EFFECTS OF DIFFERENT GEOMETRICAL STRUCTURES ON THE SOIL DISTURBANCES AND WORKING RESISTANCES OF VERY NARROW TINES APPLIED ON NATURAL GRASSLAND

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极窄齿类耕作部件形状结构参数对草地作业阻力和扰动情况的影响

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ABSTRACT

Novel tillage tools with high working performance are desired in improving degraded natural grassland tillage system. This paper aimed to find the influence of various geometry structures of very narrow tines on related soil disturbance characteristics and tillage resistances. Four shank-type tillage tines with different cutting head shapes, and the test bench were designed and manufactured. Field experiments under different working depths were conducted. The working depth uniformity, soil over-turning rate, cross-section area of disturbed soil layer, and related forces were obtained, analysed, and compared. Results showed that, the working depth uniformities were above 70%, and soil overturning rates did not exceed 5%. Furrows with V-shaped cross-section were formed. The tine with an arc-shaped cutting edge (AT) obtained a lower draft force value, and the tine with chamfer structure (TTD) presented big differences on the draft force and soil disturbance compared to the tine with blunt cutting edge (TT). Both the draft force and the area of disturbed soil cross section had a good linear relationship with the working depth, and the specific draft force increased with the working depth increasing. Using a very narrow tine with chamfers to split and break the soil layer on the natural grassland without pulling or dragging the roots could be an appropriate tillage method applied for improving degraded natural grassland, but still need further surveys.

摘要

为设计和优化退化草地开沟部件，对具有不同形状结构参数的极窄齿类耕作部件的作业效果展开研究。设计了4 种铲尖形状不同的极窄齿类开沟部件，搭建了试验台，进行了草地开沟扰动试验。试验结果表明，在 0~15 cm 作业深度范围，各部件的开沟深度稳定性系数均在 70%以上，造成的地表翻垡率不超过 5%，作业后形成具有“V”形扰动截面沟槽的扰动区域。牵引阻力和土层扰动截面积均与作业深度呈良好的线性正相关关系（R^2≥0.78），且单位面积牵引力随深度的增加而增大。入土角相同的情况下，铲尖形状对开沟部件的牵引阻力和草地扰动情况影响不显著，但有无刃口对二者具有较大影响；采用具有刃口的极窄齿类开沟部件以切断或割裂土层的方式能够有效打破板结性退化草地的土壤-根系复合土层结构，降低地表植被破坏程度，采用凹曲线的铲尖刃线形状可适当降低开沟部件的牵引阻力。

INTRODUCTION

Leymus chinensis (Trin.) Tzvel., referred to as L-C hereafter, is a native perennial rhizomatous grass, widely distributed in the natural grasslands of the Northeast China Plain, the Northern China Plain, and the Inner Mongolia Plateau of China *(Wang et al., 2004)*. It is a popular fodder grass with economic and ecological importance due to its good palatability and high forage value *(MOA, 1996).* However, in recent years, the L-C natural grasslands have been showing degradation trends with the behaviours of soil hardening, reduction of natural vegetation cover, decrease of grassland productivity, and deterioration of ecosystem conditions.

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Continuous livestock grazing was verified to be one of the main reasons resulting in soil compaction on the grassland due to trampling by the livestock *(Martınez and Zinck, 2004; Bell et al., 2011)*. In addition, the biological characteristic of long strong rhizomes and vigorous vegetative propagation was regarded as another reason causing soil compaction and pasture degradation, by consolidating the tangled long roots and soil, forming the soil-root composite structure underground on the natural grassland *(He et al., 2016).*

The degraded natural grassland restoration has been a long-term research topic in China. Apart from the measures of grassland management and excluding grazing arrangement, using tillage tools to break the hardened soil layer and the complicated soil-root structure on the degraded natural grasslands by improving the soil physical, chemical, and biological properties, was verified to be one effective practice for the degraded natural grassland restoration *(Chen et al., 2017; Tang et al., 2016; Alvarez and Steinbach, 2009; Diabate et al., 2018; You et al., 2012).* In addition, appropriate conservation tillage practices with low soil over-turning rate and surface disturbance should be taken into account, due to the soil nutrition loss and severe soil erosion problems caused by conventional tillage tools *(Su et al., 2004; Lal, 2007; Ramírez et al., 2019).*

Drilling or reseeding practice is one effective and long-standing recommendation mean for improving degraded grasslands *(Bueno et al., 2007; Liu et al., 2015; Zhou et al., 2017).* The special and complicated soil layer structure of natural grasslands are different from the common crop fields, making it hard to build a good seedbed because of the hardened soil layer and complicated soil-root structure, and the disturbance on the grassland causing by tillage tools varied as well. So, applying appropriate tillage tools is necessary. The drilling or reseeding methods used for degraded grassland restoration still mostly adopted the openers used for the conventional crop field tillage system as the furrow openers for improving degraded natural grasslands, having limitations to achieve good working performances by causing soil nutrition loss and severe soil erosion problems *(Zhao et al., 2006; Su et al., 2004).* However, limited reports about specialized openers used for natural grassland tillage system could be found.

