Analysis of black soil compaction with driver-agricultural machinery-soil system under corn sowing with high-power tractor in Northeast China

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Abstract: Soil compaction leads to crop yield reduction in Northeast of China. The interaction mechanism of driver-agricultural machinery-black soil is not clear. A comprehensive field experiment of 4 hm^2 of maize seeding was carried out in Baiquan County Cooperative. The results showed that the average increase rates of soil compaction before and after sowing were 118.82% and 71.02%. The SEM showed that waist fatigue had the greatest impact on soil compaction, and the unit fatigue of waist caused 1.51 and 1.27 unit compactions to the soil at the depths of 10 cm and 20 cm. The neck, waist, arm and leg fatigue of drivers increased the surface soil compaction by 1.83, 1.76, 1.78 and 1.55 units, and the deep soil compaction by 1.65, 1.58, 1.60 and 1.40 units. The results can provide a reference for the integration of human factor efficiency and conservation tillage.

Keywords: agriculture ergonomics, driver-machine-soil system, black soil compaction, sowing, structural equation model
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1 Introduction

Cultivated land is fundamental to ensure food security. Due to the perennial mechanical operation, especially the large-scale mechanical operation, the farmland soil compaction, the thickening of plough bottom, and the destruction of farmland ecological structure are caused. The protection of black land in Northeast China is an urgent need to ensure national food security. The state has issued a series of policy plans, such as the Ministry of Agriculture and Rural Affairs and the Ministry of Finance issued the Action Plan for Conservation Tillage of Black Soil in Northeast China (2020-2025), which adheres to the ecological priority and the combination of use and maintenance, and strives to promote the protection of black soil in Northeast China and the sustainable development of agriculture through the efforts of the government and the market, the deep integration of agricultural machinery and agronomy, the equal emphasis on scientific and technological support and main cultivation, the simultaneous promotion of key breakthroughs and overall advancement, and the balance of stable yield and high yield and cost saving and efficiency.

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Maize is one of the main food crops in Northeast China. The mechanized sowing of maize is the first mechanized link in the whole growth period of maize. Due to the farming season, the sowing link also determines the maize yield and economic benefits this year, and is the primary link to ensure maize food security. The protection of black land is a systematic project, including the study of the nature of the land itself, and the influence of external factors. There is a correlation between internal and external factors, and they jointly affect the soil. Therefore, the driver will have a certain internal psychological load when driving the tractor, and the complex working conditions in the field can lead to the external physiological load of the driver, which affects the smoothness and stability of the tractor operation, so that the tractor tires act on the soil according to the driver's control instructions, and causes different degrees of compaction on the soil.

In terms of soil compaction research, domestic research mainly focuses on soil physical properties. For example, Li et al.[1] measured the change of soil physical properties of seedbed after tractor compression, and studied the compaction effect of small four-wheel tractor on soil. Qiao et al.[2] used medium tractor to carry out compaction test, and analyzed the change rate of soil compaction and moisture content before and after compaction. Some scholars have also studied the model method with an improved model of soil compaction process[3]. Keller et al.[4] studied the soil compaction with input parameters of agricultural machinery and soil using Soilflex model, and taking soil stress-strain relationship as output to reflect soil compaction. Hallonborg et al.[5] proposed the method of using elliptical series to express the shape of tire-soil contact surface for the first time according to the contact characteristics between tire and soil with different hardness. Keller et al.[6] first used power function to express the stress distribution of contact surface in 2005; Johnson et al.[7] expressed the law of soil stress transfer by mathematical model.

In the application of structural equation model, there are some achievements in the analysis of multi-factor coupling crop model. Li et al.[8] conducted structural equation analysis on the measured evapotranspiration and net carbon sequestration of wheat and maize in the past 10 years, and found that net radiation was an important factor directly affecting net carbon sequestration. Temperature indirectly affected net carbon sequestration of crops. Saturated water vapor pressure affected net carbon sequestration through leaf area index, while soil moisture content and wind speed affected evapotranspiration in different growth seasons. Zeng et al.[9] found that starch was the main factor affecting glucose synthesis and grain number per spike was the most important factor affecting yield by modeling nitrogen application rate-photosynthesis-yield structure equation of maize at silking stage. Miao et al.[10] modeled the structure of rice population quality factor and yield component factor by using the regulation data of paddy field water level in recent 2 years, and obtained the conclusion that total water requirement is the main influencing factor of yield and canopy photosynthesis mainly affects rice population quality. Li et al.[11] analyzed the data of farmers in Ansai County, and found that if the effect of ecological environment improvement was not fully utilized, it would only have an indirect impact on economic benefits. In addition, structural equations have also achieved good application results in the fields of urban-rural bus integration[12], residents behavior choice[13], escort product design[14], and automatic driving man-machine switching[15].

