EXPERIMENTAL STUDY AND ANALYSIS OF SMALL CORN HARVESTERS ON LODGED CORN IN HILLY AREAS
/
小型玉米机在丘陵山区收获倒伏玉米的试验研究与分析

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ABSTRACT
In the harvest of lodged corn in hilly areas, over low position of corn ears and large slope of the land caused severe losses. The comprehensive performance of loss reduction and terrain adaptability was studied on three small corn harvesters. The tested harvesters were 4-row 4YZP-4Y wheeled harvester, 2-row 4YZLP-2C crawler harvester and 2-row 4YZLP-2C-AF crawler harvester that equipped with spiral lifers. The results showed the all-speed corn ear loss and grain loss of the 4YZP-4Y harvester were 55.6% and 57.6% lower than the 4YZLP-2C harvester, while those of the 4YZLP-2C-AF harvester was 23.2% and 17.3%. lower than the 4YZLP-2C harvester. The all-height corn ear loss and grain loss of the 4YZP-4Y harvester was 35.2% and 56.6% lower than the 4YZLP-2C harvester, those of the 4YZLP-2C-AF harvester was 19.9% and 24.9% lower than the 4YZLP-2C harvester. Smaller header width and larger roller compacted area of the 4YZLP-2C harvester were main factors that caused harvest loss. Wider harvester header, auxiliary feeding devices and smaller roller compacted area were key methods to reduce the harvest loss of lodged corn in hilly areas. This study provides technical scheme and design references for harvesters on lodged corn in hilly areas.

摘要
在丘陵山区倒伏玉米的收获中，过低的果穗位置和较大的地面坡度造成了严重的收获损失。本研究对三种小型玉米收获机进行了玉米收获损失和地形适应性的综合性能试验。试验所用玉米收获机机型分别为4 行4YZP-4Y 型轮式收获机、2 行 4YZLP-2C 履带式收获机和安装了螺旋提升器的 2 行 4YZLP-2C-AF 型履带式收获机。试验结果表明，在不同作业速度下，与 4YZLP-2C 收获机相比，4YZP-4Y 收获机的果穗损失和籽粒损失分别低了 55.6%和 57.6%，4YZLP-2C-AF 型收获机分别降低了 23.2%和 17.3%；在不同割台高度下，与 4YZLP-2C 收获机相比，4YZP-4Y 收获机的果穗损失和籽粒损失分别降低了 35.2%和 56.6%，4YZLP-2C-AF 型收获机分别降低了19.9%和24.9%。较小的割台宽度和较大的地面碾压面积是造成4YZLP-2C 履带式收获机收获损失的主要原因。增大割台宽度，加装辅助喂入装置以及缩小地面碾压面积是减小丘陵地区倒伏玉米收获损失的关键措施。本研究为丘陵地区倒伏玉米收获中收获机的适应性研究提供技术支撑和设计参考。

INTRODUCTION
Lodging is one of the main factors that caused corn yield reduction all over the world (*Flint-Garcia et al., 2003*). A lot of researches have been made on the causes of corn lodging. Due to these researches, insufficient application of nitrogen fertilizer, excessive planting density, and unreasonable field irrigation would aggravate lodging (*Berry et al., 2021, Wang et al., 2020*). Physically, it was the suboptimal structure that leads to the failure and fracture of corn stalk (*Ma et al., 2014*). Therefore, many studies predicted lodging resistance of corn stalk with the structural strength. For example, the rind penetrometer resistance (RPR) and the stalk crushing strength (SCS) were considered as important indicators to characterize the lodging resistance of corn (*Albrecht et al., 1986, Seegmiller et al., 2020*). Robertson et al. (*2016*) believed that the stalk flexural stiffness better represent the stalk strength than the RPR and SCS according to the beam theory. Guo et al. (*2018*) and Cook et al. (*2019*) individually designed testing devices to measure the bending forces, horizontal deformations and bending angle of corn stalks in the field.

