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Natural Recovery Dynamics of Alfalfa Field Soils under Different Degrees of Mechanical Compaction

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Abstract: Soil compaction in alfalfa fields has become increasingly severe due to the mechanization of animal husbandry and the increased use of heavy agricultural machinery. Perennial alfalfa land undergoes mechanical compaction several times during the planting period without mechanical tillage. The compacted soil structure may recover through moisture changes, freezing and thawing cycles, and plant growth, but the extent and rate of this recovery remain unknown. In this study, alfalfa plots with two different soil types (medium loam and sandy) in Gansu, China, were selected to address these issues. The areas of the plots were 120 m × 25 m and 80 m × 40 m, respectively. In the third year after sowing, three types of agricultural machinery with grounding pressures of 88 kPa, 69 kPa, and 48 kPa were used to compact the soil one, three, five, and seven times. The interval between replicates was 1 h. Each treatment had one plot of 10 m × 5 m, and the experiment was repeated 4 times, totaling 44 plots. Changes in soil bulk density, soil cone index, and saturated hydraulic conductivity were measured after 1, 4, 8, and 17 weeks, respectively. The results showed that the post-compaction soil bulk density and soil cone index largely influenced the recovery of the compacted soil. Recovery became problematic once the soil bulk density exceeded 1.5 g/cm^3. The soil bulk density recovery rate varied across different soil layers, with the top layer recovering faster than more profound layers. The initial state could be restored when the change in post-compaction soil bulk density was minimal. Sandy soil recovered faster than medium-loam soil. The recovery of the soil cone index in each layer of medium-loam soil under lower compaction was more noticeable than that under severe compaction. However, with undergrounding pressures of 88 kPa and 69 kPa, the soil cone index could not fully recover after multiple compactions. The recovery of soil-saturated hydraulic conductivity in both soil types was slower and less pronounced. The recovery of soil-saturated hydraulic conductivity in medium-loam soil was slower than that in sandy loam. After 7 compactions and 17 weeks under a grounding pressure of 88 kPa, the saturated hydraulic conductivity remained below 20% of its initial value of 20 mm/h. In contrast, sandy soils recovered faster, reaching 60 mm/h within a week of each compaction event. This research is crucial for ensuring high and stable alfalfa yields and supporting sustainable agricultural practices.

Keywords: mechanical soil compaction; soil structure recovery; alfalfa field soils; changes in soil structure

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1. Introduction

Soil compaction represents a global challenge [1], with Sonderegger T. et al. estimating that compaction and water erosion could lead to a long-term productivity decline of 10–20% worldwide, exerting particularly significant impacts on low-input agricultural systems [2]. During compaction, soils experienced densification and reduced porosity, resulting in significant alterations to soil structure and decreased hydraulic conductivity, alongside heightened soil resistance [3]. Soil structure recovery is a slow process following damage [4]. Compaction severity increases with higher soil moisture levels, more significant mechanical ground pressures, and frequent tillage operations. Soil compaction alters the soil structure, increasing bulk density and hardness, decreasing porosity, and impairing permeability.

These changes degrade the soil environment, affecting the development of the crop root system and distorting the root architecture of most crops [5]. This results in delayed crop emergence, reduced emergence rates, and increased seedling mortality, severely impacting soil productivity [6–12]. Within the soil, compaction impacts microbial and enzymatic activities and damages biodiversity [13]. Soil compaction also alters the movement of soil elements, disrupts carbon and nitrogen cycles, modifies greenhouse gas emissions, exacerbates soil erosion, and significantly degrades ecosystems, posing a severe threat to human food security and the sustainable development of soils [6,14,15].

Many scholars worldwide have extensively investigated soil compaction mitigation strategies. Rodrigues, M.F. et al. studied the impact of gradually increasing the intensity of mechanical transport on soil composition and function during timber harvesting. They found that mechanical transport affects the soil's porous system properties. Additionally, they noted that soil mechanical resistance to penetration exceeding 2 MPa can inhibit plant growth [3]. Nawaz, M.F. et al. pointed out that changes in soil physical properties due to compaction under wet conditions can alter the mobility of elements and affect the cycling of nitrogen and carbon, thereby increasing greenhouse gas emissions [16]. Song C. et al. demonstrated that no-tillage improves the topsoil aggregate structure, increases topsoil water content, reduces topsoil bulk density, and enhances topsoil organic matter content, increasing topsoil strength [17]. Nazari M. et al. suggested that selecting appropriate logging machinery, minimizing machine passes, and reducing the area covered by skid trails are crucial for mitigating soil compaction [18]. Yue L. et al. demonstrated that root growth accounts for approximately one-third of the variation in soil macroporosity under compacted soil conditions, with vertically growing roots having a more significant alleviating effect on soil compaction compared to horizontally growing roots. Variability in soil compaction relief among soybean varieties can be a reference for agricultural breeders when selecting varieties that mitigate soil compaction [19]. Schneider H. M. et al. found that multiseriate cortical sclerenchyma in maize and wheat roots enhanced tensile strength and infiltration capacity in compacted soils under controlled environments [20]. Pandey, B. K. et al. discovered that the reduced air-filled pore space due to soil compaction decreases gas diffusion, leading to ethylene accumulation in root tissues and triggering growth-limiting hormonal responses. They suggest that ethylene is an early warning signal for roots in order to avoid compacted soils. Ethylene-insensitive mutant Arabidopsis thaliana and rice roots penetrate compacted soils more effectively than their wild-type counterparts [21]. Fang, J. et al. found that increasing the pre-consolidation pressure of the soil and decreasing the soil compression index and bulk density can significantly reduce the risk of soil consolidation. Additionally, the compressive properties of the soil improved with the addition of organic carbon, organic fertilizers, biochar, and other amendments [22]. M. Z. Tekeste, et al. studied the effect of soil compaction using increased tire deflection technology and found that the soil cone index and rutting depth resulting from standard radial tire pressure treatments were significantly higher ($p < 0.05$) [23]. Bello-Bello, E. et al. emphasize the need to develop stress-tolerant crops capable of thriving in degraded soils and maintaining high yields, which are better adapted to climate change and marginal soils. Such crops can facilitate carbon dioxide sequestration and storage in deeper soil layers [24]. Capobiangelo, N. P. et al. studied the effects of two levels of soil compaction on 60 soybean genotypes. The results showed that soil compaction increased seedling emergence and asexual growth but significantly reduced soybean yield. Genotypes tolerant to compaction exhibited smaller reductions in the relative growth rate, absolute growth rate, final height, number of pods, and grain yield [25].

As the industrialization of alfalfa planting areas expands, the mechanization of alfalfa harvesting can be widely promoted. Considering the mechanized production process of alfalfa, which includes cutting and flattening, baling, and transportation, the planting machinery enters the field once for each operation. Three operations and three harvests per year result in nine machinery entries annually. Alfalfa is a perennial plant that can be grown for seven or more years, or even ten. Therefore, the cumulative number of machinery

entries is significant, highlighting the issue of mechanical soil compaction as a primary concern; multiple compactions can lead to reduced alfalfa yields. The alfalfa root system is well-developed, extending to depths of 2~5 m, with a long growth period and high water demand. The alfalfa root system interweaves within the soil, continuously extracting nutrients necessary for its growth. Soil compaction may impact this process, altering the soil's water storage capacity and affecting groundwater movement. A practical approach to mitigate soil compaction is through deep loosening or other forms of soil cultivation to break up the compacted layer and restore the soil structure. However, since alfalfa fields typically cannot be tilled during their multi-year growth cycle, the detrimental effects of mechanical compaction on alfalfa field soils are challenging to eliminate [26].

Alfalfa enhances soil fertility, increases soil organic matter and nitrogen content, and prevents secondary soil salinization, which can improve the soil structure and, to some extent, facilitate its self-repair. The well-developed alfalfa root system impacts soil-bearing capacity and contributes to soil structure improvement. Cresswell and Kirkegaard described this process as "plant drilling", where alfalfa roots act to locally reorganize the soil structure at the inter-root level [27]. The response of the alfalfa root–soil complex to mechanical compaction differs significantly from pure soil compaction, with the potential to restore the structure of compacted soil through natural growth. The extent of recovery may vary considerably, depending on the degree of compaction or the specific planting habitat. Therefore, studying the degree of recovery under different compaction conditions, exploring the mechanisms of soil compaction recovery in alfalfa fields, and investigating reasonable soil management practices are of practical significance. This approach aims to alleviate the severe problem of soil compaction in alfalfa fields, thereby improving alfalfa's growing environment and restoring the ecological environment.