Scholars also regard structural equation model as an effective method for multi-factor fusion of complex systems. Haneen Abuzaid et al.[16] applied structural equation modeling to analyze the adaptability of the UAE's photovoltaic and new energy complementary model to residents. Fernando et al.[17] analyzed the traits of Campolina horse by structural equation, and obtained the relationship between genetic traits. Alper et al.[18] analyzed the relationship between the elements of Industry 4.0 from the perspective of industrial chain by structural equation, and obtained the significant factors. The method of using structural equation model to solve multi-factor evaluation has also achieved remarkable results in public transportation[19], robot interaction[20], urban heat island effect evaluation[21], and urban migratory bird migration factors[22].

In summary, there is a lack of comprehensive test and fusion modeling of driver-tractor-soil coupling in real scenarios, and then the impact of agricultural machinery on farmland ecology is analyzed from the perspective of system view. As shown in Figure 1, it is necessary to collect test data and fusion to construct structural equations for potential factor coupling analysis, and then evaluate the impact of agricultural machinery manipulation on soil compaction.

In order to evaluate the damage degree of maize seeding operation to black soil under the mode of northeast cooperative, this study carried out a comprehensive experiment from the perspective of the real use of agricultural machinery, and carried out structural equation modeling, in order to explore the influence of fatigue of different parts of the driver's body on soil compaction from the perspective of human factors engineering.

2 Materials and methods

2.1 Overview of test fields

Baiquan County, Qiqihar City, Heilongjiang Province is the fourth batch of demonstration counties in China's Ministry of Agriculture and Rural Affairs to take the lead in basically realizing

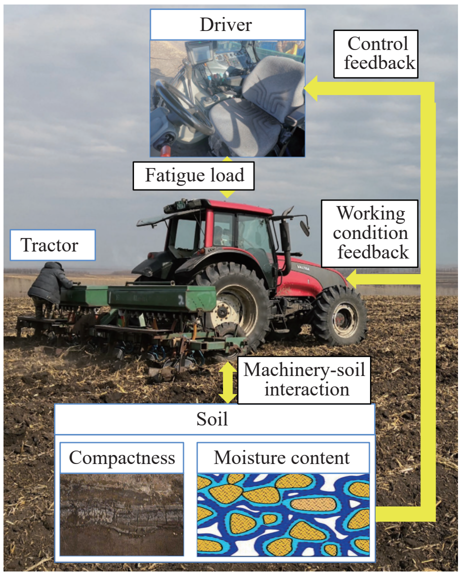


Figure 1 Logical model of driver-tractor-soil system

the full mechanization of main crop production. In view of the lack of soil compaction data under large-scale operation conditions, 4 hm^2 of corn field in Baiquan County Autonomous Modern Agricultural Machinery Professional Cooperative was selected to carry out the comprehensive test of driver-tractor-soil model representation under sowing scene. The experimental area belongs to the hilly area of Songnen Plain, Xiaoxing'anling, Baiquan County (47.63°N, 125.38°E), surface slope 4°-6°, annual average temperature 1.2°C, annual average precipitation 488.2 mm, in line with the typical characteristics of the northern corn planting area of Songnen Plain in Northeast China.

2.2 Characterization parameters

2.2.1 Driver fatigue

The commonly used measurement methods of driver fatigue in different parts are EMG test and discrete questionnaire.

Electromyography test obtains electrical signals by testing muscle current, and then obtains muscle fatigue spectrum by spectrum analysis, and then analyzes muscle fatigue process. The advantage is to directly use physiological signals to characterize fatigue. The disadvantage is that spectrum analysis may not be specific for muscle fatigue process analysis, and it cannot reveal the mechanism of fatigue biological process. The accuracy of EMG sensors is greatly affected by the test environment.