Lodging may occurr in the milky or wax ripeness stages of corn growth because of terrible weathers like strong winds and rainstorms (*Martinez-Vazquez 2016*). This kind of lodging has small impact on yield, but it brought great difficulties to harvesting (*Wang et al, 2021*). At present, most studies about late-stage lodging focused on the inducement investigation, lodging detection, and lodging area measurement. Unmanned aerial vehicles imagery, remote sensing, and high-throughput micro-phenotyping were employed to quantify the lodging areas and lodging severity (*Zhang et al., 2018, Wilke et al., 2019*). During harvest, ears on lodged corn were mostly lifted by headers with longer snouts and picked with narrow-spaced units (*Yang et al., 2016*). Xue et al. (*2018*) tested the harvest loss of lodged corn with different lodging conditions and found the loss was mainly caused by ear falling. Different from picking ears in corn harvesting, short-stem crops such as rice, wheat and soybean were gathered with whole plant due to their small size and the easiness in threshing (*Paulsen et al., 2014*). These crops were harvested by lowering the harvester headers and slowing down the speed (*Phetmanyseng et al., 2019*). Lodged sugarcane was gathered with stalk lifters. Chains or spiral blades were applied to lift the canes (*Bai et al., 2020*). However, there is no in-depth experimental study and theoretical analysis on the working conditions and technical difficulties in lodged corn harvest, including the application adaptability of different harvesters and headers.

Moreover, in the vast hilly areas like Southern and Northeast China, large harvesters are difficult to operate due to the small plot area, large land slope and poor road conditions (*Wang et al., 2012, Liu et al., 2021*). Only small harvesters could be used for the harvesting of corn in these areas. Machines with crawler were considered to be most suitable for farmwork in hilly areas because of their good traction performance, lower groundpressure, and excellent climbing ability (*Molari et al., 2012*). However, rare study was made on the adaptability of small corn harvesters in hilly areas, eapecially when the working condition was exacerbated by lodging.

This study is aimed to explore the adaptability of small harvesters on lodged corn and analyze the reasons for harvest loss in the hilly areas. A 4-row wheeled corn ear harvester (4YZP-4Y), a 2-row crawler corn ear harvester (4YZLP-2C), and a self-modified 2-row crawler corn ear harvester with spiral auxiliary feeding lifters (4YZLP-2C-AF) were employed and compared on the harvest loss under different working parameters on a land with large slope. The reasons for grain loss were analyzed with structural and operational parameters of harvester headers. This study provides technical scheme and design references for harvesters on lodged corn in hilly areas.

MATERIALS AND METHODS

Materials

- **Terrain conditions**

The plot for test was located in Changpaozi Village (E 125.341020, N 43.146970), Yitong Manchu Autonomous County, Jilin Province. It was in the hilly area of the transition from Changbai Mountain to Songliao Plain. The plot covered an area of 2.19 hectares. The maximum distance in the east-west direction was 210 m and that in the north-south direction was 190 m. The maximum altitude difference of the selected land was about 30 m, and the slope was between 7° to 10° according to the contour map, as is shown in Figure 1. The contour map was obtained from software LocaSpaceViewer 4 that development by Beijing Three Dimensional Vision Technology Co., Ltd.

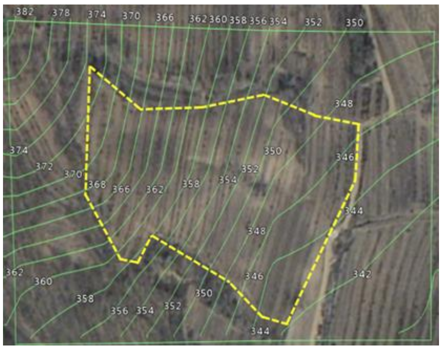


Fig. 1 - Contour distribution of tested plot (unit: m).

- **Corn lodging survey**

The morphology of corn used in the test is shown in Figure 2. The lodging occurred in Aug 27, 2020 to Sep 8, 2020, about 40 days before the test. Ridging was adopted in the land preparation before planting.

The investigations before test showed that the residual ridge height was 83 mm, the top width was 232 mm, the bottom width was 387 mm, and the ridging distance was 650 mm. As can be seen in Figure 2, most stalks lodged on the ground were cross to the ridge with an angle of 45° to 135°.

Before test, 5 plots covered 10 m × 10 m were randomly selected for the lodging investigation. The statistics was carried out according to the morphology of corn stalks. The lodging was divided into root lodging and stalk lodging. For root lodging corn, the included angle between corn stalk and the ground was measured. The heights of stalk breaking point were recorded for the stalk lodging corn.

Fig. 2 - Lodging conditions of corn stalks in the test plot.