To select an appropriate tillage implement, the soil disturbance type and degree are the prime factors but must be considered together with the working resistances for efficient operation *(Godwin, 2007; Godwin and O'Dogherty, 2007).* This paper aimed to find the influence of different geometrical structures of very narrow tillage tools on the soil disturbances and tillage forces applied on natural L-C grassland, providing basic references and supports for designing novel and specialized furrow openers applicable to natural grasslands. The Shank-type tillage tines were selected as the tillage tools working on natural grassland because of the characteristics of simple structure, easy processing, and causing low disturbance. Three types of tine geometries (i.e. triangle tine, arc tine, and convex tine) were designed, and the influence coming from the cutting edges (i.e. chamfer and blunt) were also considered. The soil disturbances and soil cutting forces were obtained, analysed, and compared between these tillage tines applied on natural grassland.

MATERIALS AND METHODS

• Experimental site description and soil physical properties survey

The experiment site was located in a typical natural grassland in Chabei district of Hebei province (41°28'31.649″N, 115°1'28.733″E, Alt.±2 m). L-C was the dominant grass species in this area. No conventional tillage practices were used in this area before and no livestock grazing was allowed in recent three years.

The soil penetration resistance (i.e., soil cone index) was measured using a hand-held cone penetrometer (SC 900, Spectrum Technologies, Inc.) with the small cone described in *ASAE standards S313.3 (2009).* Ten points were randomly selected along the diagonals of the experimental area for each soil layer with the depth interval of 2.5 cm. The maximum reading of the penetrometer at the bottom of each depth range was recorded as the cone index value. Then, the average values were calculated. The soil cone index and depth curves were shown in Fig. 1. It showed that the soil cone index reached a peak value around the depth of 5 cm, then a sharp decline came after that, when the depth of soil layer underground exceeded 10 cm, the curves turned into slightly stable gradually.

Three sites were randomly selected as sample-taken places, and three soil cores (30 cm^2 in bottom area, 4 cm in height) were randomly taken from the soil layer at each place, within the depth range of 0-5 cm, 5-10 cm, and 10-15 cm, respectively. The soil cores were weighed, oven-dried at 105℃ for 24 h, and weighed again to determine the soil moisture content and bulk density. The bulk density was calculated by the ratio of the oven dried soil sample mass to the soil core volume.

The moisture content was calculated on a dry mass basis (d.b.) according to ISO standard *(IOS, 1993),* expressed with the unit by mass, i.e., g·(100g)$^{-1}$. The soil bulk density and moisture content were shown in Table 1.

In addition, the L-C roots' distribution underground was also observed. The L-C root distribution characteristics could be summed up as shown in Fig. 2. The figure showed that the L-C roots in the horizontal direction mainly distributed in the subsoil layer at the depth range of around 5 cm, and almost no roots could be observed clearly beyond the depth of 10 cm underground. The roots and soil formed composite structure underground.

Table 1

Physical properties of the soil in the experimental area

Depth (cm)	Bulk density（g/cm^3）	Moisture content（g/(100g), d.b.)
0-5	1.04±0.05	9.99±2.43
5-10	1.26±0.13	13.68±2.42
10-15	1.34±0.12	17.18±2.35

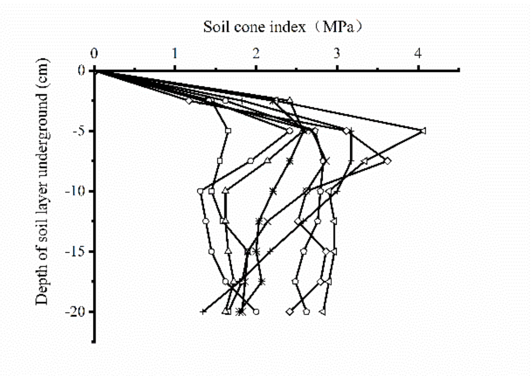


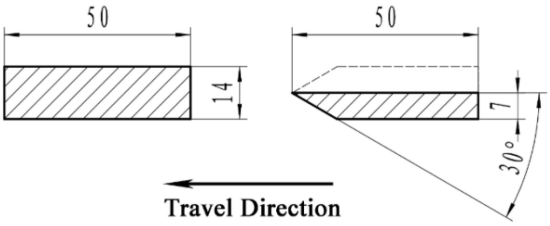
Fig. 1 - Curves of soil cone index and depth

