AN EXPERIMENTAL INVESTIGATION OF SOIL LAYER COUPLING FAILURE CHARACTERISTICS ON NATURAL GRASSLAND BY PASSIVE SUBSOILER-TYPE OPENERS
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深松铲型开沟部件作用下的天然草地耦合失效试验研究

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DOI: https://doi.org/10.35633/inmateh-61-06

ABSTRACT

Unclear soil layer coupling failure characteristics on natural grassland impeded the design and optimization of appropriate tillage tools. The coupling failure characteristics including surface disturbance and profile, disturbed cross-section area, soil over-turning rate, and coupling forces between the soil layer of natural grassland and selected passive subsoiler-type openers were investigated in this paper. Three single-shoot openers (i.e. CO, AO and WAO) and a test unit were designed, and furrow opening experiments under different working depths were conducted. Results showed that, along the passages, U-shaped disturbed cross-sections were usually created with soil-root clods overturned along the furrows. The roots were usually broken in a pulling or dragging way underground. Both disturbed cross-section area and draft force values increased with the working depth increasing linearly ($R^2 \geq 0.93$), contrary to the tendency of the specific draft force with the depth. Winged opener (i.e. WAO) had larger draft forces and disturbed soil layer cross-section areas than no-winged openers (i.e. AO and CO). The soil layer failure processes of the natural grassland were affected by its composite soil layer structure and the geometry parameters of the openers. The results provide original references for designing novel furrow openers applicable to improve degraded natural grassland.

摘要

为研究耕作部件作用下的天然草地耦合失效特性，设计了三种深松铲型开沟部件，通过搭建试验台进行了不同作业深度下的草地开沟失效试验，对草地土层失效过程、扰动情况、扰动截面积、翻垡率和作业阻力进行了分析。试验结果表明，深松铲型开沟部件作业时产生 U 形扰动截面，同时沿沟易产生翻垡的土壤-根系复合结构土块；开沟部件作业时主要通过拉扯的方式使根系拉断；开沟扰动截面积和水平方向的作业阻力均随着作业深度的增加呈线性增加的趋势（$R^2 \geq 0.93$）；而沟形面积比阻随着作业深度的增加而减少。具有双翼的开沟部件产生较大的牵引阻力和土层扰动截面积，草地土层失效过程受其复合土层结构和开沟部件的形状参数的影响。试验结果为退化草地改良用专用开沟部件的研发和优化设计提供了参考。

INTRODUCTION

Natural grasslands are important ecological screens of Northern China. Leymus chinensis (Trin.) Tzvel. (abbreviated as L-C hereafter), as a popular fodder grass, due to its good palatability and high forage value, widely spread in the natural grasslands of Northern China (*MOA, 1996*). However, the natural grasslands have been showing degradation trends including vegetation cover reducing, productivity decreasing, and ecosystem conditions deteriorating etc. recently, mainly caused by irrational management (e.g. overgrazing and over-cultivation) and climate change (*Zhao et al., 2006; Han et al., 2008; Li et al., 2018*).

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Mechanical improvement methods including aerating, fertilizing, shallow ploughing, soil gashing and root cutting, loosening, and reseeding have been applied to improve degraded natural grassland in recent years (*You et al., 2012; He et al., 2015; De Boer et al., 2018*). Among those methods, drilling or reseeding practice was one of effective and long-standing recommendation means (*Liu et al., 2015; Zhou et al., 2017*).

A furrow opener is an irreplaceable component for a planter, which is very important for building a suitable seedbed. In general, it moves in the soil layer underground and breaks the soil layer structure, creating a furrow and allowing the seeds to be deposited before being partially covered with the soil. Furrow openers such as hoe, shovel, shoe, runner, single disc, double disc, and chisel types have been widely used for many years in conventional tillage system (*Chaudhuri, 2001*). With the conservation agriculture technique developed, no-tillage farming system has been accepted and adopted gradually, openers such as disc, tine, chisel, shank types etc. have been applied, seeds are placed into crop fields by opening a narrow furrow, or hole of only sufficient width and depth to obtain appropriate seed placement and coverage (*Derpsch et al., 2014*). Numerous investigations around the furrow openers in agricultural tillage system have been conducted in recent years. Performance of various furrow openers of seed drills or planters were studied in the laboratory, and compared with the results obtained through the experiments in the field (*Chaudhuri et al., 2001*). The disturbance caused by selected furrows and related working forces was also investigated under various different soil properties, operating conditions, and geometry structures (*Sánchez-Girón et al., 2005; Solhjou et al., 2013; Matin et al., 2016; Barr et al., 2020*). In addition, the interaction relationships between the soil and furrow openers were also investigated, to supply suitable indexes for evaluating the performance or design novel tillage tools (*Hasimu and Chen, 2014; Qin et al., 2018*).

