

Effects of mechanical operation-induced root injury on maize growth and yield

Hong Hu^{1*}, Junfeng Gao², Jie Wu¹, Yijin Mao³, Jingzhu Lu¹, Qingtao Li¹

(1. Institute of Modern Agricultural Equipment, Xihua University, Chengdu 610039, China;

2. Lincoln Agri-Robotic Centre, Lincoln Institute for Agri-Food Technology, University of Lincoln, Lincoln, LN6 7TS, UK;

3. Shenzhen Escope Technology Co., Ltd., Shenzhen 518052, Guangdong, China)

Abstract: A 2-year field experiment was conducted in 2015 and 2016 by using artificial root pruning to simulate mechanical root injury caused by agricultural machinery components and reveal its effects on maize growth and yield. Quasi-level orthogonal experimental design was employed to create orthogonal tables with four factors of interest, namely, pruning time (jointing stage, JS; big trumpet period, BTP), pruning method (unilateral pruning, UNP; bilateral pruning, BIP), pruning distance (5, 10, and 15 cm) and pruning depth (5, 10, and 15 cm). Results revealed that 1) maize growth was inhibited at the beginning of root pruning; 2) stem diameter (SD) and plant height (PHE) were smaller than those of the control check (CK) but exceeded the latter after 20 d of root pruning in JS; 3) SD and PHE were always smaller than those of the CK under root pruning in BTP; 4) T_8 (BTP, BIP, 5 cm of pruning distance and 15 cm of pruning depth) can reach to a significant level ($p < 0.01$). The vertical distribution and total dry weight (TDW) of maize roots in soil were affected by different root pruning treatments. When pruning in JS, the root ratio in 0-10 cm soil was 11.6% in T_2 (JS, UNP, a pruning distance of 10 cm and pruning depth of 10 cm). When pruning in BTP, the root ratio of 10-20 cm soil layer increased by 15%. However, the TDW of maize decreased, the largest of which occurred in T_8 at 53%. With the exception of a 0.43% increase in T_3 (JS, UNP, 15 cm of pruning distance and 15 cm of pruning depth), the maize yield of all other treatments decreased compared with that of CK, and the largest reduction was in T_8 at up to 19.1%. This finding suggests that a small pruning distance and a large pruning depth greatly influence the growth and yield of maize before and during pruning in BTP. The influence of BIP is greater than that of UNP. These results provide evidence for the effects of mechanical root injury on maize growth and yield and serve as a reference for the selection of mechanical topdressing parameters.

Keywords: maize, root pruning, growth, grain yield, mechanical operation-induced injury

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1 Introduction

The crop root system plays some critical roles in support, fixation, absorption, composition, and storage during plant growth, and which is the absorptive and metabolic organ of a plant, and displays sensitive reactions to external environmental conditions^[1-6]. Consequently, its growth affects the development of other organs and determines the growth status of the whole plant^[7]. Therefore, the growth situation of the root system could be a direct indicator reflecting general information on crop growth and yield^[8,9].

Changes in root morphology and structure will lead to changes in the biomass accumulation of the overground part of crop and the utilization efficiency of water and fertilizers, thus ultimately

altering the crop yield^[10,11]. In general, physical injury, soil movement around the root system, gnawing animals, and root diseases are the main reasons for root morphological and structural changes. Among these, physical injury and the soil movement around the root system are the most important factors^[12]. In fact, deep loosening, earth-raising, weeding and other intertillage practices will cause physical injury of roots and soil movement around the root system, which directly or indirectly change the root morphology and structure.

To understand the effects of physical injury of roots induced by intertillage practices on crop growth and yield, root pruning method was widely used by researchers. Tests have shown that proper root pruning at appropriate times helps to optimize crop root structure, modulate crop growth and dry matter allocation, and improve water use efficiency and crop yield^[13-15]. Therefore, root pruning has been used extensively as a cultivation technique in the regulation of aboveground and underground plant sections to influence the vegetative growth, such as the dwarfing cultivation of fruit trees^[16,17], the enlargement of tuber biomass^[18], and the increasing of stem and leaves biomass of vegetables^[19,20]. Studies showed that the moisture content in wheat leaves decreases rapidly in a short time after 80% of primary roots of wheat are excised, but the activities of the remaining root are strengthened to provide adequate moisture uptake and compensate for the missing moisture in wheat leaves^[21]. When vertically cutting roots at different horizontal distances of summer maize, the photosynthetic of leaves

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Biographies: Junfeng Gao, PhD, Assistant Professor, research interest: agri-robotics, Email: jugao@lincoln.ac.uk; Jie Wu, PhD, Associate Professor, research interest: mechanical transmission and control, Email: jiewu09323@mail.xhu.edu.cn; Yijin Mao, PhD, research interest: computational fluid mechanics, Email: ymao.mu@gmail.com; Jingzhu Lu, PhD, Associate Professor, research interest: machine vision and image processing technology, Email: lujingzhu1103@163.com; Qingtao Li, PhD, Associate Professor, research interest: new type of transmission, Email: liqingtao@mail.xhu.edu.cn.