Fig. 2 - Distribution of L-C roots underground

- **Very narrow tines**

Four vertical very narrow shank tines with different geometry structures were designed, i.e. triangle tine (TT), triangle tine with double-side chamfer (TTD), arc tine (AT), and convex tine (CT). Three of these tools (i.e., TT, AT, and CT) were blunt, the other one was designed with a double side chamfer (symmetric) based on TT, i.e. TTD, as shown in Fig. 3. The double side chamfers were sharpened at an angle of 30° to the travel direction.

These shank tines were constructed from 14 mm thick steel. The details of their shapes were shown in Fig. 4. These tines were manufactured to be one body, mainly composed of two portions, one was the cutting head, the other one was the shank. The tines were expected to have different characteristics in terms of soil disturbance and cutting forces. Comparisons between the four tines (all with the same rake angle and working width) would reflect the effects of the geometry structures. The shank bodies had the same width and thickness, and the same fixation point (i.e. three through-holes on the shank body) as well. Among the four shank bodies, only TTD was partially chamfered along the shank edge and the cutting head.



(a) blunt (b) double-side chamfer (half body)

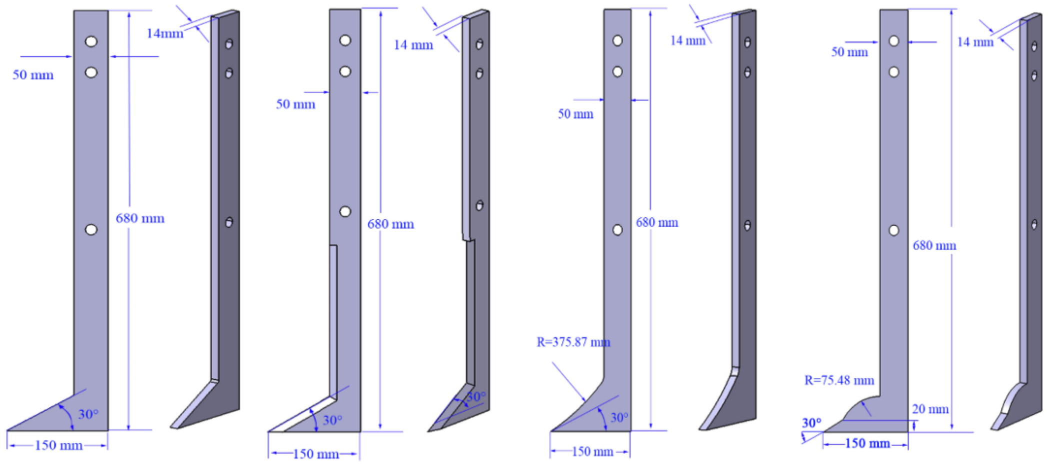
Fig. 3 - Cross-sections of shank tine geometries. Dimensions are in mm

- **Testing facility**

A test bench was designed and manufactured, which was composed of the frame and depth limiting device, making the working depth adjustable with the interval of 5 cm. The maximum working depth limit was designed as 20 cm. The test bench was linked with a tractor by three-point hydraulic suspension frames.

The tillage tine was fixed on the frame in an articulated connection way. Two tension and pressure sensors (BK-2B, China Academy of Aerospace Aerodynamics) were fixed on the frame. The sensors connected the tillage tine and the frame in horizontal and vertical direction, so that the resistances in the two directions could be monitored and collected during the on-the-go movements. The real device was as shown in Fig. 5.

A data collector (SQ 2020, Grant Squirrel) was placed and fixed on the frame, which could gather the data from the two tension and pressure sensors. During the experiments, the collector was used to gather and reserve the data from the sensors, and the data was exported to the laptop when the experiments were finished. The working principle of data collecting was as shown in Fig. 6. Besides, in order to evaluate the soil disturbance of the grassland caused by tillage tines, a profile metering device was designed and manufactured to measure the cross-section profile of disturbed soil-layer, as reported by *He et al. (2020).* By selecting the points of the disturbed area, the cross-section profile could be drawn by the Computer Aided Design (CAD) software through the coordinate values.