The natural grassland forms undisturbed soil layer structure underground, different from the usually cultivated crop field due to composite tangled and outspread L-C roots underground, which bring about different soil layer failure characteristics from that of crop fields. However, the coupling failure characteristics caused by tillage tools were still undefined, affecting the development of appropriate tillage tools used for degraded natural grassland restoration. The mechanism, type and degree of soil disturbance of the natural grassland must be considered for the design and optimization of suitable tillage tools, related coupling forces should also be considered. However, almost all related studies and experiments about the openers focused on common crop fields, limited research or reports about specific furrow openers applied for natural grassland were found. This paper was a new attempt, aimed to investigate the soil coupling failure characteristics caused by selected passive subsoiler-type openers (i.e. chisel opener, arrow opener, and winged arrow opener) operated under different working depths on natural grassland, to provide original references and support for designing novel and specialized furrow openers applicable to natural grassland. The visual analysis of grassland surface disturbance, soil over-turning rate, and cross-section area of disturbed soil layer were used for describing the coupling failure characteristics, and the failure mechanism was analysed. The coupling horizontal and vertical resistances from the soil (defined as draft force and vertical force in this paper) were also recorded as well. Working depth and its uniformity were measured so that the results could be compared at the same controlled situation.

MATERIALS AND METHODS
- ### Experimental site description

The experimental site was located in a typical natural grassland with the area of over 80 ha in Chabei district of Hebei province (41°28'31.649″N, 115°1'28.733″E). L-C was the dominant grass species of this area. No conventional tillage practices were used in this area before and no livestock grazing was allowed in recent three years. The bulk density, moisture content, and porosity of the soil layer within the depth range of 0-15 cm on natural grassland were obtained based on the survey method as He et al. (2016) reported, listed in Table 1.

Table 1

Soil physical properties of the experimental site

Depth (cm)	Bulk density (g/cm^3)	Moisture content (g/(100g), d.b.)	Soil cone index (MPa)
0-5	1.04±0.05	9.99±2.43	2.92±0.53
5-10	1.26±0.13	13.68±2.42	2.38±0.62
10-15	1.34±0.12	17.18±2.35	2.20±0.56

- **Experimental openers and test unit**

Three single-shoot subsoiler-type openers were selected. They were chisel (CO), arrow (AO), and winged arrow (WAO) openers, as shown in Fig. 1. The front working surface of the chisel opener consisted of a flat and a shank adapter, the arrow opener resembled a sweep, and the winged arrow opener had a similar configuration, but with two additional wings. These openers were designed based on typical subsoilers commonly used in conventional tillage system in China. A shared shank was designed without any cutting edges. In the experiments, the openers were mounted on the same shank. The other parameters of the openers and the shank were similar to those listed in the MOMI standard (*MOMI, 1999*).
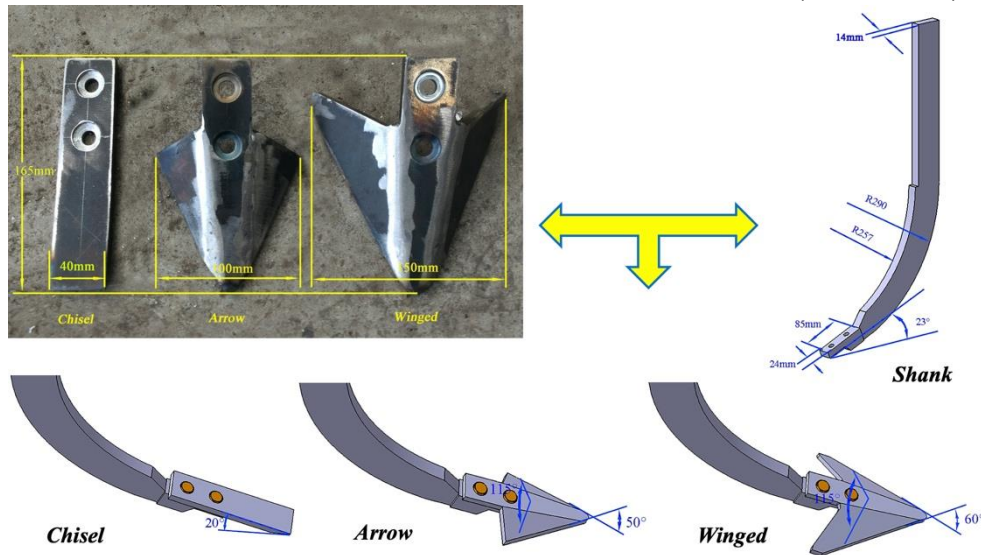