***Corresponding author:** Hong Hu, PhD, Lecture, research interest: agricultural mechanization technology and equipment in hilly and mountainous areas. Institute of Modern Agricultural Equipment, Xihua University, Chengdu 610039, China. Tel: +86-28-87723323, Email: huhong@mail.xhu.edu.cn.

was significantly affected, the growth of leaves before anthesis was inhibited, the root shoot biomass and grain yield decreased, the influence degree increases with the decrease of root cutting distance^[22]. Root pruning for hybrid rice showed that the root length, superficial area, dry matter amount of overground and underground, the nitrogen content of plants, and nitrogen accumulation were inferior to those of rice plants with full roots to a different degree. The decreasing trend persisted when the root pruning amount was increased^[23]. At the same time, the effects of root pruning on crop growth and yield are different with different pruning times. It is suggested that spring root pruning of winter wheat could promote tillers and spikes, increase photosynthesis of flag leaf after anthesis, improve the seed setting characteristics, and increase grain yield and water use efficiency (WUE)^[24]. When root pruning at JS, the results showed a reduction in the transpiration rate of wheat leaves and tillers, an increase in the WUE, a delay in the senility of late stage leaves, and prolonged function period when the water supply was sufficient. Ultimately, the grain yield of wheat was increased^[25-27]. In summary, current studies have proved that root pruning has positive or negative effects on crop growth and yield formation, but the effects were not uniform even for the same crop, and most root studies mainly focused on the effect of a single factor, without considering the combined effects of multiple factors, and most of them are pot experiments.

Maize is an intertillage crop that needs mechanical weeding and topdressing during its growth, and these operations are prone to root injury. This work performed a 2-year investigation of 2015 and 2016 on the effects of root pruning time, pruning method, pruning distance, and pruning depth on maize stem diameter, plant height, total dry weight, and hundred grain weigh through artificial root pruning treatment in the jointing stage (JS) and big trumpet period (BTP) of field maize. This study aimed to determine the effects of mechanical root injury on maize growth and yield and supply a meaningful reference for the selection of mechanical topdressing parameters.

2 Materials and methods

2.1 Sample preparation

The field experiments were conducted in 2015 and 2016 at Gushanzi Village, Qingyuan Manchu Autonomous County, Fushun City, Liaoning Province, China (125°7'E, 42°11'N, 292 m above sea level) with the continental monsoon climate type. The mean temperature is 22.8 °C during the growing seasons of maize, which is 6 months between May and October in 2015 and 2016 when the mean rainfall values are 813 and 790 mm, respectively.

The soil at the experimental station comprises black loam soil that was buried under pine tree seedlings fallowed for 5 years prior to the start of the first cropping period. Soil samples were collected at the upper 30 cm soil depth. The sampled soil has a pH value of 7.2 and contains 20.50 g/kg organic matter, 0.76 g/kg total N, 101.4 mg/kg available N, 21.6 mg/kg available P, and 82.6 mg/kg rapidly available K.

2.2 Experimental preparation

The cultivar of maize adopted in the experiment is 'Jinongyu 409' because it is widely planted by farmers in this area and its germination rate is over 95% with a growth period of 154-161 d. The orthogonal experimental design was employed in the field experiments, and the combined effects of pruning time (JS; BTP), pruning way (unilateral pruning, UNP; bilateral pruning, BIP), pruning distance (5, 10, and 15 cm), and pruning depth (5, 10, and

15 cm) on growth and yield of maize were the factors of interest because they are directly affected by mechanical operation. Sample with no pruning treatment was treated as the control check (CK). A multi-factor mixed-level test was performed, and the quasi-level method was adopted to reconstruct the standard $L_9(3^4)$ orthogonal table (Table 1).

Table 1 Orthogonal table of mechanical root pruning test

Treatments	Factors			
	Pruning time	Pruning method	Pruning distance/cm	Pruning depth/cm
T ₁	JS	UNP	5	5
T ₂	JS	BIP	10	10
T ₃	JS	UNP	15	15
T ₄	BTP	UNP	10	15
T ₅	BTP	BIP	15	5
T ₆	BTP	UNP	5	10
T ₇	BTP	UNP	15	10
T ₈	BTP	BIP	5	15
T ₉	BTP	UNP	10	5

Note: JS: Jointing stage; BTP: Big trumpet period; UNP: Unilateral pruning; BIP: Bilateral pruning.

Two repetition tests were conducted for each treatment with a total of 20 plots each with 1.5 m×6.0 m dimension. Furrows 12 cm in width and 20 cm in depth were used to separate each plot. Row spacing was 60 cm, and plant spacing was 25 cm as shown in Figure 1.

