Stomatal conductivity, canopy temperature and evapotranspiration of maize (*Zea mays* L.) to water stress in Northeast China

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Abstract: The Northeast China Plain (NECP) is one of the main maize (*Zea mays* L.) production regions in China but is now subject to drought because of climate change and a rain-fed cultivation system.   A two-year experiment was conducted in a typical maize cultivation region in the NECP to investigate the responses of plant physiological factors and evapotranspiration (*ET*) to water stresses at different growth stages.   Results show that the responses of plant physiological factors to water stress can be divided into three levels based on soil water content (*SWC*) in the main root zone: when *SWC* was greater than 0.22 cm³/cm³ (equivalent to 62% field capacity (FC)), stomatal conductivity (g_s) and *ET* reached their highest values, and the canopy temperature (T_c) was close to the air temperature; when *SWC* was within 0.15-0.22 cm³/cm³ (43%-62% FC), the g_s and *ET* decreased, and T_c increased as *SWC* decreased; and when *SWC* was lower than 0.15 cm³/cm³ (<43% FC), g_s and *ET* reached their lowest values and T_c was greater than 1.2 times the air temperature.   The ratio of canopy temperature to air temperature (R_T), is closely related to stomatal conductivity and soil water content, and especially linearly related to crop water stress index (*CWSI*), and can be used as an alternative to *CWSI* for evaluating maize water stress because of easily data achieving and simple calculation processes.   In a conclusion, R_T of 1.2 can be used as an index to identify a severe water stress status, and maintaining *SWC* greater than 60% FC at the heading and grain-filling stages is important for supporting maize normal *ET* and growth in the study region.
Keywords: water stress, drought indices, canopy temperature, crop evapotranspiration, stoma conductivity, maize, soil water
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1 Introduction

The Northeast China Plain (NECP) includes Liaoning Province, Jilin Province and Heilongjiang Province and is one of main grain production regions in China. In 2017, the total maize grain production in the NECP was 87.4 million t and accounted for 33.8% of all maize grain production in China (259.1 million t). The average maize yield per hectare in the NECP was 6874 kg, which is 12.5% higher than the national value (6110 kg/hm²). Maize yields greater than 10 t/hm² in the NECP were also reported[1]. Therefore, the high maize grain production in the NECP is the basis for food security in China.

Because of plentiful precipitation and radiation in NECP, most maize fields have no irrigation systems, and the traditional cropping system for maize is rainfed[2,3]. In this case, maize production in the NECP is subject to climate change[3-6]. Over the past 50 years, the climate in NECP was generally getting warmer and drier, with the precipitation amount decreasing and evaporation potential increasing in most regions[4,7]. Droughts occurred

frequently, which represent some of the most important meteorological disasters in the NECP[4,8,9]. For example, in 2000, 2007 and 2009, fields in the NECP that suffered from drought totaled 9.3, 11.6 and 9.4 million hm² and correspondingly resulted in grain yield reductions of 38.0%, 32.6%, and 22.2%, respectively[10]. Khan et al.[11] predicted extreme drought events in the future (2016-2099) and reported a long period of drought from 2060-2099 in the NECP. Therefore, accurate and timely identification of water stress for maize is important for choosing methods to reduce the impact of drought on crop growth and yield.

Maize is sensitive to water stress, especially given the high yield objective. Published literature has shown that water stress does greatly affect maize growth and yield. After a three-year experiment in Vojvodina in Northern Serbia, Kresović et al.[12] reported that the mean maize grain yield was reduced by 10%-30% with a 25%-100% irrigation water reduction compared to full irrigation. Wang et al.[13] reported after a pot experiment that maize evapotranspiration decreased by 40% and 53% and that dry biomasses decreased by 34% and 50% by controlling the soil water content at 60% and 40% of field capacity, respectively, compared to full irrigation. Compared to irrigated land, the maize yields in rain-fed land were reduced by more than 55% and suffered much greater year-to-year variability due to climate and precipitation variation[14-17]. Kerridge et al.[18] reported that precipitation is a limiting factor in achieving high yields in the Northeast region as well as most regions in China. They predicted a potential maize yield in a water-limited region as 10.7 t/hm², which is much lower than the yield of 14.2 t/hm² in water sufficient conditions. Therefore, evaluating and then reducing water stress is important

for maintaining a high maize yield.