Fig. 1 - Selected openers used in the experiments

A test bench (Fig. 2) was designed and applied in the experiments, which was mainly composed of a data collection system, an image collecting device, frames and depth limiting device. The test bench was linked with a tractor by three-point hydraulic suspension frames. The openers were fixed on the frame in an articulated connection way. Two tension-pressure sensors (BK-2B, China Academy of Aerospace Aerodynamics) used for monitoring force data were fixed on the frame in horizontal and vertical directions, respectively. A data collector (SQ 2020, Grant Squirrel) was placed on the frame, which could gather the data from the two sensors. During the experiments, the data was reserved by the collector, then was exported to the laptop when the experiments were finished. An image collecting device (GoPro video) was fixed on the frame to capture the images, moving processes and interactive behaviours between the openers and soil layer on the natural grassland.
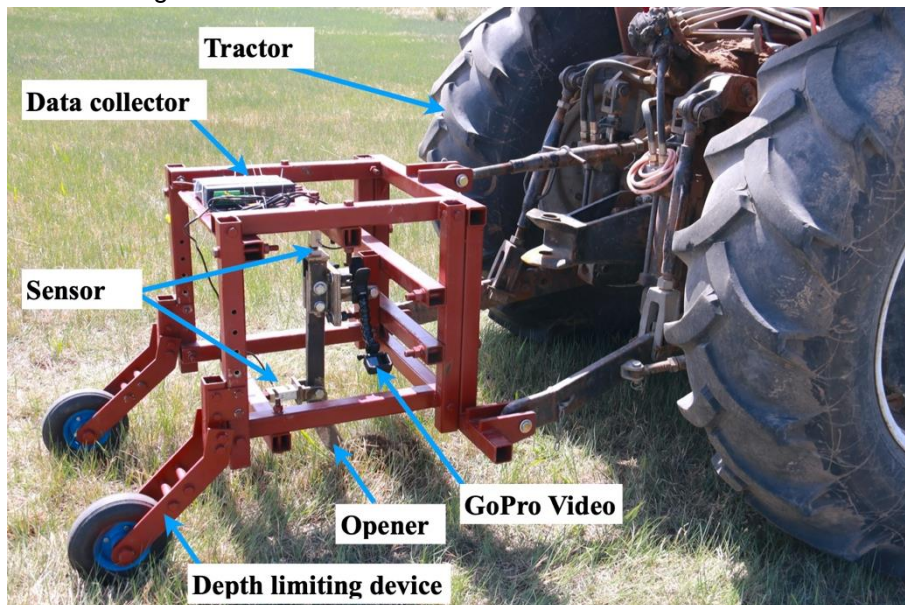