- **Corn harvesters**

Three types of small corn harvester were selected for the test, as shown in Figure 3. The first was the 4YZP-4Y 4-row wheeled corn harvester (Figure 3a), the second was the 4YZLP-2C 2-row crawler corn harvester (Figure 3b). They were both manufactured by Shandong Juming Agricultural Machinery Co., Ltd. The same corn picking units were equipped on them with different rows according to their operating width. The third harvester was the 4YZLP-2C-AF crawler corn harvester (Figure 3c) that modified from the 4YZLP-2C harvester with spiral auxiliary stalk lifters, the structure diagram of 4YZLP-2C-AF harvester is shown in Figure 4. The main structural and technical parameters of the three corn harvesters are shown in Table 1. Among the parameters, the roller compacted area was calculated with the ratio of total width of the wheels or the crawlers to the harvester header width.

(a) (b) (c)

Fig. 3 - Working scene of the 3 corn harvester in the test.

(a) – the 4YZP-4Y 4-row wheeled corn harvester, (b) – the 4YZLP-2C 2-row crawler corn harvester, (c) – the 4YZLP-2C-AF corn harvester equipped with spiral auxiliary stalk lifters.

Table 1

Structural and technical parameters of 3 corn harvesters used in the test

Corn Harvester Model	Overall Dimension [mm×mm×mm]	Engine Power [kW]	Travel Mechanism	Header Width [mm]	Header Rows	Header Inclination [°]	Roller compacted area [%]
4YZP-4Y	8130×2850×3550	147	Wheel	2550	4	10°-30°	27.4
4YZLP-2C	5310×1750×2680	48	Caterpillar	1510	2	10°-30°	37.1
4YZLP-2C-AF	5870×1750×2680	48	Caterpillar	1730	2	10°-30°	32.4

The 4YZLP-2C-AF harvester lifted lodged corn stalks with spiral lifters. Its power was provided by the axle of stalk shredder with the chain transmission system. Gearboxes were applied to transfer the power to the spiral lifters. The specific parameters of the refitted working parts are as follows: the outer diameter of the spiral lifter was 150 mm; the inner diameter of the spiral lifter was 50 mm; the pitch of the spiral lifter was 150 mm; the length of the spiral part was 1500 mm; the inclination angle of the spiral lifter was 30° which consistent with the header; the speed of the spiral lifter was 300 r/min (*Fu et al., 2022*).

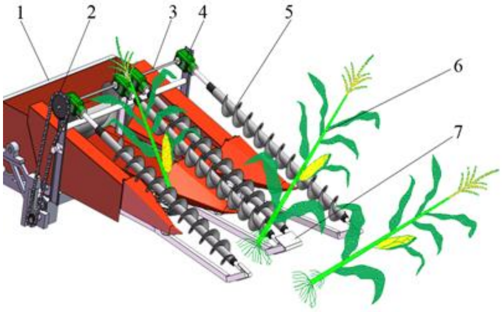


Fig. 4 - Structure diagram of the 4YZLP-2C-AF corn harvester.
1 – Corn harvester header; 2 – Chain transmission system; 3 – Horizontal shaft; 4 – Gearbox; 5 – Spiral lifter; 6 – Corn plant; 7 – Crop divider.

Test Factors

- **Harvester forward speed**

Harvest loss was directly related to the forward speed of corn harvester. The standard speed of the corn harvesters in this test was 0.55 m/s to 1.1 m/s. In the harvest of the lodged corn, the corn headers may be blocked by the stalks. So the forward speed of harvesters was tested lower than the standard speed. The test speeds were 0.3 m/s, 0.5 m/s, 0.7 m/s, 0.9 m/s and 1.1 m/s, while the average height of corn headers were controlled at 80 mm.

- **Header height**

The header height was a key factor that influence the harvest loss of lodged corn. As the land slope may cause inconsistent of height between different sides of the headers, the average header height was adopted, as shown in Figure 5 and the following equation:

$$h = (h_L+h_R)/2 \text{ [mm]} \tag{1}$$

where:

h was the average header height, h_L was the height of the left side, h_R was that of the right side.