(a) TT (b) TTD (c) AT (d) CT

Fig. 4 - Details of shank tine shapes

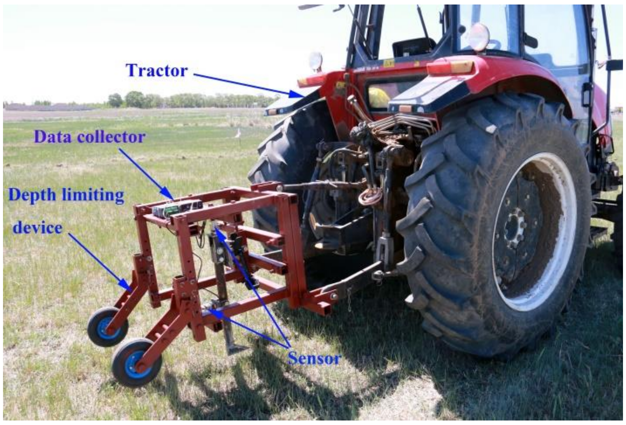


Fig. 5 - The picture of the real device

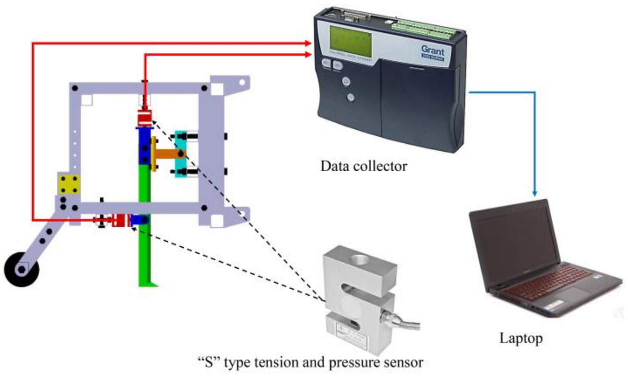


Fig. 6 - Working principle of data collecting

- **Experiment procedure and calculation**

Based on the pre-experiments, the tines always went through two phases when they were working, i.e. the phases of penetrating into the soil and moving stably. The tillage tines usually gradually entered the soil layer at the first distance of 1 meter along the moving direction, and then kept on-the-go movements stably. During the stable movement phase, the results were obtained from every 8 meters along the length. There were three repetitions for each tine. The tines were operated at a forward speed of 1.08±0.14 km·h^{-1} along the length direction pulled by the tractor. The operating depth were 5 cm, 10 cm, and 15 cm, respectively.

The depth uniformity was used to describe the stability of the working depth during the tillage movements. The soil disturbance status of the grassland (i.e. the visual analysis of grassland surface disturbance, soil overturning rate, and cross-section area of disturbed soil layer), and the draft force were chosen as the main indexes to evaluate the working performances of the tillage tines. Besides, specific draft forces were also calculated and compared, which was defined as the force per unit area of soil disturbed.

The depth uniformity, soil overturning rate, and specific draft force were described as reported by *He et al. (2020)*, and calculated by the formulas as shown in Table 2.

Table 2

Formulas for calculating the depth uniformity, soil overturning rate, and specific draft force

Parameters	Formulas	
Depth uniformity (MOMI, 2003)	$U = \left(1 - \frac{V}{100}\right) \times 100\%$	(1)
	$V = \frac{S}{h} \times 100\%$	(2)
	$S = \sqrt{\frac{\sum_1^n (h_i - h)^2}{N-1}}$	(3)
Soil overturning rate (MOMI, 1993)	$F_L = \frac{L_f}{bL} \times 100\%$	(4)
Specific draft force	$S.D = \frac{F}{A}$	(5)

Note: Where U is the uniformity of working depth, V is the coefficient of variation, S is the standard deviation of depth, h is the average value of depth, h_i is the measured depth value at the point i, N and n are the numbers of the measurement points in the operation area. F_L is soil over-turning rate, L_f is the average value of the total length of overturned soil clods, b is the numbers of tillage tines while working, L is the travel distance. S.D is specific draft force, F is draft force of the tillage tine, A is soil loosened area. Average draft force and disturbed soil layer area were used to calculate the specific draft force.

