Morphological plasticity of root growth under mild water stress increases water use efficiency without reducing yield in maize

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Abstract

Large yield gap exists in rain-fed maize (*Zea mays* L.) production in semi-arid regions, mainly caused by frequent droughts halfway the crop growing period due to uneven distribution of rainfall. It is questionable if irrigation systems are economically required in such a region since the total amount of rainfall do generally meet crop requirements. This study aimed to quantitatively determine the effects of water stress during jointing to grain-filling on root and shoot growth and the consequences for maize grain yield, above- and below-ground dry matter, water uptake (WU) and water use efficiency (WUE). Pot experiments were conducted in 2014 and 2015 with a mobile rain shelter to achieve conditions of no, mild or severe water stress. Maize yield was not affected by mild water stress across two years, while severe stress reduced yield by 56%. Both water stress levels decreased root biomass slightly but shoot biomass substantially. Mild water stress decreased root length but increased root diameter, resulting in no effect on root surface area. Due to the morphological plasticity in root growth and the increase in root/shoot ratio, WU under water stress was decreased, and overall WUE for both above-ground dry matter and grain yield increased. Our results demonstrate that an irrigation system might be not economically and ecologically necessary because the frequently occurring mild water stress did not reduce crop yield much. The study helps to understand crop responses to water stress during critical water-sensitive period (middle crop growing season) and to mitigate drought risk in dry land agriculture.

Keywords: root diameter; root length; root surface area; root/shoot ratio; yield components; water utilization

1. Introduction

Maize (*Zea mays* L.) is the most important crop globally, and also a major food crop in northeast China with an average yield around 5.3 t ha^{-1} (Dong et al., 2017). However, the yield gap to the potential of 10.9 t ha^{-1} is still large (Liu et al., 2012), mainly due to frequent summer droughts. Due to the increasing probability of extreme climate events (IPCC, 2007), water stress for agricultural production is likely to increase in this region (Song et al., 2014; Yu et al., 2014) which is detrimental for crop photosynthesis and yield (Richards, 2000).

Although the averaged total rainfall during crop growing season can meet the requirements of rain-fed maize in the semi-arid northeast of China, the yearly and seasonal variations often cause droughts (mostly mild water stress) during summer, resulting in yield loss. Since quantitative information on the effects of water stress on maize performance is lacking, it can be questioned whether irrigation systems using underground water are economically and ecologically required in this situation.

Yield reduction by water stress has been attributed to decreased crop growth (Payero et al., 2006), canopy height (Traore et al., 2000), leaf area index (NeSmith and Ritchie, 1992) and root growth (Gavloski et al., 1992). Crop shoot development and biomass accumulation are greatly reduced by soil water deficit at seeding stage (Kang et al., 2000). Short-duration water deficit during the rapid vegetative growth period causes around 30% loss in final dry matter (Cakir, 2004). The reduction in maize yield by water stress can be observed in all yield components such as ear density, number of kernels per ear and kernel weight (Ge et al., 2012), especially for stress during or before maize silk and pollination period (Claassen and Shaw, 1970). Biomass and harvest index (the ratio of grain yield over total aboveground dry matter) are decreased under water stress during anthesis (Traore et al., 2000).

Water use efficiency (WUE, expressed in kg yield obtained per m^3 of water) is notably reduced by severe water stress. However, a moderate water stress at V16 (with 16 fully expanded leaves) and R1 (silking) stages in maize increased WUE (Ge et al., 2012). Intentional irrigation deficits before the maize tasseling stage are often used for improving WUE in regions with serious water scarcity, e.g. North China Plain (Qiu et al., 2008; Zhang et al., 2017). Under water stress, plant photosynthesis and transpiration decreases due to a decrease in stomatal conductance (Killi et al., 2017) induced by increasing concentration of abscisic acid (ABA) (Beis and Patakas, 2015). However, limited knowledge exists on how much the growth and biomass partitioning between shoot and root in maize is affected by water stress during mid and late growing stages, and if changes in root growth and morphology caused by water stress could affect maize yielding and water use efficiency.

Since field experiments that aim at quantifying the effects of water stress are difficult to carry out in rain-fed agriculture, a mobile rain shelter is often used in studies to control water stress in the field (NeSmith and Ritchie 1992). The objective of this study was to quantify maize shoot and root growth, grain yield and WUE under different water stress levels during the mid crop growing season with a well-controlled mobile rain shelter, to understand the crop response to water stress.