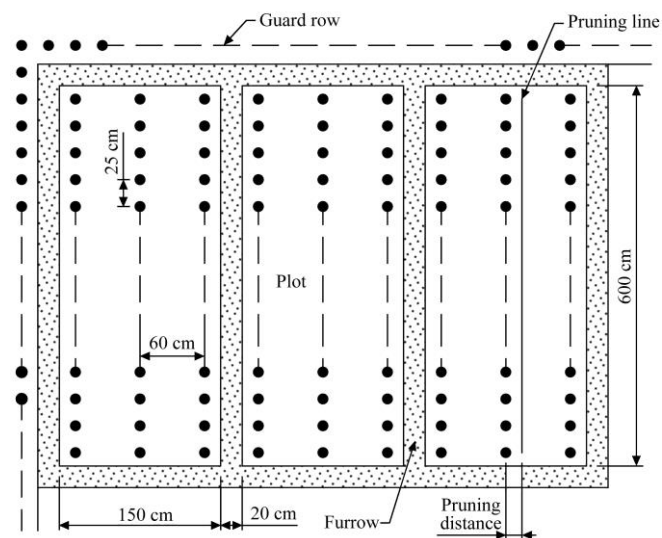


Figure 1 Layout diagram of the test plot

Sowing was conducted on May 8, 2015 and May 7, 2016. Chemical fertilizer (N, P, and K) and urea fertilizer were applied at 375 and 150 kg/hm², respectively, in BTP. Similar field management measures were adopted for all treatments. Harvesting was performed on October 18, 2015 and October 15, 2016.

2.3 Experimental methods

2.3.1 SD and PHE

In terms of maize growth situation in the experimental field, June 20 and July 18 were considered as the beginning of JS and BTP, respectively, and were treated as the pruning time. For comparison, the day before JS, namely, June 19, was taken as the first point for data acquisition, which was conducted every 7 d, that is, June 19, June 26, July 3, July 10, July 17, July 24, and July 31.

Five plants with highly similar growth situations were selected by diagonal sampling and marked in each plot. The stem diameter (SD) and plant height (PHE) at the time of interest for each plant

were measured and recorded during growth. A Vernier caliper was used to measure SD, which is defined as the maximum diameter of the first full outcrop knob. A portable plant height meter named TPYM-G-1 produced by Zhejiang TOP Instrument Co., Ltd. was employed to measure the PHE of sample plants.

2.3.2 RDW in different soil layers

Roots surrounded by a cuboid (30 cm×30 cm×45 cm) centering on the maize stalk were collected for root dry weight (RDW) measurement. Based on the soil depth, the roots were cut into pieces and grouped into four layers, namely, 0-10, 10-20, 20-30, and 30-40 cm. The dehydrated weight of roots was measured as follows: 1) the roots were cleaned by wrapping them in a 0.5 mm nylon mesh bag for deep rinsing; 2) the cleaned roots were dehydrated at a constant temperature of 80 °C in a dryer until the weight remained constant; 3) weight was measured using an electronic scale (± 0.01 g). The RDW at each soil layer represents the mean weight.

2.3.3 Grain yield

Serpentine sampling was employed to predict grain yield in maize harvest, and five ears were chosen for each plot. Ear rows (ERS) and grains per row (GPR) were recorded. Yield or hundred-grain weight (HGW) was obtained after threshing and drying. The yield can be calculated as follows:

$$Y = (H \times M \times W) / 100000 \quad (1)$$

where, Y is the maize yield, kg/hm²; H is the ear number per hectare of maize; M is the kernels per spike; W is the hundred-grain weight (HGW), g. The value of H , in this case, was 67 000 as calculated by the spacing of row and plant.

2.4 Statistical analysis

Data were presented as mean \pm standard error (SE) in figures. Statistical analysis was performed in IBM SPSS Statistics 19.0, which is widely used for variance analysis and multiple correspondence analysis. Tables were created in Microsoft Excel 2007.

3 Results

3.1 SD and PHE

The SD and PHE of root-pruned maize plants were smaller than those of non-pruned maize plants, and the differences were dependent on the pruning distance and depth.

The root pruning treatments in JS include T_1 , T_2 , and T_3 ; among which, T_1 had a highly significant effect on SD ($p < 0.01$, similarly hereinafter), T_2 had less influence on SD ($p < 0.05$, similarly hereinafter), and T_3 had no significant influence. The SD values of T_1 and T_2 were significantly smaller than that of CK from June 26 to July 10, and no significant change occurred after July 10. Compared with that of CK, the SD of T_1 was smaller by 14.4%, 10.5%, and 6.1%, and that of T_2 was smaller by 12.1%, 8.6%, and 4.9%. T_4 to T_9 are the root pruning treatments in BTP; among which, T_4 , T_6 , and T_8 had highly significant influences on SD, T_7 and T_9 had relatively less significant influence, and T_5 did not have significant influence compared with CK. Nevertheless, the degree of influence was weakened after a certain period. According to the results, the ascending order of the SD with different root pruning treatments in BTP was T_8 , T_6 , T_4 , T_9 , T_7 , T_5 , CK after July 17 (Table 2).