Discrete questionnaire was used to measure the subjective feeling of muscle fatigue. The advantage is that it can reflect the real fatigue feeling of the participants. The disadvantage is that the data obtained by the discrete five-point method for the options belong to the discrete data, which cannot reflect the fatigue degree between the two adjacent options, and cannot be used to construct the continuous variable model.

In this study, continuous questionnaire method was used to measure muscle fatigue (arm, leg, waist and cervical spine), which can not only accurately measure the continuous data of muscle fatigue, but also provide a basis for subsequent structural equation modeling. According to the tractor operation process, the fatigue of the driver's arm, leg, waist and cervical spine at different times was collected. The fatigue calculation method is as follows :

$$F = \pm\frac{x}{L} \tag{1}$$

As shown in Figure 2, x is the length of the line segment corresponding to the test score, mm; L is the total length of one side line, mm: ‘+’ means comfort. ‘–’ means uncomfortable.

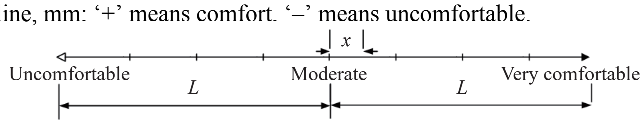


Figure 2 Continuous option questionnaire

2.2.2 Tractor fatigue

The cooperative uses the high-power tractor for seeding operations. The specific parameters are listed in Table 1.

Table 1 Paramaters of high-power tractor

Parameters	Value
Weight/kg	5951
Power/kW	138
Hydraulics pressure/kPa	19 600
Wheelbase/cm	274
Front tire type	16.9R28 Diagonal tire
Rear tire type	20.8R38 Diagonal tire

In this study, the speed value of tractor speed meter is read as the speed of each sampling point.

2.2.3 Soil moisture content and compactness

Soil moisture content and compactness were selected as the main characterization parameters of soil compaction. Soil moisture content is represented by the relative proportion of water in the soil three-phase body (solid skeleton, water or aqueous solution, air) ; soil compactness refers to the ability of soil to resist external compaction and crushing, which is composed of soil shear resistance, compression force and friction force, and is a composite index of soil strength. Soil compaction can predict soil bearing capacity, tillage and root extension resistance. Soil compaction can affect the perforation and growth of crop roots. It is an important soil physical property index for evaluating soil tillage. Too tight soil will prevent water infiltration, reduce fertilizer use efficiency, affect plant root growth, and lead to crop yield reduction.

In this study, the soil moisture content and compactness at 10 cm and 20 cm depths of each sampling point before and after the tractor seeding operation were measured, and the measuring instruments are listed in Table 2.

Table 2 Paramaters of instrument

Instrument	Parameters	Value
Lynd soil moisture measuring instrument	0-50%	±2%
	>50%-100%	±3%
	Resolution	0.1%
	Probe diameter	3 cm
	Cylinder length	6 cm
SeaasCompactometer TJS100S	Range	0-100%
	Precision	±0.1%
	Resolution	0.01 kPa
	Depth	0-450 mm
	Pressure	0-10 MPa

2.3 Testing procedures

Based on the actual corn sowing mode of autonomous cooperatives, the comprehensive test of driver-tractor-soil model characterization parameters was carried out. The test steps are as follows:

1) The test area was divided into two 2 hm² plots (500 m×40 m in each test area). In order to eliminate the mutual interference between the two plots, the distance between the two plots was set to 40 m. Each plot has 36 ridges of corn, and the operating width of the planter is 660 cm. The local corn ridge planting method and the layout of the test sampling points are shown in Figure 3. In order to reduce the interference of farmland boundary on the test area and ensure the typicality of rut shape and representativeness of soil compaction effect, the test experiment was carried out in the ridges and ditches in the middle part of each plot. One road (from south to north, from north to south) was selected in each 2 hm² residential area, and the left and right wheel ruts of each road were sampled at the same time. A total of 4 ruts were sampled, and 12 sampling points in average (red points) were set in each rut, and a fixed sampling point was set every 40 m. There were 4 ruts in two residential areas, a total of 48 sampling points.