Also, the height differences between right and left sides of the corn headers were compared to see their relationship with the land slope and the harvest loss. To test the effect of land slope on the header height differences, harvesters were driven along contour lines with the same direction. Before harvesting, the headers were set to the target height with the hydraulic control system. The actual height of the outermost snouts on both sides were measured respectively. For the 4YZP-4Y and 4YZLP-2C harvesters, the measuring points of the headers were at the tip of snouts on the outermost sides. For the 4YZLP-2C-AF harvester, the measuring points were at the tip of crop dividers. According to the height of corn ears that shown in Table 2, the target header average heights were determined to be 40 mm, 80 mm, 120 mm, 160 mm and 200 mm, respectively. In this test, the forward speed of the corn harvesters was 0.5 m/s.

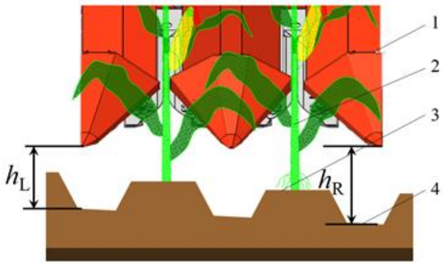


Fig. 5 - Measure method of the average header height.
1 – Corn header; 2 – Corn plant; 3 – Ridge top; 4 – Ridge bottom.

Metrics and test methods

- **Ear loss rate**

In the harvest of lodged corn, grain loss was mainly in the form of corn ear dropping (*Xue et al., 2018*). So, the ear loss rate was taken as the first experimental metrics in this test. To keep consistency of the test area, the working distance of the 4YZLP-2C harvester and the 4YZLP-2C-AF harvester was 20 m, and that of the 4YZP-4Y harvester was 10 m. After harvesting, corn ears left on the ground were collected and counted. The total number of corn ears was determined by the residual roots on the ground. The ratio of dropped ears and the total number of corn plants was the ear loss rate. Each trial was repeated for 3 times.

- **Grain loss mass**

Grain loss mass was the mass of detached kernels on the ground. It did't consist kernels on the dropped corn ears. It indicated the harvest loss that could not be recovered with human hands as these kernels scattered on the ground dispersedly. It could be compensated by picking up grains manually after harvesting. In this metrics, an area of 1 m^2 was randomly selected after harvesting to collect the kernels on the ground. After removing the stalk segments, all grains scattered on the ground except the ones attached on corn cobs were collected. Each trial was repeated for 3 times.

RESULTS AND DISCUSSION

Lodging morphology

The statistical results of lodging morphology are shown in Table 2. It can be seen that the lodging was serious. Most of the lodging was on corn root. A small part of lodging was caused by stalk breaking.

Table 2

Statistics result of lodging morphology in the test field

Term		Total Lodging Rate [%]	Root Lodging Rate [%]	Root Lodging Angle [°]	Stalk Lodging Rate [%]	Stalk Lodging Height [mm]	Corn Peduncle Height [mm]
Sampling Plot	1	92.3	83.6	11.4	8.7	366.5	201.27
	2	87.7	80.3	9.5	7.4	427.1	163.85
	3	94.5	88.2	10.8	6.3	345.4	186.59
	4	93.6	89.9	15.2	3.7	410.6	254.18
	5	99.2	98.4	13.7	0.8	455.2	216.64
Average		93.46±3.70	88.08±6.17	12.12±2.05	5.38±2.82	400.96±39.98	204.51±30.33

The lodging angles of the rood lodged stalks were large. As the corn ears were lower than their peduncles because of self-weight, most corn ears were below 200 mm. For the stalk lodged corn, the fracture points were mostly at the third or fourth internode of the stalks. These internodes borne large forces under the combined function of root anchorage and the wind (*Albrecht et al., 1986*). The upper part corn stalks would fall to the ground after stalk lodging. It made corn ears difficult to pick in their inverted orientation.

Header height

Figure 6 shows the height of harvester headers on different sides. The height on different sides of the harvester headers showed no clear regularity. But the fluctuation amplitude and standard deviation of the 4YZP-4Y wheeled harvester was much larger than that of the 4YZLP-2C crawler harvester and the 4YZLP-2C 2-row crawler harvester. Considering the harvesters had same mechanical connection between header and frame, it could be drawn that the factor affecting height difference was the bumping of headers rather than the plot slope (*Liu et al., 2021*). As the 4YZP-4Y wheeled harvester had a wider header, its fluctuation amplitude would be larger when they have same fluctuation angle. The fluctuation of corn headers would cause miss picking of corn ears in lodging situation. Therefore, in hilly areas, the harvester headers width should be limited within a reasonable scope to avoid header fluctuation.

