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Effects of soil moisture content and tractor wheeling intensity on traffic-induced soil compaction

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Abstract

Soil compaction causes deleterious effects on physical and mechanical proprieties of agricultural soils. In order to investigate the effect of soil moisture content and tractor wheeling intensity on traffic-induced soil compaction, this study was carried out on a field with clay loam soil. Soil dry bulk density and hydraulic conductivity as well as emergence percentage of corn seedlings and dry mass of the sampled mature plants were considered the dependent variables of the experiment. Independent variables consisted of soil moisture content with five levels (12, 15, 17, 19, and 21%), traffic intensity with three levels (four, two, and zero passes of tractor wheel (tractor model: John Deere 3350) from the entire area of the plot), and soil sampling depth with three levels (0-10, 10-20, and 20-30 cm). According to the results of this study, gradual increase in soil water content generally resulted in an increase in soil bulk density; moreover, increasing the tractor wheeling intensity from 0 to 4 passes increased bulk density by 13%. Furthermore, the driest soil water content had the highest and the wettest soil water content had the lowest emergence percentage of corn seedlings among the treatments; moreover, traffic intensity treatment inversely affected the emergence percentage of corn seedlings and the dry mass of mature plants. To sum up, these results indicate that, for improving water permeability and reducing dry bulk density of the examined clay loam soil, as well as better emergence of corn seedlings and ultimately increasing crop yield, it is recommended to avoid wheeling when soil moisture content is high, reduce the number of machinery wheel passes from the farm as low as possible, and restrict the wheel passes to fixed strips along the field, whenever possible.

Keywords: bulk density, hydraulic conductivity, soil compaction, soil tillage, soil water content

Introduction

Traffic-induced soil compaction causes deleterious effects on seedbed quality; soil strength and bulk density; pore space, water holding capacity, infiltration, and drainage characteristics of soil, and vehicle and implement performance.

Arvidsson and Håkansson (1996) summarized their many years of work on the subject of soil compaction effects on seedbed quality. They stated: "Soil compaction was found to increase the tensile strength and size of individual aggregates and thus reduce the aggregate size distribution and ultimately the heterogeneity of the soil components. Greater cloddiness is an underlying feature of compacted soils and therefore seedbed and root bed qualities are more assured under a controlled traffic regime".

Chamen (2011), in abstracting extensive literature review on the subject of soil compaction effects on soil strength and bulk density concluded that: "Imposed wheel loads caused an increase in soil bulk density, even when flood irrigation was utilized. This issue recommends that the level of soil damage was more affected by susceptibility and vulnerability of soils rather than wheel loads by itself. This issue is expected, because soil responses depend on the initial state of soil, ground pressure of the applied loads, and soil moisture content, few of which are constant between soil types. Although greater stresses in the soil were reported using heavier vehicles, lighter vehicles can cause just as much damage when used repeatedly". On the other hand, it was found that mechanical compaction can cause harmful effects on water infiltration rate of any type of soil (Li et al., 2001). Without wheelinduced compaction, soil water infiltration rate increased by 84 to 400% together with rises in plant available water (Boydell and Boydell, 2003); in these circumstances, not only the risk of flooding is reduced, but also rainfall interception is enhanced, which is an advantage, particularly for regions where the risk of drought is high (Li et al., 2007).

Finally, removing wheel-induced compaction from agricultural soils reduces power requirements of tillage as well as the need for tillage by itself; for example, experiments on the effects of different traffic systems across northern Europe in the early 1980s resulted in 29-87% saving in energy requirement of zero traffic system within cereal rotations compared to the other systems (Chamen et al., 1992). In controlled-traffic systems, energy savings are comprised of savings from fewer operations, shallower depths of operation, and lower draft requirements of the involved implement. Moreover, operation of tillage implements in non-compacted fields resulted in an increase of implement durability due to less abrasion from lower density soils (Owsiak, 1999).

On the other hand, severity of the wheel-induced soil compaction depends on the following parameters: soil texture and structure (Jones et al., 2003), soil moisture content (Yavuzcan et al., 2005), type and dynamic load of compressing wheel (Javadi and Spoor, 2006), Aksakal and Oztaş, 2010), velocity of tractor (Stafford and Mattos, 1981), and number of tractor passes (Botta et al., 2006).