2. Materials and methods

2.1. Experimental design

The experiments were conducted at Shenyang (41°48′N, 123°23′E), Liaoning province, northeast China in 2014 and 2015. The experimental site is 45 m above sea level. On average from 1965 to 2015, annual potential evaporation is 1445 mm, with a total precipitation 720 mm, and mean air temperature 8 ^{o}C. The frost-free period is

150-170 days. Average relative humidity is 63 %. Annual mean wind speed is 3.1 m s^{-1}. The climate is a typical continental monsoon climate with four distinct seasons, characterized by a hot summer and cold winter. The annual mean air temperature was 9.5 ^{o}C in 2014 and 9.1 ^{o}C in 2015. The mean air temperature during crop growing season (May to September) was 20.2 ^{o}C in 2014 and 19.4 ^{o}C in 2015 (Fig. 1).

Maize plants were grown in pots in three treatments: (1) no water stress; (2) mild water stress and (3) severe water stress (Table 1). The levels of water stress were based on historical rainfall frequency analysis. The water supply was controlled by a mobile rain shelter with steel frame and transparent PVC cover. The mobile rain shelter is built on a mechanical movement track equipping with an electricity motor to move the shelter with a remote control. The shelter was moved away from the experimental plots in no rain days and covered before a rain came, therefore the effect of shelter on incoming radiation could be ignored. The mobile rain shelter is 9 m in width, 30 m in length and 4.5 m in height. The top and both sides of the shelter have PVC transparent boards to prevent outside rainfall. There is a water gutter at out side of movement track to drain the rain water. Therefore the rain water intrusion can be avoided. Water treatments began from maize jointing (V6, with 6 fully expended leaves) to filling stages (R3, milk) (Abendroth et al., 2011). Water treatments were conducted by supplying irrigations once per 5 days before starting water treatments with same amount for all pots, and once per 3 days during the period of water treatments. The detail amount of water supplied to each treatment was listed in Table 1. The experiments entailed a completely randomized block design with three replicates. Each treatment consisted of 12 pots (one plant per pot) and divided into 3 replicates (4 pots each). At each sampling (4 samplings in total at an interval of approximately 30 days), one pot was used.

Each pot was 40 cm in diameter and 50 cm in height, filled with 40 kg naturally dried soil with a bulk density of 1.31 g cm^{-3}. Large size of pots in the experiments effectively avoided space effect for growing good maize. The soil was sandy loam with a pH of 6.15, total N of 1.46 g kg^{-1}, total of P 0.46 g kg^{-1} and total K of 12.96 g kg^{-1}. 46.5 g compound fertilizer (N 15 %, P_2O_5 15 % and K_2O 15 %) and 15.5 g diammonium phosphate (N 18 % and P_2O_5 46 %) were applied to each pot before sowing. There was no other fertilizer applied during maize growing season. Maize cultivar used in both years was Liaodan 565, a locally common used drought-resistant cultivar. One plant was grown in each pot. Maize was sown on 13 May and harvested on 30 Sept in both 2014 and 2015.

2.2 Dry matter and grain yield measurements

To determine maize dry matter, four plants were harvested on 49 (V6, jointing), 77 (VT, tasseling), 113 (R3, milk) and 141 (R5, dent) days after sowing (DAS) in 2014, and one sampling was done on 132 DAS in 2015. The samples were separated into root and shoot and oven-dried at 80 °C for 48 hours until reaching a constant weight. The shoot/root ratio was calculated using measured organ-specific dry matters.

Grain yield was measured by harvesting all cobs in a pot in maize harvesting time. The grain was sundried to a water content of 15%. Yield components i.e. ear (cob) numbers per plant, kernel numbers per ear and thousand kernel weight were measured for each plot.

2.3 Root measurements

Root growth and morphological traits (root length, diameter and surface area) were measured four times during crop growing season on 49, 77, 113, 141 DAS in 2014. The whole roots were collected per pot at the time of dry matter measurements. Root samples were carefully washed with tap water to remove soil. The cleaned roots were placed on a glass plate of a root system scanner. Scanned root images were analyzed by a plant root image analyzer WinRHIZO PRO 2009 (Regent Instruments Inc., Canada) to quantify total root length (m), diameter (mm) and surface area (m^2) per plant (pot).

2.4 Measuring soil moisture content, water uptake and water use efficiency

Soil moisture contents were measured by a soil auger at sowing and harvesting times for each plot (3 replicates per treatment). Soil cores were taken from the mid pot for each 10 cm soil layer. After measuring fresh soil weight, soil samples were oven-dried at 105 ^{o}C for approximately 48 hours until a constant weight was reached. The gravimetric soil moisture contents (%, g g^{-1}) measured by soil auger were calculated into volumetric soil moisture content (%, m^3 m^{-3}) by multiplying with soil bulk density.

