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Straw-Soil-Rotary Blade Interaction: Interactive Effects of Multiple Operation Parameters on the Straw Movement

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Abstract: Conventional soil-tool interaction has been upgraded to straw-soil-tool interaction due to plenty of straw remains in the field after harvesting. Understanding the straw-soil-tool interaction relationship and quantifying the straw movement and distribution characteristics at various tillage operation parameters is critical for straw management and the design of tillage tools. Here, in order to investigate the interactive effects of key operation parameters on the displacement and burial of straw, a specific field test rig was developed to perform straw movement test. According to the singe-factor test and multifactor interactive experiment, we investigated the effect of straw length, tillage depth and rotary speed on straw movement, and established a mathematical model between operation parameters and straw movement. The results showed that the significant order of the influence on the displacement and burial of straw was as follows: the tillage depth, the straw length, the rotary speed. As determined by response surface analysis, the optimal combination of parameters for straw incorporation was straw length of 5 cm, tillage depth of 13 cm, and rotary speed of 320 rpm, and the corresponding straw burial rate and straw displacement were 95.5% and 27.6 cm, respectively. The relative errors of the optimization results are less than 5%. These results indicated that the mathematical model can be used to predict and evaluate straw movement. Therefore, it is feasible to enhance the straw incorporation performance by a reasonable setting of operation parameters, which may provide a comprehensive strategy to improve the working quality of tillage tools.

Keywords: straw movement; rotary tillage; operation parameters; straw displacement; straw burial

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1. Introduction

Over the past decades, soil-tool interaction research has been the main focus of the areas of soil tillage mechanism and tool optimization design [1–4]. As high-yielding agriculture leads to plenty of crop straw left in the field, which is detrimental to seeding operation, seed germination, and early plant growth [5–7]. Crop straw incorporating into the soil thus has become an urgent tillage requirement in soil-tool interaction system. Considering the existence of crop straw, the conventional soil-tool interaction has been upgraded to soil-straw-tool interaction [8]. Straw-soil-tool interaction including interactions between straw and soil, straw and tool, as well as soil and tool, is a complicated system affected by many factors [9]. In the interaction system, investigating the soil and straw movement characteristics under different tillage tools is conducive to comprehensively analyze the interaction mechanism of straw-soil-tool. A better understanding of the effect of different operation parameters (e.g., straw length, tillage depth, and working speed) on the tillage performance is also critical for straw management and the optimal design of tillage tools.

Investigation on the straw-soil-tool interaction has been conducted mainly through three test methods: the simulation model, soil bin test, and field experiment. Numerous studies have been carried out to obtain the detailed data on straw-soil-tool interaction as affected by operation parameters, soil and straw conditions, and tool types. For the simulation model, the results of a straw-soil-sweep interaction model using the discrete element method showed that increasing the travel speed of the sweep increased soil cutting forces (draft force, vertical force, and lateral force), soil and residue displacements, and residue cover reduction [9,10]. Fang [11] concluded from a straw-soil-rotary blade simulation model that the straw displacement increased with increasing rotational speed of blade. For the soil bin test, three different designed discs were tested in a soil bin with rice straw indicated that the biomimetic disc achieved higher straw-cutting efficiencies and lower force requirements than the plain disc and the notched disc [12]. The straw-soil-sweep interaction study in a soil bin test showed that higher tillage speed resulted in larger soil and straw displacement that also buried more straw [13,14]. A soil bin test on straw cover soil at different depths and speeds of disc tillage tool showed that further soil disturbance area and straw burial rate were larger when disc tillage tool speed and depth were increased [15]. For the field experiment, many studies have been conducted to explore the working performance of various tillage tools such as the rotary blade [16–18], moldboard plow [19,20], disc-type furrow openers [21,22], and fluted coulters [23,24].

Despite this large number of studies, a better understanding of the relationships existing between tillage performance and soil and straw parameters has not been elucidated. All studies to date have been based on the single factor experiment to explore the effect of a specific factor such as straw length, tillage depth, and tillage tool on the soil disturbance and straw movement [25–29]. Although some studies provide the detailed data on the working quality of tillage tools under each operation parameter, the optimal combination of tillage parameters under multiple operation factors was not explored [8,30]. In actual agricultural production, a better tillage performance is often the result of the joint action of multiple parameters [31]. For example, in order to obtain a better straw incorporation quality by rotary tillage, it is necessary to select the optimal combination of parameters among straw length, forward speed, tillage depth, rotary speed, blade type. Although the importance of investigating the straw-soil-tool interaction under the action of multiple factors has been emphasized by a number of authors, the detailed test data on model optimization of multiple operation parameters are still lacking. This is particularly true for the field investigation of straw movement characteristics.

In the intensive rice-wheat rotational farming carried out in East-China, excessive residue is left in field after harvesting [12,32]. Farmers' typical practice of conventional tillage was to cut the residue into a proper length and then incorporate the residue uniformly into the soil by rotary tillage [8,31,33]. However, straw incorporation quality after rotary tillage varies widely due to differences in the tillage operation parameters. Previous studies indicated the straw length, tillage depth, and rotary speed are the key operation parameters affecting the quality of straw incorporation [19,34], but unfortunately the quantitative relationship between operation parameters and straw incorporation quality has not been illustrated. A comprehensive understanding of straw movement characteristics is a prerequisite for optimizing the operation parameters to improve the straw incorporation quality. Therefore, more detailed field test data of straw movement characteristics under the action of multiple operation parameters are required.