It seems that, among these parameters, a farmer is able to control the value of soil moisture content and some of the tractor-related parameters; therefore, the aim of this study is the examination of the effects of soil moisture content and number of tractor passes on the compaction of a clay loam soil. The dependent variables are soil dry bulk density, coefficient of hydraulic conductivity of soil samples taken from three different sampling depths, percentage of silage-corn seedling emergence, and dry mass of mature plant before harvest.

Materials and Methods

Experiments were conducted during 2013 growing season at IAU-Isfahan Branch Research Station Farm (32°2´ N, 51°25´ E, 1600 m above sea level) in central Iran. Texture of the examined soil was clay loam. In order to loosen the pre-compacted soil, the considered area was tilled deeply. Then, after disk harrowing, leveling, and ridging, the prepared plots were irrigated thoroughly and were allowed to be dried naturally. In order to perform the required experiments, fifteen plots were prepared to be compacted with tractor wheels; however, these plots were randomly divided into five groups, each which consisting of three plots. Every one of the five groups was devoted to one level of soil moisture content treatment, i.e. five different moisture contents (12, 15, 17, 19, and 21%) were considered the main independent variable.

Each of the three plots in every main group was devoted to one level of soil compaction treatment, i.e. the second independent variable was compaction treatment consisting of three levels. Different levels of the compaction treatment were accomplished using different numbers of passes of tractor wheel (tractor model: John Deere 3350) from the entire area of the plot. Three levels of compaction treatment were in accordance with four, two, and zero passes of tractor wheel from the entire area of the plot. The examined soils were sampled from three different sampling depths (0-10, 10-20, and 20-30 cm), i.e. sampling depth was considered the third independent variable with three levels. The soil samples were obtained by penetrating a metal ring with 5.3 cm internal diameter and 5.6 cm height into the soil with a rubber hammer and removing it from the ground with a shovel. The dependent variables were soil dry bulk density (BD) calculated from the weight of soil samples after 24 h of oven drying divided by the volume of the sampling ring, and hydraulic conductivity (K) of the soil samples. The hydraulic conductivity of soil was measured using falling head method of the soil permeability test which is suitable for measuring the hydraulic conductivity of fine-grain soils. Soil hydraulic conductivity was calculated using the formula

$$K = \frac{2.3 \times a \times l \times log\left(\frac{h_1}{h_2}\right)}{A \times (t_2 - t_1)}$$

(BS standard 1377-5: 1990). The measuring apparatus of K consisted of a thin pipe seamlessly connected to the soil sampling ring. The pipe forms a passage to flow water to the saturated soil sample. In the formula of K, a and A are the thin pipe and the soil sample cross sectional area respectively; h_1 and h_2 are the heights of water in the thin pipe at time t_1 and t_2 respectively, and L is the length of soil sample. The above-mentioned dependent variables i.e. soil dry bulk density (BD) and hydraulic conductivity (K) of the soil samples were measured with three replications. Then, silage corn seeds were manually planted in the examined plots and emergence percentage of corn seedlings as well as the dry mass of the sampled mature plants (average weight of the three sampled plants) obtained from the plots with different moisture contents during the application of tractor wheeling intensity treatment were measured as well. The acquired data were analyzed in SAS software (SAS 9.1.3 Service Pack 4).

Results and Discussion

a) Soil dry bulk density and hydraulic conductivity

Values of soil dry bulk density (BD) and hydraulic conductivity (K) measured from different levels of soil water content, number of tractor wheel passes, and soil sampling depth treatments are presented in Table 1 (Note: In all tables mean values followed by the same letter(s) are not significantly different at probability P<0.01 according to least significant difference (LSD)). All of the examined treatments had significant effects on BD. Gradual increase in soil water content generally resulted in an increase in BD. The standard proctor test (BS 1377-4: 1990) conducted on this soil (Figure 1) indicates that the optimum soil water content for the compaction of this type of soil was about 20%; therefore, the obtained result is rational. It is necessary to note that the compaction of soil is the process by which the solid particles are packed more closely together, usually by mechanical means, thereby increasing the dry density of the soil. The dry density, which can be achieved, depends on the degree of compaction applied and on the amount of water present in the soil. For a given degree of compaction of a given cohesive soil there is a moisture content at which the dry density obtained reaches a maximum value. In the standard proctor test, this moisture content is considered as the optimum water content.

