Impact of tire compaction on hydro-thermal feature of sandy and loam soils

Wang Xianliang, Wang Qingjie*, Li Hongwen, He Jin, Lu Caiyun, Niu Qi, Xu Qimeng, Zhang Yufan, Huang Xingyuan

(College of Engineering, Beijing Key Laboratory of Optimized Design for Modern Agricultural Equipment, China Agriculture University, Beijing, 100083, China)

Abstract: In order to study the effect of soil compaction on soil hydro-thermal feature, field experiments were carried out on sandy and loam soils in Hebei Province. The experiments were performed in randomized complete block design with three replications. Effects of five different kinds of compaction frequencies (1, 3, 5, 7 and 9 times) and a control treatment of no compaction on soil volume water content, soil water storage, soil temperature and crop yield were analyzed. The results showed that soil compaction could increase soil bulk density under sandy and loam soils at 0-40 cm soil depth. From the entire growth cycle analysis, soil compaction treatment significantly increased the soil volume water content and water storage, the 9 passes maximum increase by 35.4%, 34.1% respectively, compared to control treatment on sandy soil; 3 passes treatment could increase the soil volume water content and water storage on loam soil, the maximum growth rate were 12.4%, 9.1% respectively, compared to control treatment, at 0-20 cm soil depth. Reversely, soil compaction could decrease volume water content and soil water storage on sandy and loam soil at 20-80 cm soil depth. During the whole growing season, soil compaction decreased soil temperature at 0-10 cm soil layer, the range of temperature reduction were 6.8%-19.3% on sandy soil, 6.7%-50.3% on loam soil, respectively. However, soil compaction treatment has no significant effect on soil temperature at 20 cm depth on flaxen and loamy soil. . Soil compaction could decrease maize yield, caused a decline in maize yield of 0.3%, 1.0%, 5.6%, 6.1%, 9.3% in sandy soil, 0.6%, 3.6%, 6.9%, 12.0%, 17.1% in loam soil, respectively, with 1, 3, 5, 7 and 9 pass, compared to control treatment. So, we can take advantage of the soil hydro-thermal feature principle in farm production, such as adjusting the suppression device combination the climate, to keep the good moisture and temperature condition. And this study also can be helpful in the promotion of the soil hydro-thermal feature in compacted areas under different soil type in North China.

Keywords: tire, soil compaction, soil hydro-thermal feature, crop yield

Citation: Wang, X. L., Q. J. Wang, H. W. Li, J. He, C. Y. Lu, Q. Niu, Q. M. Xu, Y. F. Zhang, and X. Y. Huang. 2017. Impact of tire compaction on hydro-thermal feature of sandy and loam soils. International Agricultural Engineering Journal, 26(3): 1–11.

1 Introduction

The distribution of water and heat in soil is an important indicator of the energy cycle of soil material, which has important influence on soil comprehensive characteristics and crop growth. Research shows that the suitability of soil moisture and temperature is the most important environmental feature for crop growth. For instance, the unsuitable soil moisture and temperature significantly delayed crop growth, especially in seedling stage (Helms et al., 1996). At present, agricultural machinery in China increasingly developed into the large scale, and operations were up to 11 times from sowing to harvesting, which destroyed the soil structure and caused soil compaction (Botta et al., 2008; Wang et al., 2015). Soil compaction decreases porosity between soil particles, reduces soil macrospores, water movement and the energy exchange between the upper and lower layers, which ultimately affects crop growth (Botta et al., 2016;

Received date: 2017-07-03 **Accepted date:** 2017-07-20

* **Corresponding author:** Wang Qingjie, Associate Professor, College of Engineering, China Agricultural University, No.17, Qinghua East Road, Haidian District, Beijing 100083, China. Email: wangqingjie@cau.edu.cn.

Wang et al., 2016). Therefore, further study on the effect of soil compaction on soil temperature and moisture characteristics is of great significance to the sustainable development of soil.

Currently, studies on soil compaction mainly focused on effects of compaction on soil properties and crop growth. For example, Ewa A Czyz et al. (2004) studied effects of agricultural machinery rolling on soil bulk density and barley growth, the results showed that compaction could increase soil bulk density, reduce soil oxygen flux and reduce barley yield. Onã da Silva Freddi et al. (2007) studied on effects of soil compaction on root growth and maize yield, the results indicated that compaction could seriously inhibit the growth of maize roots and reduce the yield.

Studies on soil thermal and moisture regimes mainly focused on the effects of surface cover and irrigation on soil hydrothermal properties. For instance, Yin et al. (2014) studied on effects of no-tillage straw mulching mode and straw -plastic film dual mulch mode on soil temperature and moisture characteristics, the results showed that dual mulch mode could effectively increase the surface soil temperature and improve the water content of topsoil in the early stage, and provide good hydrothermal condition for maize growth. Chen et al. (2013) studied on effects of straw mulching quantity on the spatiotemporal variation of soil moisture in freezing season, results showed that straw mulching thickness of 10-15 cm could maximumly ease the freezing damage and enhance soil moisture. By studding effects of drip irrigation frequency on the growth of spring maize and distribution of soil water and heat in North China, Wang et al. (2008) found that high frequency irrigation could significantly promote the distribution of spring maize roots in the upper soil (0-40 cm) and suggested low frequency drip irrigation for spring maize in north China. In summary, researchers mainly studied soil compaction and soil temperature and moisture characteristics, while effects of soil compaction on soil moisture and temperature were not studied systematically.

In this paper, field experiments were conducted in the typical soil types of sandy and loam. By measuring soil moisture, water storage, temperature and maize yield, we studied the effects of soil compaction on soil thermal and moisture regimes and maize yield. The relationship between soil compaction and soil hydro-thermal feature under two soil types was shown clearly in this paper. This paper can provide some guidance for the further understanding of soil compaction.

2 Materials and method

2.1 Site and climatic conditions

Experiments were conducted in sandy and loam soil at two sites, respectively. Experiment 1 was conducted in Tillage Conservation and Observation Experimental Station of China Agricultural University (Site 1), which located in Dongchengfang town (39°28′N, 115°56′E) of Zhuozhou, Baoding City, Hebei Province. Experiment 2 was conducted in Nanbingshang Village (40°00′N, 113°40′E) (Site 2) of Dongwenshan, Laishui County, Hebei Province. The soil in site 1 and site 2 was classified as sandy soil and loam soil, and the mean field capacity of each site in 0 to 80 cm were11.3% and 18.6%, wilting water content were 1.2% and 8.1%, and thermal conductivity were 0.52 and 0.31 W m^{-1} k^{-1} respectively. The specific soil properties were shown in Table1. The average yields of maize in the past 5 years were 10015.5 and 11024.6 kg hm^{-2} respectively.