In conclusion, a comprehensive understanding of soil-straw-tool interaction under the action of multiple factors is conducive to optimizing operation parameters for improving working quality of tillage tools. All existing studies of straw-soil-rotary blade interaction are based on the single factor test, the data of the optimal combination of operation parameters under the action of multiple factors was still lacking. Therefore, our study explores for the first time the use of a specific field test rig to investigate the interactive effects of multiple operation parameters on the straw movement. The specific objectives include: (i) develop a specific field test rig to perform straw movement characteristics of rotary tillage (ii) investigate the interactive effects of three key operation parameters (straw length, tillage depth, and rotary speed) on the displacement and burial of straw and, (iii) obtain the optimization model data of soil-straw-rotary blade interaction under three operation parameters of previous item.

2. Materials and Methods

In June 2021, experiments were conducted in the Babaiqiao farm, Nanjing Agricultural University, China. The farm is located in a suburb of Nanjing (32°25′ N, and longitude of 118°55′ W). The tillage test was carried out in the field after the wheat crop harvesting in summer. The soils in the field were clay loam and site had a long history of rice-wheat rotation. The straw and soil parameters were measured and the results showed in Table 1.

Table 1. Soil and straw parameters of the test site.

Type	Parameters	Value
Straw	Straw length	0–15 cm
	Wet density	4377 kg ha^{-1}
	Dry density	3493 kg ha^{-1}
Soil	Dry bulk density	1.28 g cm^{-3}
	Cone index	752, 1185, 1093 kPa at 5, 10, and 15 cm depths, respectively
	Moisture content	18.6, 20.3, 22.7% at depth of 0–5, 5–10 and 10–15 cm, respectively

2.1. Field Test Rig

In order to obtain the detailed field test data of straw movement characteristics under the action of multiple operation parameters, a specific field test rig was developed for this study. Its main features include a movable carriage, a rotary tiller, a traction motor, four lifting motors, two traction chains, and a control system (Figure 1). The test bench is 8000 mm long and 2000 mm wide, and constructed by the rectangular steel tubes of various sizes. The movable carriage is transported on twin lead rails, driven by a traction motor with an adjustable speed at 0.05–1 m s^{-1}. Four lifting motors drive the carriage to move up and down, which is easy to operate through a wireless control handle. The test rig was powered by a 13.5 kW electric generator, and there was a complex control system to complete power transmission and operation control. The specific operation process of field test rig is to first start the electric generator to provide power for the whole system, and then operate the lifting motors to drive the carriage to move up and down for adjusting the tillage depth, and operate the traction motor to control the forward speed of tillage tools. All operation parameters can be adjusted with the wireless control handle.

2.2. Description of the Tillage Tool

The rotary tillage tools are shown in Figure 2. A 225-mm-rotary radius blade based on axis of rotation of the cutter shaft (IT225, shown in Figure 2b.) was selected for the tests. This conventional blade use left- and-right hand bent C blades with a cutting width of 45 mm and angle 46°, which is commonly used for land preparation in the annual rice-wheat rotating fields managed in East China regions. The material of IT225 rotary blade is 65 Mn and available for tillage in cohesive soil due to its high strength. Referring to the design parameters of the conventional small-sized rotary tiller (e.g., width of about 0.8 m, cutter shaft speed range among 200–350 rpm and maximum nominal power of 10 HP), all blades are mounted on a 0.8 m long cutter shaft with a double spiral arrangement (Figure 2a). The rotary cutter shaft was driven by a 7.5 kW motor, and the rotary speed was adjustable from 0 to 600 rpm. The rotary tillage tools were mounted on the moveable carriage of the test rig, driven by a traction motor with an adjust speed at 0.05–1 m s^{-1}.

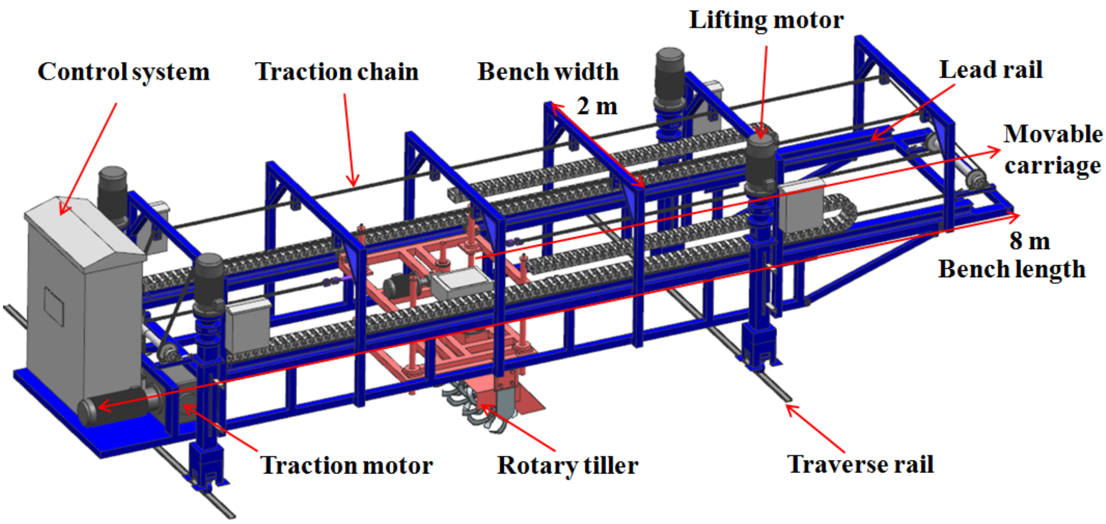

Figure 1. Schematic structure of field test rig.