The disturbance range of soil underground causing by tillage tines was described by the value of disturbed cross-section area, which was defined as Askari (2013) reported, calculated as equation (6):

$$\mathrm{A} = \left[\left(2 \sum_{i=1}^{n} d_i\right) - (d_1 + d_n)\right] \times \frac{l}{2} \tag{6}$$

where *A* is soil loosened area; d_i is profile meter reading; d_1 and d_n are the first and the last profile meter readings for every section of the profile, respectively; and *l* is the interval distance of every two adjacent measurement points, which was controlled at 10 mm along horizontal direction in this study.

RESULTS

• Working depth and its uniformity

Table 3 showed that the actual working depths of all tines were basically located in the range of 0-5 cm, 5-10 cm, and 10-15 cm as desired. For the same tine, significant differences existed between different working depths. Within the depth of 0-5 cm, there were no significant differences between the tillage tines. In the depth range of 5-10 cm and 10-15 cm, the depth values of AT, TT, and TTD had significant differences at the significance level of 0.05, but no significant differences existed between AT and CT, there were no significant differences between TT, TTD and CT.

The working depth uniformity was obtained based on equations from equation (1) to (3). All the tillage tines had good working depth uniformities with the values of more than 71%, even went over 83% within the depth range of 5-10 cm and 10-15 cm, demonstrating that the tillage tines have stable movements when they were working.

Table 3

The actual working depth of all tillage tines

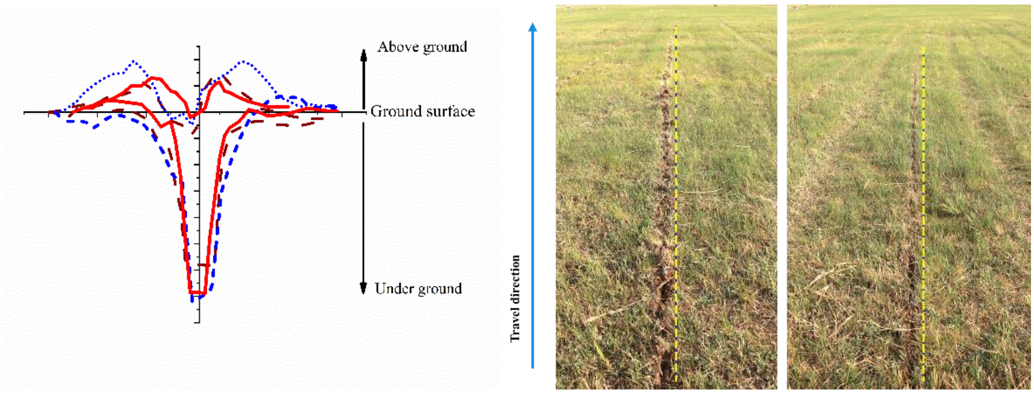
Tines	Desired depth of 0-5 cm	Desired depth of 5-10 cm	Desired depth of 10-15 cm
		Actual working depth (cm)	
TT	5.5±1.59aC	8.3±1.31bB	11.73±0.50bA
TTD	3.6±0.62aC	8.6±1.13bB	11.67±1.89bA
AT	5.17±1.32aC	10.77±0.5aB	14.5±0.96aA
CT	4.8±0.1aC	9.5±0.95abB	13.3±1.42abA

Note: The letters (i.e. a, and b) in each column, and the letters (i.e. A, B, and C) in each row, represent the significant difference at the significance level of 0.05 by the Duncan Multiple Range Test.

• Soil disturbance characteristics on the grassland

The disturbed soil surface profiles were measured via the profile meter device aforementioned. Results showed that the cross-section profiles of the furrows underground were all like a “V” type, as shown in Fig. 7(a). It was also observed that within the zone near to the bottom of the furrow, the width of the disturbed cross-section was closed to the thickness of the tine, especially, when the working depth increased, this characteristic showed more obviously.

There were two kinds of disturbed surface remained after working, one was that small clods were overturned along the furrow, the other one was only narrow slit with no clods overturned left. Only TTD brought about the second disturbance situation described above, and the other three tines caused the small clods overturned along the opening furrow when they were moving. The disturbed surfaces were as shown in Fig. 7(b) and Fig. 7(c).