Table 1 Soil properties of the experiment field

Field	Agrotype	Mechanical composition, %			Bulk density, g/cm	Organic matter, g/kg	pH
		<0.002 mm	≥0.002-0.02 mm	≥0.02-2 mm			
1	Sandy	13.6	25.1	61.3	1.42	5.38	7.6
2	Loam	14.9	35.8	49.3	1.33	11.5	7.9

Two sites are characterized by a typical warm temperate of semi-humid continental monsoon climate. During the experimental period, the average temperature and total accumulated temperature were 11.6°C and 4198°C (with 178 frost-free days), respectively, and the annual rainfall was 450 mm. The temperature and rainfall of the two sites were shown in Figure 1. The planting system is double cropping of winter wheat and summer maize.

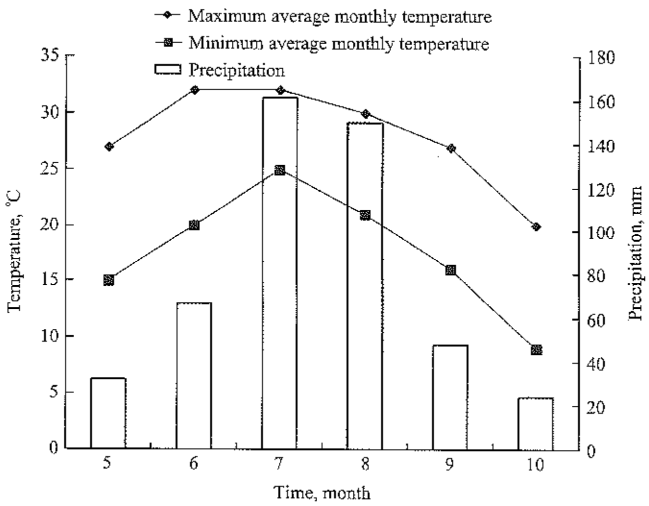


Figure 1 Temperature and rainfall during maize growth period in 2016

2.2 Agronomic measures

Site 1: The farming system was adopted as follow: wheat harvest—No-tillage maize planting—spraying—maize harvest—straw crushing and returning—No-tillage wheat planting from 2011.

Site 2: The farming system was adopted as follow: wheat harvest—No-tillage maize planting—spraying and weed controlling—maize harvest—partial straw crushing and returning—subsoil—wheat planting from 2013.

During the experimental period, the variety of maize was Zhengdan 958, the type of seeder was 2BMZH-3, the maize was uniformly planted with a spacing of 20 and 60 cm respectively, and fertilizers were applied at the following rates: 284 kg N ha^{-1}, 102 kg P_2O_5 ha^{-1} and 95 kg K_2O ha^{-1}. During the entire growing season of maize, there was no water treatment and plow pan phenomenon because the no-tillage treatment and subsoil treatment were applied in site 1 and site 2, respectively.

2.3 Experimental design

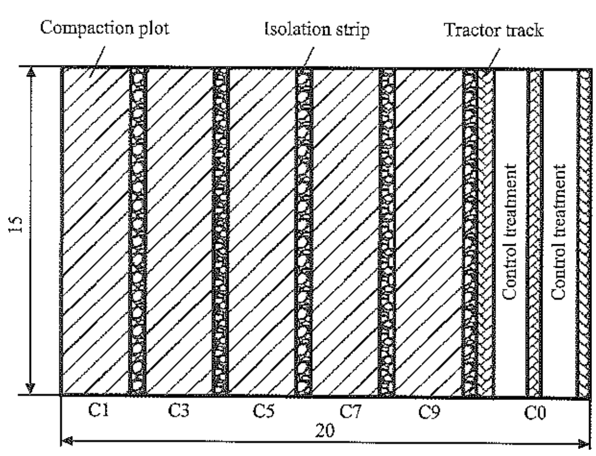
Select Lovol Lepopard 904 tractor as compaction equipment in the experiment, its weight was 4155 kg. The tire parameters were shown in Table 2.

Table 2 Parameters of compactness tractor

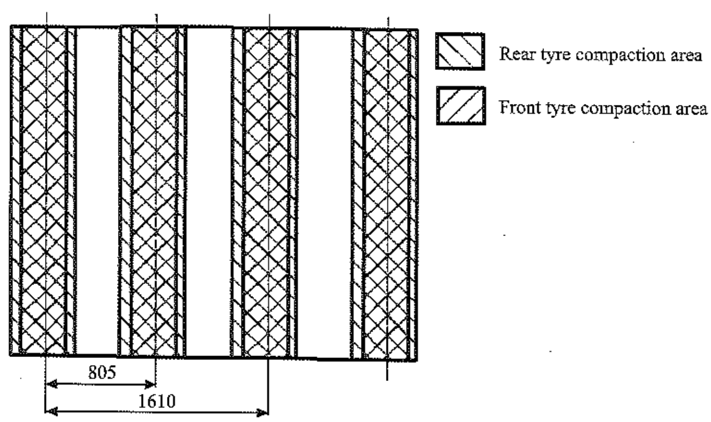
Specification	Standard type	Tire width, mm	Tire pressure, kPa	Wheelbase, mm
Front tires	12.4-24	315	85	1610
Rear tires	16.9-34	430	100	1608

Six treatments of different compaction time were designed: 0(C_0), 1(C_1), 3(C_3), 5(C_5), 7(C_7) and 9(C_9). No-compaction treatment 0 was control group, where the crop zone was permanent separated with machine compaction zone to avoid soil compaction caused by field management. Each treatment was tested three times, namely18 compaction experiments were set in total. The field experimental design of each treatment was shown in Figure 2, and each plot was 15 m wide by 20 m long.