Fig. 2 - The photograph of the test facility

A profile metering device was used to measure the surface profile of disturbed soil-layer, as shown in Fig. 3. The spirit level was placed on the fixed plate to keep the horizontal ruler overlapping with the horizontal line. Coordinate value of a point of the disturbed area could be confirmed through the readings of the two rulers, then the cross-section profile could be drawn by Computer Aided Design (CAD) software through the coordinate values.
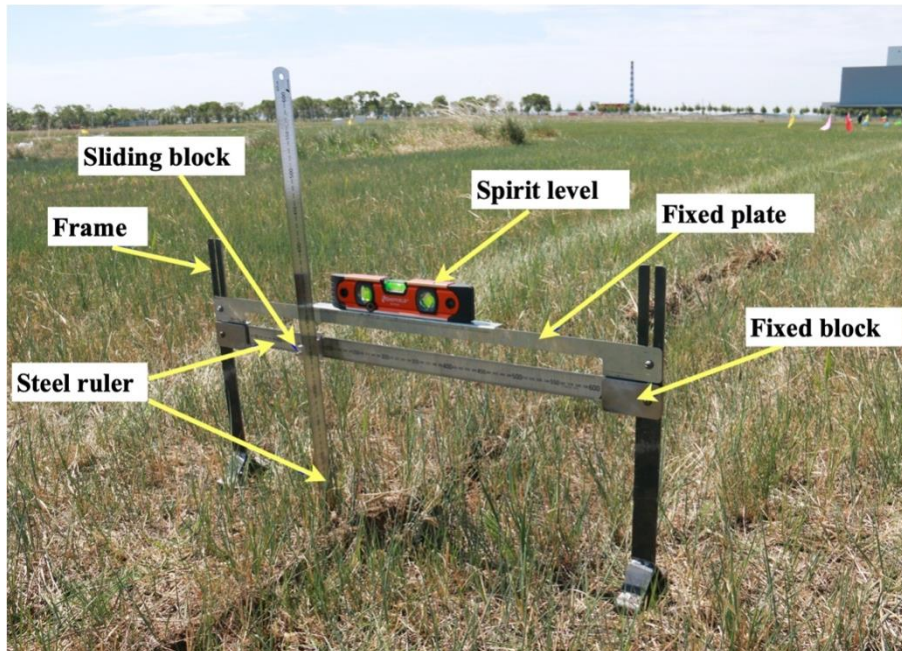

Fig. 3 - Profile meter

- **Experimental procedure and calculation**

Based on the pre-experiments, the openers always went through two phases when they were working, i.e. the phases of penetrating into the soil and moving stably. The dimensions of the experimental field area were 25 m ×18 m (length × width). The openers usually entered the soil layer gradually at the first distance of 1 meter along the moving direction, then kept on-the-go movements stably underground along the last distance of 24 meters. During the stable movement phase, the results were obtained from every 8 meters along the length. There were 3 repetitions for each opener. The openers were operated at a forward speed of 1.08±0.14 km/h pulled by the tractor moving at a slow speed of No.2 level. The operating depth was 5 cm, 10 cm, and 15 cm, respectively.

The depth uniformity was used to describe the stability of working depth during the tillage movements of the openers, taking the Chinese NY standard (MOA, 2003) as a reference, calculated as follows:

$$U = \left(1 - \frac{V}{100}\right) \times 100\% \tag{1}$$

$$V = \frac{S}{h} \times 100\% \tag{2}$$

$$S = \sqrt{\frac{\sum_1^n (h_i - h)^2}{N-1}} \tag{3}$$

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.

The soil over-turning rate was defined as the total length of overturned soil clods divided by the travel distance of the opener (MOMI, 2007), calculated by:

$$F_L = \frac{L_f}{bL} \times 100\% \tag{4}$$

where:

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 opener while working, L is the travel distance.

The disturbance range of soil layer underground caused by the openers was described by the value of disturbance cross-section area, which was defined as Askari (2013) reported, calculated by equation (5) as follows:

$$A = [(2 \sum_{i=1}^{n} d_i) - (d_1 + d_n)] \times \frac{l}{2}$$ (5)

where:

A is disturbance cross-section area;

d_i is profile meter reading, which represented the depth from the disturbed bottom surface underground to the grassland surface;

d_1 and d_n are the first and the last profile meter readings for every section of the profile, respectively;

l is the interval distance of every two adjacent measurement points, which was controlled at 10 mm along horizontal direction in this study.

The specific draft force was calculated using the following equation:

$$S.D = \frac{F}{A}$$ (6)

where:

$S.D$ is specific draft force;

F is the draft force of tillage openers. Average draft force and disturbed soil layer area were used to calculate the specific draft force.

RESULTS

- **Working depth and its uniformity**

Table 2 showed that the actual working depths of all openers were basically located in the range of 0-5 cm, 5-10 cm, and 10-15 cm as desired. The actual working depth had no significant differences between the three openers within the depth range of 10-15 cm. In the range of 0-5 cm and 5-10 cm, significant differences existed between the depth values of CO and AO at the significance level of 0.05, but no significant differences were found between CO and WAO. There were three gradients in the working depths, implying that the working performance of the same opener could be compared under various working depths.