(a) (b) (c)

Fig. 7 -Soil disturbance characteristics on the grassland

(a) typical geometry of disturbed soil layer cross-section area; (b) overturned small clods along the furrow; (c) only narrow slit

In addition, it was found that the TTD tine cut the soil layer like a blade, the roots were cut by the chamfers instead of pulled out, and the tine was mainly wrapped by dry grass aboveground (Fig. 8 (a)). However, for the other three tines, the roots in the soil layer were pulled by the tines, and the aboveground parts of the tines were usually wrapped by the composite structure of soil and roots, clods and dry grass, especially for the tine of CT (Fig. 8 (b)).

(a) (b)

Fig. 8 - Soil layer disturbance situation

(a) soil layer and roots were cut by the tine, dry grass wrapped the tine; (b) soil layer were disturbed, and roots were pulled by the tine, which was wrapped by clods, soil-roots composite, and dry grass aboveground

- **The soil over-turning rate and cross-section area of disturbed soil layer**

The soil over-turning rate was less than 5%, obtained by measuring and calculating through equation (4), as shown in Table 4. TTD had the least values of the soil over-turning rates, which demonstrated that it would cause less surface disturbance on the grassland.

Table 4

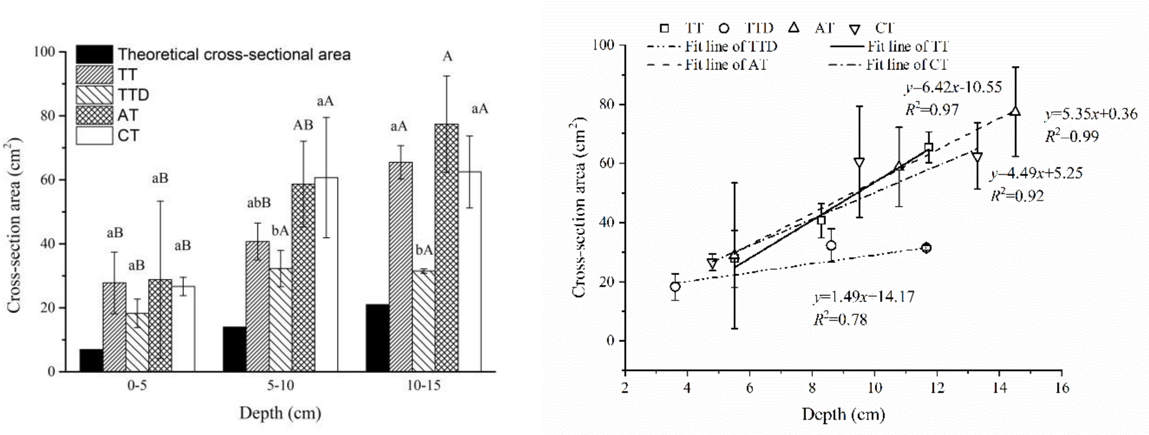
Soil over-turning rates of different tillage tines

Depth（cm）	**Soil over-turning rate (%)**			
	TT	**TTD**	**AT**	**CT**
0-5	3.16	0.00	3.60	-
5-10	3.88	0.00	2.52	3.08
10-15	1.76	0.00	4.08	-

Note: The values of soil over-turning rates were obtained based on measuring the over-turned clods with the diameter of more than 5 cm along the furrows.

The area of disturbed soil layer cross-section underground was calculated by equation (5), listed in Fig. 9. The line graph (Fig. 9(b)) presented that the cross-section area of the disturbed soil layer underground increased with the working depth increasing linearly with the R^2 value of more than 0.78. In Fig. 9(a), it could be seen that all the cross-section areas of tillage tines were larger than that of theoretical cross-sectional areas which were calculated by actual working depths and theoretical shank widths.

It implied that the tillage tine caused disturbances in surrounding areas when it was moving in the soil layer, and the disturbed area was wider than its thickness. TTD had the smallest disturbed cross-section area, with the value range of 18-35 cm^2, was 35.6% less than that of TT on average. The disturbed cross-section areas of the other three tines were located in the range of 26-78 cm^2.



(a) (b)

Fig. 9 - Cross-section area of disturbed soil layer underground

(a) comparison between different tillage tines; (b) relationship between cross-section area and working depth

Note: In Fig.9 (a), the lowercase letters reflect the significant differences between cross-section areas of different tines at the same depth range at the significance level of 0.05 by the Duncan Multiple Range Test. The capital letters represent the significant differences between cross-section areas at different depth ranges of the same tine at the significance level of 0.05 by the Duncan Multiple Range Test.