Two weeks before the experiment, the field was completely subsoiled at a depth of 50 cm. In the experimental process of soil compaction, there was a 2 h interval among the each compaction of tractor.



a. Experimental plots arrangement



b. Compaction method

Figure 2 Field specific operation

2.4 Measurement

2.4.1 Soil bulk density

Soil bulk density was measured by drying method. Aiming at two kinds of soil in site 1 and site 2, all the undisturbed core samples were collected at the 0 to 10, 10 to 20, 20 to 30, 30 to 40 cm soil depths, which were taken by using a stainless steel core sampler (50.46 mm diameter by 50 mm length) and then stored in aluminum boxes (100 cm^3). Every soil sample was taken on the tractor lane under different compaction frequencies randomly. Then the samples were dried at 108°C to a constant weight, weighed soil bulk density.

2.4.2 Soil water content monitoring of different depth in maize growing period

Soil water content was measured at four keys growing period including seeding stage, elongation stage, filling stage and maturation stage, and it was measured at 0 to 10, 10 to 20, 20 to 30, 30 to 40, 40 to 60, 60 to 80 cm soil depths respectively by using AZS-2 soil moisture measurement instrument.

Soil water storage was calculated as follow:

$$C=\sum(\Delta\theta_V \times h_i) \qquad (1)$$

where, C is soil water storage, mm; $\Delta\theta_V$ is a layer of soil volume water content,%; h_i is the thickness of a layer soil, mm; i is soil layer.

2.4.3 Dynamic change of soil temperature

The soil temperature was recorded by HOBO soil temperature and moisture real-time system which consisted of data collector (4/15 channel), temperature sensor and solar energy panel. The temperature sensor probe was embedded in 10 cm and 20 cm under soil surface among the maize, and the stainless steel probe had a strong anticorrosion ability, which can be embedded in soil layer to monitor soil temperature in a longtime. The data was automatically collected and recorded every 30 minutes.

2.4.4 Maize yield

According to the principle of random sampling, select three 1 × 1 m^2 zones in each ploy, and record maize spike number, row number per maize spike and grain number per row in this zone. After threshing and drying to a constant weight, calculate the hundred-grain weight of maize, thus the yield can be calculated as:

$$Y=(H\times M\times W)/100000 \qquad (2)$$

where, Y is maize yield, kg hm^{-2}; H is maize spike number per hectare; M is grain number; W is hundred-grain weight, g.

2.5 Data analysis

The experimental data was analyzed by Microsoft Excel 2003 software and IBM SPSS Statistics 20 software, significance test was performed by LSD method, and significance level was selected as 0.05.

3 Results

3.1 Soil bulk density

Table 3 shows the effects of different compaction times on soil bulk density in sandy soil and loam soil, respectively. As is shown in Table 3, soil bulk density of 0-40 cm increased with the soil depth increasing for each treatment. Soil compaction can significantly increase soil bulk density in 0-40 cm soil layer, compared with C_0 treatment, the average soil bulk density of sandy soil treated with C_1, C_3, C_5, C_7 and C_9 increased by 6.3%, 20.3%, 22.7%, 29.7%, 34.4%, respectively. The average soil bulk density of loam soil treated with C_1, C_3, C_5, C_7 and C_9 increased by 10.3%, 19%, 24.6%, 36.5%, 39.7%, respectively.

Table 3 Varieties of soil bulk density under different experiment treatment

Soil	Soil depth	Bulk density for treatment						LSD $P\leq0.05$
		C_0	C_1	C_3	C_5	C_7	C_9	
Sandy	0-10	1.22	1.30	1.47	1.49	1.62	1.68	0.022
	10-20	1.25	1.33	1.51	1.53	1.66	1.72	0.017
	20-30	1.31	1.40	1.58	1.61	1.67	1.73	0.028
	30-40	1.33	1.41	1.59	1.63	1.69	1.75	0.047
	Average	1.28	1.36	1.54	1.57	1.66	1.72	0.032
Loam	0-10	1.18	1.39	1.47	1.49	1.68	1.69	0.021
	10-20	1.23	1.44	1.53	1.57	1.71	1.74	0.04
	20-30	1.29	1.34	1.50	1.61	1.73	1.79	0.012
	30-40	1.35	1.39	1.51	1.62	1.76	1.80	0.048
	Average	1.26	1.39	1.50	1.57	1.72	1.76	0.033

3.2 Soil moisture content

Figure 3 is the effect of soil compaction on soil volumetric moisture content during the critical growth period of summer maize under sandy and loamy soil. From Figure 3a, it can be seen that under the sandy soil condition, the volume moisture content of soil surface (0-20 cm) increased with the increase of soil compaction times. At seedling stage, the volumetric moisture content of soil treated with C_0 was 8.6%, 9.4%, 21.6%, 26.6%, 33.8% lower in comparison with C_1, C_3, C_5, C_7 and C_9, respectively; At elongating stage, it was 24.8%, 32.5%, 30.9%, 25.6% and 25.9% lower, respectively; at grain filling stage, it was lower than 9.1%, 11%, 8.5%, 8.3%, 8.4%, accordingly; at maturation stage, it was lower than

54.8%, 60.7%, 63.7%, 65.5%, 66.1%, accordingly. However, the average soil volumetric water content in 20~80 cm soil layer decreased with the increase of soil compaction times, at seedling stage, the volumetric moisture content of soil treated with C_0 was 20.3%, 32.4%, 51.7%, 60.2%, 69.9% higher in comparison with C_1, C_3, C_5, C_7 and C_9, respectively; at elongating stage, it was higher than 20.3%, 24.4%, 31.1%, 37.2%, 39.3%, accordingly; at grain filling stage, it was higher than 2.6%, 5.9%, 11.2%, 17.9%, 23.7%, accordingly; at maturation stage, it was higher than 48.3%, 83.6%, 103%, 165.4%, 215.9%, respectively.

Figure 3b shows that under the loam soil condition, the volumetric moisture content in the 0-20 cm soil layer from top to bottom is C_3, C_1, C_0, C_5, C_7, C_9 during the whole growth period, and the average volume moisture contents are 20.1%, 18.8%, 17.9%, 16.2%, 14%, 13.1%, respectively. However, soil compaction could decrease moisture content at 20-80 cm layer, the mean volumetric moisture content from C_0 to C_9 treatment, during the whole growth period were 23.1%, 20.8%, 19.6%, 17.7%, 16.5%, 15.8% respectively.