The working depth uniformity was obtained based on equations from equation (1) to (3).

All openers had good working depth uniformities with the value of exceeding 76%, especially it went over 85% for WOA within the depth range of 0-15 cm. The results demonstrated that the openers had stable movements when they were working.

Table 2

The actual working depth of all openers

Tines	Desired depth of 0-5 cm	Desired depth of 5-10 cm	Desired depth of 10-15 cm
	Actual working depth (cm)		
CO	3.23±0.15bC	8.17±1.94bB	12.33±2.61aA
AO	5.37±1.27aC	11.3±0.72aB	14.63±0.23aA
WAO	4.23±0.45abC	8.37±0.45bB	15.03±2.22aA

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

- **Soil layer coupling failure characteristics on the grassland**

The L-C roots in the horizontal direction were mainly distributed in the subsoil layer at the depth of around 5 cm, and there were almost no roots that could be observed clearly beyond the depth of 10 cm underground. The rhizomes and soil formed composite structure underground. The disturbed soil layer surface profile was measured via the profile meter aforementioned; it could be concluded that it usually formed a "U" type disturbed cross-section profile underground after the opener making a furrow. Three main disturbed grassland surfaces remained after working, one was that big clods were overturned along the furrow, another one was only small over-turning clods left after working, the other one was that the soil layer on the grassland surface was ruptured, and bulged but not overturned after the opener moving. These selected openers easily caused the soil-root clods overturning when they were moving underground on the natural grassland. The soil over-turning rate was more than 5% for all openers calculated by measuring the

over-turned clods with the diameter of more than 5 cm along the furrows. Within the depth range of 5-10 cm, the soil over-turning rate even reached 26.08 %.

Among all the disturbed results, the situation with big clods overturned occupied most, and it was hard to produce soil backfill. The typical disturbed situations were as shown in Fig. 4.

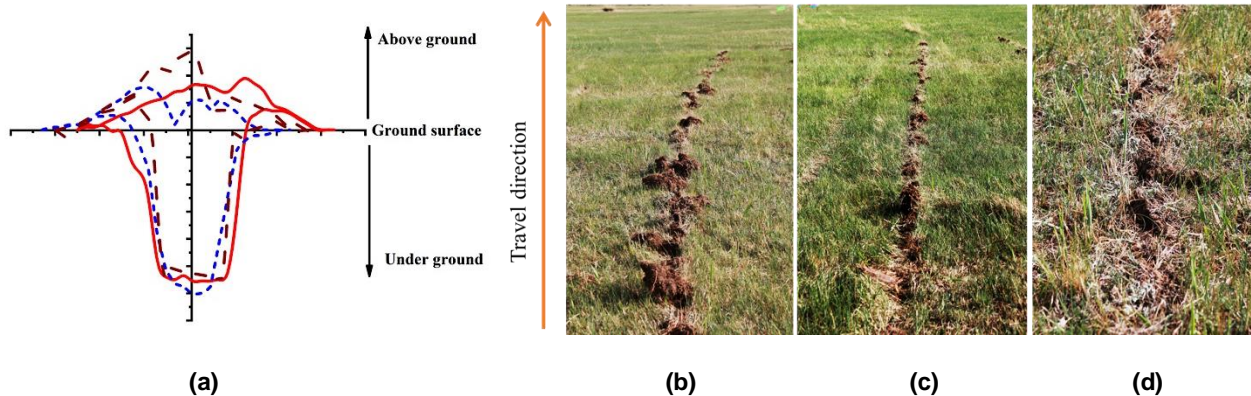| (a) | (b) | (c) | (d) |

Fig. 4 - Soil disturbance on grassland: (a) typical profile of disturbed soil layer cross-section (b) big clods along the furrow; (c) small clods along the furrow; (d) soil layer bulged without overturning

When the opener was moving underground, the front surfaces of the opener lifted up the soil-root complicated layer structure and push them laterally, as shown in Fig. 5 (a). In addition, it was observed that the roots in the soil layer were broken by the openers in a pulling or dragging way. The aboveground part of the shank was usually wrapped by the composite structure of soil and roots, clods and dry grass during on-the-go movements.