Water uptake (WU) of maize was calculated using a simplified soil water balance equation (Kang et al., 2002). Because the experiments were sheltered, rainfall, drainage and capillary rise of water did not occur in this situation and therefore were not taken into account in the calculation:

$$WU = I + \Delta S \qquad (1)$$

where WU (mm) is crop water uptake (mm) during whole crop growing season, I is the amount of water supplied to each pot (mm). ΔS is the change of total soil water between sowing and harvesting dates.

Water use efficiency (WUE) was calculated by measured final yield or above-ground dry matter and total WU during crop growing season (Zhang et al., 2007).

$$WUE = Y/WU \quad (2)$$

where WUE (g m^{-2} mm^{-1} or kg m^{-3}) is water use efficiency expressed in gain yield WUE_Y or dry matter WUE_{DM}. Y (g m^{-2}) is grain yield or dry matter.

2.5. Statistical analysis

Analysis of variance on yield, WU, WUE, and dry matter for shoot and root were performed using General Linear Model of SPSS 20 (SPSS Inc., Chicago, USA). The differences between means were evaluated through LSD multiple comparison tests at a significant level of 0.05.

3. Results

3.1 Variation and frequency distribution of rainfall

The average rainfall during maize growing season (May to September) at experimental site from 1965 to 2015 was 531 mm with a standard deviation of 134 mm (Fig. 2 a). Rainfall in the experimental years was much less than in a normal year, 296 mm in 2014 and 379 mm in 2015. The frequency of years with rainfall above 500 mm was 68.6 % during past 51 years. For years with mild drought stress (350-450 mm), this was 27.5 % and with severe drought stress (200-300 mm) it was 3.9 % (Fig. 2 b), indicating that the maize growing in this region mainly suffered mild water stress.

3.2 Yield and yield components

Maize yield under mild water stress across two years was not significantly different, while in severe stress yield was 55.6 % lower than no water stress control (Table 2). The decrease of maize yield in severe water treatment was due to the decreases in ear and kernel numbers as well as harvest index (HI). However, water stress did not affect kernel weight, while other yield components were decreased. Year effect was only significant for HI, which was likely caused by the variation in air temperature: the cooler weather in 2015 during maize growing season decreased HI comparing with a warmer year in 2014. There were no interactions between year and treatment.

3.3 Above- and below-ground dry matters

Mild water stress did not reduce root dry matter (Fig. 3 a, b), but greatly reduced shoot dry matter, especially at grain-filling stage (113 DAS) (Fig. 3 c, d). The severe water stress decreased both root and shoot dry matter compared with no stress control, but the magnitude of the decrease in shoot was much larger than in root. At maize tasseling stage (77 DAS), as taproots reached their maximum size, root dry matter under severe water stress was much lower than mild and no water stress treatments. However, it became less different later in the season, which indicated a strong complementarily growth of root system under water stress. Due to the different responses of shoot and root to water stress, the root/shoot ratios under water stress increased (Fig. 3 e, f), especially during crop rapid growing period (77 to 113 DAS).

3.4 Root length, diameter and total surface area affected by water stresses

Root length per plant was much lower under severe water stress than the control, especially at tasseling stage (77 DAS). The decrease of root length under mild water stress during maize mid growing season was much smaller than under severe stress

(Fig. 4 a). Root diameters under both mild and severe water stress treatments were much higher than under no water stress control (Fig. 4 b), especially during late growing season. Total root surface area was less changed (Fig. 4 c), especially during maize reproductive growth period (113 DAS).

3.5 Water uptake and use efficiency

Total water uptake (WU) reduced by 28.9 % under mild water stress and by 54.6 % under severe stress compared with no stress control (588 mm) (Fig. 5). Water use efficiency for maize above-ground dry matter (WUE_{DM}) under both water stress treatments across all years increased 31.2 % compared with no stress control (Fig. 5 b). The WUE_{DM} in severe water stress was the highest (14.4 kg m^{-3}), which was 42.2 % higher than the control, while that in mild stress increased 20.2 %. However, WUE for grain yield under severe water stress (3.51 kg m^{-3}) was not significantly different with that in the control (3.38 kg m^{-3}), while WUE_Y in mild water stress across two years increased 17.3 % (Fig. 5 c). The difference between WUEs in dry matter and grain yield was due to the extent of decreasing HI under the levels of water stress (Table 2).