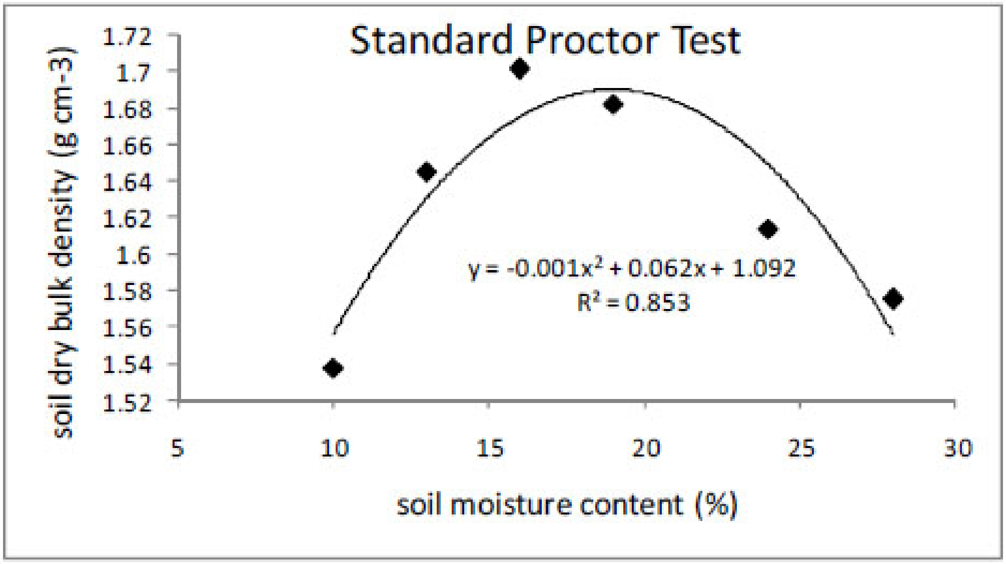

Figure 1. Standard proctor test indicating the optimum moisture content from which the most dry bulk density value will be resulted using laboratory experiment procedure

Moreover, on average, increasing the tractor wheeling intensity from 0 to 4 passes increased BD by 13%. Furthermore, increasing soil sampling depth from 0-10 cm to 20-30 cm led to the decreased BD by 5%.

Table 1. Dry bulk density and hydraulic conductivity of the soil samples as affected by five levels of soil water content, three levels of compaction treatment, and three different sampling depths*

Treatment	Dry bulk density of soil sample ($g*cm^{-3}$)	Hydraulic conductivity of soil samples ($cm*min^{-1}$)
Soil water content (% dry basis)		
12	1.46 ^{e}	0.298 ^{a}
15	1.52 ^{d}	0.288 ^{b}
17	1.55 ^{c}	0.265 ^{c}
19	1.58 ^{b}	0.255 ^{d}
21	1.63 ^{a}	0.242 ^{e}
Number of tractor wheel passes		
0	1.42 ^{b}	0.357 ^{a}
2	1.62 ^{a}	0.229 ^{b}
4	1.61 ^{a}	0.223 ^{c}
Soil sampling depth (cm)		
0-10	1.59 ^{a}	0.269 ^{a}
10-20	1.55 ^{b}	0.27 ^{a}
20-30	1.51 ^{c}	0.27 ^{a}

*In each column, within treatment (soil water content, number of tractor wheel passes or soil sampling depth), means followed by the same letter are not significantly different at probability $P<0.01$ according to least significant difference (LSD)

Hydraulic conductivity measurements showed significant differences among soil water content and traffic intensity treatments, while soil sampling depth had no effect on the hydraulic conductivity of the soil samples (Table 1). Increasing the tractor wheeling intensity from 0 to 4 passes and soil water content from 12 to 21% decreased soil permeability by 6% and 23%, respectively. The soil moisture content×compaction intensity interaction for BD and K is shown in Table 2.