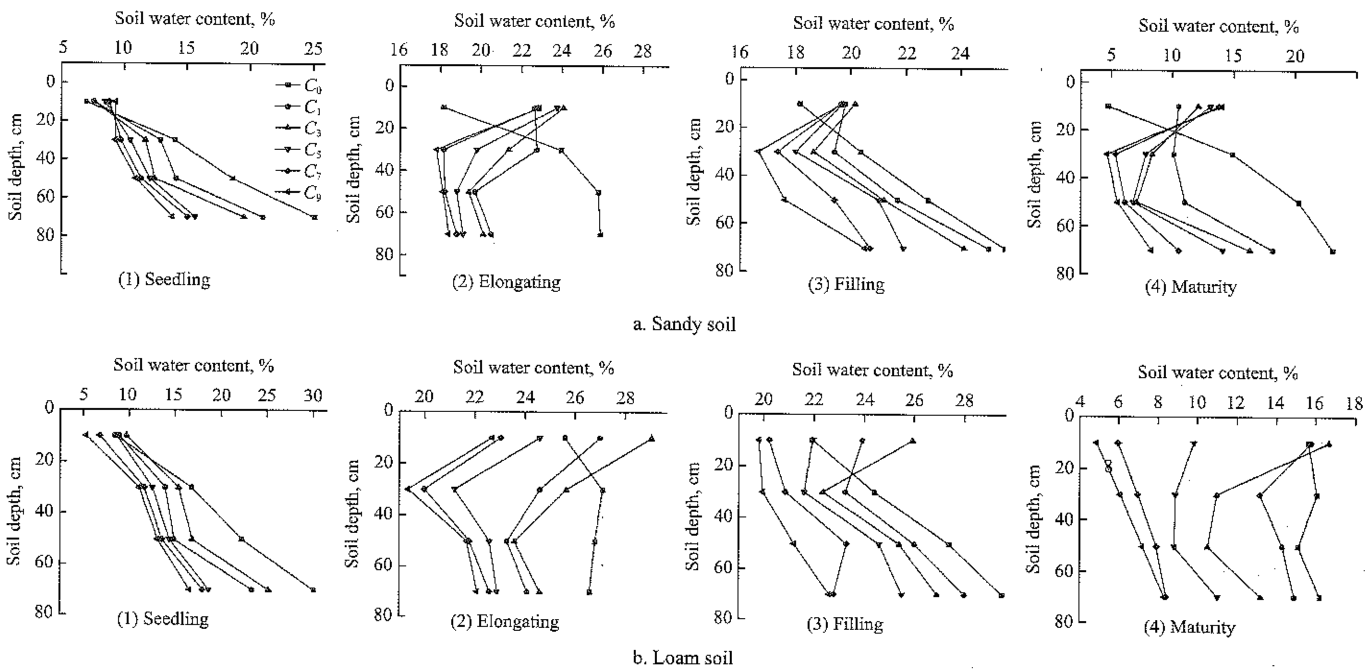


Figure 3 Effect of soil compaction on soil volumetric water content

3.3 Soil water storage

Table 4 shows the influence of soil compaction on soil water storage during the critical growth period of maize. Under the sandy soil condition, the effect of soil compaction on soil water storage displayed differences at four critical maize growing seasons. During seeding and maturity growth stage, C_3, C_5, C_7 and C_9 treatment could significantly increase soil water storage compared to C_0 and C_1 treatment at 0-20 cm depth. During elongating and filling stage, C_3 treatment has the maximum soil water storage compared to C_0, C_1, C_5, C_7 and C_9 treatment at 0-20 cm depth. Under the loam soil, during seeding and maturity growth stage, C_3 treatment has the maximum soil water storage, while C_0 has maximum soil water storage during elongating and filling stage at 0-20 cm depth. The soil compaction could decrease soil water storage during each four growth stage at 20-80 cm depth.

Under the sandy soil condition, the average water storage of soil, during the whole season, treated with C_0 in 0-20 cm soil layer was 20.7%, 24.9%, 26.2%, 26%, 27% lower than that of C_1, C_3, C_5, C_7 and C_9 soil, respectively; in 20-80 cm soil layer, it was 18.2%, 27.8%, 37.8%, 50.4%, 58.5% higher, respectively. Under the loam soil condition, C_0, C_1, C_3 treatment could significantly increase the average water storage in the 0-20 cm soil layer compared to C_5, C_7, C_9 treatment. And the C_3 treatment, which has maximum soil water storage, is 4.3% higher compared to C_0 treatment. C_9 treatment, which has minimum soil water storage, is 41.8% lower compared to C_0 treatment. In the 20-80 cm soil layer, the water storage of soil treated with C_0 was higher than C_1, C_3, C_5, C_7, C_9 by 11.4%, 17.6%, 31.1%, 41.0%, 47.6%, respectively.

Table 4 Effect of soil compaction on soil water storage under critical growth period of maize

Type	Depth, cm	Time	C_0	C_1	C_3	C_5	C_7	C_9
Sandy soil	0-20	Seedling	13.9^{c}	15.1^{b}	16.2^{a}	16.9^{a}	17.6^{a}	18.6^{a}
		Elongating	36.3^{c}	45.3^{b}	48.1^{a}	47.5^{a}	45.6^{b}	45.7^{b}
		Filling	36.3^{c}	39.6^{a}	40.3^{a}	39.4^{a}	39.3^{a}	39.2^{a}
		Maturity	9.5^{c}	21^{b}	24.2^{b}	26.2^{a}	27.5^{a}	28^{a}
	Average		24^{c}	30.3^{b}	32.0^{a}	32.5^{a}	32.5^{a}	32.9^{a}
	20-80	Seedling	107.6^{a}	91.2^{b}	82.8^{c}	72.8^{d}	68.6^{e}	64.8^{f}
		Elongating	149.4^{a}	128.6^{b}	123.3^{b}	116.3^{c}	110^{d}	108.2^{d}
		Filling	132.2^{a}	128.3^{b}	123.9^{c}	118.4^{d}	112.2^{e}	107.1^{f}
		Maturity	109.8^{a}	74.1^{b}	60.2^{c}	54.8^{d}	41^{e}	34.7^{f}
	Average		124.7^{a}	105.5^{b}	97.5^{c}	90.5^{d}	82.9^{e}	78.7^{f}
Loam soil	0-20	Seedling	17^{b}	17.8^{b}	20.4^{a}	17.3^{b}	13.6^{c}	10.6^{d}
		Elongating	52.5^{c}	52^{a}	52.1^{a}	49.2^{d}	46.1^{e}	45.4^{e}
		Filling	49.9^{a}	49.8^{a}	50.3^{a}	43.9^{b}	40.43^{c}	39.6^{c}
		Maturity	31.2^{a}	30.5^{a}	31.3^{a}	19.6^{b}	11.9^{c}	9.7^{c}
	Average		37.6^{a}	37.9^{a}	38.1^{a}	32.5^{b}	28^{c}	26.3^{c}
	20-80	Seedling	129^{a}	109.4^{b}	99.3^{c}	87.3^{d}	82.35^{e}	77.9^{f}
		Elongating	161.4^{a}	149.9^{c}	144.3^{b}	131.9^{d}	126.6^{e}	123.8^{f}
		Filling	158.6^{a}	150.8^{b}	145.5^{c}	140^{d}	131.7^{e}	125.6^{f}
		Maturity	95.1^{a}	83.3^{b}	68.4^{c}	56.3^{d}	45.3^{e}	41.4^{f}
	Average		136.0^{a}	123.1^{b}	114.6^{c}	103.8^{d}	96.5^{e}	92.1^{f}