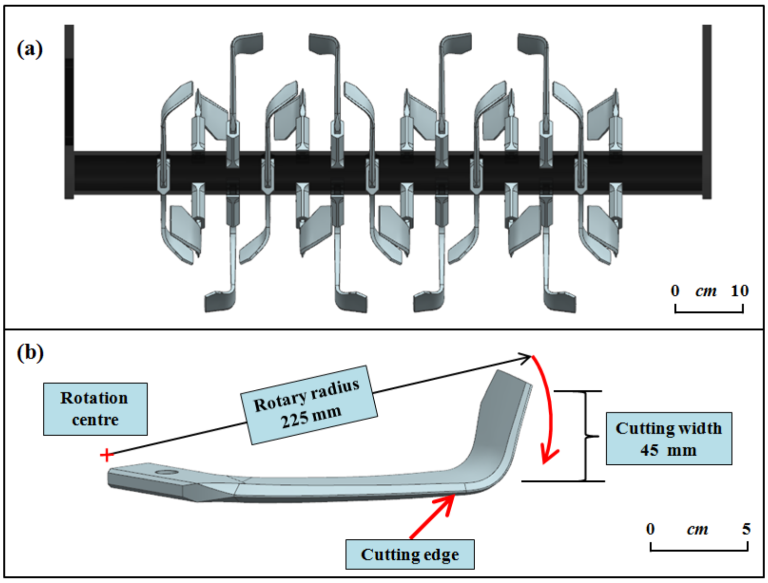

Figure 2. Rotary tillage tools (**a**) the cutter shaft, (**b**) the rotary blade.

2.3. Straw Preparation

Wheat is one of the major crops in the Middle-Lower Yangtze River. Thus, wheat straw was used to represent crop residue in this study. Farmers use harvester with choppers to spread straw in field. The chopping length of wheat straw ranged from 50 to 150 mm and is adjustable. Therefore, experimental straw was cut into three lengths of 5, 10, and 15 cm, and stored separately. A precisely controlled field test bench was used to quantitatively investigate the effects of tillage operation parameters on the displacement and burial of straw (Figure 3a). The straw tracers for tracking straw displacement and surface straws for measuring straw burial rate were laid manually before rotary tillage. The specific operation method was to place the straw tracers on the ground first, and then place surface straws on top of tracers (Figure 3b). The tracer method was used to study the straw displacement on soil surface after rotary tillage, and the placement positions of three different straw tracers were shown in Figure 3c. The travel direction is the forward direction of the rotary tiller along the lead rails on the main frame. The marked seven red and seven blue straws represent the longitudinal (tillage travel direction) straw and lateral (tillage width direction) straw, respectively. Straw movement in the depth direction under different operation parameters were explored by surface straw incorporation test. The amount of surface straw was 4377 kg ha^{-1}, and had the same straw density as the actual field condition. In addition, the surface straw was evenly spread manually according to the straw distribution state after harvest.

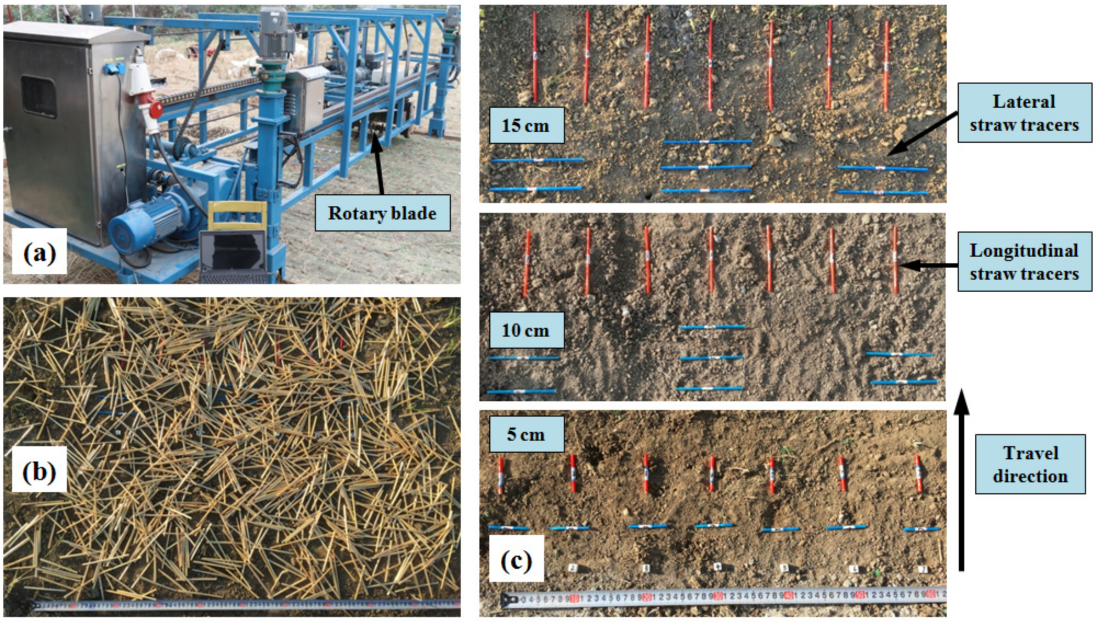

Figure 3. Straw preparation (**a**) place field test bench, (**b**) place straw tracers and surface straws, (**c**) examples of straw tracers.