Table 2. Interactive effect of soil moisture content and compaction intensity on BD and K*

Soil water content (% dry basis)	Dry bulk density of soil sample (g*cm^{-3}) Number of tractor wheel passes			Hydraulic conductivity of soil samples (cm*min^{-1}) Number of tractor wheel passes		
	0	2	4	0	2	4
12	1.43 ^{gh}	1.49 ^{fg}	1.47 ^{gh}	0.364 ^{a}	0.269 ^{d}	0.262 ^{d}
15	1.44 ^{gh}	1.57 ^{de}	1.55 ^{ef}	0.368 ^{a}	0.254 ^{e}	0.244 ^{f}
17	1.43 ^{gh}	1.61 ^{d}	1.6 ^{de}	0.357 ^{b}	0.226 ^{g}	0.213 ^{h}
19	1.41 ^{h}i	1.68 ^{bc}	1.66 ^{cd}	0.354 ^{b}	0.207 ^{i}	0.204 ^{i}
21	1.38 ^{i}	1.73 ^{ab}	1.78 ^{a}	0.347 ^{c}	0.191 ^{j}	0.189 ^{j}

*In each dependent variable (dry bulk density or hydraulic conductivity) within treatment (soil water content × tractor wheel intensity), means followed by the same letter are not significantly different at probability $P<0.01$ according to least significant difference (LSD)

The results indicate that, under the moistest condition (21%), compaction of the soil with four passes of tractor wheels yielded a significantly higher value of BD and lower value of K than the other traffic intensities.

The effect of two-way interactions between soil sampling depth and compaction intensity on BD and K is given in Table 3.

Table 3. Interactive effect of soil sampling depth and compaction intensity on BD and K*

Soil sampling depth (cm)	Dry bulk density of soil sample (g*cm^{-3}) Number of tractor wheel passes			Hydraulic conductivity of soil samples (cm*min^{-1}) Number of tractor wheel passes		
	0	2	4	0	2	4
0-10	1.38 ^{d}	1.40 ^{d}	1.48 ^{c}	0.355 ^{a}	0.356 ^{a}	0.360 ^{a}
10-20	1.57 ^{b}	1.62 ^{a}	1.65 ^{a}	0.230 ^{b}	0.229 ^{b}	0.229 ^{b}
20-30	1.57 ^{b}	1.63 ^{a}	1.63 ^{a}	0.222 ^{c}	0.224 ^{c}	0.222 ^{c}

*In each dependent variable (dry bulk density or hydraulic conductivity) within treatment (soil sampling depth × tractor wheel intensity), means followed by the same letter are not significantly different at probability $P<0.01$ according to least significant difference (LSD)

At a given soil sampling depth, the K value was statistically similar for all traffic intensities; but, at a given traffic intensity, the value of K for shallow depth was significantly higher than that for the deeper one. Moreover, the BD was statistically similar for trafficked areas for all the sampling depth treatments, except for 0-10 cm, at which the value of BD for shallow depth was significantly lower than that for other depths. The same trend was observed for BD between different sampling levels of non-trafficked treatment.

The soil moisture content×soil sampling depth interaction for K is shown in Table 4.

Table 4. Interactive effect of soil moisture content and soil sampling depth on K*

Soil water content (% dry basis)	Hydraulic conductivity of soil samples (cm*min^{-1})		
	Soil sampling depth (cm)		
	0-10	10-20	20-30
12	0.298 a	0.296 ab	0.301 a
15	0.285 c	0.291 bc	0.288 c
17	0.263 d	0.267 d	0.267 d
19	0.255 e	0.255 e	0.255 e
21	0.246 f	0.240 f	0.242 f

*Means followed by the same letter are not significantly different at probability P<0.01 according to least significant difference (LSD)

The results indicate that, under the moistest condition (21%), the K values for different sampling depths were at their lowest level; however, with decreasing soil moisture content, higher K values were resulted regardless of the soil sampling depth treatment levels.

The soil moisture content×soil sampling depth×compaction intensity interactions were significant (P<0.01) for soil hydraulic conductivity. Under dry conditions (12%), deep soil sampling (20-30 cm) from non-trafficked plots resulted in the highest value for the parameter of soil water permeability than the other compaction intensity treatments (Table 5).

Table 5. Interactive effect of soil moisture content, soil sampling depth, and compaction intensity on K*