The author published the results of the impact of mechanical compaction on the soil structure of different alfalfa fields in the journal *Forestry Machinery and Woodworking Equipment* in 2019. Based on these results, this article will focus on the recovery situation of the soil structure after compaction. Until now, there have been few reports at home and abroad on the recovery situation of the soil structure in alfalfa fields after compaction. Previous research results show that under ground pressures of 48~88 kPa, compared to non-compaction treatments, the bulk density of loam soil within a depth of 0~10 cm increases by 3.2%~32.5% with one to seven compactions, while the soil volume density of sandy loam alfalfa fields within the same depth increases by 4.7%~21.2% with one to seven compactions. Additionally, the bulk density of loam soil within a depth of 10~20 cm increases by 2.9%~23.7% with one to seven compactions, and the bulk density of sandy soil within the same depth increases by 0.8%~16.5%. Under ground pressures of 69~88 kPa, one to seven compactions increase the soil volume density within a depth of 20~30 cm by 8.2%~12.2%, and increase the bulk density of sandy soil within the same depth by 5.5%~13.5%. When the ground pressure is 48 kPa, it has an insignificant impact on the soil volume density in the 20~40 cm layer. When the ground pressure is 88 kPa and 69 kPa, the first three compactions have an undeniable impact on the soil cone index in a soil layer of 0~35 cm. When the ground pressure is 48 kPa, one to seven compactions gradually increase the soil cone index in a soil layer of 0~20 cm and have little impact on the soil cone index in the soil layer below 30 cm. There is a correlation between the soil-saturated hydraulic conductivity and the number of compactions [28].

This paper focuses on the natural recovery process of the soil structure after compaction. Specifically, it examines the temporal changes in soil bulk density, the soil cone index, and soil-saturated hydraulic conductivity. This is the natural change process following mechanical compaction when the soil bulk density is relatively high. It may be influenced by moisture, freeze–thaw alternations, and plant growth. The paper discusses the impact of these uncertain factors on soil structural parameters. The aim is to comprehensively evaluate the trend of soil changes over time under the combined influence of these factors after mechanical compaction and assess its self-recovery ability.

2. Materials and Methods

2.1. Test Site Overview

The experimental sites were in Xiaojin Town, Xifeng District, Qingyang City, and Qinchuan Town, Yongdeng County, Lanzhou City, both in Gansu Province, China. Xiaojin Town is situated within geographic coordinates ranging from 107°27′42″ to 107°52′48″ E and 35°25′55″ to 35°51′11″ N, with an average elevation of 1240 m above sea level. This region experiences an annual sunshine duration of 2400~2600 h, annual precipitation of 400~600 mm, and an annual average temperature of 10 °C. The annual frost-free period is 160~180 days. Qinchuan Town is located within geographic coordinates ranging from 103°30′ to 103°45′ E and 36°35′ to 36°43′ N, with an average elevation of 2100 m above sea level. This region receives an annual precipitation of 250~300 mm. The annual evaporation is 1800 mm, with an annual average temperature of 6.5 °C. The annual frost-free period is 120~130 days.

The test site was planted with alfalfa, strip-seeded and manually harvested. Prior to the experiment, the site needed to be mechanically compacted. Considering that alfalfa is at its peak of growth in the third year after planting, we chose to conduct the experiment in the third year after sowing. The test site was compacted using three different grounding pressures of agricultural machinery. Two experimental plots were established with 120 m × 25 m and 80 m × 40 m. The soil types were medium-loam and sandy soil; the medium-loam soil was unirrigated, while the sandy soil was diffusely irrigated before winter. A particle analysis test was conducted using the densitometer method before the experiment. The measured soil particle content and initial state for the two soils are presented in Table 1.

Table 1. Initial parameters of soil.

Soil Type	Depth (cm)	Bulk Density (g·cm^{-3})	Moisture (%)	Porosity (%)
medium loam	0~10	1.26	15.8	52.4
	10~20	1.35	16.4	49.0
	20~30	1.47	19.1	44.5
	30~40	1.48	19.3	44.1
sandy soil	0~10	1.27	18.2	52.0
	10~20	1.27	19.3	52.0
	20~30	1.26	17.1	52.4
	30~40	1.18	14.8	55.5

2.2. Experimental Equipment

The compaction machinery included three different models of tractors, as follows: the HW320 self-propelled mower manufactured by New Holland; the Dongfanghong LX750 tractor; and the Dongfanghong SE250 small four-wheeled tractor. Their ground pressures were 88 kPa, 69 kPa, and 48 kPa, respectively. The parameters of these models and their tires are presented in Tables 2 and 3. The testing equipment for soil cone parameters included, as follows: a CP20 soil cone penetrometer manufactured by Agridry Rimik Pty Ltd. (Toowoomba, QLD, Australia), which was utilized to measure the hardness of the soil; a ring knife for sampling soil cores; the YP-100001 electronic balance produced by Shanghai Yueping Scientific Instrument Co., Ltd. (Suzhou, China), which has a precision of 0.1 mg for weighing soil samples; and a CSIRO disc permeameter produced by A.L. Franklin Engineers (Franklin, TN, USA), which was used to determine soil permeability and penetration resistance.

Table 2. Parameters of machine.

Type	Power (Hp)	Gross Weight (Kg)	Outline Dimension (mm)	Front Wheel Track (mm)	Rear Wheel Track (mm)
HW320	108	5371	6578 × 4500 × 3099	3175	2286
LX750	75	3720	4250 × 2890 × 3160	2360	2280
SE250	25	1280	3320 × 1280 × 1418	1020	1000

Table 3. Parameters of driving wheel.

Tire Specifications	Tire Section Width (m)	The Outer Diameter (m)	Contact Area (m^2)	Contact Pressure (kPa)
16.9–24	0.45	1.35	0.18	88
14.9–30	0.38	1.41	0.16	69
9.5–24	0.24	1.09	0.08	48

2.3. Methods

2.3.1. Experimental Site Preparation

According to the different grounding pressures, the experiment was set up with three treatments: heavy (88 kPa), medium (69 kPa), and light compaction (48 kPa). These treatments were represented by the New Holland HW320 mowing and flattening machine, the Dongfanghong LX750 large-scale tractor, and the Dongfanghong SE250 tractor, respectively. The grounding pressures of each model are shown in Table 3. Each model was grounded for 1, 3, 5, and 7 passes. Repetitive compaction treatments were conducted by passing the machinery over the same track, with a one-hour interval between repetitions to allow for the partial recovery of soil moisture. One plot was allocated for each treatment, each being 10 m × 5 m in size. The experiment was replicated 4 times, resulting in 44 plots. The following randomization measures were implemented: treatments were randomly assigned within the experimental cells; and the order of block tests and the sequence of tests within the cells were also determined randomly throughout the experiment.

2.3.2. Data Recorded

Soil Cone Index measurement: Three points were randomly selected in each plot before and after mechanical crushing to determine the soil cone index. At each point, three consecutive measurements were made using a CP20 soil firmness meter, probing in the depth direction from 0 to 40 cm. These measurements were recorded in a file at 2 cm intervals;

Soil bulk density measurement: For soil bulk density measurement, within a radius of 30 cm around each of the three soil firmness determination points in each test plot, one additional point was sampled. At each point, samples were collected at 0 cm, 10 cm, 20 cm, and 30 cm using a ring knife. Soil samples from the same depth across the three measurement points in each plot were bagged, weighed, and numbered for storage. Subsequently, the samples were dried in an oven at 105~110 °C and reweighed;

Soil-saturated hydraulic conductivity measurement: To measure the saturated conductivity of the soil, one point was selected within a 30 cm radius around each of the three soil firmness measurement points in each plot. Surface soil was collected using a ring knife at these points, weighed, and bagged to determine soil moisture content. Then, the soil permeability at each point was tested using a CSIRO disc permeameter [29,30].