2.4. Experimental Design

Previous studies indicated that straw length, tillage depth, and rotary speed are the key operation parameters affecting the quality of straw incorporation. Decreasing the straw length can improve the quality of straw incorporation by rotary tillage, and increase the tillage depth can effectively improve the straw burial rate. In addition, appropriately increasing the rotary speed is also conducive to burying more straws into the soil and obtaining a better quality of straw incorporation. Furthermore, the quality of straw incorporation main includes straw burial quality along the soil depth direction and straw distribution quality along the soil horizontal direction, and corresponding evaluation indexes are straw burial rate and straw displacement, respectively. In rotary tillage, the higher straw burial rate represents a better tillage burying performance, and the greater straw displacement means more even straw distribution in the soil. Therefore, the experimental design takes straw length, tillage depth, and rotary speed as the experimental factors, and selects the straw displacement and straw burial rate as the evaluation indexes to conduct the single factor basic experimental study and the multifactor interactive experimental study of the influence of above three key parameters on straw movement characteristics.

Two experiments were conducted to study the soil-straw-rotary blade interaction:

Experiment 1 was a single factor basic experimental study. The goal was to acquire basic data of straw movement under different tillage operation parameters. Three straw lengths (5, 10, and 15 cm), three tillage depths (7, 10, and 13 cm) and three rotary speeds (240, 280, and 320 rpm) were selected for this study of straw movement characteristics. The straw displacement and straw burial rate reflect the movement of straw in the horizontal and depth directions, respectively. In addition, the conventional small-sized rotary tiller usually performed rotary tillage operation at a constant forward speed of 0.5 m s^{-1}. So the experiment was conducted with straw displacement and straw burial rate as evaluation indicators, and each test was repeated three times with a constant forward speed of 0.5 m s^{-1}.

Experiment 2 was a multifactor interactive experimental study. The purposes were to explore the interactive effects of the above three parameters on the displacement and burial of straw, as well as optimize the parameters for improving working quality. According to the results of single factor test, the three factor of straw length, tillage depth, and rotary speed were selected for the BOX-Behnken experiment in the Design-Expert 8.0 software, and the levels of test factors were shown in Table 2. The three factor and three-level test designed according to principle of the BOX-Behnken experiment includes 17 runs of tests, and each level test is repeated three times. In addition, according to the operation parameters commonly used by local farmers, the 0 level of each parameter is set as 10 cm straw length, 10 cm tillage depth, and 280 rpm rotary speed, respectively.

Table 2. Levels of test factors.

Levels	Straw Length *A*/cm	Tillage Depth *B*/cm	Rotary Speed *C*/rpm
−1	5	7	240
0	10	10	280
1	15	13	320

2.5. Measurements

2.5.1. Straw Displacement

Straw displacement is a common index to evaluate the straw movement characteristics in the horizontal direction. The larger straw displacement means that straw can be fully mixed with the soil and evenly distributed in the soil. According to the straw tracer method, straw displacements were acquired by measuring the position changes of the tracers before and after rotary tillage. The origin of the reference system was the middle point of the first two support columns of the test rig in Figure 1, and the middle point of straw tracers was used as detection point. As shown in Figure 4a, the x and y coordinate values of straw tracers before and after tillage were measured with mutually perpendicular rulers, and the displacement values of tracers were calculated according to the absolute difference between the original position and final position. The straw displacement was taken as the average value of 7 groups of tracers. Considering that the straw tracers may move along the tillage travel direction or tillage width direction, the two-dimensional coordinates of the straw tracers along these two directions are measured. The tracer displacement value was calculated with the following equation:

$$L = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{1}$$

where x_i and y_i are coordinate values of straw tracers along the tillage width direction and tillage travel direction, respectively.

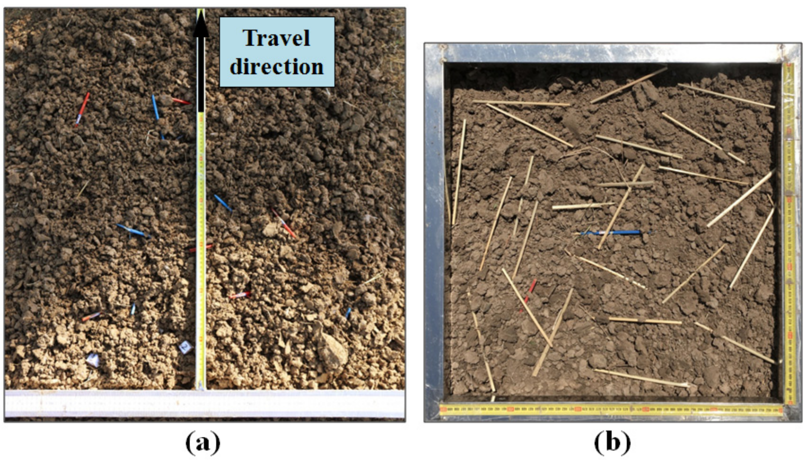

Figure 4. (**a**) Displacement measurement method, (**b**) Sampling to obtain straw burial rate.

2.5.2. Straw Burial

The straw burial rate is one of the important indexes to evaluate the straw movement characteristics in the depth direction. The higher straw burial rate implies that the greater displacement of straw movement in the depth direction. The amount of surface straws before and after rotary tillage was collected by a steel sampling frame (used to keep the same area for each measurement) with dimensions of 500 × 500 mm, and the change value of straw weight was obtained by an electronic scale (Figure 4b). The specific operation to obtain the weight of straw after tillage was to cut the exposed surface straws in the sampling frame with a scissor and weight them. The burial rate of straw was measured according to the difference of total weight of straw on the soil surface before and after rotary tillage, which was calculated with the following equation:

$$Y = \frac{m_q - m_h}{m_q} \times 100\% \qquad (2)$$

where m_q (kg) is the total weight of straw before tillage and m_h (kg) is the total weight of straw after tillage.