Note: Values with different letters (horizontal) show significant differences among treatments (P<0.05).

3.4 Soil temperature

Figure 4 shows the effect of soil compaction on soil temperature in 0-20 cm soil layer aimed at two soil types, and the effect varies with depth and climate temperature. By Figure 4a, under the sandy soil, when the average temperature is higher than 22°C, the soil temperature of 0-10 cm depth decreases with the increase of soil compactness, soil temperature treated with C_0 was 6.8%, 7.7%, 10.9%, 17.1%, 19.3% higher in comparison with C_1, C_3, C_5, C_7, C_9 treatment, respectively; when the average temperature is lower than 22°C, the C_1, C_3, C_5 treatments have the higher temperature, while temperature of C_7, C_9 is lower, compared to controlled treatment C_0. And the average temperatures were 16.4°C, 17.3°C, 16.8°C, 16.6°C, 15.6°C, 15.3°C, accordingly. Figure 4b shows that in the whole growth period, the soil temperature of 20 cm depth from top to bottom was C_0, C_1, C_3, C_5, C_7, C_9 successively, and the average temperatures were 14.62°C, 14.33°C, 13.7°C, 13.21°C, 11.96°C, 10.92°C, respectively.

By Figure 4c, under the loam soil, when the average temperature is higher than 25°C, the soil temperature of 0-10 cm depth decreases with the increase of soil compactness, soil temperatures treated with C_0 were 6.7%, 11.4%, 21.5%, 35.1%, 50.3% higher in comparison with C_1, C_3, C_5, C_7, C_9 treatment, respectively; when the average temperature is lower than 25°C, the C_1, C_3 treatments have the higher temperature, while temperature of C_5, C_7, C_9 is lower, compared to the controlled treatment of C_0. The average soil temperatures from top to bottom C_1, C_3, C_0, C_5, C_7, C_9 were 17.2°C, 18.5°C, 17.8°C, 16.4°C, 14.7°C and 13.3°C, respectively. As shown in Figure 4d, the soil temperatures of 20 cm depth ranged from top to bottom were C_0, C_1, C_3, C_5, C_7, C_9, successively, and the average temperatures are 16.5°C, 16.2°C, 15.5°C, 15.1°C, 14.8°C, accordingly.

3.5 Maize yield

Table 5 shows the effects of soil compaction on maize yield under different soil types. Soil compaction can reduce maize yield, under loam soil condition, compared with C_0 treatment, maize yield dealt with C_1, C_3, C_5, C_7 and C_9 treatments decreased by 0.6%, 3.5%, 6.5%, 10.7%, 14.6%, respectively, their hundred-grain weight decreased by 0.2%, 1.3%, 3.2%, 5.1%, 13.6%, accordingly. Under sandy soil condition, compared with

C_0 treatment, maize yield dealt with C_1, C_3, C_5, C_7 and C_9 treatments decreased by 0.3%, 1.0%, 5.3%, 5.7%, 8.5% respectively, their hundred-grain weight decreased by 0.5%, 1.7%, 4.7%, 7.9%, 13.1%, accordingly.