4. Discussion

Mild water stress from maize jointing (V6) to filling stages (R3) did not significantly reduce maize grain yield. It is different with previous report that maize yield is much more affected by water stress during flowering stage than other stages (Doorenbos et al., 1979). Our result differed with a previous study, which showed mild water stress seriously reduced crop production (Kang et al., 2000). This is likely due to our choice of a drought-resistant variety (Zhengdan 565) and the difference in ecological zones. Genotype-dependent relationships between yield and crop growth rate would be stronger under water stress than under no stress condition (Lake and Sadras, 2016).

Mild water stress during mid crop growing period can maintain maize yield but substantially reduces the water consumption at the same time in our study. Thus, the water use efficiency was increased (Liu et al., 2016). Mild water stress reduced total water uptake, resulting a 20.2 % higher WUE in dry matter and 17.3 % in yield. The increase in WUE under mild water stress was benefit from the morphological responses of shoot and root growth to water stress, as an increase in root/shoot ratio. The water stress reduced root length; however, this reduction was compensated by an increase in root diameter. The maintenance of crop growth under water deficit was limited by the severity of the stress. Under severe water stress, maize growth fails to be compensated by plant plasticity.

Severe water stress greatly reduced both shoot and root biomass. Large decrease in shoot growth, i.e. less biomass and leaf area, reduces the light interception and transpiration (Monteith, 1981). Under mild water stress during vegetative and tasselling stages, the shoot growth was not significantly reduced in this study but did in previous report, e.g. plant height and leaf area (Cakir, 2004). Mild soil water deficit may also reduce water loss of plants through physiological regulation (Davies and Zhang, 1991). A moderate soil drying at the vegetative stage encourages root growth and distributing in deep soil (Jupp and Newman, 1987; Zhang and Davies, 1989), which is consistent with our findings. Large root system with deep distribution is beneficial for water-limited agriculture (McIntyre et al., 1995). These mechanisms explained why maize yield under mild water stress was not decreased in our study.

We found an increase in root diameter under water stresses. This result indicated that the lateral roots under water stress were probably less than under no water stress. That may limit water absorption since the lateral roots is younger and more active in uptake function (Lynch, 1995). Average root diameters in all treatments decreased from 77 to 113 DAS, which was caused by highly emerged lateral roots after the taproot reached its maximum (VT stage). The higher root diameter under water stress than in no water stress control at 141 DAS was probably due to a fast senescence of late developed lateral roots.

Our results on root morphological plasticity under mild water deficit provided another evidence for the explanation of enhancing WUE and maintaining yielding in relation to crop-water response. However, the mechanism that determines crop response to water stress may also involve other processes, e.g. intercellular CO_2, stomatal conductance, photosynthetic rate, oxidative stress, sugar signaling, membrane stability and root chemical signals (Xue et al., 2006; Dodd, 2009). The relationship between carbon assimilation and water stress have been widely explored to understand the physiological mechanism for improving WUE (Ennahli and Earl, 2005; Xue et al., 2006; Zhang et al., 2013). The abscisic acid (ABA)-based drought stress chemical signals regulates crop vegetative and reproductive development and contributes to crop drought adaptation (Killi et al., 2017). Increased concentration of ABA in the root induced by soil drying may maintain root growth and increase root hydraulic conductivity, thus alleviates water deficit in the shoot (Liu et al., 2005). The increase of ABA can also induce stomatal closure and reduces crop transpiration (Haworth et al. 2016), net photosynthesis and crop growth (Killi et al., 2017).

The maize yield in 2015 was much lower than in 2014 independent of water stress. That might be caused by a higher maximum air temperature in 2015 (32.0 ^{o}C) than in 2014 (29.1 ^{o}C) during flowering period. High air temperature reduces maize pollination (Muller and Rieu, 2016) and directly affects yield formation and HI.

5. Conclusions

This study clearly demonstrates that the maize yield under mild water stress during summer does not decrease but the water use efficiency increases due to changes in root and shoot growth. A higher root/shoot ratio under mild water stress allows plant efficiently use limited soil water. In studied region (Liaoning province), maize mainly grows in rain-fed condition (2.4 million ha), covering 73 % of total area for grain crops. To reduce the possible effect of drought on maize production, the wells system piping ground-water to irrigate crop is planned recently. The wells need to be 60 to 70 m deep with an average cost of 12,000 Yuan for each. Each well can only irrigate 9 to 10 ha of maize. According to our results, only severe water stress significantly reduces maize yield by 55.6 % across two experimental years (Table 2), which occurs only 3.9 % during 1965 to 2015. Mild water stress occurs much frequently (27.5 % of years), however, it does not affect maize yield significantly. Our study suggested that the well system in this region might not be economically and ecologically necessary. Other agronomy practices such as intercropping maize with crops requiring less water (e.g. peanut), cultivar selection, adjusting sowing windows (Liu et al., 2013; Lu et al., 2017) and ridge-furrow with covering plastic film (Dong et al., 2017) are likely more applicable in optimizing crop yield and regional sustainability. Our study provides more evidences to understand crop responses to water stress, especially in relation to root morphological plasticity in a drought environment. The results can be further applied combining with crop model (Mao et al., 2015) to mitigate climate risk in dry land agriculture.