2.6. Data Analysis

The data of experiment 1 were subjected to statistical analysis by one way factorial analysis of variance (ANOVA) using IBM-SPSS Statistics 22 software (IBM Corp., Armonk, NY, USA). When the F-test indicated statistical significance at the p = 0.05 probability level, treatment means were separated by the least significant difference ($LSD_{0.05}$) test. The statistical data of experiment 2 were performed using Design Expert Statistical Software package 8.0 trial version (Stat Ease Inc., Minneapolis, MN, USA). In this software, the lack of fit and the significance of the linear and cross product effects of the independent and dependent variables on the displacement and burial attributes are determined and the F value is the ratio of the mean square due to regression and the mean square due to real error.

3. Results and Discussions

3.1. Effect of Single Factor on the Straw Displacement

The effect of single factor (straw length, tillage depth, and rotary speed) on the straw displacement was studied, as shown in Figure 5. The straw displacement decreased with increasing the straw length and tillage depth, but increased with the increase of rotary speed. Figure 5a indicated that the straw displacement after rotary tillage was decreased from 27.9 cm to 22.4 cm with the increasing straw length from 5 cm to 15 cm. The straw displacement of long straw was 20% less than that of short straw. So the long straw after tillage had less straw distribution range in the horizontal soil space. The main reason was that movement of long straw was more restricted by the soil, resulting in the decrease of straw displacement. Figure 5b showed that the straw displacement after rotary tillage was decreased from 30.8 cm to 23.2 cm with the increasing tillage depth from 7 cm to 13 cm. The results indicated that the straw displacement changed significantly as a change of tillage depth. Compared with the former two factors, the straw displacement after rotary tillage was increased from 23.3 cm to 26.8 cm with the increasing rotary speed from 240 rpm, to 320 rpm, as shown in Figure 5c. In order to obtain a better straw distribution quality, the rotary speed could be increased appropriately for enlarging the straw displacement in the mixing of straw and soil. Therefore, according to the results of single factor test, tillage operation parameters such as straw length, tillage depth, and rotary speed had a significant effect on straw displacement.

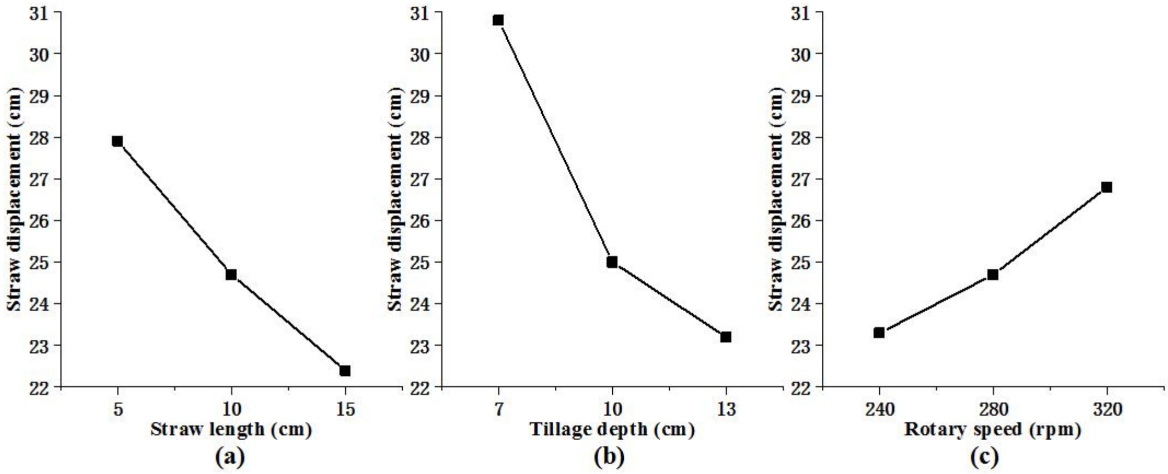

Figure 5. Effect of single factor on straw displacement (**a**) relationship between straw length and straw displacement, (**b**) relationship between tillage depth and straw displacement, (**c**) relationship between rotary speed and straw displacement.

3.2. Effect of Single Factor on the Straw Burial

The effect of single factor (straw length, tillage depth, and rotary speed) on the straw burial was studied, as shown in Figure 6. The results indicated that the straw burial rate increased with increasing the tillage depth and rotary speed, but decreased with the increase of straw length. Figure 6a showed that the straw burial rate after rotary tillage was decreased from 90.1% to 78.2% with the increasing straw length from 5 cm to 15 cm. The long straw after tillage had less straw burial rate in the depth direction of soil space. The main reason was that long straw was not easy to incorporate into the soil because of its larger geometry. Figure 6b showed that the straw burial rate after rotary tillage was increased from 66.6% to 90.2% with the increasing tillage depth from 7 cm to 13 cm. Increasing tillage depth had a great improvement on straw burial rate, and the straw burial rate of 13 cm tillage depth was about 35% more than that of 7 cm tillage depth. The same trend as tillage depth, the straw burial rate after rotary tillage was increased from 82.1% cm to 86.2% with the increasing rotary speed from 240 rpm, to 280 rpm, as shown in Figure 6c. The possible reason was that the soil was more broken to incorporated more straw under the condition of high rotary speed. Thus, according to the results of single factor test, changing the values of straw length, tillage depth, and rotary speed had a significant effect on straw burial.