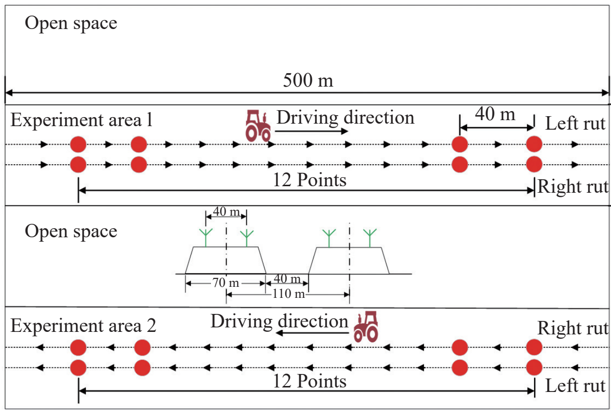


Figure 3 Sampling point layout

2) According to the actual driving route of cooperatives, test area 1 drives from west to east, and test area 2 drives from east to west. Each test area is compacted once. The test process is shown in Figure 4, insert a sign at the sampling point, whenever the car to the sign, read the speed from the instrument, and use the questionnaire to record the driver fatigue. At each sampling point, two adjacent points in the middle of the rut were selected to carry out soil moisture content and soil compactness tests at 10 cm and 20 cm depths.

Figure 4 Field sowing comprehensive test scenario

3) The data of 10 cm and 20 cm depth were analyzed, and the driver-tractor-soil system based on structural equation model was constructed to analyze the influence of driver fatigue on soil compaction.

3 Results and discussion

3.1 Descriptive analysis

The mean values of characterization parameters before and after sowing are listed in Table 3. It shows that after sowing, due to the impact of large tractors on soil compaction, soil compaction increased significantly, 10 cm soil compaction increased by 118.82%, 20 cm soil compaction increased by 71.02%. This shows that the influence of large agricultural machinery on the compaction of black soil is obvious, and the compaction effect of soil surface to deep layer is gradually reduced. This is due to the physical compaction of the surface soil caused by the tire, and the compaction of the deep soil is affected by the vertical vibration wave.

Table 3 Mean value of each characterization parameter before and after sowing

Depth 10 cm	Moisture content/%	Compactness/ kPa	Waist fatigue	Neck fatigue
Before sowing	25.22	1609.10	/	/
After sowing	22.57	3521.11	3.30	2.73
Rate of change/%	–10.51	118.82	/	/
Depth 10 cm	Arm fatigue	Leg fatigue	velocity/ km/h	oil consumption
Before sowing	/	/	/	/
After sowing	2.15	0.58	10.0	20.0
Rate of change/%	/	/	/	/
Depth 20 cm	Moisture content/%	Compactness/ kPa	Lumbar fatigue	Neck fatigue
Before sowing	20.66	4047.48	/	/
After sowing	18.86	6922.36	3.30	2.73
Rate of change/%	–8.71	71.02	/	/
Depth 20 cm	Arm fatigue	Leg fatigue	Velocity/ km/h	Oil consumption
Before sowing	/	/	/	/
After sowing	2.15	0.58	10.0	20.0
Rate of change/%	/	/	/	/

After sowing, the soil moisture content decreased by 10.51% and 8.71% at 10 cm and 20 cm, respectively. The surface soil moisture content changed more than the deep soil moisture content. This is because the surface soil is seriously compacted by a large tractor, and the water in the soil pores is directly extruded. Deep soil due to vibration wave transmission in the process of gradual weakening, and black soil viscosity and specific surface area is larger, soil particles capillary water and bound water affected by external force is small, did not reach the degree of water extrusion, making the field water holding capacity is high, so the measured moisture content changes little.

When the driver drives the tractor, the speed is set to 10 km/h by constant speed setting, and the average actual observed speed at the measurement point is also 10 km/h. The whole fuel consumption is about 20 L, indicating that the farmland pavement in the experimental area is relatively flat and the fluctuation is relatively uniform, which is in line with the typical characteristics of the hilly area in the Songnen Plain of Xiaoxing'anling, and has the representativeness of the test and the popularization of the research results.

It can be seen from Table 3 that with the extension of working time, the fatigue degree of each part of the driver gradually increases. The average fatigue degree of each part of the driver corresponding to all test points is selected to characterize the comprehensive fatigue degree of corn seeding operation. The calculation results show that the waist fatigue is the largest, the neck fatigue is the second, and the leg fatigue is the smallest. This is due to the fact that the driver often needs to observe the situation of the seeder and the ridge groove backward in the seeding operation, making the waist and neck twist, which is not in line with the natural biomechanical state of the human body, resulting in a large increase in fatigue, and ultimately making the driver feel tired as a whole. The operation mode of the tractor is gradually rough, resulting in the increasingly strong effect of tires on the soil, resulting in increased damage to farmland soil by agricultural machinery. This shows that improving driver's working comfort is of certain significance for improving farmland soil compaction and farmland environment.