3. Results

3.1. Recovery Dynamics of Soil Bulk Density in Compacted Alfalfa Fields

Over time, the soil structure undergoes a complex dynamic change under the influence of biological activity, water infiltration, temperature fluctuations, and other external forces. To investigate the impact of these changes on the soil structure, we conducted the experiment, which analyzed soil bulk density at different time intervals (1 week, 4 weeks, 8 weeks, and 17 weeks) following compaction. It was found that the initial soil bulk density in each layer varied but remained within ±2% of the baseline values (see Figures 1–3). Analyzing the recovery of soil bulk density for clarity, we found that the slight variations in initial soil bulk density were considered negligible. Because the three types of machinery primarily altered the soil structure in the top 30 cm of the soil profile, the soil structure below this depth was relatively dense. Mechanical compaction acts instantaneously and primarily affects the soil surface. Changes in soil bulk density at deeper layers are typically gradual and influenced by the self-weight of the overlying soil and the gradual settling into the subsoil. Therefore, this study did not conduct observations below 30 cm in depth.

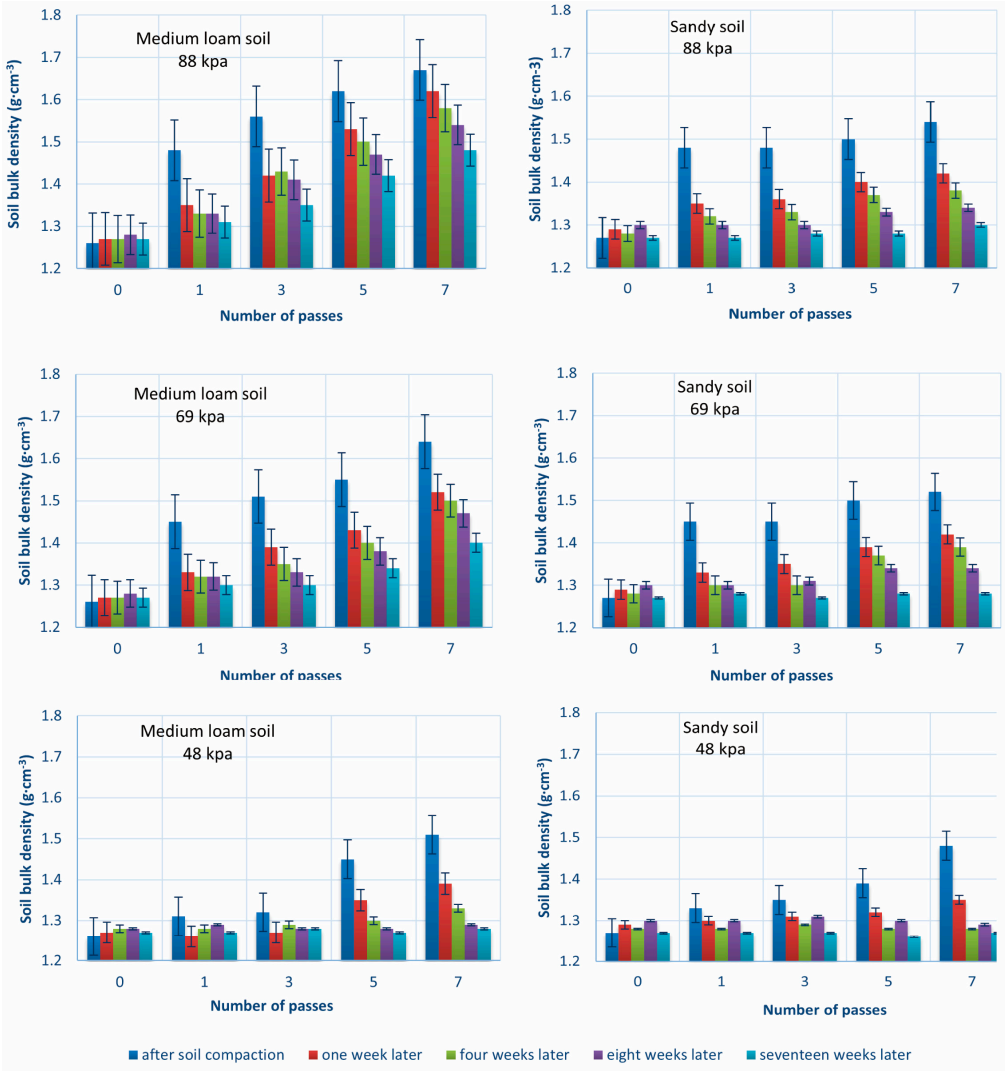


Figure 1. Different types of alfalfa field 0~10 cm depth soil bulk density changes after compaction.

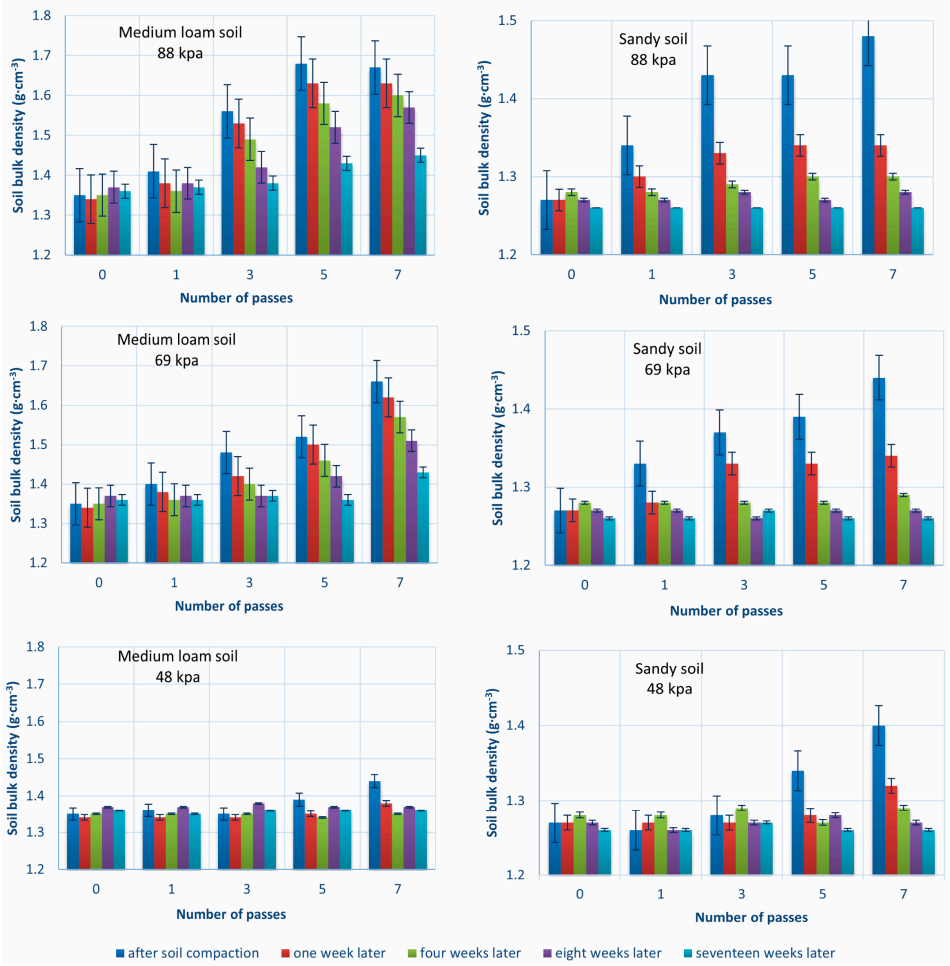


Figure 2. Different types of alfalfa field 10~20 cm depth soil bulk density changes after compaction.