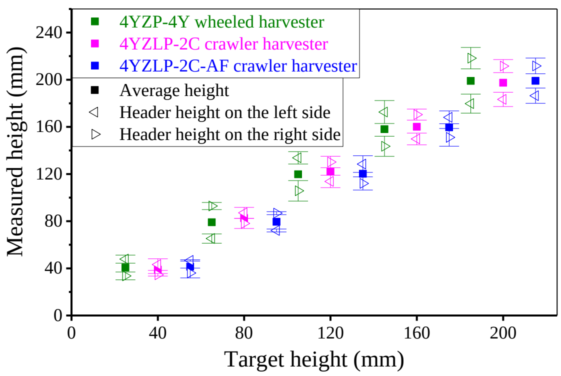
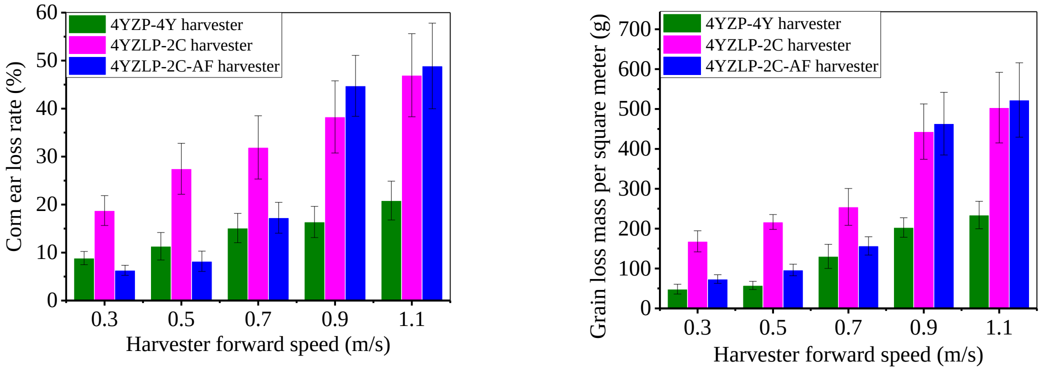


Fig. 6 - Statistics of headers' height at different target height.

Effect of harvest speed

The corn ear loss and grain loss mass of the corn harvesters in dealing with the lodged corn at different travel speeds are shown in Figure 7.

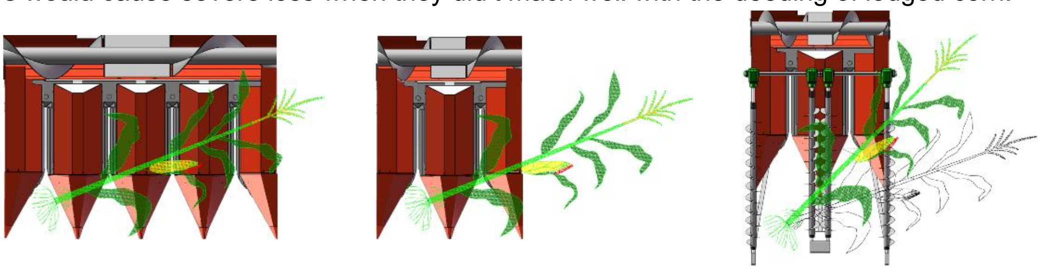


(a) **(b)**

Fig. 7 - Ear loss rate and grain loss mass per square meter of the 3 corn harvesters at different forward speed.
(a) – corn ear loss rate; (b) – grain loss mass per square meter

It can be seen from Figure 7 that the corn ear loss and grain loss of the harvesters increased obviously when the forward speed got higher. Among them, the corn ear loss rate of the 4YZP-4Y harvester, 4YZLP-2C harvester and the 4YZLP-2C-AF harvester increased from 8.85%, 18.76% and 6.31% to 20.84%, 46.95% and 48.89%, while the grain loss mass per square meter of them increased from 48.32, 168.14 and 73.54 g/m^2 to 234.10, 503.55 and 522.56 g/m^2 respectively. The increasing was consistent with the conclusion of Paulsen et al. (*2014*).