3.2 Driver-tractor-soil coupling model

3.2.1 Construction and test of structural equation model

Structural equation model is a method for establishing, estimating and testing causal relationship models. The model contains both observable significant variables and potential variables that cannot be directly observed. Structural equation model can replace multiple regression, path analysis, factor analysis, covariance analysis and other methods to clearly analyze the role of individual indicators on the overall and the relationship between individual indicators. The driver-tractor-soil coupling model has the characteristics of high nonlinearity and complex relationship between factors. The structural equation model can ideally solve the problem of multi-factor fusion in agricultural scenes, making the research conclusion more reliable.

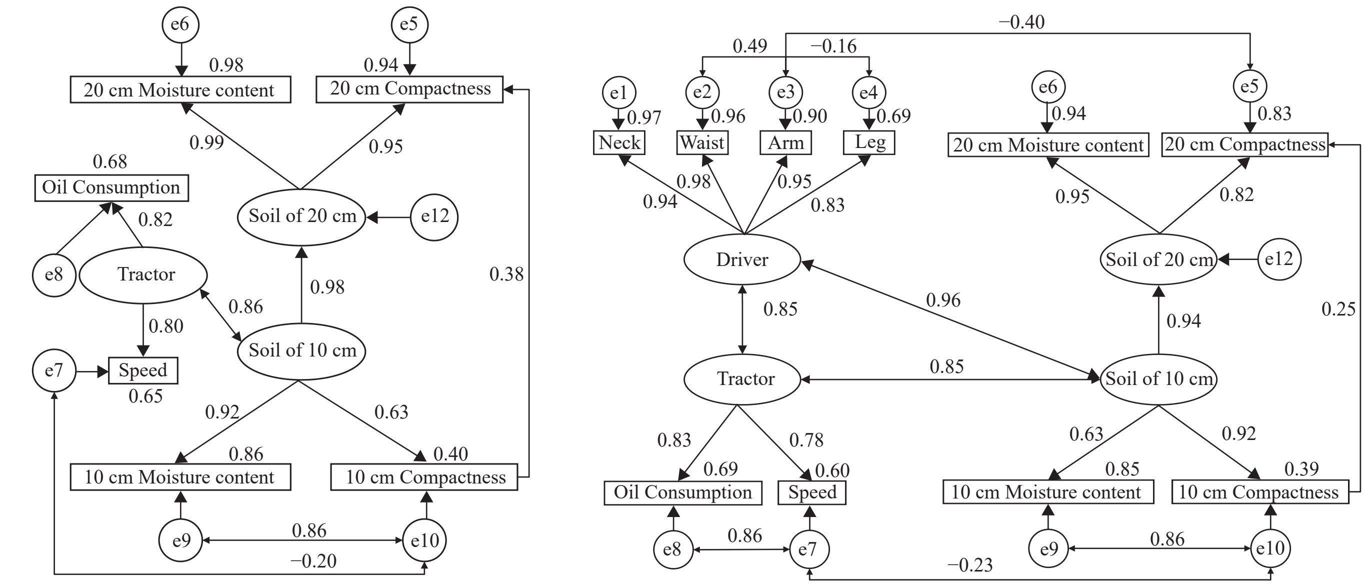
In order to explain the indirect effect of manipulator fatigue on soil compaction, the standardized structural equation models of driver-tractor-soil system and tractor-soil system are shown in Figure 5. Table 4 shows the convergence parameters of the two models. The convergence of model 2 is better than that of model 1, and the variance of soil compaction variables in model 2 is significantly reduced, indicating that the ability of the model to better reveal the causes of compaction is improved after considering the fatigue factor of manipulator. As can be seen from the Figure 5b, the correlation coefficient between manipulator fatigue and topsoil is 0.96, indicating that manipulator fatigue has an indirect impact on topsoil by directly affecting tractor auxiliary handling behavior.