Author contribution

Z. Sun, Y. Zhang, J. Zheng and Q. Cai conceived and designed the experiments. Q. Cai, W. Bai, Y Zhang, Y. Liu, L. Feng, C. Feng, Z. Zhang and N. Yang performed the experiments. L. Zhang, Q. Cai and J.B. Evers analyzed the data and wrote the paper.

Competing interests

The authors declare that they have no conflict of interest.

Special issue statement

Special issue: Ecosystem processes and functioning across current and future dryness gradients in arid and semi-arid lands.

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Table 1 Water treatments during crop growing seasons in 2014 to 2015.

Year	Water treatment	Initial volumetric soil moisture content (%)	Actual water supply at three growing periods (mm)			
			Early (16-29 DAS[1])	Middle (30-102 DAS)	Late (103-121 DAS)	Total
2014	No stress	24.4	11.9	478	56	545
	Mild stress	24.8	11.9	299	56	366
	Severe stress	24.9	11.9	122	56	190
2015	No stress	25.3	11.9	510	32	553
	Mild stress	25.3	11.9	334	32	378
	Severe stress	24.4	11.9	159	32	203

[1] DAS refers days after maize sowing.

Table 2 Yield and yield components affected by different water stresses from 2014 to 2015

Year	Water treatment	Ear number	Kernel number	Thousand kernel weight	Yield per plant	Harvest index
		ears plant^{-1}	kernels ear^{-1}	g	g plant^{-1}	g g^{-1}
2014	No stress	2.0±0.0a	354±32a	440±6.8a	301±33a	0.36±0.01a
	Mild stress	2.0±0.0a	350±16a	416±1.2b	276±14a	0.37±0.01a
	Severe stress	2.0±0.0a	245±35b	412±3.7b	166±25b	0.27±0.02b
2015	No stress	2.0±0.0a	341±67a	426±12a	240±60a	0.29±0.04a
	Mild stress	2.0±0.0a	244±53a	427±22a	168±42ab	0.25±0.03a
	Severe stress	1.3±0.3b	172±46a	412±16a	81±22b	0.17±0.04a
mean	No stress	2.0±0.2a	347±38a	432±7.5a	266±36a	0.32±0.03a
	Mild stress	2.0±0.0a	289±36ab	422±12a	214±32a	0.30±0.03ab
	Severe stress	1.6±0.0b	203±31b	412±8.5a	118±23b	0.21±0.03b
P	Treatment	0.021	0.003	0.556	0.005	0.013
	Year	0.184	0.514	0.889	0.237	0.039
	Treat×Year	0.111	0.664	0.555	0.835	0.758

Same small letters indicate no significant difference between water treatment within same year at *a*=0.05.