The lodged corn would stack in the front of harvester headers in harvesting. They would be pushed forward instead of being rolled down by the stalk rolls (*Xue et al., 2018*). As a result, the corn ears would be miss-picked and dropped to the ground. The all-speed corn ear loss rate of the 4YZP-4Y harvester and the 4YZLP-2C-AF harvester were lower than the 4YZLP-2C harvester with the percentage of 55.6% and 23.2%. It can be inffered that the width of the 2-row harvester header was too small to hold the corn plant when the harvester moved perpendicular to the lodging direction, as shown in Figure 8(a) and 8(b). However, the spiral lifters on the 4YZLP-2C-AF harvester could help to lift the stalks and feed them to the corn picking position, as shown in Figure 8(c). That was why the corn ear loss of the 4YZLP-2C-AF harvester lower than the 4YZLP-2C harvester. The corn ear loss rate of the 4YZLP-2C-AF harvester increased sharply when the forward speed got higher than 0.7 m/s. It indicated that the spiral lifter mached well with the header at low speed. When the harvester forward speed got higher, the stalk fquantity exceeded the dealing capacity of the spiral lifters. The spiral lifters would cause severe loss when they did’t mach well with the deeding of lodged corn.



(a) **(b)** **(c)**

Fig. 8 - Corn ear picking process on different corn harvester headers.
(a) – 4YZP-4Y harvester header; (b) – 4YZLP-2C harvester header; (c) – 4YZLP-2C-AF harvester header

Figure 7(b) showed the grain loss increased with the harvester speed, just like the corn ear loss. A small part of grains on the ground were induced by the impact between corn ears and the harvester header working parts (*Fu et al., 2019*). More grain loss were caused by the roller compact on wheels or crawlers. Among the harvesters, the grain loss of the 4YZP-4Y harvester was the lowest at all time, while the 4YZLP-2C-AF harvester had low grain loss at low speed. The all-speed grain loss of the 4YZP-4Y harvester and the 4YZLP-2C-AF harvester were lower than the 4YZLP-2C harvester with the percentage of 57.6% and 17.3%. The conclusion was just the same as the study of Shauck et al. (*2011*) that wider header could reduce harvest loss. The dropped corn ears would be rolled by the wheels or the crawlers, and the grains would be threshed, which made up a larger part of grain loss, as shown in Figure 9.

Meanwhile, the crawler harvesters would cause unrecoverable loss because of the larger roller compacted area compared to the wheeled harvesters. Therefore, even the crawler machines were more adaptive in the hilly areas, the crawler harvesters were not competent in the lodged corn harvesting.

Fig. 9 - Kernels detached after the rolling of corn harvesters.

Effect of header height

The ear loss rate and grain loss per square meter of the corn harvesters at different harvester header heights are shown in Figure 10.

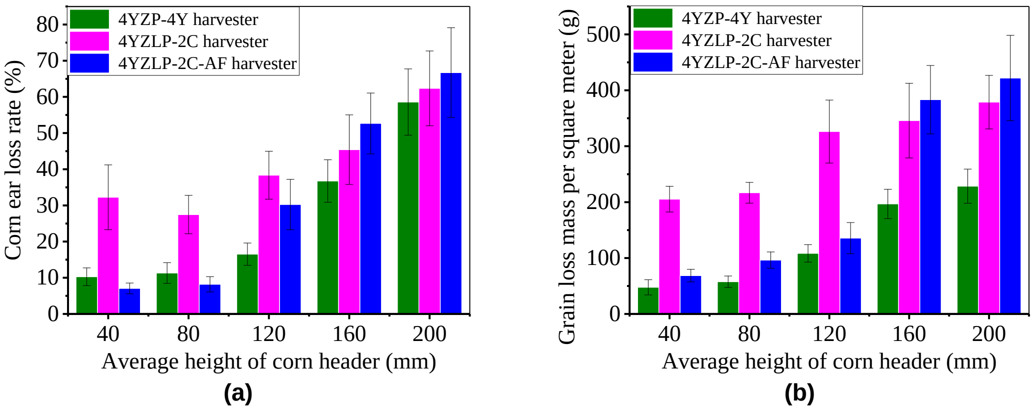


Fig. 10 - Corn ear loss rate and grain loss mass of the 3 corn harvesters at different header heights.
(a) – corn ear loss rate; (b) – grain loss mass per square meter