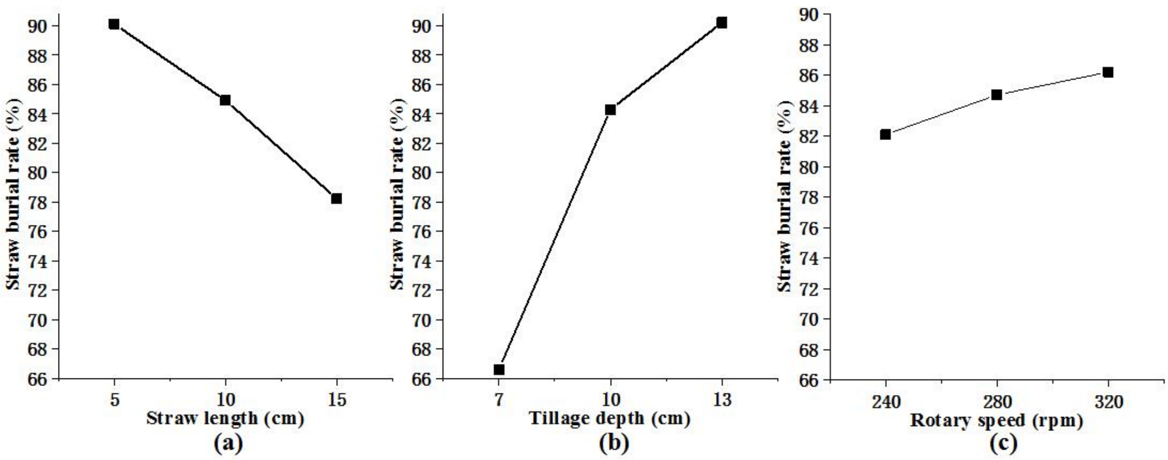

Figure 6. Effect of single factor on straw burial (**a**) relationship between straw length and straw burial, (**b**) relationship between tillage depth and straw burial, (**c**) relationship between rotary speed and straw burial.

3.3. Interactive Effects of Operation Parameters on the Displacement and Burial of Straw

3.3.1. Experimental Results

The experimental results were shown in Table 3. The mathematical models of the effects of straw length, tillage depth, and rotary speed on the displacement and burial of straw can be established by using the Design Expert software, and the interactive relation between various factors also can be analyzed. Table 3 described the values of straw displacement and straw burial rate in 17 runs of experiments. Test results show that reducing straw length, increasing tillage depth and rotary speed can increase straw displacement and straw burial rate, so as to improve the quality of straw incorporated into the soil.

Table 3. Test design and results.

	Coded Levels of Variable			Response	
Runs	**Straw Length (*A*, cm)**	**Tillage Depth (*B*, cm)**	**Rotary Speed (*C*, rpm)**	**Displacement (*L*, cm)**	**Burial Rate (*Y*, %)**
1	5 (−1)	7 (−1)	280 (0)	34.3	73.5
2	5 (−1)	10 (0)	240 (−1)	26.2	87.1
3	5 (−1)	10 (0)	320 (+1)	29.9	91.6
4	5 (−1)	13 (+1)	280 (0)	27.1	94.7
5	10 (0)	7 (−1)	240 (−1)	29.7	64.2
6	10 (0)	7 (−1)	320 (+1)	32.8	67.9
7	10 (0)	10 (0)	280 (0)	24.6	84.9
8	10 (0)	10 (0)	280 (0)	24.8	85.5
9	10 (0)	10 (0)	280 (0)	25.1	84.1
10	10 (0)	10 (0)	280 (0)	23.9	83.5
11	10 (0)	10 (0)	280 (0)	25.3	84.9
12	10 (0)	13 (+1)	240 (−1)	21.3	88.3
13	10 (0)	13 (+1)	320 (+1)	25.5	91.1
14	15 (+1)	7 (−1)	280 (0)	30.7	55.4
15	15 (+1)	10 (0)	240 (−1)	20.6	75.5
16	15 (+1)	10 (0)	320 (+1)	25.1	79.6
17	15 (+1)	13 (+1)	280 (0)	18.9	84.5

3.3.2. Analysis of Straw Displacement Model

According to the experimental results of straw displacement in Table 3, multiple fitting and regression analysis were carried out by using the Design Expert software to establish the response regression model between the three independent variables of straw length, tillage depth, and rotary speed, as shown in the following equation:

$$L = 24.74 - 2.77A - 7.23B + 1.94C - 1.92AB + 0.20AC + 0.46BC + 0.57A^2 + 6.78B^2 + 0.14C^2 \quad (3)$$

In order to further determine the fitting accuracy of the model, and the primary and secondary order of the effect of various factors on straw displacement, the data of straw displacement was analyzed by variance analysis and ternary quadratic regression analysis. As shown in Table 4, the R^2 and adjusted R^2 are 0.9897 and 0.9764, respectively; and in the model significance test, F = 74.41, $p < 0.0001$. This data indicates that the difference between regression models is very significant. Moreover, in the lack of fit test, F = 1.94 $p > 0.1$, which is not significant. So it shows that the model has high fitting accuracy with the actual results, and can accurately describe the relationship straw displacement *L* and the three parameters (straw length *A*, tillage depth *B* and rotary speed *C*). Therefore, it could be used for prediction and analysis of the straw displacement. In addition, according the F value in the model, it could be found that the primary and secondary order of influence on straw displacement is tillage depth, straw length and rotary speed.

Table 4. Variance analysis of straw displacement.