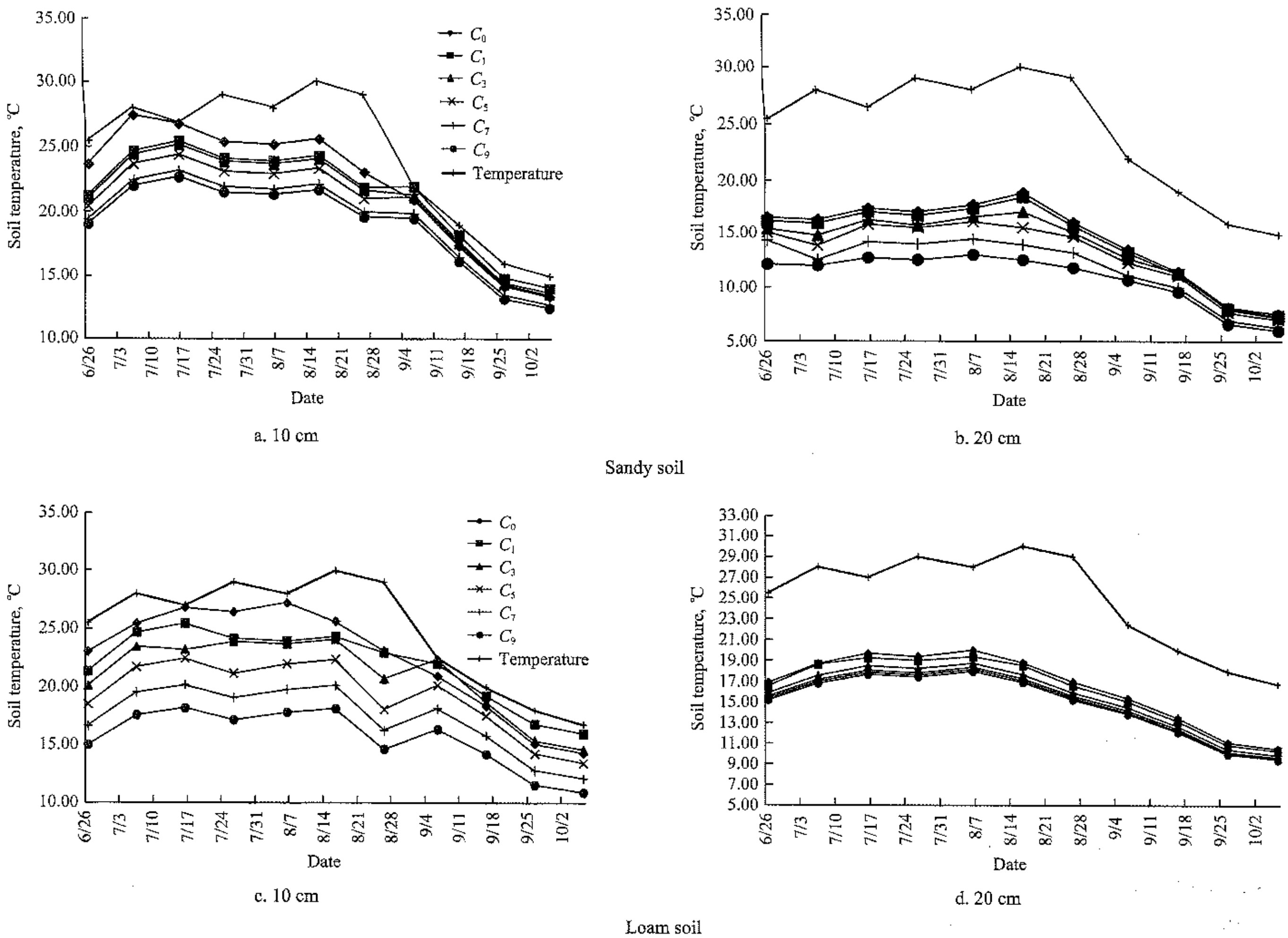


Figure 4 Effect of soil compaction on soil temperature during maize growth period

Table 5 Effect of soil compaction on maize yield

Soil type	Treatment	Grain number per ear	100-grain weight, g	Yield, kg hm^{-2}
Sandy	C_0	632.1^{a}	40.6^{a}	10023.2^{a}
	C_1	627.7^{a}	40.4^{a}	9993.1^{a}
	C_3	617.3^{a}	39.9^{a}	9924.0^{a}
	C_5	613.7^{a}	38.7^{a}	9491.7^{b}
	C_7	581.0^{b}	37.4^{a}	9446.9^{b}
	C_9	544.4^{c}	35.3^{b}	9170.4^{c}
Loam	C_0	645.1^{a}	45.3^{a}	11082.4^{a}
	C_1	638.1^{a}	45.2^{a}	11016.3^{a}
	C_3	625.7^{b}	44.7^{a}	10697.3^{a}
	C_5	618.5^{b}	43.9^{a}	10367.1^{b}
	C_7	584.3^{c}	43.1^{a}	9895.0^{b}
	C_9	549.0^{d}	39.9^{b}	9464.0^{c}

Note: The difference between the letters in each column indicates a significant difference under different soil types.

4 Discussion

4.1 Effect of soil compaction on soil bulk density

Soil bulk density is an important index to judge whether the soil is compacted by external forces and has a great significance to judge whether the soil is suitable for crop growth (Ewa et al., 2004). Patel et al (2011) found that the soil bulk density changes caused by tractor compaction 16 times were mainly concentrated in 0-20 cm soil layer, and the maximum soil bulk density appeared in 15-20 cm soil layer. Horn et al. (1998) found that the soil bulk density increased by 10 times soil compaction was mainly concentrated in 0-30 cm soil layer. The results showed that soil compaction 9 times can significantly increase the soil bulk density of 0-40 cm, and the main reason for the deviation of the results of Patel and Horn is that the soil texture is different, which leads to the different bearing capacities of the soil to the external force, and the different factors such as the weight of the compaction device, the grounding area caused by compaction device tire type. Soil moisture content is the most important factor affecting soil compaction (Nidal et al., 2003), which could increase soil stress transmission coefficient (He et al., 2017), the soil stress could propagate to deeper soil and increase deep soil bulk density.

4.2 Effects of soil compaction on soil moisture

A large number of studies (Wang et al., 2000, Wang et al., 2014, Li et al., 2000, Li et al., 2002) have shown that soil infiltration, evaporation, soil organic matter content, soil aggregate content, bulk density and other soil parameters have a decisive effect on soil water content during the crop growth cycle. Under sandy soil condition, the soil moisture contents of 0-20 cm treated soil layer with C_0 treatment were 24.3%, 28.4%, 31.2%, 31.5%, 33.6%, less than C_1, C_3, C_5, C_7 and C_9 in the whole corn growing period. The main reason for the increase in soil moisture content is that soil compaction increases soil capillary space, while non capillary voids and water holding spaces decrease significantly. Porosity is the key factor affecting soil water infiltration, which results in the decrease of soil infiltration rate and the influence of soil moisture on deep movement during rainfall irrigation (Qin, 2003). The precipitation mainly concentrated on the surface, and increase the compaction of soil capillary porosity content, increase capillary force (Huang, 2000), reduce soil evaporation, increase soil field capacity (Botta et al., 2008, Li et al., 2000, Yang et al., 2006), to a certain extent, the soil moisture enhanced drought ability, this also explains that compaction can increase soil water storage in sandy soil of 0-20 cm. However, under loam soil condition, during the whole growth period of corn, the average volume moisture contents of 0-20 cm surface soil from large to small are C_3, C_1, C_0, C_5, C_7 and C_9, the main reason of the difference between two types of soil is that the soil micro aggregate composition and sensitivity to soil compaction (Lu et al., 2015), under the condition of loam soil, the multiple compaction of the tractor can cause serious soil compaction, destroy soil aggregates, reduce soil porosity (Botta et al., 2009), reduce soil water infiltration, and lead to water runoff and evaporation. It should be noted that although compaction can increase soil moisture content to a certain extent, compaction increases soil penetration resistance and increases soil wilting point, so the maximum available water content of compacted soil is reduced (Yang et al., 2006). During the whole growth period, the average soil water contents and storage capacities of 20-80 cm soil from large to small were C_0, C_1, C_3, C_5, C_7, C_9 under the condition of sandy soil and loam soil, the main reason may be that soil compaction prevents soil moisture from moving downward, leading to the difficulty of supplying deep soil moisture, and the absorption of deep soil moisture by maize roots, resulting in a decrease in soil moisture.