For TTD and CT, the cross-section area values showed significant differences with the depth ranges changing, respectively. Within the depth range of 0-5 cm, no significant differences could be observed between the areas. For the range of 5-10 cm and 10-15 cm, the cross-section area value of TTD showed significantly different from CT, while TT and CT did not. Combined with Table 3, it could be found that there were no significant differences ($P<0.05$) between the actual working depths of AT and CT within the depth range of 5-10 cm and 10-15 cm, implying significant differences caused by depth changes would not be compared by using multiple comparison method because of the sample numbers less than three, so the method of Independent Samples Test was used at the significance level of 0.05, related results were listed in Table 5. Table 5 showed there were no significant differences between the cross-section areas of AT and CT in the depth range of 5-10 cm and 10-15 cm, respectively.

Table 5

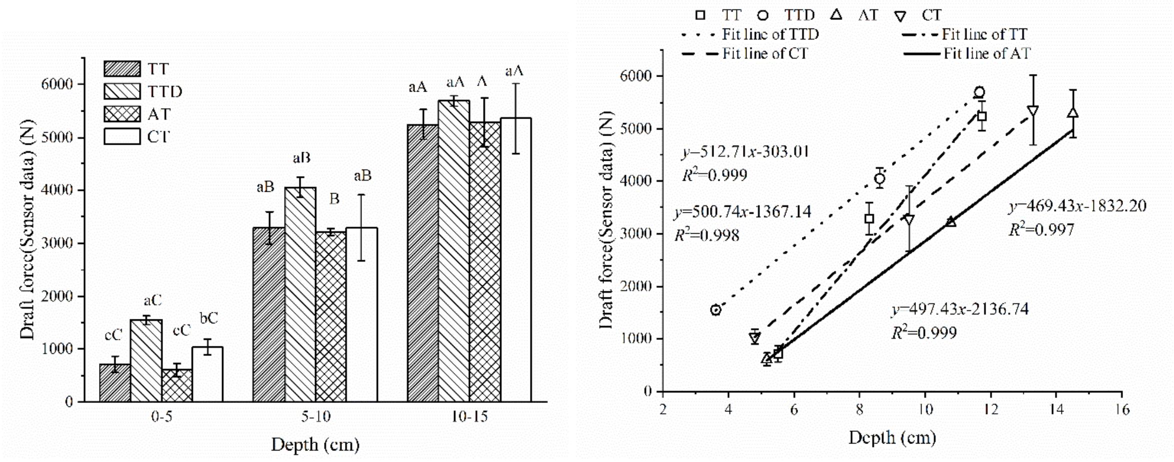
Independent Samples Test of disturbed soil layer cross-section area

Depth (cm)		Levene's Test for Equality of Variances		t-test for Equality of Means		
		F	Sig.	t	df	Sig. (2-tailed)
5-10	Equal variances assumed	.876	.402	-.149	4	.889
	Equal variances not assumed			-.149	3.613	.890
10-15	Equal variances assumed	.297	.615	1.378	4	.240
	Equal variances not assumed			1.378	3.699	.246

- **Soil cutting forces**

The sensor data in the horizontal direction reflected the soil resistance, i.e. the draft force. In Fig.10, the column graphs showed that AT had the smallest draft force among all the tillage tines, TT came after that. TTD owned the largest average draft force value, and no significant differences were observed between the other three tines under the same working depth. Fig. 10(b) also presented that the draft forces increased with the actual working depth increasing, and good linear relationships could be found between draft force and working depth with the R^2 value of exceeding 0.99. As the working depth increasing, the draft force of TT increased sharply by observing a high slope value, AT and CT showed the increasing characteristic more slightly compared to TT, and the slopes had no big differences. The draft force of TTD always stayed in the highest value with the working depth increasing.

It could be found that there were significant differences between the draft forces of the same tillage tine under different working depths at the significance level of 0.05. Combined with Table 3, the actual working depths of AT and CT showed no significant differences ($P<0.05$) at the depth range of 5-10 cm and 10-15 cm, significant differences between draft forces caused by the depth variation could not be compared by using multiple comparison method. Independent Samples Test was used at the significance level of 0.05, related results were listed in Table 6. It showed that there were no significant differences between the draft forces of AT and TT within the depth range of 5-10 cm and 10-15 cm, respectively.



(a) (b)

Fig. 10 - Soil cutting forces

(a) draft force; (b) relationship between draft force and working depth

Note: In Fig. 10 (a), the lowercase letters reflect the significant differences between the forces of different tines at the same depth range at the significance level of 0.05 by the Duncan Multiple Range Test. The capital letters represent the significant differences between the forces at different depth ranges of the same tine at the significance level of 0.05 by the Duncan Multiple Range Test.