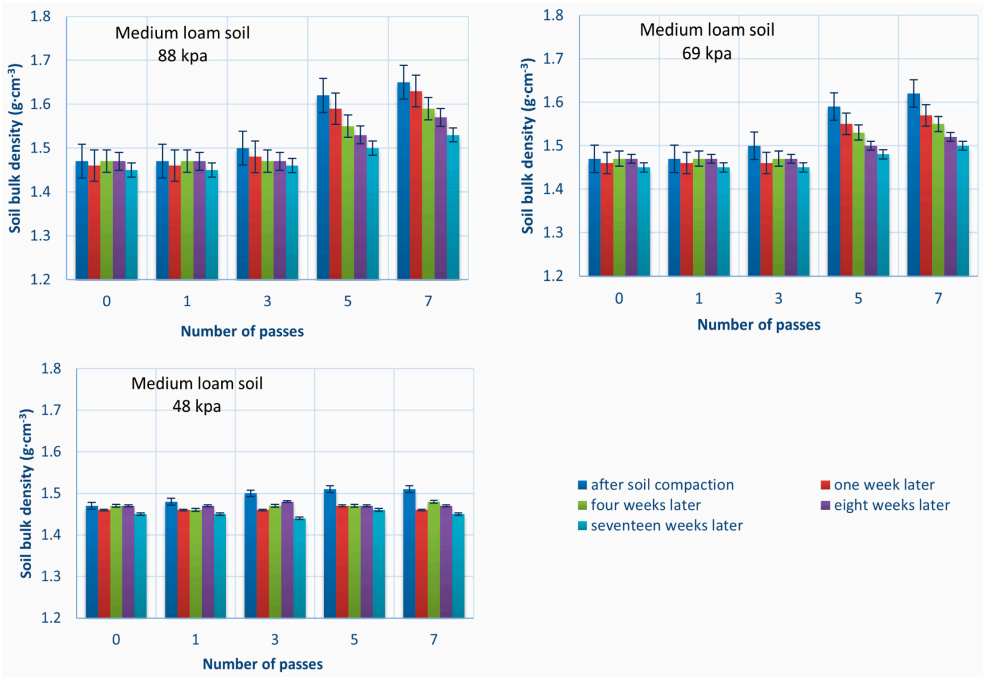


Figure 3. Different types of alfalfa field 20~30 cm depth soil bulk density changes after compaction.

3.1.1. Dynamics of Soil Bulk Density Recovery in the 0~10 cm Soil Layer

Figure 1 illustrates the study of the process of how soil bulk density changes over time in the 0~10 cm layer of medium-loam and sandy soils under three different compaction pressures. As shown in the figure, over time, and with changes in the external environment, the soil bulk density in the 0~10 cm layer of medium-loam soil under each compaction pressure exhibited varying degrees of recovery. The three pressures induced similar trends in soil bulk density changes. One week after compaction, the soil bulk density in the 0~10 cm layer showed a noticeable recovery. For clarity, the rate at which soil bulk density recovered was analyzed; the recovery rate gradually decreased from one to four weeks. The soil bulk density changes were generally minor by four to eight weeks. After 17 weeks, the soil bulk density had not fully recovered to pre-compaction (i.e., the state before any compaction process was applied) levels under compaction pressures of 88 kPa and 69 kPa. However, under 48 kPa compaction, the soil bulk density was wholly recovered after 17 weeks. This indicates that the degree of alfalfa soil compaction recovery is related to the compaction intensity and that, under specific compaction pressures, the soil bulk density may not fully recover to pre-compaction levels even after 17 weeks. The degree of recovery is related to the compaction intensity; higher compaction pressures and more compaction cycles resulted in more severe compaction and slower recovery. The soil bulk density of the 0~10 cm sandy soil layer showed significant recovery under all compaction conditions, with a trend consistent with that of the loamy soil in this layer. The soil bulk density of this layer was restored mainly to pre-compaction levels after 17 weeks. Notably, there was a significant recovery within the first week after compaction, followed by a gradual decrease in the rate of change in soil bulk density over the subsequent periods (1 to 4 weeks, 4 to 8 weeks, and 8 to 17 weeks). The recovery status for soil bulk density was similar across the various experimental intervals. In order to minimize the impact of mechanical compaction on the soil structure of alfalfa land in the 0~10 cm medium-loam layer, efforts should focus on reducing the number of passes by heavy machinery over the same track or enhancing soil-bearing capacity. Post compaction, the topsoil bulk density should be maintained below 1.5 g/cm^3. Over time, the effects of mechanical compaction on the bulk density of alfalfa land in the 0~10 cm sandy soil layer will gradually recover.

3.1.2. Dynamics of Soil Bulk Density Recovery in the 10~20 cm Soil Layer

Figure 2 illustrates the changes in soil bulk density for both soil types from 10~20 cm during the experimental cycle. The figure shows that the process and rate of change in the bulk density of the medium-loam soil in this layer following compaction differ from those in the 0~10 cm layer. The soil bulk density in this layer recovered after compaction under various grounding pressures, and the recovery rate accelerated over time, particularly for the compaction pressures of 69 kPa and 88 kPa. Seventeen weeks after compaction, the recovery degree of the alfalfa field soil bulk density was more pronounced; after the seventh compaction event, the recovery rates for soil bulk density were 6.6% and 5.1%, compared to pre-compaction levels. After the first one to three compactions, the soil bulk density was nearly fully recovered. Following compaction at 48 kPa grounding pressure, the soil bulk density was recovered entirely after 17 weeks. This indicates that the structure of the soil layer after compaction is conducive to recovery, especially for shallower soils. The recovery rate accelerates further when the soil bulk density reaches a specific value.

Such facts indicate that the soil layer's structure after compaction is conducive to recovery, especially for shallower soils. The recovery rate accelerates further when the soil bulk density reaches a specific value. This is primarily due to the shallow position of this soil layer. When subjected to mechanical compaction, the water within the soil pores is extruded. Additionally, this layer has significantly developed the alfalfa's secondary roots and hair roots. Upon unloading the compaction force, the elastic deformation of the alfalfa roots exerts a restoring force on the surrounding soil, leading to the breakup and rearrangement of soil particles. The soil moisture that was initially extruded gradually refills the soil pores during the soil structure recovery process. This layer typically has

a higher soil moisture content than the surface layer, making it less prone to air-drying. The more potent biological activity in this layer also contributes to these effects. After compaction at grounding pressures of 88 kPa and 69 kPa, the degree of soil bulk density recovery in this layer followed the order of 8 to 17 weeks, 4 to 8 weeks, 1 to 4 weeks, and within the first week. At a grounding pressure of 48 kPa, the soil bulk density was fully recovered within the first four weeks after the initial seven compaction events.

The compaction of the medium soil showed a gradual recovery over time. Between 8 and 17 weeks, the soil experienced alternating freeze–thaw cycles and a slightly more extended testing period, resulting in the most excellent recovery. After each compaction at a grounding pressure of 88 kilopascals, the soil bulk density recovered by 60%, 73.6%, 51.6%, and 33.3%, respectively, from the increase in bulk density after compaction, at 4, 8, 12, and 16 weeks. After 17 weeks, the soil bulk density recovered 100%, 91.6%, 100%, and 76.6%, respectively, from the increase in bulk density after compaction. The degree of recovery of the soil bulk density following each compaction at a grounding pressure of 69 kPa was consistent with that at 88 kPa. The recovery speed of the sandy soil bulk density at depths of 10~20 cm was faster than that of the medium soil, and the soil bulk density can be restored to the pre-compaction state within four weeks after each compaction at a grounding pressure of 69 kPa. The speed of soil bulk density recovery within the first week after compaction was higher than during the following three weeks. The recovery speed of soil bulk density within the first week post compaction was higher than that observed in the subsequent three weeks. This can be primarily attributed to the sandy soil's higher coarse grain content, the test area's drier climate, and the irrigation conditions, which resulted in more vital soil permeability and evaporation properties than that of the medium soil. Alternating wet and dry conditions led to a faster recovery of the sandy soil bulk density, allowing it to return to its normal within one month, thereby minimizing the impact on alfalfa growth.

3.1.3. Dynamics of Soil Bulk Density Recovery in the 20~30 cm Soil Layer

The 20~30 cm soil layer is close to the plough sublayer. The first few compaction times have little effect on the soil bulk density of this layer. After three times of compaction, the soil bulk density gradually becomes more extensive, and the increase is insignificant. The soil bulk density in this layer has a relatively higher initial value. At the same time, the porosity is relatively lower, so the extent of soil recovery differs significantly from that in the 0~20 cm layer. Studying soil recovery in this layer is crucial for understanding the status of soil structure alterations near the plough subgrade and for developing scientifically sound tillage practices.