Table 2 Stem diameter in different root cutting treatments ($n=20$)

Treatment	SD/mm						
	June 19	June 26	July 3	July 10	July 17	July 24	July 31
T_1	12.2 \pm 0.5	18.4 \pm 2.3**	23.0 \pm 1.5**	29.0 \pm 0.8*	32.2 \pm 1.4	34.9 \pm 1.4	36.2 \pm 0.9
T_2	11.9 \pm 1.2	18.9 \pm 1.5*	23.5 \pm 1.0*	29.4 \pm 1.2*	32.3 \pm 1.6	35.2 \pm 1.3	36.7 \pm 1.4
T_3	12.6 \pm 1.0	20.5 \pm 0.4	25.2 \pm 0.5	29.5 \pm 0.6	32.6 \pm 1.0	34.4 \pm 0.8	37.0 \pm 1.1
T_4	13.2 \pm 2.4	21.0 \pm 1.0	25.0 \pm 1.6	30.4 \pm 1.5	32.4 \pm 0.6	32.4 \pm 0.9**	35.0 \pm 2.1*
T_5	11.6 \pm 0.5	20.6 \pm 1.2	26.2 \pm 1.2	30.9 \pm 0.9	31.7 \pm 1.0	33.8 \pm 1.2	35.7 \pm 1.5
T_6	10.8 \pm 0.8	22.9 \pm 1.5	25.6 \pm 0.8	29.4 \pm 1.4	33.2 \pm 0.4	32.3 \pm 1.1**	34.3 \pm 0.7**
T_7	11.3 \pm 2.5	21.3 \pm 3.6	26.4 \pm 2.4	30.3 \pm 1.3	31.9 \pm 1.6	33.2 \pm 1.5*	35.6 \pm 1.3*
T_8	12.6 \pm 1.2	22.1 \pm 0.9	24.3 \pm 1.2	31.0 \pm 1.6	30.8 \pm 1.0	32.3 \pm 0.9**	33.5 \pm 2.0**
T_9	12.6 \pm 1.8	20.8 \pm 3.2	25.5 \pm 1.0	30.1 \pm 0.4	32.8 \pm 2.2	32.9 \pm 1.2*	35.1 \pm 1.6*
CK	12.1 \pm 0.8	21.3 \pm 1.1	25.4 \pm 1.6	30.5 \pm 1.8	32.4 \pm 2.4	34.8 \pm 1.7	36.9 \pm 1.5

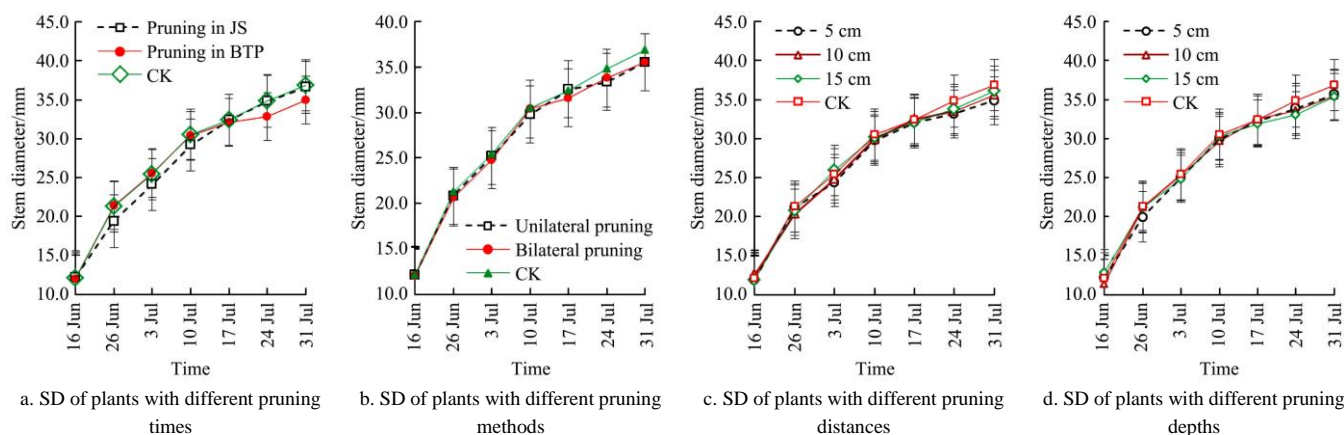
Note: n : Number of sampling points; SD: Stem diameter; CK: Control check; * represents a significant difference at the level of 0.05; ** represents a highly significant difference at the level of 0.01; similarly hereinafter.