Assuming that the driver's limb fatigue can reflect the overall working load, the increase rate of soil compaction and the decrease rate of water content can reflect the soil ecological parameters, the vehicle speed and fuel consumption can reflect the overall working condition of the tractor, and there is an interaction between the driver, the tractor and the soil. The driver fatigue (arm, leg, waist, and cervical vertebra), vehicle speed, fuel consumption, the change rate of soil moisture content at 10 cm and 20 cm, and the change rate of soil compaction measured at the rutting sampling points in the two test areas were taken as the measurement variables, and the driver, tractor, and soil were taken as the latent variables to construct the driver-tractor-soil system coupling model.

In order to eliminate the influence of the dimension of the observed variables and make each variable compare at the same level, the standardized structural equation model is. The calculated convergence evaluation parameters are listed in Table 4. It can be seen that all indicators meet the convergence range, and each path coefficient is significantly indigenous at the 0.05 level. Therefore, the path coefficient can be used to evaluate the fatigue degree of different parts of the driver and the change rate of soil compaction.

3.2.2 Descriptive analysis of driver fatigue on soil compaction

As shown in Figure5, in each measurement model, except that the measured data of soil compactness at 10 cm depth only explain 39% of the model, the other measured data can explain more than 60% of the model, indicating that this model can better carry out multi-factor fusion according to the measured data. It can be seen from the path coefficient that waist fatigue, fuel consumption, 10 cm



a. Structural equation model 1 without considering manipulator fatigue

b. Structural equation model 2 considering manipulator fatigue

Figure 5 Comparison of structural equation models

Table 4 Model convergence parameters

Parameters	Criterion	Model 1	Model 2
χ^2/df	0-5	1.033	1.441
GFI	0.90-1.00	0.980	0.916
AGFI	0.85-1.00	0.857	0.868
RMSEA	0-0.08	0.027	0.067
CFI	0.95-1.00	0.998	0.988

compactness and 20 cm moisture content have significant effects on the latent variable driver, tractor, 10 cm soil and 20 cm soil, respectively.

In each structural model, there is a two-way influence between the latent variable driver, tractor and soil compaction at 10 cm depth, and the remaining variables are one-way influence. It shows that there is a direct interaction between the driver, the tractor and the 10 cm deep soil, while the 20 cm deep soil has an indirect effect through the remaining variables.

There are also correlations in each residual variable. The correlation coefficient between fuel consumption and vehicle speed, 10 cm soil moisture content change rate and compactness change rate is 0.86. This is because tractors and surface soil are complex systems. There are still many characterization parameters, and there are also interactions between them. The measurement variables selected in this study only characterize some of the characteristics, but the overall convergence effect of the model is better, so the residual does not affect the subsequent model analysis.

3.2.3 Driver-tractor-soil system interaction analysis

The correlation coefficient between the series variables is the product of each path coefficient, and the correlation coefficient between the parallel variables is the sum of each path coefficient. Therefore, the relative influence degree between all variables is listed in Table 5.

Table 5 Influence degree between variables

Data	Waist	Neck	Arm	Leg	Dri	Tra	Oil	Speed	10 cm Soil	Com 10 cm	Moi 10 cm	20 cm Soil	Com 20 cm	Moi 20 cm
Waist	1	0	0.49	–0.08	0.98	1.77	1.47	1.38	1.94	1.83	1.22	1.86	1.65	1.77
Neck	0	1	0	0	0.94	1.70	1.41	1.33	1.86	1.76	1.17	1.78	1.58	1.70
Arm	0.49	0	1	–0.16	0.95	1.72	1.43	1.34	1.88	1.78	1.18	1.80	1.60	1.71
Leg	–0.08	0	–0.16	1	0.83	1.50	1.25	1.17	1.64	1.55	1.04	1.58	1.40	1.50
Driver	0.98	0.94	0.95	0.83	3.7	1.81	1.50	1.41	1.98	1.87	1.06	1.90	1.68	1.80
Tractor	1.77	1.70	1.72	1.50	1.81	1.61	0.83	0.78	1.96	1.86	1.35	1.88	1.69	1.79
Oil	1.47	1.41	1.43	1.25	1.50	0.83	1	0.86	1.63	1.54	1.12	1.56	1.40	1.48
Speed	1.38	1.33	1.34	1.17	1.41	0.78	0.86	1	1.53	1.45	1.05	1.47	1.32	1.39
10 cm Soil	1.94	1.86	1.88	1.64	1.98	1.96	1.63	1.53	1.55	0.86	0.63	0.94	0.77	1.07
Com 10 cm	1.83	1.76	1.78	1.55	1.87	1.86	1.54	1.45	0.86	1	0.86	0.87	1.45	1.02
Moi 10 cm	1.22	1.17	1.18	1.04	1.06	1.35	1.12	1.05	0.63	0.86	1	0.59	1.30	0.68
20 cm Soil	1.86	1.78	1.80	1.58	1.90	1.88	1.56	1.47	0.94	0.87	0.59	1.77	0.82	0.95
Com 20 cm	1.65	1.58	1.60	1.40	1.68	1.69	1.40	1.32	0.77	1.45	1.30	0.82	1	0
Moi 20 cm	1.77	1.70	1.71	1.50	1.80	1.79	1.48	1.39	1.07	1.02	0.68	0.95	0	1