Source	Sum of Squares	Degree of Freedom	F Value	*p*-Value
Model	275.47	9	74.41	<0.0001
A-Straw length	61.61	1	149.76	<0.0001
B-Tillage depth	150.51	1	365.89	<0.0001
C-Rotary speed	30.03	1	73.01	0.0001
AB	5.29	1	12.86	0.0089
AC	0.16	1	0.39	0.5526
BC	0.30	1	0.74	0.4195
A^2	1.36	1	3.30	0.1123
B^2	25.12	1	61.06	0.0001
C^2	0.085	1	0.21	0.6623
Residual	2.88	7		
Lack of fit	1.71	3	1.94	0.2646
Pure error	1.17	4		
Total	278.35	16		
R^2	0.9897			
Adjustment of R^2	0.9764			

According to the model, the response surface of each influencing factor to straw displacement is obtained by using the Design Expert software. The strength of their interaction effect and the influence law on straw displacement can be analyzed by the response surface diagram. The results showed that the interaction between straw length and tillage depth had a significant effect on straw displacement; but the interaction between straw length and rotary speed, and the interaction between tillage depth and rotary speed had no significant effect on straw displacement. The response surface diagram of the interaction between straw length and tillage depth on straw displacement was shown in Figure 7, which can indicate that the straw displacement decreases with the increase of straw length and tillage depth. The main reason for this phenomenon was that the straw weight increases with the increasing straw length, and the movement speed of straw is small under the same force of rotary blade. Moreover, with the increase of tillage depth, straw movement will be hindered by more soil, which will reduce the straw displacement. Therefore, appropriately decreasing the straw length and tillage depth can increase the straw displacement, make the straw evenly distributed in the soil, and improve the quality of straw incorporation.

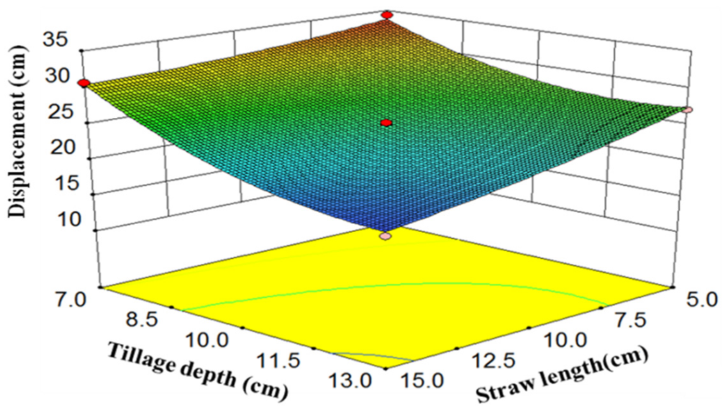

Figure 7. Response surfaces of straw length and tillage depth on straw displacement.

3.3.3. Analysis of Straw Burial Model

According to the experimental results of straw burial rate in Table 3, multiple fitting and regression analysis were carried out by using the Design Expert software to establish the response regression model between the three independent variables of straw length, tillage depth, and rotary speed, as shown in the following equation:

$$Y = 84.58 - 6.49A + 20.33B + 1.89C + 3.29AB - 0.10AC - 0.37BC - 0.99A^2 - 18.24B^2 - 0.14C^2 \quad (4)$$

In order to further determine the fitting accuracy of the model, and the primary and secondary order of the effect of various factors on straw burial rate, the data of straw burial rate was analyzed by variance analysis and ternary quadratic regression analysis. As shown in Table 5, the R^2 and adjusted R^2 are 0.9961 and 0.9911, respectively; and in the model significance test, F = 199.04, $p < 0.0001$, which indicates that the difference between regression models is very significant. Moreover, in the lack of fit test, F = 2.42, $p > 0.1$, which is not significant. Therefore, it can accurately describe the relationship between straw burial rate Y and the three parameters (straw length A, tillage depth B and rotary speed C). Therefore, it could be used for prediction and analysis of the straw burial rate. In addition, according the F value in the model, it could be found that the primary and secondary order of influence on straw burial rate is tillage depth, straw length and rotary speed.

Table 5. Variance analysis of straw burial rate.

Source	Sum of Squares	Degree of Freedom	F Value	*p*-Value
Model	1762.10	9	199.04	<0.0001
A-Straw length	336.70	1	342.30	<0.0001
B-Tillage depth	1190.72	1	1210.52	<0.0001
C-Rotary speed	28.50	1	28.98	0.0023
AB	15.60	1	15.86	0.0053
AC	0.04	1	0.041	0.8459
BC	0.20	1	0.21	0.6638
A^2	4.13	1	4.20	0.0797
B^2	181.47	1	184.49	<0.0001
C^2	0.083	1	0.084	0.7805
Residual	6.89	7		
Lack of fit	4.44	3	2.42	0.2067
Pure error	2.45	4		
Total	1768.98	16		
R^2	0.9961			
Adjustment of R^2	0.9911			

According to the model, the response surface of each influencing factor to straw burial rate is obtained by using the Design Expert software, and the interactive effects of straw length, tillage depth and rotary speed on the response value of burial rate were further analyzed. The results showed that the interaction between straw length and tillage depth had a significant effect on straw burial rate; but the interaction between straw length and rotary speed, and the interaction between tillage depth and rotary speed had no significant effect on straw burial rate. The response surface diagram of the interaction between straw length and tillage depth on straw burial rate was shown in Figure 8. When the rotary speed is at 0 code level, the straw burial rate gradually decreases with the increase of the straw length during the tillage depth is at a high level. The main reason was that certain tillage depth can fully mix the straw with the soil, so as to incorporate the straw into the soil, and the displacement of the longer straw was small to fully mix with soil, which resulted that the straw burial rate decreased with the increasing straw length. Moreover, when the tillage depth is at a high level and the straw length is at a low level, the straw burial rate appears a maximum, which shows that a smaller straw length and a larger tillage depth can be conducive to the full mixing of straw and soil and improve the straw burial rate. The possible reason is that there is a thick layer of loose and crushed soil on the surface at a large tillage depth, which can be fully mixed with short straw, so as to achieve a better straw incorporation quality.