The SD of plants with roots pruned in JS was smaller than that of CK before July 17 but returned to normal growth afterward. The SD of plants with roots pruned in BTP was smaller than those of CK and plants with roots pruned in JS after July 17. The SD of unilaterally and bilaterally pruned plants was smaller than that of CK all the time after root pruning, and that of bilateral pruned plants was the smallest. The variation trends of SD of the plants with different pruning times, pruning methods pruning distances and pruning depths are shown in Figure 2.

PHE was highly significantly influenced on June 26 and July 3 and significantly influence on July 10. In addition, T_2 had a highly significant influence on PHE on June 26 and a significant influence on July 3, and T_3 had no significant influence. The PHE of T_1 and T_2 plants were significantly smaller than that of CK from June 26 to July 17, and no significant change occurred after July 10. Compared with that of CK, the PHE of T_1 was smaller by 10.7%,

8.0%, and 7.9%, and that of T_2 was smaller by 8.0%, 6.0%, and 5.4%, and the difference was significant. T_4 , T_6 , T_8 , and T_9 had highly significant influences on PHE on July 24, and T_5 and T_7 had relatively less significant influences on PHE. On July 31, T_4 , T_6 , and T_8 still had highly significant influences on PHE, T_9 had a relatively less significant influence, and T_5 did not have significant influence (Table 3).

The PHE of plants with roots pruned in JS was smaller than that of CK before July 17 but matched with that of CK after July 17. Meanwhile, the PHE of plants with roots pruned in BTP was smaller than that of CK and those pruned in JS all the time after July 17. The PHE of unilaterally and bilaterally pruned plants was smaller than that of CK after July 17, and no significant difference was observed before July 17. The variation trends of PHE of the plants with different pruning times, pruning methods pruning distances and pruning depths are shown in Figure 3.



Note: CK: Control check; SD: Stem diameter; JS: Jointing stage; BTP: Big trumpet period.

Figure 2 SD of plants with different root pruning treatments

Table 3 Plant height in different root cutting treatments (n=20)

Treatment	PHE/cm						
	June 19	June 26	July 3	July 10	July 17	July 24	July 31
T ₁	59.6±6.4	71.9±2.0**	92.9±3.1**	118.7±1.6*	179.9±7.7	242.2±7.3	322.3±5.8
T ₂	62.3±2.0	74.1±3.4**	94.9±3.4*	122.0±3.3	183.2±9.3	243.9±5.6	326.4±7.9
T ₃	58.1±1.2	80.8±4.5	100.8±4.2	128.8±3.7	186.6±3.9	245.6±6.8	327.2±9.4
T ₄	54.9±5.2	78.4±4.5	98.2±3.4	128.3±4.6	186.1±7.1	227.3±6.2**	311.6±6.9**
T ₅	60.9±3.1	82.1±1.8	103.2±5.1	129.0±6.9	180.4±2.1	239.2±8.3*	324.5±9.3
T ₆	57.6±4.9	79.9±4.8	99.5±2.4	130.9±6.7	185.1±5.1	224.9±6.4**	307.9±5.4**
T ₇	59.2±2.1	82.9±2.6	102.8±2.6	126.4±2.7	184.7±8.7	233.3±7.7*	319.5±7.8*
T ₈	56.6±2.8	80.9±4.4	100.0±2.1	126.9±2.3	183.4±4.5	219.2±6.3**	305.0±6.5**
T ₉	58.8±4.3	79.0±3.6	104.1±3.4	131.9±5.9	186.2±5.9	233.7±8.8**	317.8±9.8*
CK	58.7±3.5	80.5±2.9	101.0±2.4	128.9±4.7	185.3±6.2	245.9±9.6	326.3±7.9

Note: PHE: Plant height.