Figure 3 illustrates the changes in the bulk density of the medium-loam soil throughout the experimental cycle. As can be seen, the bulk density of the soil layer remains above 1.47 g/cm^3 before and after each compaction. After more than three compactions, the bulk density increases to over 1.5 g/cm^3, narrowing the soil pore space and making recovery more challenging. Over the 17-week recovery period, after three compactions at 88 kPa and 69 kPa grounding pressures, the soil bulk density did not fully recover, with a slower recovery rate than the upper soil layers. Notably, after seven compactions at 48 kPa grounding pressure, the soil bulk density fully recovered within one week following each compaction. The deeper soil layer was influenced by the self-weight compaction effect of the overlying soil and the repeated compaction over the years due to the lack of tilling in the alfalfa fields. Except for the 88 kPa grounding pressure, which increased the bulk density of the soil in this layer during the one to seven compactions, the 66 kPa and 48 kPa grounding pressures had minimal effects on the bulk density of the sandy soil in this layer. The degree of recovery under these pressures was not further tested.

3.2. Recovery Dynamics of Cone Index in Soils with Different Degrees of Compaction

The soil cone index, a crucial metric for measuring soil penetration resistance, directly influences plant root penetration. An excessively high cone index can impede alfalfa root growth. The impact of the soil cone index on crop growth is a globally recognized concern. Mechanical compaction leads to substantial changes in the cone index across different soil layers, affecting alfalfa root development. Studying the temporal changes in the soil cone index following mechanical action is significant for elucidating the impact of compaction on alfalfa biomass and improving alfalfa harvesting mechanization. The experiment was conducted to investigate the recovery pattern of the cone index in compacted soil. The experiment measured changes in two soil cone indexes at 1, 4, 8, and 17 weeks post compaction. These results are presented in Figures 4–8.

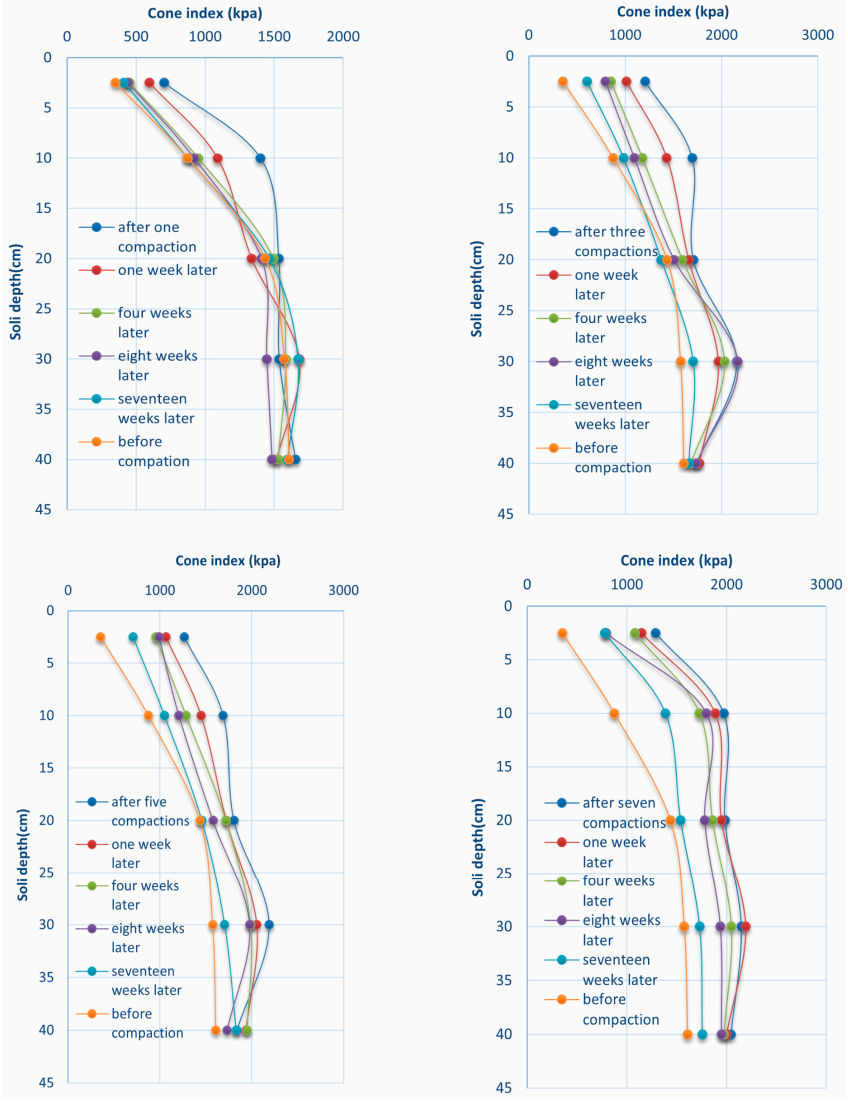


Figure 4. The trend of medium-loam soil firmness over time under different compaction frequencies at a ground pressure of 88 kPa.

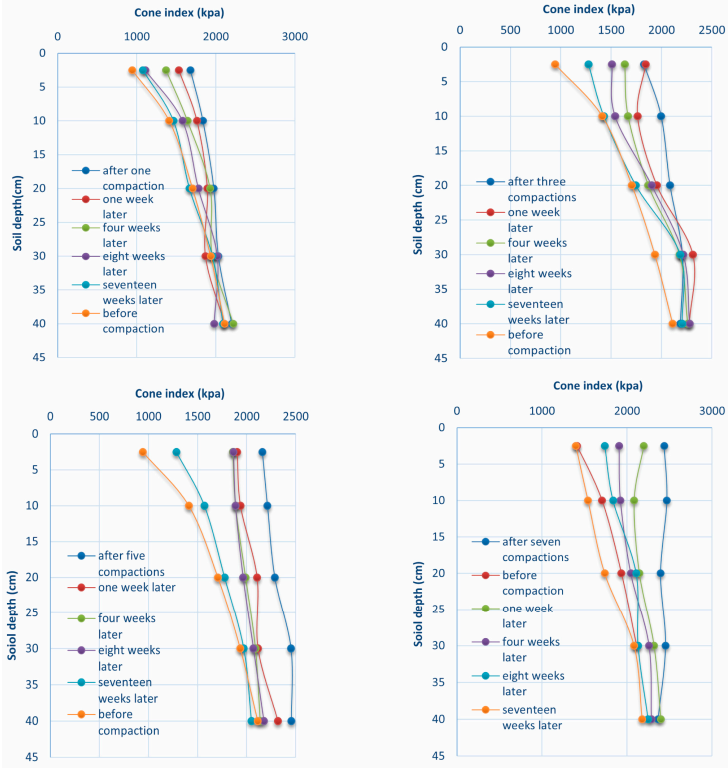


Figure 5. The trend of sandy soil firmness over time under different compaction frequencies at a ground pressure of 88 kPa.

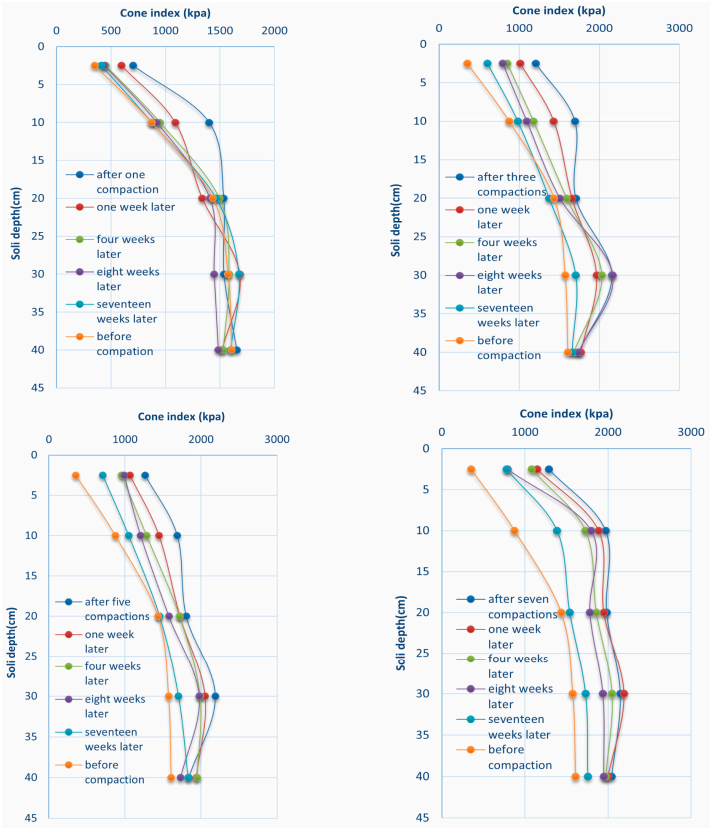


Figure 6. The trend of medium-loam soil firmness over time under different compaction frequencies at a ground pressure of 69 kPa.