| (a) | (b) |

Fig. 5 - Soil disturbance underground: (a) schematic diagram of the coupling failure mechanism between opener and soil layer, (b) broken roots caused by openers

Two kinds of actions of the soil layer usually generated with the opener moving along the passage. a) When the opener was moving in the soil layer, the front surface contacted with the soil layer, producing disturbance and fracture. During the experiments, the fracture line of the soil layer was usually created randomly, not always along the symmetry line of the shank and front surface. The soil root clod was disturbed and lifted up, then moved along the front surface of the shank. Under the connecting function by the rhizomes with the undisturbed soil layer, the disturbed soil root clod moved laterally, and fell back subsequently. This coupling mechanism resulted in the surface disturbance characteristic with bulged soil layer but not overturning. The coupling procedure was as shown in Fig. 6 (a). b) The soil layer was lifted up by the front contact surface of the opener, then it moved along the shank, under the action of the shank, the soil layer was separated into two soil-root clods. Due to the tangled rhizomes, the two clods were still connected and went forward with the shank. With the opener moving underground, the soil layer ahead the front surface was lifted up again, and higher rising height following, the disturbed and uplifted soil layer prevented the two clods from moving forward. The tangled roots were pulled apart and broken by the ongoing shank, and the clods were overturned along the passage. Related coupling procedure was as shown in Fig. 6 (b).
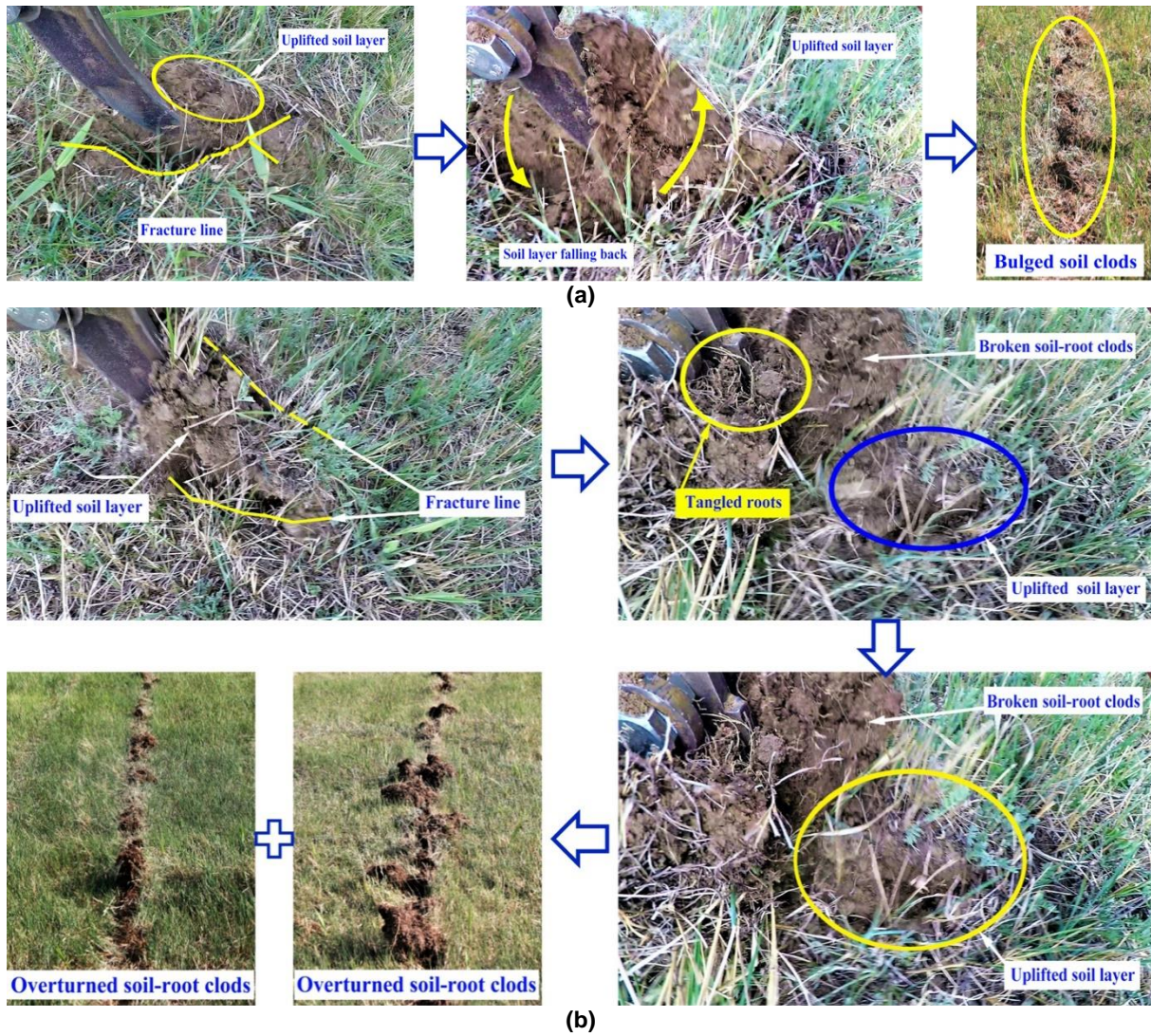
(a)