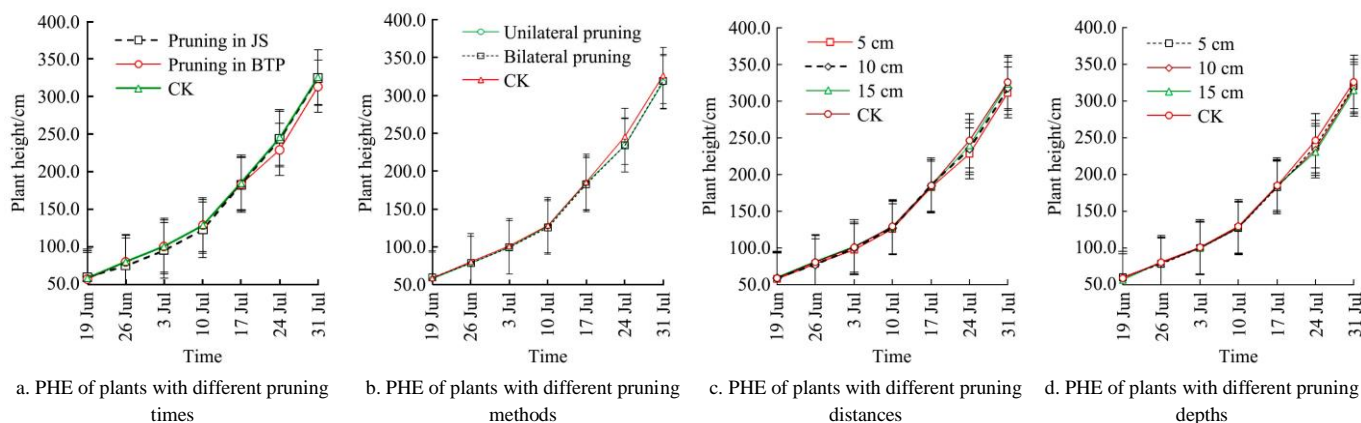


Figure 3 PHE of plants with different root pruning treatments

3.2 RDW

Most roots (90%) are located at the depth ranging from 0 cm to 20 cm soil layer and are rarely found in soil depth of more than 30 cm (less than 5%). The total RDW of maize had a small difference among T₁, T₂, T₃, T₅, and CK but was significantly larger than that of T₄, T₆, T₇, T₈, and T₉. In particular, the descending order of total RDW for all root pruning treatments was T₂, T₃, CK, T₅, T₁, T₇, T₉, T₄, T₆, T₈. The RDW at depth of 0-10 cm accounted for 60% of the total RDW after root pruning in JS, and this value was significantly greater than that for any other soil layer. Therefore, root pruning in JS could promote root growth and increase the root weight/volume in soil layer with a depth of

0-10 cm. In general, the RDW of maize in 0-10 cm soil layer had minimal difference compared with that of the soil layer with a depth of 10-20 cm after root pruning in BTP. The RDW in 0-10 cm soil layer diminished, but that in soil depth of 10-20 cm increased compared with that of CK. These results showed that the total RDW of maize was generally low in all treatments, and the effects varied according to pruning time and method. Root pruning in JS increased the RDW in 0-10 cm soil layer by 5%, whereas root pruning in BTP reduced the RDW at 0-10 cm soil depth but increased it in 10-20 cm soil layer by 15%. Therefore, root pruning has minimal influence on the RDW of soil layer with more than 20 cm depth as shown in Figure 4.

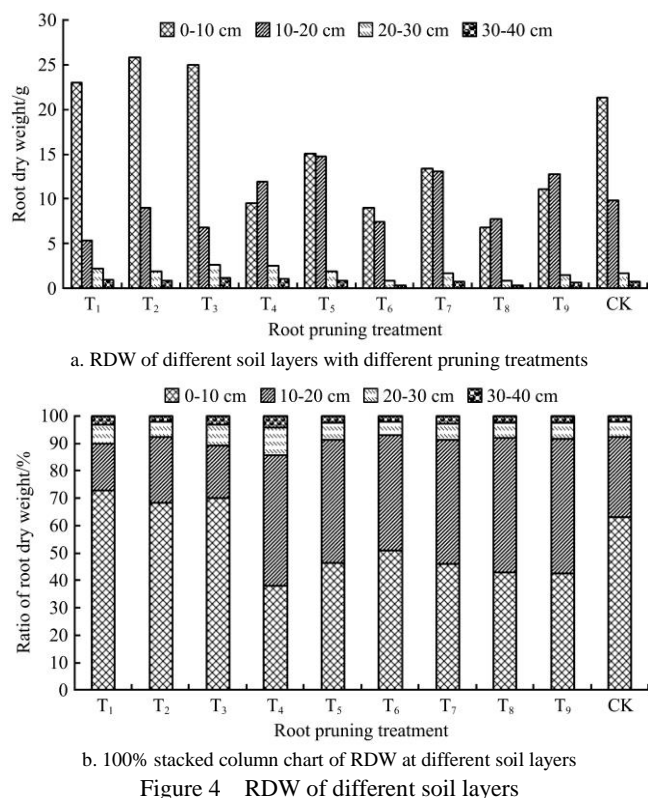


Figure 4 RDW of different soil layers

3.3 Grain yield

Table 4 indicates that different treatments have various effects on maize yield and yield component. For ear height, no significant difference was observed in T₁, T₂, T₃, T₄, T₅, T₇, and T₉, a significant difference was found in T₆ (decreased by 5.6%), and highly significant difference was noted in T₈ (decreased by 7.7%) compared with CK. Maize yield component mainly consists of spike number per hectare, kernels per spike, and HGW. Given that the spike number per hectare depends on the cropping pattern, the maize yield is mainly determined by kernels per spike and HGW. Compared with those of CK, the kernels per spike increased for T₁, T₂, and T₃ but decreased for the other treatments. A significant difference was found for T₉ (decreased by 4.0%) and highly significant difference for T₄ (decreased by 5.4%), T₆ (decreased by 7.1%), and T₈ (decreased by 8.8%). Except for T₃ (increased by 0.43%), the HGW of all treatments decreased, with T₈ showing the highest reduction (19.1%).