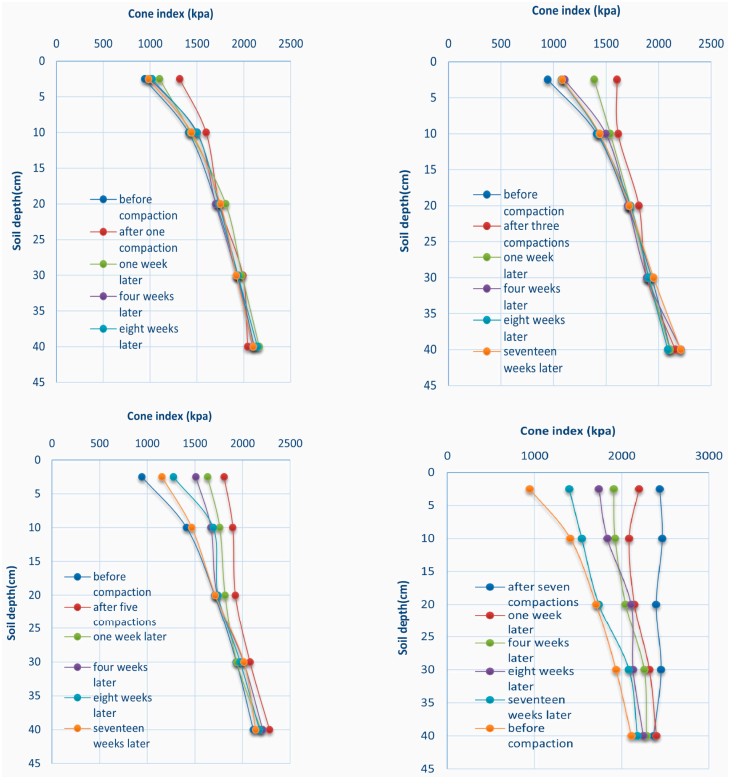


Figure 7. The trend of sandy soil firmness over time under different compaction frequencies at a ground pressure of 69 kPa.

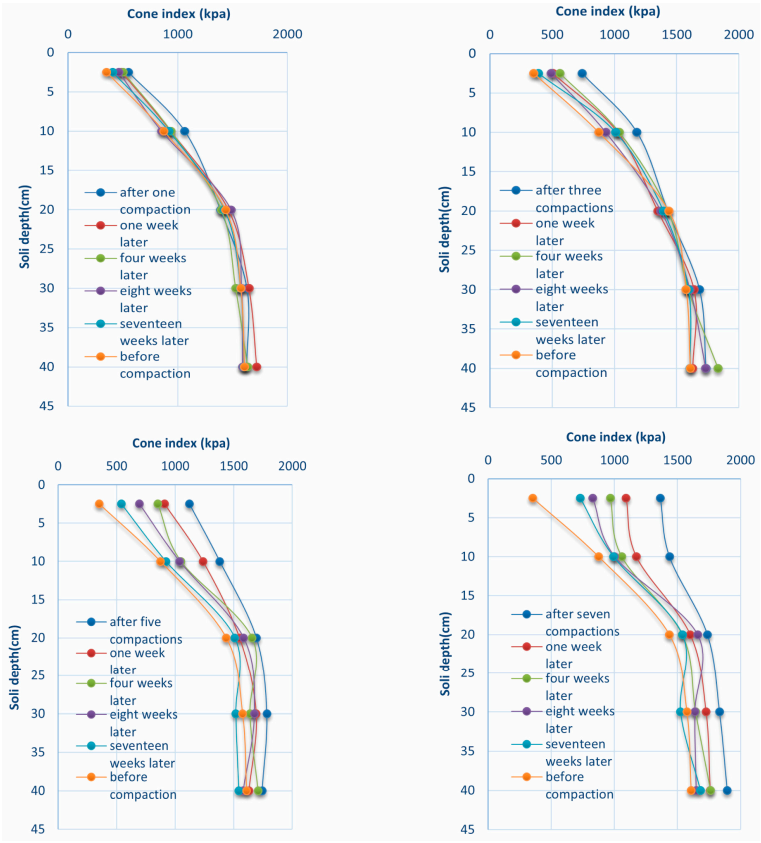


Figure 8. The trend of medium-loam soil firmness over time under different compaction frequencies at a ground pressure of 48 kPa.

As can be seen in Figure 4, with a grounding pressure of 88 kPa, the soil solidity of the medium soil exhibits varying degrees of recovery after each compaction event. Following initial compaction, the soil cone index decreases, moving from the surface downwards. For instance, the 2.5 cm surface layer shows a reduction in the soil cone index from 932 kPa to 656 kPa after one week, which is higher than the pre-compaction state of 352 kPa, with minimal subsequent changes. The soil cone index in the 10~30 cm layer gradually decreased to its initial state over one to eight weeks. The situation indicates that after a single compaction event, the soil cone index decreases layer by layer with time, moving downward through the soil profile. Surface soil is more significantly disturbed by external factors, resulting in faster recovery rates. As we move down the soil profile, the soil cone index increases due to various influences, such as soil moisture dynamics, organic matter decomposition, alfalfa root penetration, and the activities of organisms like earthworms, which collectively slow the process of soil loosening. After three compactions, the soil cone index of each layer further increased, showing a gradual decrease in the rate of increase over time. After surface compaction, the soil cone index in the surface layer was lower than that in the 10~30 cm soil layer, and its recovery speed was slow. After 17 weeks, the cone index in the 20~30 cm layer was still higher than that in the surface layer after three compactions, indicating that the soil retained a significant self-recovery capacity, even after multiple compactions. The three compactions did not significantly alter the cone index of the soil at a depth of 40 cm, and the cone index of the soil below this layer decreased slightly after 17 weeks, indicating that the soil still retained a considerable self-recovery capacity after five to seven compactions. The soil cone index of the 0~30 cm layer increased after five to seven compactions. In contrast, the index of the layer below 30 cm showed no significant change after 17 weeks compared to pre-compaction levels. This suggests that the layer below 30 cm became densely compacted, and that external factors led to some densification in the upper layer, inhibiting the self-repair of the underlying soil structure, which is primarily due to the lower soil becoming overly compacted and forming a hard plow subsoil layer that reduced pore space and affected moisture infiltration. The lower soil layer experienced minimal moisture changes. Additionally, the experimental area, located in a dry farming region of China, is consistently dry with limited irrigation.

Figure 5 illustrates the recovery of the soil cone index for sandy soil following each compaction cycle at a grounding pressure of 88 kPa. As depicted, the initial cone index of the sandy soil at depths ranging from 0~40 cm is relatively high. After compaction using this equipment, the cone index across all layers tends to become uniform, with each layer achieving a cone index exceeding 2000 kPa after three to seven compaction cycles. This value is notably higher than that observed in medium soils. Over time, the surface layer (0~20 cm) exhibits specific behavior. After one to three compaction cycles, it naturally recovers over 17 weeks. The cone index of the 0~20 cm soil layer was higher than that before compaction, owing to a significant increase in the cone index of the upper soil layer post compaction, which led to a relatively slower recovery rate. However, the cone index of the sandy soil at depths less than 20 cm recovered to levels comparable to those before compaction. Specifically, after five to seven compaction cycles, the cone index of the sandy soil at depths less than 20 cm was restored to values similar to those prior to compaction. Compaction significantly impacts the soil cone index, resulting in highly dense soil. Over time, the compactness of various soil layers decreases, but it remains significantly higher compared to conditions without any applied pressure. One week after compaction, the soil in the 0~30 cm layer became looser, with little change. During the 8- to 17-week period, due to the soil's overwintering and the alternating effects of freezing and thawing, there was a more pronounced recovery of the soil cone index. The soil cone index continued to recover; ultimately, the cone index of each soil layer essentially returned to its pre-compaction state.