4.3 Effects of soil compaction on soil temperature

Soil temperature is one of the most important factors in the soil microbes and crop growth. The root and seedling growth were affected by soil temperature characteristics directly, moreover the atmosphere near the ground warm conditions also was affected by the soil moisture evaporation and migration directly or indirectly (Zhai et al., 2012; Cai et al., 2013). The climate played an important role for the topsoil temperature, when the average temperature is higher than 22°C, the temperature presented a decreasing order of C_0, C_1, C_3, C_5, C_7 and C_9, while the temperature is lower than 22°C, temperature presented a decreasing order of C_1, C_3, C_5, C_0, C_7 and C_9, under sandy soil condition. Under the loam soil condition, when the average temperature is higher than 25°C, temperature presented a decreasing order of C_0 to C_1, C_3, C_5, C_7 and C_9, while the temperature is lower than 25°C, temperature presented a decreasing order of C_1, C_3, C_0, C_5, C_7 and C_9. That is because of the soil compaction destroyed soil physical properties, furthermore blocked soil gas exchange with the atmosphere (Kuncoro et al., 2014). Figure 1 shows that the climate temperature in the early stage of corn growth is low, and gradually increasing, reached to the highest temperature in July. In August, the temperature began to decline, and the soil temperature also decreased. The results showed that when soil temperature declined from the peak, soil compaction increased daily minimum temperature; on the contrary, it will decrease daily minimum temperature (Botta et al., 2008). The soil is compacted, soil temperature was blocked about temperature exchange between atmosphere and soil at maize early growing stage at 0-10 cm depth. So, that principle finally leads to the slowly change of soil temperature as atmosphere temperature variation. The main reason for the inconsistency between the two soils is that the loam is more cohesive and sensitive to soil compaction than the sand soil (Thomas et al., 2010). Therefore, C_5, C_7, C_9 treatments resulting in soil structure destroyed seriously, smaller soil heat capacity and higher thermal conductivity because of reducing soil pore under loam soil (Tetiana et al., 2013), consequently, the C_5, C_7, C_9 have lower temperatures than C_0. Under two soil types, the temperature was decreased with the increasing compactness during the whole corn growing season at 20 cm depth. Because of the cumulative effect, soil compaction has a negative effect on soil porosity and energy circulation (Shen et al., 2011, Wang et al., 2011). But the soil temperature differences between treatments are not significant at 20 cm depth, which is consistent with the results of Wang et al. (2008).

4.4 Effects of soil compaction on maize yield

The results showed that soil compaction could decrease maize yield, whether in sandy soil or loam soil. Under sandy condition, compared with C_0 treatment, C_1, C_3, C_5, C_7 and C_9 corn yield decreased by 0.3%, 1.0%, 5.3%, 5.7%, 8.5%; while under the loam soil condition, compared with C_0 treatment, C_1, C_3, C_5, C_7 and C_9 maize yield decreased by 0.6%, 3.5%, 6.5%, 10.7% and 14.6%. It was found that soil drought and crop accumulated temperature were the most important factors for affecting crop yield in two cropping areas a year (Zhang et al., 2013). Soil compaction could reduce differences between the maximum and minimum temperatures each day (Botta et al., 2008). That phenomenon could lead to lower soil temperature at the early stage of maize growth, thereby impairing the root growth and development of maize. And at later stage of maize growth, soil compaction also resulted in a small temperature difference between day and night, which is harmful to sugar accumulation, finally decrease the crop yield (Wu et al., 1998). Soil compaction could decrease soil water storage at 20-80 cm, which resulting in water supply deficiency maize growth needed at critical stage. And compaction hindered the soil water infiltration, which is not conducive to deep soil water supply (Wang et al., 2014). In summary, soil compaction affected the growth of maize yield seriously.

5 Conclusions

In this paper, the research of soil moisture, soil temperature and yield was conducted to study the effects of soil compaction on soil hydro-thermal feature and maize yield by field experiment. The following conclusions were drawn:

(1) Soil compaction could increase soil bulk density both under sandy and loam soils at 0-40 cm soil depth. Soil compaction could increase soil moisture content and soil water storage at 0-20 cm depth, and reduce soil moisture content and soil water storage in 20-80 cm soil layers both under sandy and loam soils.

(2) Soil compaction could reduce crop yields, and 5 passes compaction could significantly decrease maize yields both under sandy and loam soil conditions.

(3) The precipitation condition after compaction could significant decreased the variety of compaction frequency on deep soil (20-80 cm), water content and water storage.

The results show that the compaction has significant influence on soil hydro-thermal feature. Therefore, the results of this study are of guiding significance for the study of tire soil compaction in the double cropping area.

Acknowledgements

This work was supported by the National Key Research and Development Program (2016YFD0700301). We thank all the graduate students working at the Conservation Tillage Research Center, Ministry of Agriculture, providing their inputs to this work.

[References]

[1] Abu-Hamdeh, N. H. 2003. Compaction and subsoiling effects on corn growth and soil bulk density. *Soil Science Society of America Journal*, 67(4): 1213–1219.

[2] Botta, G. F., A.Tolon-Becerra, and D. Rivero. 2016. Compaction produced by combine harvest traffic: Effect on soil and soybean (Glycine max l.) yields under direct sowing

in Argentinean Pampas. *European Journal of Agronomy*, 74: 155–163.

[3] Botta, G. F., A. T. Becerra, and F. B. Tourn. 2009. Effect of the number of tractor passes on soil rut depth and compaction in two tillage regimes. *Soil and Tillage Research*, 103(2): 381–386.

[4] Botta, G. F., D. Rivero, M. Tourn, F. B.Melcon, O. Pozzolo, G. Nardon, and R.Balbuena. 2008. Soil compaction produced by tractor with radial and cross-ply tyres in two tillage regimes. *Soil and Tillage Research*, 101(1): 44–51.

[5] Cai, T. Y., Z. C. Chen, and H. J. Huang. 2013. Effects of different modes of cropping systems using straw mulch on the soil temperature and soil water on the Weibei highland region of China. *Journal of Agro-Environment Science*, 32(7): 1396–1404.