Soil water content (% dry basis)	Number of tractor wheel passes	Hydraulic conductivity of soil samples (cm*min^{-1}) Soil sampling depth (cm) 0-10	10-20	20-30
12	0	0.362^{bcd}	0.356^{cde}	0.375^{a}
	2	0.271^{f}	0.269^{fg}	0.267^{fgh}
	4	0.260^{fghi}	0.265^{fgh}	0.263^{fghi}
15	0	0.359^{bcd}	0.370^{ab}	0.365^{abc}
	2	0.254^{hijk}	0.258^{fghij}	0.251^{ijk}
	4	0.242^{k}	0.245^{k}	0.247^{jk}
17	0	0.352^{de}	0.359^{bcd}	0.361^{bcd}
	2	0.225^{lmn}	0.229^{l}	0.226^{lm}
	4	0.213^{no}	0.215^{mno}	0.213^{no}
19	0	0.354^{cde}	0.355^{cde}	0.354^{cde}
	2	0.208^{o}	0.205^{op}	0.209^{o}
	4	0.205^{opq}	0.207^{o}	0.203^{opq}
21	0	0.352^{de}	0.344^{e}	0.345^{e}
	2	0.194^{pqr}	0.188^{r}	0.193^{pqr}
	4	0.192^{qr}	0.189^{r}	0.188^{r}

*Means followed by the same letter are not significantly different at probability P<0.01 according to least significant difference (LSD)

The general trend that can be obtained from Table 5 is that the lowest K values were resulted with increasing the level of soil moisture content and traffic intensity treatments. However, the parameter of K was statistically similar for shallow (0-10 cm), moderate (10-20 cm), and deep (20-30 cm) sampling depths for all traffic intensity and soil water content treatments, except for the soil samples taken from the driest plot with no-traffic treatment, in which the value of K for deep sampling depth was significantly higher than that for moderate and shallow sampling depths.

The present experiment data about the close dependence of soil bulk density and traffic intensity were similar to the results obtained by Dao (1996). He concluded that reduced traffic intensity and lack of tillage were the reasons for both lower surface and sub-surface density of no-till compared with ploughing. Similarly, Unger (1996) noted that increases in bulk density and penetration resistance within no-till and conventional tillage (discing and disc bedding) production systems for wheat and grain sorghum on a clay loam, were confined to traffic zones, not tillage method. Furthermore, in this study, increasing soil sampling depth from 0-10 cm to 20-30 cm led to the decrease of BD by 5%. Similarly, Botta et al. (2008) investigated cross and radial ply tire effects on soil penetration resistance and found increased penetration resistance to 15 cm depth, but lower resistance in the 15-30 cm profile.

Results obtained regarding the effect of tractor wheeling intensity and soil water content on soil permeability were in agreement with those obtained by Lamers et al. (1986) in their experiment on controlled traffic farming in the Netherlands. They found that permeability on the non-trafficked soil was approximately doubled compared with the trafficked soil (3 m day^{-1} compared to1.5 m day^{-1}).

b) Emergence percentage of seedlings and dry mass of mature plants

The emergence percentage of corn seedlings as well as dry mass of the sampled mature plants (average weight of three sampled plants) obtained from the plots with different moisture contents during the application of tractor wheeling intensity treatment is tabulated in Table 6.

Table 6. Effect of soil water content and compaction intensity on the emergence percentage of corn seedlings and dry mass of the sampled mature plants*

Treatment	Emergence percentage of corn seedlings (%)	Dry mass of the sampled mature plants (kg)
Soil water content (% dry basis)		
12	89 ^{a}	0.89 ^{b}
15	84 ^{b}	0.92 ^{a}
17	77 ^{c}	0.89 ^{b}
19	66 ^{d}	0.88 ^{b}
21	63 ^{d}	0.75 ^{c}
Number of tractor wheel passes		
0	97 ^{a}	1.25 ^{a}
2	72 ^{b}	0.82 ^{b}
4	59 ^{c}	0.52 ^{c}

*In each column, within treatment (soil water content or number of tractor wheel passes), means followed by the same letter are not significantly different at probability $P<0.01$ according to least significant difference (LSD)

The driest soil water content had the highest and the wettest soil water content had the lowest emergence percentage of corn seedlings among the treatments;

furthermore, traffic intensity treatment inversely affected the emergence percentage of corn seedlings (Table 6), which may be attributed to increased dry soil bulk density and reduced water permeability in soil resulting from the increase in soil water content and traffic intensity treatments (Table 2). The interaction of soil moisture content×number of tractor wheel passes for the emergence percentage of corn seedlings and dry mass of the sampled mature plants is shown in Table 7.