Figure 6 shows the changes in the soil cone index of the medium soil layer after each compaction at a grounding pressure of 69 kPa. The figure shows that the effect of compaction at this pressure on the soil cone index is similar to that at 88 kPa. Due to one compaction, the soil cone index of the soil layer above 20 cm was restored to the pre-

compaction state after eight weeks. The restoration speed was fast and then slow; the effect of one compaction on the soil cone index of the soil layer below 20 cm was insignificant. Figure 6 illustrates the changes in the soil cone index of the medium soil layer following each compaction cycle at a grounding pressure of 69 kPa. As can be seen, the effect of compaction at this pressure on the soil cone index is similar to that observed at 88 kPa. Due to a single compaction event, the soil cone index of the soil layer above 20 cm was restored to its pre-compaction level after eight weeks, with the recovery rate initially fast and then slowing down. The impact of a single compaction event on the soil cone index of the soil layer below 20 cm was minimal. After three to five compaction cycles, while the cone index of each soil layer increased, the cone index decreased over time. The cone index of the 0~20 cm soil layer initially recovered faster and then slowed down, whereas the 20~30 cm depth soil initially recovered slower and then faster. This indicates that the restoration of the upper layer of medium soil was primarily due to the natural changes in the soil's structure. At the same time, the alternation of freezing and thawing mainly influenced the recovery of the lower soil layer. Four weeks after compaction, the cone index of the 0–40 cm depth soil layer had recovered approximately 50% of its increased value. After 17 weeks, the cone index of each layer had not fully recovered to its initial state. Following seven compaction cycles, the cone index of the soil layer below 10 cm approached 2000 kPa, with a slight decrease in the first eight weeks. The cone index of the surface layer (0~20 cm depth) recovered about 50%, as did the soil layer below 20 cm depth. The cone index of the soil layer below 20 cm decreased by approximately 300~400 kPa.

The effect of this pressure on the soil cone index of the sandy soil layer was more significant, as shown in Figure 7. Each compaction cycle primarily altered the soil cone index of the 0~20 cm soil layer, with this depth experiencing significant recovery over time. After seven compaction cycles, the soil cone index gradually increased along the soil profile; ultimately, the cone index of each soil layer became nearly equal over time. Following this compaction, the soil cone index decreased gradually from the surface downward. The lower soil cone index changes were insignificant, fluctuating around the initial value over time. The soil layer above 30 cm decreased gradually over time. After a 17-week recovery period, the surface soil cone index was equivalent to the level after one compaction cycle. One to three compaction cycles were restored to their original state after one week, while five to seven compaction cycles required one week for the fastest recovery. The recovery speed was the fastest between 8 and 17 weeks; after 17 weeks, more than 70% of the soil cone index was recovered.

Figure 8 depicts the changes in the soil cone index of each soil layer of medium soil after each compaction cycle at a grounding pressure of 48 kPa. The results indicate that after one to seven compaction cycles in this model, the soil cone index at depths up to 2.5 cm can be essentially restored to the state without any applied pressure after a 17-week recovery period. The decrease in the soil cone index mainly occurs in the first eight weeks, gradually slowing down as the depth increases along the soil profile.

Given that the sand cone index of each layer after seven compaction cycles at this grounding pressure is equivalent to the level of three to five compaction cycles at a grounding pressure of 69 kPa, the changes in the soil cone index under this state should be similar, and therefore were not repeated.

3.3. Recovery Dynamics of Saturated Hydraulic Conductivity in Soils with Different Degrees of Compaction

Figure 9 illustrates the trends of the saturated hydraulic conductivity of the two soil types following compaction. As can be seen from the figure, the soil-saturated hydraulic conductivity is extremely sensitive to changes in the degree of compaction. When compaction reaches a certain degree, there is a sharp decrease in soil-saturated hydraulic conductivity. After the compaction of the two soils, the soil-saturated hydraulic conductivity changes over time according to different rules. For the lighter degree of compaction in the medium-loam soil (one to three compaction cycles at a grounding pressure of 69 kPa,

one to five compaction cycles at 69 kPa, and one to seven compaction cycles at 48 kPa), the alfalfa field soil hydraulic conductivity was significantly higher than that immediately after compaction within one week. Changes were not noticeable in the following weeks.

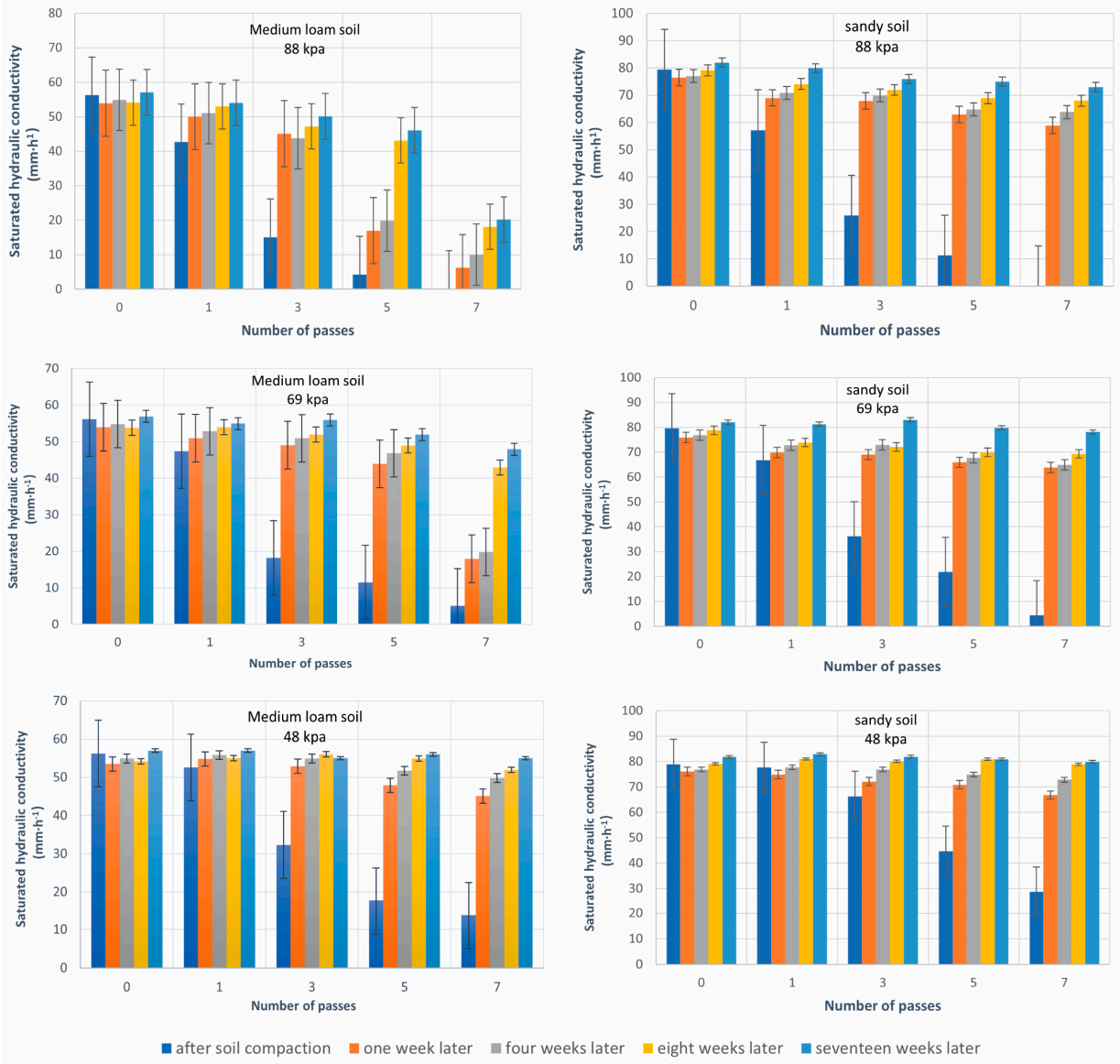


Figure 9. The recovery tread of saturated hydraulic conductivity at different ground pressures.