[6] Chen, J. F., X. Q. Zheng, Z. D. Qin, P. Liu, H. F. Zang, and F. Sun. 2013. Effects of maize straw mulch on spatiotemporal variation of soil profile moisture and temperature during freeze-thaw period. *Transactions of the Chinese Society of Agricultural Engineering*, 29(20): 102–110. (In Chinese with English abstract)

[7] Ewa A. Czyz. 2004. Effects of traffic on soil aeration, bulk density and growth of spring barley. *Soil and Tillage Research*, 79(2): 153–166.

[8] Freddi, O. S., C. J. Frederico, and N. B. Amauri. 2007. Effect soil compaction on root growth and maize yield. *Revista Brasileira De CiêNcia Do Solo*, 31: 627–636.

[9] He, T. F., Q. S. Ding, Y. N. Li, R. Y. He, J. L. Xue, and W. Qiu. 2017. Stress transmission coefficient: a soil stress transmission property for a loading process. *Soil and Tillage Research*, 166: 179–184.

[10] Huang, Y. C. 2000. Soil Science. *Beijing: China Agriculture Press*.

[11] Helms, T. C., E. Deckard, and R. J. Goos, and J. W, Enz. 1996. Soil moisture, temperature, and drying influence on soybean emergence. *Agronomy Journal,* 88(4): 662–667.

[12] Horn, R., H. Kretschmer, T. Baumgartl, K. Bohne, and A. Neupert. 1998. Soil mechanical properties of a partly reloosened (split plough system) and a conventionally tilled over consolidated gleyicluvisol derived from glacial till. *International Agrophysics,* 12(3): 143–154.

[13] Kuncoro, P. H., K. Koga, N. Satta, Y. Muto. 2014. A study on the effect of compaction on transport properties of soil as and water. II: soil pore structure indices. *Soil and Tillage Research*, 143(12): 180–187.

[14] Li, H. W., H. W. Gao, J. D. Chen, and W. Y. Li. 2000. Study on controlled traffic with conservation tillage. *Transactions of the Chinese Society of Agricultural Engineering*, 16(4): 73–77. (In Chinese with English abstract)

[15] Li, R. X., C. H. Lin, and H. W. Gao. 2002. The research of soil compaction caused by tractor. *Transaction of the Chinese Society for Agricultural Machinery*, 1(33): 126–129. (In Chinese with English abstract)

[16] Lu, Q. Q., E. H. Wang, and X. W. Chen. 2015. Effect of mechanical compaction on soil micro-aggregate composition and stability of black soil. *Transactions of the Chinese Society of Agricultural Engineering*, 31(11): 54–59. (In Chinese with English abstract)

[17] Patel, S. K., and M. Indra. 2011. Effect of multiple passes of tractor with varying normal load on subsoil compaction. *Journal of Terramechanics*, 48(4): 277–284.

[18] Qin, Y. D. 2003. Soil Physics. *Beijing: Higher Education Press*.

[19] Thomas, K., and L. Mathieu. 2010. Challenges in the development of analytical soil compaction models. *Soil and Tillage Research*, 111(1): 54–64.

[20] Shen, L.X., P. Wang, and L. L. Zhang. 2011. Effects of degradable film on soil temperature, moisture and growth of maize. *Transactions of the Chinese Society of Agricultural Engineering*, 27(6): 25–30. (In Chinese with English abstract)

[21] Tetiana, N. F., S. T. Mykola, L. A. Karim, B. Walter, and B. Rafic. 2013. Methods and results of experimental researches of thermal conductivity of soils. *Energy Procedia*, 42: 775–783.

[22] Wang, J. D., S. H. Gong, and J. Sui. 2008. Effects of drip irrigation frequency on the farmland soil water-heat distribution and spring maize growth in North China. *Transactions of the Chinese Society of Agricultural Engineering*, 24(2): 39–45. (In Chinese with English abstract)

[23] Wang, M., H. X. Wang, Q. F. Han, and R. Zhang. 2011. Effects of different mulching materials on soil water, temperature, and corn growth. *Acta Agronomica Sinica*, 37(7): 1249–1258.

[24] Wang, Q. J., C. Y. Lu, H. W. Li, J. He, K. S. Khohan, J. R. Rabi, and Z. H. Liang. 2014. The effects of no-tillage with subsoiling on soil properties and maize yield: 12-Year experiment on alkaline soils of Northeast China. *Soil and Tillage Research*, 137(3): 43–49.

[25] Wang, X. L., Q. J. Wang, H. L. Li, J. He, and W. Y. Li. 2015. Current research status of soil compaction by agricultural machinery. *Chinese Journal of Tropical Agriculture*, 35(6): 72–76.

[26] Wang, X. Y., H. W. Gao, and Y. X. Li. 2000. Effect of tractor wheel compaction on runoff and infiltration. *Agricultural Research in the Arid Areas*, 18(4): 57–60.

[27] Wang, X.L., Q. J. Wang, X. C. Zhang, K. Zheng, and H. Hu.

2016. The soil compaction forms and research status. *Journal of Agricultural Mechanization Research*, 53(9): 264–268.

[28] Wu, S., S. Y. Zhang, and Y. G. Shen. 1998. Influence of temperature difference between day and night on the growth characteristics in wheat. *Acta Agronomica Sinica*, 24(3): 333–337.

[29] Yang, J. L., G. L. Zhang, Y. G. Zhao, W. J. Zhao, Y. He, and X. L. Ruan. 2006. Effect of compaction on soil water characteristics. *Acta Pedologica Sinica*, 43(1): 33–38.

[30] Yin, T., W. Q. He, C. R. Yan, and S. Liu. 2014. Effects of plastic mulching on surface of no-till straw mulching on soil water and temperature. *Transactions of the Chinese Society of Agricultural Engineering*, 30(19): 78–87. (In Chinese with English abstract)

[31] Zhai, Z. F. 2012. Comprehensive Evaluation of Agricultural Water-Saving Technologies Adapting Climate Change. *Beijing: Chinese Academy of Agricultural Sciences*. (in Chinese with English abstract)

[32] Zhang, X.C., H. W. Li, J. He, Q. J. Wang, Z. Q. Zheng, and P. Jing. 2013. Effects of different tillage managements on characteristics of soil and crop in annual double cropping areas in Northern China. *Transaction of the Chinese Society for Agricultural Machinery*, S1: 4477–8271. (In Chinese with English abstract)