The unit fatigue of each part of the driver's limbs contributes 3.7 units to the overall fatigue, of which the neck and waist fatigue has the greatest impact on the total fatigue, and the leg fatigue has the least impact. This is due to the driving posture makes the legs relatively relaxed, and the lack of consideration of the upper body comfort design.

The driver's unit fatigue has a 0.85 unit effect on the tractor, and the effects on fuel consumption and vehicle speed are 0.83 and 0.78, respectively. The waist fatigue has the greatest impact on fuel consumption, which is 1.47 units.

The driver's unit fatigue acts on the 10 cm surface soil through the tractor. In addition, the driver's own psychological changes directly affect the 10 cm surface soil, a total of 1.98 units of influence, indicating that the driver's psychological load can have a greater impact on the surface soil. In particular, the compactness of 10 cm surface soil is most affected by driver fatigue, and the influence coefficient is 1.87. The 10 cm surface soil could affect 0.94 units of 20 cm deep soil and 0.77 units of deep soil.

Therefore, the driver's neck, waist, arm and leg fatigue caused 1.83, 1.76, 1.78 and 1.55 unit compaction effect on the surface soil after a large tractor compaction; it caused 1.65, 1.58, 1.60 and 1.40 unit compaction effects on deep soil, respectively.

The degree of surface soil compaction is positively correlated with the degree of deep soil compaction in contact with it, and the correlation coefficient is 0.94, indicating that the higher the degree of surface soil compaction is, the higher the degree of deep soil compaction in contact with it is. In other words, the vibration generated by agricultural machinery walking will be transmitted in the form of waves, so the soil compaction effect will be transmitted between the soil at different depths.

Driver fatigue has a great influence on the distribution of soil moisture content. The influence coefficient of surface and deep soil is 1.06 and 1.80, respectively. The deep soil has less water content, and the volume of soil particles decreases after compaction, resulting in a significant decrease in water content. After one compaction, the driver's neck, waist, arm and leg fatigue caused 1.22, 1.17, 1.18 and 1.04 unit reduction in surface soil moisture content, respectively. Deep soils were reduced by 1.77, 1.70, 1.71 and 1.50 units, respectively.

Thus, driver fatigue load has a significant impact on black soil destruction. Reducing the overall fatigue of drivers, especially the waist fatigue, is of certain significance to the protection of black soil under the large-scale mechanical operation mode.

4 Conclusions

1) In the cooperative mode, before and after maize sowing, the change rates of soil compaction at 10 cm and 20 cm depths of the tractor equipped with ordinary skew tires were 118.82% and 71.02%, respectively, and the change rates of moisture content were-10.51% and-8.71%, respectively.

2) Manipulator fatigue can produce indirect compaction on the plough layer. Fatigue of driver's neck, waist, arms and legs can increase surface soil compaction by 1.83, 1.76, 1.78 and 1.55 units, and increase deep soil compaction by 1.65, 1.58, 1.60 and 1.40 units.

3) Fatigue of driver's neck, waist, arm and leg can reduce surface soil moisture content by 1.22, 1.17, 1.18 and 1.04 units, and deep soil moisture content by 165, 158, 160 and 140 units.

4) Driver fatigue will have an indirect impact on the plough layer. Driver fatigue directly affects tractor operation behavior, which indirectly affects surface soil compaction. Surface soil compaction directly affects the compactness and moisture content of deep plough layer.

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