In general, root pruning in JS did not affect ear height and kernels per spike; however, a significant influence on maize yield and kernels per spike occurred when the pruning distance was 5 cm. Root pruning in BTP greatly influenced maize yield and yield component. Therefore, a small pruning distance and a large pruning depth led to low ear height, kernels per spike, HGW, and maize yield (Table 4).

Root pruning in JS and BTP lowered the maize yield by 2.89% and 11.10%, respectively. In addition, the maize yield decreased for the groups with unilateral and bilateral pruning, but the difference was not significant. The influence on maize yield was strengthened when the pruning distance was decreased. The maize yield decreased by 2.90%, 9.24%, and 12.96% at pruning distances of 15, 10, and 5 cm, respectively. The maize yield decreased by 6.39% and 10.27% when the pruning depth was 5 and 15 cm, respectively, indicating that a large pruning depth could proportionally reduce the maize yield. T₈ had the greatest influence on the maize yield by increasing it to 19.10% as shown in Figure 5.

Table 4 Maize yield and yield component ($n=20$)

Treatment	Ear height/cm	Kernels per spike	HGW/g	Yield/kg hm^{-2}
T ₁	135.2±3.8	523.0±8.5	45.7±1.1*	16145±208*
T ₂	135.7±4.1	526.0±2.8	46.1±0.8	16360±47
T ₃	140.5±3.0	525.0±7.7	48.3±1.6	17102±121
T ₄	128.7±2.1	493.0±4.9**	45.1±0.8**	14967±243*
T ₅	137.9±6.3	522.0±12.7	47.3±0.4	16637±289
T ₆	127.9±2.3*	484.0±9.9**	44.5±1.2**	14546±250**
T ₇	132.2±3.7	520.0±4.9	45.2±0.7*	15864±258*
T ₈	125.1±4.7**	475.0±8.7**	43.0±1.0**	13771±159**
T ₉	129.6±1.2	500.0±6.3*	44.6±1.6**	15038±173*
CK	135.5±4.3	521.0±7.4	48.3±0.7	17028±397

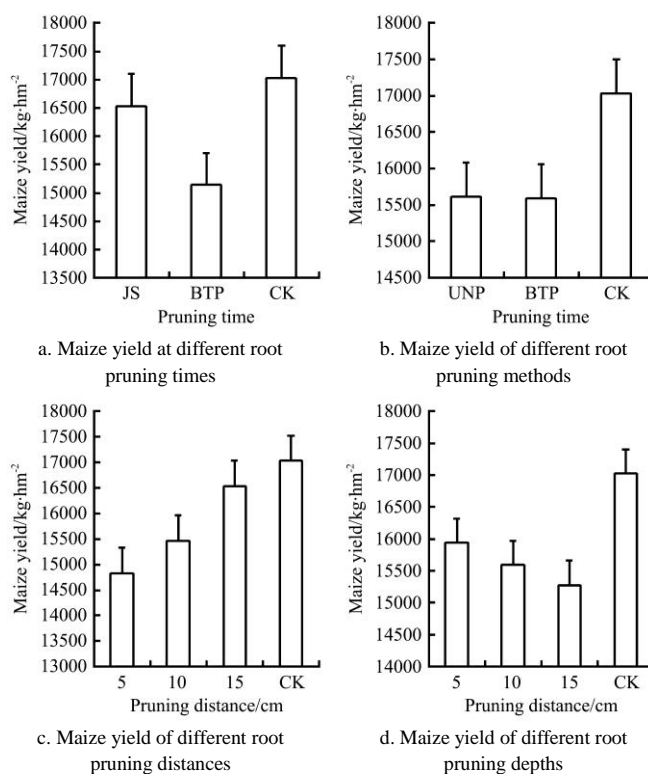


Figure 5 Maize yield with different root pruning treatments

4 Discussion

4.1 Influence on maize growth

Many agronomic traits indicate that root pruning can moderately promote crop growth in the seedling stage. Nonetheless, the damage could not be large; otherwise, it could inhibit crop growth^[28,29]. In general, when root pruning is performed early, the plants could adjust their growth and modulate the resource allocation immediately, and the crops could rapidly return to normal growth^[30,31]. This finding lays a good foundation for the later robust growth of crop plants. When root pruning is performed late, plant reaction is delayed, and plant is greatly affected^[32]. Root pruning when the plant is in an important stage directly decreases the supply of water and nutrients for the overground parts of the plant^[33]. This work revealed that root pruning in JS and BTP influence the SD and PHE of maize to different extents. The SD and PHE are smaller than those of CK at the beginning of root pruning, those of plants root-pruned in JS can recover and even exceed those of CK after some time, and those of plant root-pruned in BTP are consistently lower than those of CK.