It can be seen from Figure 10 that the corn ear loss and grain loss of the 3 harvester increased significantly when the harvester header got higher. Among them, the corn ear loss rate of the 4YZP-4Y harvester, the 4YZLP-2C harvester and the 4YZLP-2C-AF harvester increased from 10.28%, 32.25% and 7.05% to 58.57%, 62.35% and 66.71%, while the grain loss mass per squre meter increased from 47.68, 205.33 and 68.63 g/m^2 to 228.51, 378.81 and 421.95 g/m^2, respectively. The all-height corn ear loss rate and the grain loss mass per square meter of the 4YZP-4Y harvester was lower than that of the 4YZLP-2C harvester with the percentages of 35.2% and 56.6%. Those of the 4YZLP-2C-AF harvester was 19.9% and 24.9% lower than the 4YZLP-2C harvester.

After lodging, the corn ears were too low for the working parts of the headers to pick up. The results in Figure 10 showed corn harvester headers even couldn't pick the ears smoothly when they were a little lower than the corn ear position. It was necessary to reserve a height to make sure the ears be rolled down by the working parts of corn harvester headers, or they would be left to the bottom of corn headers (*Lopes et al., 2002*). Particularly, the corn ear loss rate of the 4YZLP-2C-AF harvester was the lowest when the header worked at low positions. But it became the highest when the corn header got higher. It was indicated that the additional mechanical kinematics aggravated corn ear loss when the corn stalks were not fed with the whole plant. Just as Yang et al. (*2016*) verified that the direct contact between corn ears and working components may cause high loss rate. The corn ear loss of the 4YZP-4Y harvester increased largely when the header got higher. It might be the jigging motion of its header that caused miss picking of corn ears, as indicated in Figure 6.

The changes of grain loss showed strong consistency with corn ear loss. The dropped corn ears would be rolled by the harvester to thresh the grains. Although the corn ear loss could be retrieved by picking up manually, it still need to be reduced.

The above analysis showed harvesters had different adaptability when dealing with the lodged corn in hilly areas. Even the 2-row 4YZLP-2C crawler harvesters had better trafficability in hilly area, it was still not qualified for the harvest of lodged corn because of the small header width and the limited stalk lifting ability. The larger roller compacted area even made the grain loss more serious. The 2-row 4YZLP-2C-AF crawler harvester that equipped with spiral lifter could reduce the corn ear loss by lifting stalks and help with the feeding. For the 4-row 4YZP-4Y harvester, the larger header width could reduce corn ear loss, and smaller roller compacted area of the wheels could reduce the grain loss caused by the rolling corn ears. But it should be pointed out that the jigging motion would increase corn ear loss when of the 4YZP-4Y harvester header stayed at higher positions. As a conclusion, application of wider harvester header and auxiliary feeding devices and reduce the roller compacted area were key methods to reduce the harvest loss of lodged corn in hilly areas.

CONCLUSIONS

Harvesting test on three types of corn harvester showed the 4-row 4YZP-4Y wheeled harvester and the 2-row 4YZLP-2C-AF crawler harvester that equipped with spiral lifters were more adaptive than the 2-row 4YZLP-2C crawler harvester for the harvesting of lodged corn in hilly areas. The all-speed corn ear loss rate and grain loss mass of the 4YZP-4Y harvester was lower than the 4YZLP-2C harvester with the percentage of 55.6% and 57.6%, while those of the 4YZLP-2C-AF harvester was lower than the 4YZLP-2C harvester with 23.2% and 17.3%. The all-height corn ear loss rate and grain loss mass of the 4YZP-4Y harvester was lower than the 4YZLP-2C harvester with the percentage of 35.2% and 56.6%, while those of the 4YZLP-2C-AF harvester was lower than the 4YZLP-2C harvester with 19.9% and 24.9%.

Even the 2-row 4YZLP-2C crawler harvesters had better trafficability in hilly area, it was still not qualified for the harvest of lodged corn. The small header width and the limited stalk lifting ability restricted its ear picking capacity on lodged corn. The larger roller compacted area even made the grain loss more serious. Fitting wider harvester headers, applying auxiliary feeding devices and reducing the roller compacted area were key methods to reduce the harvest loss of lodged corn in hilly areas.

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