(b)

Fig.6 - Coupling procedure between the grassland surface and opener. (a) coupling procedure for disturbed surface with overturning soil clods, (b)coupling procedure for disturbed surface with bulged soil layer

The area of disturbed soil layer cross-section underground was calculated by equation (5), listed in Fig.7.
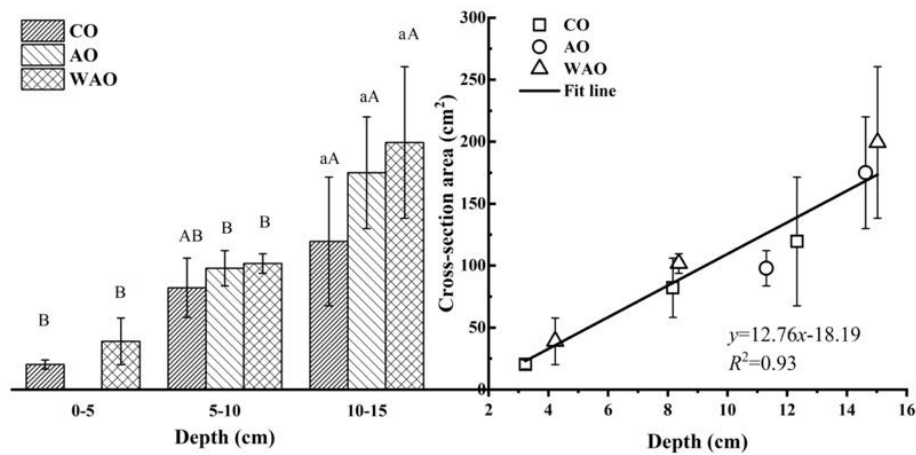

Fig. 7 - Cross-section area of disturbed soil layer underground

Note: The different lowercase letters reflected the significant differences between cross-section areas of different openers at the same depth range at the significance level of 0.05 by the Duncan Multiple Range Test. The different capital letters represented the significant differences between cross-section areas at different depth ranges of the same opener at the significance level of 0.05 by the Duncan Multiple Range Test.

It presented that the disturbance cross-section area increased with the working depth increasing linearly with the R^2 value of 0.93. WAO had the largest value, the second place was AO, and CO produced the lowest cross-section area underground, within the depth range of 5-10 cm and 10-15 cm. However, no significant differences were found between these three openers at the depth of 10-15 cm. For the same opener, the disturbed cross-section areas within the depth ranges of 0-5 cm and 5-10 cm, showed differences from that at the depth of 10-15 cm significantly. Although the disturbed cross-section area of CO was lower than that of WAO, no significant differences could be found within the depth range of 0-5 cm and 5-10 cm through the method of Independent Samples Test at the significance level of 0.05 within the depth range of 0-5 cm and 5-10 cm, respectively, as shown in Table 3.