Table 6

Independent Samples Test of draft force

Depth (cm)		**Levene's Test for Equality of Variances**		**t-test for Equality of Means**		
		F	**Sig.**	**t**	**df**	**Sig.(2-tailed)**
5-10	Equal variances assumed	12.410	.024	-.202	4	.850
	Equal variances not assumed			-.202	2.040	.858
10-15	Equal variances assumed	1.007	.372	-.151	4	.887
	Equal variances not assumed			-.151	3.554	.888

At the depth of 0-5 cm, the draft force of TTD was significantly different from that of the other tines ($P < 0.05$), which was 2.5 times larger than that of AT. There were no big differences between the draft forces of TT and AT within the depth range of 0-5 cm. At the depth range of 5-10cm and 10-15 cm, the draft forces of TT, TTD, and CT had no significant differences ($P < 0.05$), but the draft force of TTD increased by 24.27% and 7.51% averagely compared to the other three tillage tines. The draft force of TTD was larger than TT with a percentage of 23.44 and 8.62 at the depth of 5-10 cm and 10-15 cm, respectively, but the differences were not significant.

The specific draft forces were calculated through equation (6), and the relationship between specific draft force and working depth was obtained and drawn in Fig. 11.

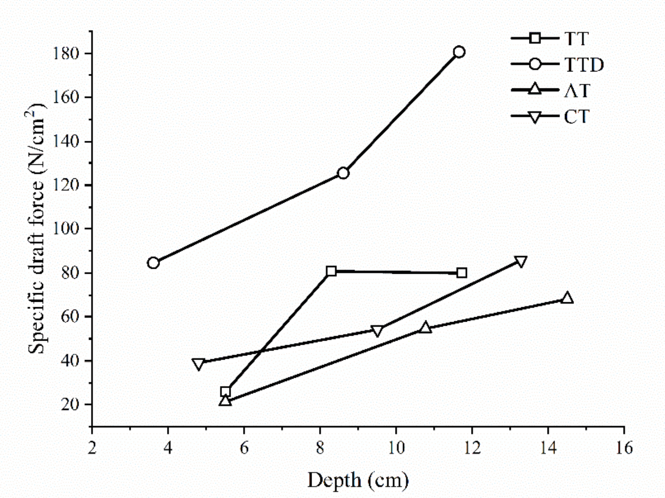


Fig. 11 - Relationship between specific draft force and working depth

The lines showed the specific draft forces of the tillage tines increased with the working depth increasing. TTD had the largest value. The Specific draft force-depth curves of TT, AT, and CT had no big differences, implying the specific draft forces were not affected by various geometry structures significantly, but the tine with a double side chamfer (symmetric) did result in big differences between the specific draft forces.

CONCLUSIONS

(1) The selected shank type tillage tines could break the soil layer underground and create disturbance on natural grassland. Different geometry structures of the tines showed different influences on the working resistance and disturbance characteristics caused by the tines. The cutting heads with different shapes showed no significant effects on the draft force and soil disturbed cross-section area on natural grassland under the same rake angle, but had influences on the translocations of soil clods and soil-root composites.

(2) Chamfers presented large influences on draft force and soil disturbance on natural grassland. The chamfers enhanced the cutting resistances for the tillage tines, but reduced the disturbed cross-section areas of the soil layer underground. For the tines with chamfered cutting edges, both the draft force and the area of disturbed cross-section increased with the depth increasing linearly with the R^2 value exceeding 0.78.

(3) The working depth affected the soil working resistance and disturbed cross-section area underground significantly ($P<0.05$), both draft force and disturbed cross-section area had good linear positive correlation relationship with the working depth, respectively. The specific draft force increased with the working depth increasing.

(4) V-shaped disturbed soil layer cross-sections were produced by very narrow tillage tines after tillage operation. Shank-type tillage tine with chamfers could cut and break the hardened soil layer on natural grassland with low disturbance and no pulling or dragging roots, indicating it could be an appropriate tillage tool applied for improving degraded natural grassland with low disturbance, but still need further surveys.

(5) The draft force, soil over-turning rate, area of disturbed cross-section, and specific draft force could reflect the tillage resistances coming from the soil layer and related disturbance characteristics produced by tillage tines on the grassland well, these parameters may become the evaluation indicators of the specialized tillage tools used for natural grassland, and supportive references for designing and optimizing related tillage tools for grassland.

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