), saturated hydraulic conductivity showed a gradual increasing trend. These findings indicate that appropriate tillage practices can increase soil organic carbon, thereby improving soil structure and enhancing soil permeability.

Conclusions and Discussion

Subsoiling and no-tillage can promote increases in soil organic matter content, improve soil structure [22,24-25], enhance structural stability, and ameliorate the soil moisture environment [26]. Long-term subsoiling and no-tillage exert important influences on soil profile physical properties. This study found that water movement was rapid in layers above 35 cm, particularly under subsoiling. Below 35 cm, conventional tillage showed markedly slower water movement, while subsoiling maintained relatively rapid infiltration. The total time for water to infiltrate from the column top to bottom followed the order: conventional tillage > no-tillage > subsoiling. During the 0–2.0 h period, infiltration rates differed substantially among treatments, with subsoiling highest, followed by no-tillage and conventional tillage lowest. Over time, infiltration rates gradually declined and stabilized, remaining highest under subsoiling, followed by no-tillage. Saturated hydraulic conductivity reflects differences in soil structure among layers, while water storage capacity reflects the ability of different measures to improve soil structure. Previous studies have focused primarily on the plow layer. For different layers throughout the soil profile, this study found that in the 0–10 cm and 50–60 cm layers, no-tillage was most conducive to increasing saturated hydraulic conductivity, followed by subsoiling, with conventional tillage lowest; whereas in the 10–50 cm and 60–100 cm layers, subsoiling produced the highest values. These results indicate that subsoiling breaks up the plow pan, improves soil pore conditions [14], increases soil permeability [27], promotes local water infiltration and movement to deeper layers [28], and enhances soil water content [16]. The favorable soil structure formed under no-tillage increases effective capillaries with continuous, uninterrupted connectivity, thereby facilitating rapid water movement [29] and improving infiltration capacity. These findings contrast with those of Gao Jianhua et al. [30] and Yu Tongyan et al. [12] but align with Dao [31] and Hati et al. [32], possibly related to no-tillage duration [33], soil type, cropping system, and other factors requiring further investigation. Additionally, implementing no-tillage and subsoiling increased cumulative infiltration, expanded the soil water reservoir, and reduced ineffective evaporation. Among treatments, subsoiling was more favorable for water infiltration, while no-tillage was more beneficial for water retention. Some studies [18] have shown that no-tillage after one year of subsoiling can also promote water storage, though the effects of no-tillage following long-term subsoiling require further research.

Soil infiltration processes and water storage capacity are closely related to soil structure [34] and organic matter content [35]. Improving soil structure through increased organic matter can regulate water transformation, retention, and supply in soil, thereby enhancing soil productive and ecological functions. This study found that soil organic carbon content initially increased (in the 10–20 cm layer) then decreased with depth, stabilizing below 70 cm. In the 0–60 cm layer, no-tillage showed the highest organic carbon content, followed by subsoiling, with conventional tillage lowest. These results indicate that long-term no-tillage and subsoiling benefit water retention, promote crop root growth and soil biological activity, while root residues, root exudates, and soil biological feces further increase soil organic carbon content and improve soil structure. Consequently, >0.25 mm water-stable aggregate content also initially increased (in the 10–20 cm layer) then decreased with depth. Except in the 60–80 cm layer, subsoiling produced the highest >0.25 mm water-stable aggregate content, followed by no-tillage, with effects most pronounced in layers above 60 cm. Chen Qiang et al. [36] reported similar conclusions, whereas Gao Jianhua et al. [30] found no-tillage had minimal effects on soil structure improvement, possibly related to tillage duration or soil type and requiring further investigation. Moreover, most related research has focused on surface soil, with limited investigation of deep soil layers.

In summary, appropriate long-term tillage measures can increase soil organic carbon content throughout the profile, thereby improving soil structure and enhancing soil permeability and water storage capacity. Subsoiling is more conducive to local water infiltration, while no-tillage is more beneficial for organic carbon accumulation and water storage. However, this study represents results after eight years of long-term field experiments. The effects of longer-term no-tillage, subsoiling, or combinations of continuous no-tillage followed by subsoiling and continuous subsoiling followed by no-tillage on soil profile physical characteristics warrant further investigation.

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