Table 3

Independent Samples Test of disturbed soil layer cross-section area for CO and WAO

Depth (cm)		Levene's Test for Equality of Variances		t-test for Equality of Means		
		F	Sig.	t	df	Sig. (2-tailed)
0-5	Equal variances assumed	6.017	.070	-1.692	4	.166
	Equal variances not assumed			-1.692	2.149	.224
5-10	Equal variances assumed	1.670	.266	-1.357	4	.246
	Equal variances not assumed			-1.357	2.432	.287

- **Soil cutting forces**

Within the depth range of 0-15 cm, CO had the lowest draft force of all the selected openers, WAO had the largest values, approximately twice larger than CO. All the horizontal force data increased with the working depth increasing linearly with the R^2 values of exceeding 0.99 (Fig.8(a)). Significant differences existed between the draft forces of the same opener with the working depth varying. For the vertical resistance data, it varied with the working depth and opener geometry. The vertical force of CO increased with the working depth increasing. However, for AO and WAO, the sensor was in a compression situation in the depth range of 0-5 cm, but under stretch within the depth range of 5-15 cm.

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. 8(b). The lines showed the specific draft forces of the openers decreased with the working depth increasing. CO always had the lowest specific draft force when it operated at different working depths, smaller than that of WAO.
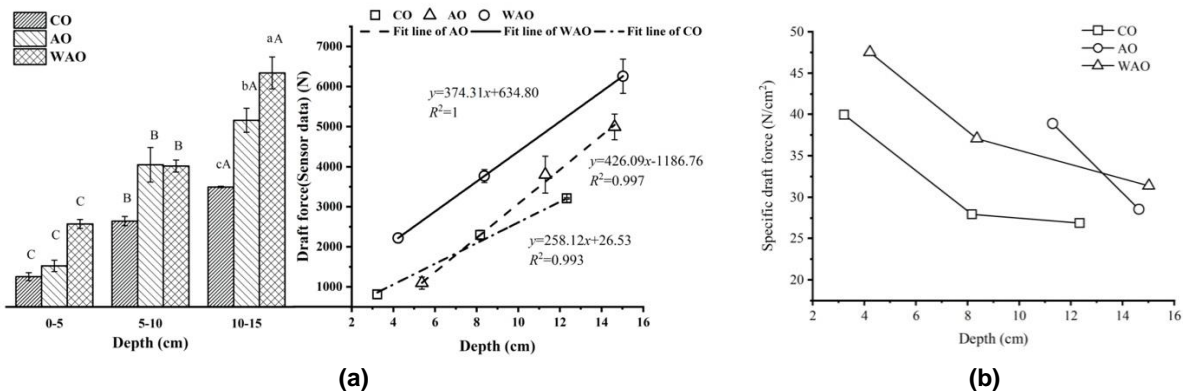

Fig. 8 - Typical soil resistance curves: (a) horizontal sensor data with depth, (b) specific draft force with depth

Note: Different lowercase letters reflected the significant differences between the forces of different openers at the same depth range at the significance level of 0.05 by the Duncan Multiple Range Test. Different capital letters represented the significant differences between the forces at different depth ranges of the same opener at the significance level of 0.05 by the Duncan Multiple Range Test.

CONCLUSIONS

(1) The selected subsoiler-type openers could break the soil layer underground and create disturbance on natural grassland. The manners of opener penetrating into the soil layer and its on-the-go movements, the geometry parameters of the front surfaces and shank of the openers, affected the ways of roots fracture and the translocations of soil underground a lot. Wings or wider working width could increase the draft forces and create larger soil disturbance area. However, the differences of disturbed soil layer cross-section areas between the winged opener and no-winged opener is not significant.

To obtain the same disturbance effect, using a no-winged or a narrow opener could be an effective choice compared with the winged opener.

(2) Tangled L-C roots and the soil underground, and withered grass on the surface, formed a complicated structure on natural grassland, brought about large soil over-turning rate (maximum value of 26.08%) and little soil backfill for the typical subsoiler-type openers (i.e. CO, AO, and WAO) during their passages, making them not suitable to be used to create necessary furrows for drilling or reseeding because of the possibility of resulting in severe soil erosion problems and improper roots damage. Adding cutting chamfers or adjusting appropriate structure parameters may be alternatives for subsoiler-type openers to achieve desirable soil loosening or soil fragmentation situations, but needs further research.

(3) The soil layer failure processes of the natural grassland were affected by its composite soil layer structure and the geometry of tillage tool. Coupling failure mechanism, working resistance, soil over-turning rate, area of disturbed cross-section, and specific draft force reflected the working performance of these subsoiler-type openers well, 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.

ACKNOWLEDGEMENT

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