Table 7. Interactive effect of soil moisture content and compaction intensity on the emergence percentage of corn seedlings and dry mass of the sampled mature plants*

Soil water content (% dry basis)	Emergence percentage of corn seedlings (%)			Dry mass of the sampled mature plants (kg)		
	Number of tractor wheel passes			Number of tractor wheel passes		
	0	2	4	0	2	4
12	97 ^{a}	88 ^{c}	82 ^{cd}	1.26 ^{ab}	0.95 ^{d}	0.64 ^{g}
15	98 ^{a}	84 ^{cd}	71 ^{e}	1.28 ^{a}	0.88 ^{e}	0.58 ^{h}
17	97 ^{a}	69 ^{e}	65 ^{f}	1.26 ^{ab}	0.86 ^{e}	0.54 ^{hi}
19	97 ^{a}	56 ^{g}	46 ^{h}	1.24 ^{b}	0.76 ^{f}	0.46 ^{j}
21	96 ^{ab}	64 ^{f}	30 ^{i}	1.21 ^{bc}	0.66 ^{g}	0.39 ^{k}

*In each dependent variable (emergence percentage of corn seedlings or dry mass of the mature plants) within treatment (soil water content × tractor wheel intensity), means followed by the same letter are not significantly different at probability P<0.01 according to least significant difference (LSD)

The results indicate that, under the moistest condition (21%), compaction of soil with four passes of tractor wheels yielded significantly lower value of emergence percentage of corn seedlings and dry mass of the sampled mature plants compared to the lower traffic intensity treatments (Figure 2), which could be explained by the fact that less compacted plots resulted in the development of better plant root system (with thicker root branches) than more compacted plots (Figure 3).

Figure 2. Images of the experimental plots taken two months after planting for the treatment of a) non-trafficked and b) trafficked with four passes of tractor wheel (soil moisture content: 21%)

Figure 3. Images showing plant size and root volume obtained from the experimental plots for the treatment of a) non-trafficked and b) trafficked with four passes of tractor wheel (soil moisture content: 21%)

In this study, traffic intensity treatment inversely affected the emergence percentage of corn seedlings, which was in accordance with Botta et al. (2006) who found that multiple passes with a tractor (1 ton maximum wheel load) had deleterious effects in direct drilled topsoil, rendering it unsuitable for seedling emergence. With 10-12 passes of this tractor, compaction effects (increases in BD and penetration resistance) reached 60 cm depth in the same profile.

The present study indicates that, under the moistest condition, compaction of soil with four passes of tractor wheels yielded a significantly lower value of emergence percentage of corn seedlings and dry mass of the sampled mature plants compared to the lower traffic intensity treatments. Similarly, Håkansson I. (2005) reported that, "Compaction implies a decrease in total pore volume and particularly affects the larger pores and voids between aggregates. The continuity of the macro-pore system is also impaired, leading to poor aeration, infiltration, and transport of water. Resultant tighter bonding between soil particles and aggregates increases soil strength and, together with poor soil aeration, leads to reduced crop root growth and poorer uptake of water and nutrients".

Conclusion

A field experiment was carried out to investigate the effect of soil moisture content and tractor wheeling intensity on traffic-induced soil compaction, in a clay loam soil in central Iran. Five different moisture contents (12, 15, 17, 19, and 21%) were considered the main independent variable. The second independent variable was compaction treatment consisting of three levels. Three levels of compaction treatment were in accordance with four, two, and zero passes of tractor wheel from the entire area of the plot. The examined soils were sampled from three different sampling depths (0-10, 10-20, and 20-30 cm), i.e. sampling depth was considered the third independent variable with three levels. The dependent variables were soil dry bulk density (BD) and hydraulic conductivity (K) of the soil samples. Then, silage corn seeds were manually planted in the examined plots and emergence percentage of corn seedlings as well as the dry mass of the sampled mature plants (average weight of the three sampled plants) obtained from the plots with different moisture contents during the application of tractor wheeling intensity treatment were measured as well. According to the results of this study, gradual increase in soil water content generally resulted in an increase in soil bulk density; moreover, increasing the tractor wheeling intensity from 0 to 4 passes increased bulk density by 13%. Furthermore, the driest soil water content had the highest and the wettest soil water content had the lowest emergence percentage of corn seedlings among the treatments; moreover, traffic intensity treatment inversely affected the emergence percentage of corn seedlings and the dry mass of mature plants. To sum up, these results indicate that, for improving water permeability and reducing dry bulk density of the examined clay loam soil, as well as better emergence of corn seedlings and ultimately increasing crop yield, it is recommended to avoid wheeling when soil moisture content is high, reduce the number of machinery wheel passes from the farm as low as possible, and restrict the wheel passes to fixed strips along the field, whenever possible.

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