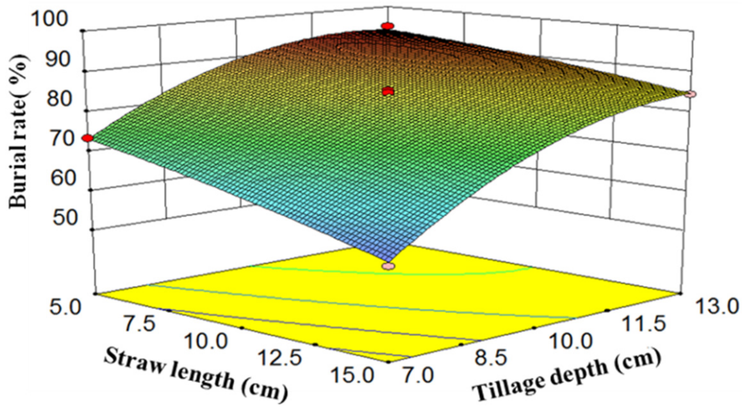

Figure 8. Response surfaces of straw length and tillage depth on straw burial rate.

3.3.4. Parameters Optimization and Model Verification

In order to improve the quality of straw incorporation, the tillage operation parameters were optimized to achieve maximum straw burial rate and straw displacement using the second-order polynomial model in the straw incorporation by rotary tillage. Thus, the double objective function model of straw burial rate Y and straw displacement L was established, and the constraints were as shown in the following equation:

$$\begin{cases} \max Y \\ \max L \\ 5 \leq A \leq 15 \\ 7 \leq B \leq 13 \\ 240 \leq C \leq 320 \end{cases} \quad (5)$$

The methodology of desired function was applied and the optimum level of various operation parameters variables were obtained to indicate that 5 cm straw length, 13 cm tillage depth, and 320 rpm rotary speed gave the maximum of 95.4% straw burial rate and 29.5 cm straw displacement. In order to verify the accuracy of the optimized parameters, the tillage operation parameters were adjusted close to the optimal solution, and three repeated experiments were carried out. The specific operation was that straw incorporation test by rotary tillage was conducted under the condition of 5 cm straw length, 13 cm tillage depth, and 320 rpm rotary speed. The verification test result showed that the straw burial rate and straw displacement were 93.6% and 30.4 cm, respectively. Therefore, the model was reliable due to the relative error between the test value and the model optimization value is less than 5%.

3.4. Discussion of Studying Soil-Straw-Rotary Blade Interaction Using the Specific Field Test Rig

The field investigation demonstrates that operation parameters affect the movement characteristics of straw. Operation parameters such as straw length, tillage depth, and rotary speed have significant effects on the displacement and burial of straw. Although not all interactions between each operation parameters have significant effects ($p < 0.05$), the over results indicated that it is feasible to select an appropriate combination of operation parameters to improve the quality of straw incorporation. Most previous studies of straw-soil-tool were conducted through the simulation model, soil bin test, and field test system with tractor traction [35–37]. However, few studies focus on the straw-soil-tool interaction using a specific field test rig. Although the benefits of simulation model and soil bin test are well known (e.g., save time and cost), they are difficult to completely characterize the complicated situation in the actual field. Therefore, some accurate data of straw-soil-tool interaction under field conditions are still needed. To some extent, the field test system of tractor traction could obtain some field data, but it has many limitations, such as it is difficult to accurately control test parameters (e.g., forward speed, tillage depth, and rotary speed), unable to avoid the soil structure damage of tractor roller compaction, and unable to eliminate the adverse effect of tractor vibration on data quality [38]. In the present study, a specific field test rig was built to investigate the interactive effects of multiple operation parameters on the straw movement in the straw-soil-rotary blade interaction, and quantitatively describe the relationship between three key parameters (straw length, tillage depth, and rotary speed) and the displacement and burial of straw. The field test results indicated that shorter straw, lager tillage depth and higher rotary speed had positive effect on increase straw incorporation, which is similar to previous soil bin test results, and a better working quality could be achieved by appropriate selection of operation parameters. These field data of straw movement characteristics would be very important for establishing mathematical model between operation parameters and straw incorporation, so as to provide guidance for tillage parameters optimization, straw management and the optimal design of tillage tools. However, although the field test rig has the advantages of accurately controlling test parameters, it is still different from the actual operating conditions. Therefore, in the straw-soil-tool experiment, the relationship and different between field rig test and actual test of tractor traction needs to be further explored.

4. Conclusions

In this study, we used the field testing bench to investigate the effect of tillage operation parameters on the displacement and burial of straw, and obtained the detailed data of soil-straw-rotary blade interaction. Conclusions drawn were as follows:

(i) The results showed that the significant order of the influence on the displacement and burial of straw was as follows: the tillage depth, the straw length, the rotary speed. The interaction between straw length and tillage depth had a significant effect ($p < 0.01$) on the displacement and burial of straw, and the interaction of other parameters was not significant.

(ii) The methodology of desired function was applied and the optimum level of various operation parameters variables were obtained to indicate that 5 cm straw length, 13 cm tillage depth, and 320 rpm rotary speed gave the maximum of 95.4% straw burial rate and 29.5 cm straw displacement.

(iii) The relative errors of the optimization results are less than 5%. Therefore, the mathematical model was reliable due to the preliminary verification test, and could be used to predict and evaluate straw movement. Although the accuracy of the model needs to be further verified based on the complexity of field tillage, it is feasible to enhance the straw incorporation performance by a reasonable setting of operation parameters, which may provide a comprehensive strategy to improve the working quality of tillage tools.

Considering the advantages of the field test rig in accurately control test parameters (e.g., forward speed, tillage depth, and rotary speed), and data acquisition and processing (e.g., torque, power consumption, and tillage force), the influence of tillage parameters on the working time and tillage energy consumption will be further explored in the future.

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