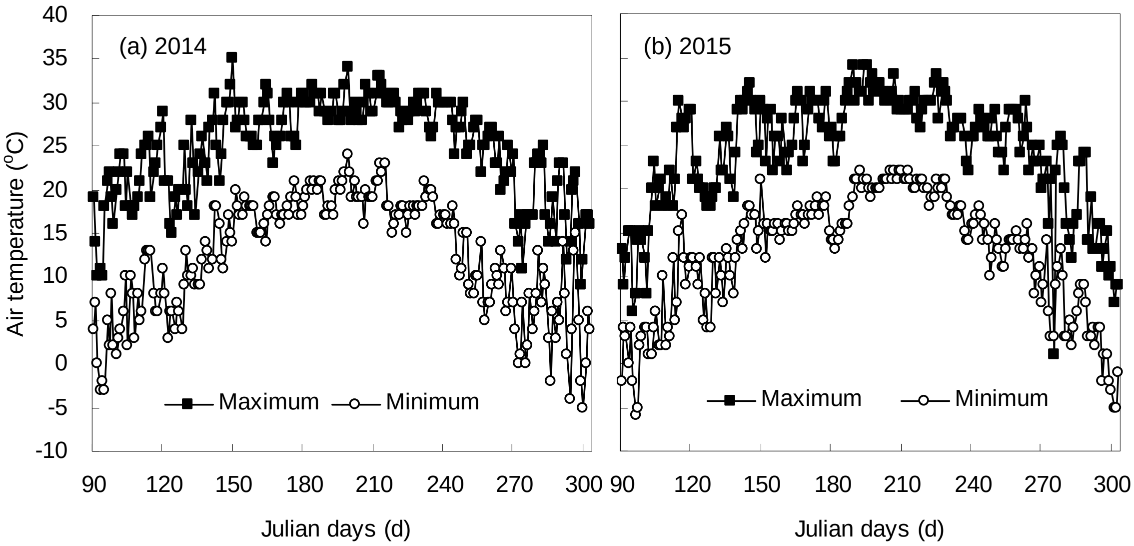

Fig. 1 Daily maximum and minimum air temperatures in 2014 and 2015 in Shengyang, Liaoning, China

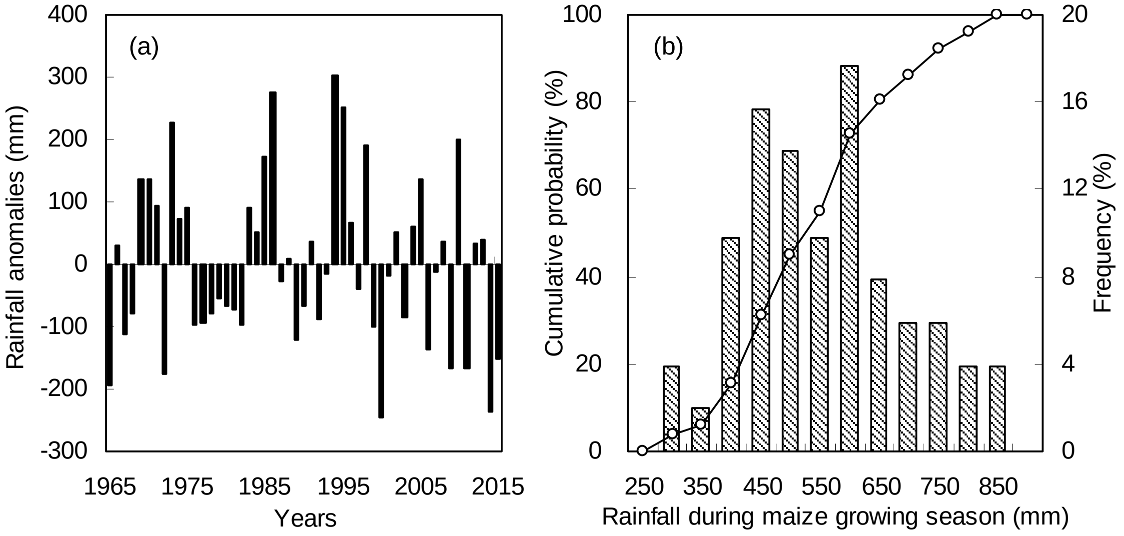

Fig. 2 Anomalies and cumulative frequency of rainfall during maize growing season (May to September) from 1965 to 2015 at Shengyang, Liaoning.