When the mechanical compaction reached a certain level, the soil-saturated hydraulic conductivity increased within four weeks after compaction, but the increase was insignificant. The saturated hydraulic conductivity of the medium soil was below 20 mm·h^{-1} at four weeks after five compaction cycles at a grounding pressure of 88 kPa. After 8 to 17 weeks, the saturated hydraulic conductivity of the soil recovered to approximately 45 mm·h^{-1}, which was lower than the initial saturated hydraulic conductivity (56 mm·h^{-1}). After 7 compaction cycles, the saturated hydraulic conductivity remained below 20 mm·h^{-1} even 17 weeks later, which was much lower than the pre-compaction level. The soil-saturated hydraulic conductivity was below 20 mm·h^{-1} within four weeks after seven compaction cycles at a grounding pressure of 69 kPa and recovered to between 40~50 mm·h^{-1} after eight weeks. After compaction, the saturated hydraulic conductivity of the sandy soil recovered faster, attaining a value of 60 mm one week subsequent to each compaction cycle, a figure that exceeds the initial saturated hydraulic conductivity of the medium-loam soil.

4. Discussion

Our analysis of the variance of the test data shows that the recovery time of compacted soil, the number of compactions, and the grounding pressure significantly impact soil bulk density and the soil cone index. Over time, the recovery speed of surface bulk density for both soil types was significantly faster than that of other layers. For medium-loam soil, when the compaction degree was low, the recovery of the soil cone index in each layer was more pronounced. However, when the compaction degree was high, the soil cone index of medium-loam soil did not change significantly and remained relatively high. Additionally, grounding pressure and the number of compactions significantly influenced the recovery of soil hydraulic conductivity.

The above phenomena indicate that when mechanical pressure causes the soil bulk density to reach a specific value, regardless of the soil layer, it is difficult for it to recover to its pre-compaction state. This value was generally more than 1.5 g/cm^3 for the tested soils. The surface layer of the two types of soil showed a more remarkable recovery in weight compared with other soil layers. The increase in soil bulk density was more significant in the surface layer than in deeper layers. This is because the surface layer is directly exposed to the external environment, while deeper layers are relatively shielded. The effects of natural forces such as day–night temperature variations, wind, and rain are more pronounced on the surface than on the deeper layers [31]. Also, the soil permeability is more significant in the surface layer [32,33]. The 10~20 cm loamy soil layer had a similar resistance to mechanical compaction and surface layer conditions, meaning that after one to seven compaction cycles at grounding pressures of 69 kPa and 88 kPa, the increase in bulk density was not much different from that in the surface layer. However, due to its slightly lower depth, the soil has strong water retention and moisture retention capabilities, similar to those at the surface layer. Coupled with the gravitational effect of the overlying surface layer, its recovery degree and speed are slightly slower than those of the surface layer. Compaction at a grounding pressure of 48 kPa seven times had a lesser impact on the bulk density of both soils, as the soil structure was not destroyed, allowing for more robust self-repair capabilities and a faster recovery process. The 10~20 cm sandy soil layer was able to recover after four weeks, indicating a more vital self-repairing ability. Primarily, sandy soil particles in this layer were looser than those in other soil layers, the pore space was more significant than that in other layers, and the test site had better irrigation conditions compared with other places, which led to rapid water infiltration and a relatively more stable soil structure than other types of soil [34]. Although the change in the bulk density of the medium-loam soil layer below 20 cm was not significant, its self-repairing ability was weaker. The sandy soil's bulk density did not increase much and was able to recover independently.

Before compaction, the two soils exhibited different soil cone indices due to their differing textures. As a result, the soil cone index of the medium loam in the 0~40 cm soil layer was significantly lower than that of the sandy soil, indicating that the penetration resistance of the medium loam was less than that of the sandy soil. After compaction, the increase in the soil cone index in sandy soil was significantly smaller than that in the medium loam due to the sandy soil's higher bearing capacity. However, the soil cone index of each layer after a single compaction was higher than that of the medium loam after seven compactions with all machine models. Therefore, planting alfalfa in a sandy soil environment significantly increases the resistance of alfalfa roots to growth [35]. Within a certain period after compaction, both soil cone indices recovered to varying degrees, as evidenced by the decrease in the soil cone index of the 0~40 cm measured soil layer after each compaction cycle compared to that of the soil cone index immediately after compaction.

According to Rodrigues, M. F. et al., when soil mechanical resistance exceeds 2 mega-pascals, plant growth may be affected [3]. For the medium-loam soil, when the grounding pressure is greater than 69 kPa, three compactions resulted in the soil cone index of the 10~40 cm layer approaching or slightly exceeding the critical value. However, after one

week of recovery, the value returned to below the critical value. For sandy soil, when the grounding pressure was greater than 69 kPa, one to five compactions caused the soil cone index in the 10~40 cm layer to approach or exceed the critical value. Within four weeks, the value returned to below the critical value. Additionally, since alfalfa roots can reach over 2 m deep, this enhances water absorption. However, as compaction primarily affects the soil cone index in the 10~40 cm layer, it can lead to a reduction in crop yield.

Comprehensive analysis shows that water, climate changes, freeze–thaw cycles, and plant growth significantly influence the restoration of compacted soil structures over time. Such a situation occurs because water promotes the movement and rearrangement of soil particles. Plant root growth penetrates the compacted soil layer, creating tiny channels that improve air and water permeability. Root activities also displace and reorganize soil particles, enhancing the soil structure. Freeze–thaw cycles further break down the compacted structure and promote particle rearrangement, aiding in soil restoration.

5. Conclusions

(1) The recovery of compacted soil is significantly influenced by soil bulk density and firmness. It becomes difficult for soil to recover once the bulk density exceeds 1.5 g/cm^3. The recovery process of the cone index for compacted soil slows down after the ground pressure exceeds 48 kPa. Sandy soils recover more quickly than medium-loam soils, and in terms of saturated hydraulic conductivity, medium-loam soils recover more slowly than sandy soils;

(2) The experiment demonstrates that the recovery degree of surface soil bulk density for both soils is greater than that of other soil layers. The recovery degree and speed of the 10~20 cm layer of medium-loam soil are slightly slower than that of surface soil. A grounding pressure of 48 kPa does not severely damage the soil structure, leading to a faster recovery. The 10~20 cm sandy soil layer can recover within four weeks. The capacity of the medium-loam soil layer below 20 cm does not vary much, but the soil is less able to self-repair. The capacity of sandy soil does not increase much and can recover independently. The capacity of the medium-loam soil layer below 20 cm can be restored after four weeks. However, the change in the capacity of the medium-loam soil layer below 20 cm is insignificant; the soil can still recover by itself;

(3) As time progresses, the recovery degree of the soil cone index for each layer of medium-loam soil with lower compaction is more noticeable. After recovering the soil cone index, the cone index of medium-loam soil with higher compaction remains high. The change in the cone index of each layer of sandy soil after compaction at various grounding pressures is influenced by multiple factors. Except for the firmness not fully recovered after multiple compactions at 88 kPa and 69 kPa, the rest of the soil cone indices can be restored to their pre-compaction state after compaction;

(4) The soil hydraulic conductivity in the alfalfa field significantly increased within one week after compaction of the lighter medium-loam soil compared to that immediately after compaction, with little change in the subsequent weeks after five compactions with a grounding pressure of 88 kPa. The saturated hydraulic conductivity of the medium-loam soil remained below 20 $mm \cdot h^{-1}$ within four weeks. After 17 weeks, the saturated hydraulic conductivity of the soil recovered to around 45 $mm \cdot h^{-1}$. However, after 7 compactions, the saturated hydraulic conductivity of the soil was still below 20 $mm \cdot h^{-1}$ even after 17 weeks, which was significantly lower than the pre-compaction level. After seven compactions with a grounding pressure of 69 kPa, the soil's saturated hydraulic conductivity was lower than 20 mm/h^{-1} for four weeks and then recovered to 40–50 mm/h^{-1} after eight weeks. The saturated hydraulic conductivity of sandy soil recovered faster, reaching 60 mm/h^{-1} in one week after each compaction.

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administration, A.G.; funding acquisition, A.G. and W.S. All authors have read and agreed to the published version of the manuscript.

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