The two methods of root pruning to control the SD and PHE of

maize include inhibition-promotion and inhibition approaches. The former moderately inhibits growth by root pruning in the early stages and then promotes the growth later, and the latter severely prunes roots in the early stages or moderately prunes roots in the middle and late stages of maize growth, which are the key phases for maize growth and development. The capability of maize plants to absorb soil water and nutrients diminishes after root pruning; as a response, the photosynthetic efficiency and supply capacity of critical nutrients for the upper part of maize growing are reduced^[18,34], thus affecting the thickening or division of maize stem radial cells^[35]. Ultimately, SD and PHE are affected.

4.2 Influence on root system

As a direct physical operation on the root, pruning has a focused effect on the development of root system in the soil at different depths^[36]. The root system might require a long time to recover after root pruning, hence, maize growth could be inhibited for some time. Given that its compensated growth promotes the germination of secondary root aftermath, the root system could then grow fast and vigorously^[18,25,37]. The total amount of root system recovers or surpasses that of CK when the total potential of compensating growth exceeds the damage caused by root pruning; however, the total amount of root system could be always lower than that of CK when the total potential is insufficient^[38]. In this experiment, the total RDW with root pruning in JS does not greatly differ from that of CK but becomes larger than that of CK when the pruning distance is greater than 5 cm. When root pruning occurs in JS, the RDW has the highest value in the 0-10 cm soil layer and accounts for approximately 70% of the total RDW, which is 5% more than that of CK. Nevertheless, the total RDW with root pruning during BTP is generally lower than that of CK, excluding the case with pruning distance of 15 cm. The RDW in 0-10 and 10-20 cm soil layers are almost identical. Compared with that of CK, the RDW for 0-10 cm soil layer decreases, whereas that for 10-20 cm soil layer increases. The test showed that plants form a defensive system against any damage to their own system, such as mechanical injury^[39]. In long-term co-evolution, mechanical injury on the roots can stimulate their development by growing secondary roots at the injured locations, strengthening metabolism, and achieving self-repair^[38,40]. Hence, the damage increases the RDW ratio in the 0-10 cm soil layer during JS. During BTP, the root system beneath the soil surface is already well developed, and pruning could cause larger damage than during JS. The amounts of newly formed secondary roots can be lower than the amount of pruned roots. Meanwhile, the roots in 10-20 cm soil layer grow rapidly. As a consequence, the RDW ratio in the 0-10 cm soil layer is diminished, whereas that in 10-20 cm soil layer increases during BTP. Therefore, the specific rate of change is closely related to the pruning distance and depth.

4.3 Effect on maize yield

The growth environment of maize root system is closely related to yield because a large root biomass can yield a high biomass^[41]. The test indicated that development periods, pruning distances, and pruning depths influence the maize yield at different degrees. When roots are pruned in JS, maize yield is increased by adopting a pruning distance of 15 cm but is reduced when the distance is less than 10 cm. With the degree of root pruning increased and the root pruning time elapsed, the maize yield decreases severely^[42-44]. A large root pruning surface, small root pruning distance, deep root pruning depth, and late root pruning time can reduce the yield by a large margin. This result is consistent with previous studies.

BTP is the key period for maize ear formation and determines the seed setting rate of maize ear. When roots are pruned in BTP, the photosynthetic efficiency of leaves decreases, and the capability of absorbing and supplying soil nutrients for ear development diminishes, resulting in low seed setting rate, long baldness, and insufficient maize pellet^[45]. Consequently, the kernels per spike and HGW of the maize ears could decrease, causing a high reduction in maize yield.

5 Conclusions

The effects of root pruning in JS on SD and PHE decreases gradually with maize growth, and the plants recover or exceed normal growth speed after some time. In general, a small pruning distance and a large pruning depth lead to small SD and PHE during root pruning in BTP.

Compared with that of CK, the total RDW is reduced when the pruning distance is reduced, the pruning depth is increased, and the root pruning time is prolonged. The results showed that root pruning in JS increases the proportion of roots in 0-10 cm soil layer by approximately 5%, whereas root pruning in BTP decreases that in 0-10 cm soil layer but increases that in 10-20 cm soil layer by approximately 15%. For soil under 20 cm, the effect of root pruning is negligent.

The field experiment also showed that the maize yield slightly increases during JS when the pruning distance is 15 cm but reduces when the pruning distance is 10 cm or less. In addition, the maize yield decreases when root pruning is performed in BTP and could decrease dramatically with the reduced pruning distance and increased pruning depth.

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