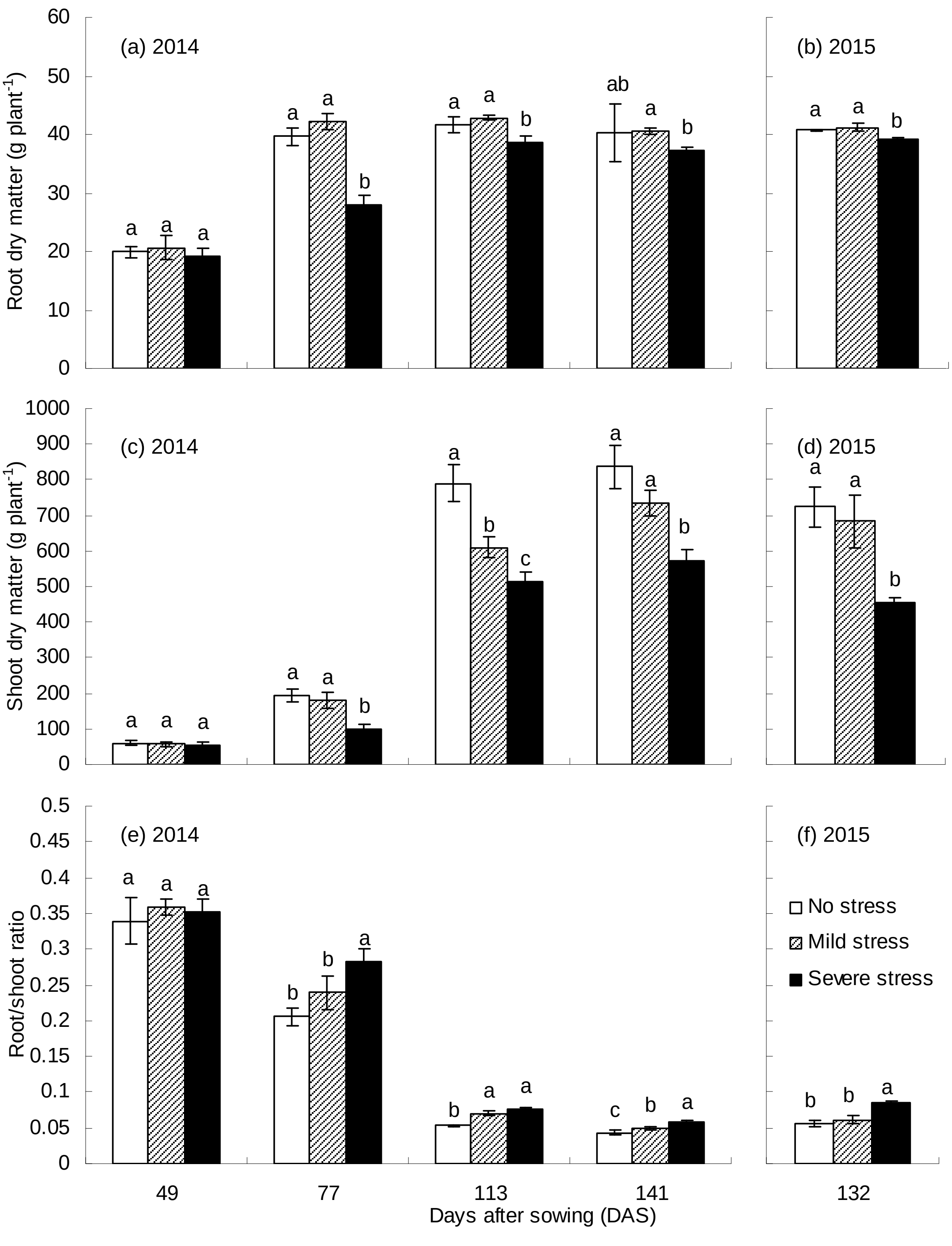

Fig. 3 Root and shoot dry matters of maize under water stress at different growing stages in 2014-2015.

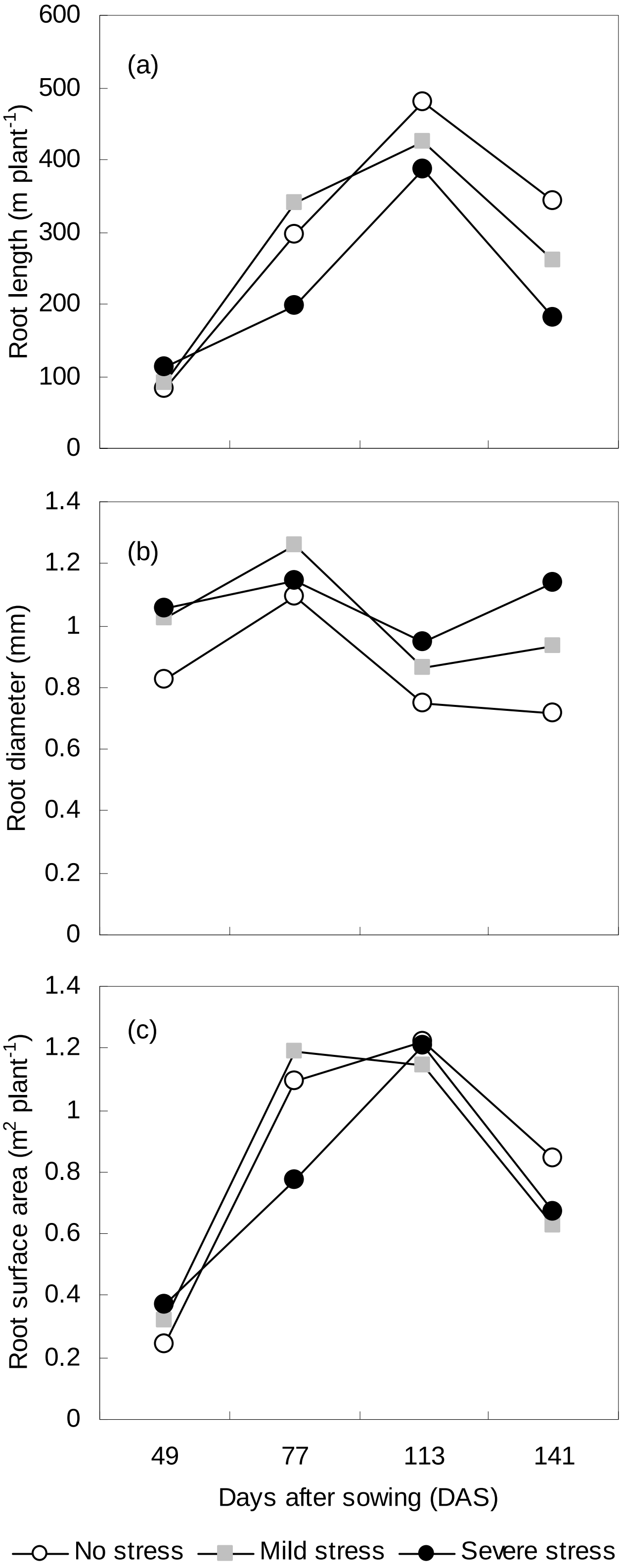

Fig. 4 Total root length, average diameter and total surface area per plant affected by water stress in 2014

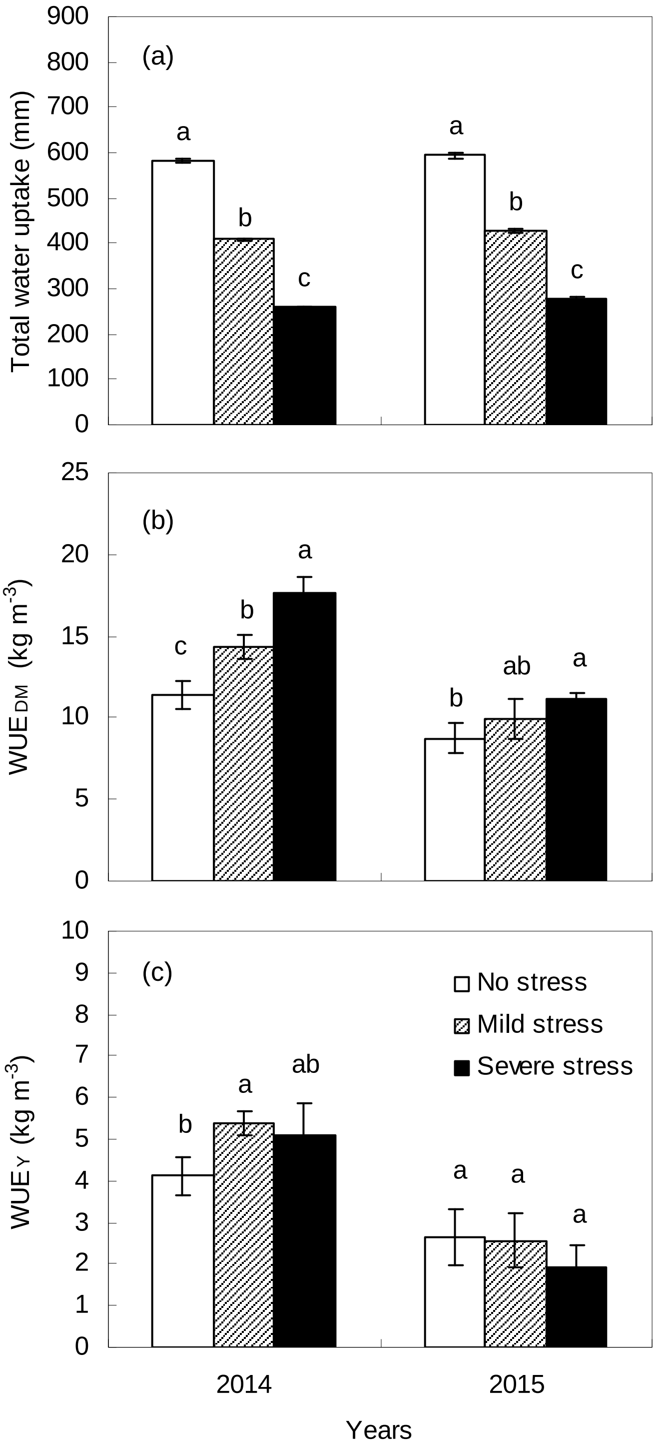

Fig. 5 Total water uptake (WU) during crop growing season and water use efficiency for above-ground dry matter (WUE_{DM}) and grain yield (WUE_{Y}) under water stress in 2014-2015