Physiological indices, including canopy/stomata conductance, leaf potential, and canopy temperature are sensitive to water stress and therefore are used to evaluate the water stress status[19,20]. Among these indices, canopy temperature has been studied for crops, orchards trees and forests[21-23]. Han et al.[24-27] measured the temperature differences between the sunlit and shaded parts of a maize canopy to estimate the maize water stress. They found that the temperature differences increased as the leaf water potential decreased and soil water deficit increased, while the differences decreased when stomatal conductance increased. Based on canopy temperature, a crop water stress index, CWSI, was proposed to evaluate the water stress condition. To calculate CWSI, canopy temperatures in real conditions, non-water-stress conditions and conditions where transpiration has completely halted are required because canopy temperatures in the latter two conditions vary according to maize growth and climate condition[22,28-30]. Therefore, there is greater uncertainty when using the CWSI indices reported in a region to evaluate crop stress in another region. Hence a simple and robust temperature-based water stress index could be practical to help farmers to evaluate water stress status.

In this study, a two-year experiment was conducted in the NECP to investigate the responses of maize's physiological factors and evapotranspiration to water stress, and propose a simple and reliable indicator to evaluate the crop water stress status. The results of this study will help farmers and agricultural extension administrators to manage maize fields efficiently to achieve a high yield in the NECP.

2 Material and methods

2.1 Experimental site

A two-year experiment (the 2014 and 2015 seasons) was conducted at the Lishu Experimental Station at China Agricultural University (124°26′9″E, 43°16′47″N, 171 m above mean sea level), located in Siping City, Jilin Province, Northeast China. The Siping region is a typical maize cultivation region in Northeast China[31]. In 2014, the maize cultivation area accounted for 93.7% of the total farmland in the Siping region. The climate in this region is a typical sub-humid continental climate. The annual mean temperature is 6.5°C, the wind speed is 3.0 m/s, and the annual total sunshine hour is 2700 h. The mean annual rainfall is 631 mm, and more than 70% occurs from July to September. Recently, great climate variation has been observed in this region, including significant trends of temperature increases and radiation decreases[32]. This change may greatly affect maize production.

The soil texture is uniform over the root zone in the research region. In the 0-100 cm depth, the soil texture is a silty clay loam with 14.8% sand, 49.1% silt and 36.1% clay. The bulk densities in the 0-20 cm soil layer were measured as 1.41 g/cm³ and 1.53 g/cm³ in the 20-100 cm soil layer. The average saturated water content, field capacity (FC) and permanent wilting point (PWP) in the 0-100 cm depth were measured as 0.40-0.46 cm³/cm³, 0.35-0.36 cm³/cm³ and 0.07-0.09 cm³/cm³, respectively.

2.2 Experimental design

The experiment was conducted from May to September in the 2014 and 2015 maize growth periods. During each maize growth season, water stress treatments were set in the elongation stage (S1), heading stage (S2), and grain-filling stage (S3). Four water treatments were conducted depending on the soil water status and duration of the water stress days. The start point of water stress was set when the soil water content is lower than the 60% FC following the standards of "Grade of Agricultural Drought" and "Grades of Meteorological Drought"[33,34].

Treatment T1: irrigating plants when soil water content is just found at 60% FC. In this case, soil water is higher than 60% FC and sufficient, then maize plants don't suffer water stress[33,34]; The total irrigation events were 54 and 55 times in the 2014 and 2015 experimental seasons, respectively;

Treatment T2: irrigating plants 2-3 d after T1, then maintain full irrigation in the following growth periods;

Treatment T3: irrigating plants 2-3 d after T2, or 4-6 d after T1, then maintain full irrigation in the following growth periods;

Treatment T4: irrigating plants 2-3 d after T3, or after 6-8 d after T1, then maintain full irrigation in the following growth periods.

Three replications occurred for each treatment.

To precisely control the soil water and irrigation, the maize plants were cultivated in round buckets 50 cm in diameter and 60 cm in height. The soil in these buckets was taken from the 0-20 cm soil layer in the experimental station. It was firstly dried on ground under natural conditions, then screened through a 2 mm pore sieve and mixed to prepare a uniform soil texture for all plants, lastly filled into the buckets. The height from the soil surface to the upper rim of the bucket was approximately 10 cm. The soil bulk density in the bucket was 1.4 g/cm³, the saturated soil water content was 0.42 cm³/cm³, and the field capacity was 0.35 cm³/cm³, thus replicating the soil physical properties in the field. In both years, the maize variety Liangyu 11, a widely cultivated variety in this region, was used. Three maize seeds were planted in each bucket at a 3-4 cm depth on May 1 for both seasons. When the plant grew 2-3 leaves, only one plant was kept, and other plants were removed from each bucket.

When preparing the soil to fill the buckets, 12 g of compound fertilizer (N: P_2O_5: K_2O = 24%:13%:15%) was applied per bucket. This applied amount was based on local practice and was sufficient to support maize growth in a season. Therefore, there was no top-dressing fertilizer in either season. The soil in these buckets was covered with a plastic sheet to reduce soil evaporation through the growth season. On rainy days, a rain shelter was used to protect the bucket from the rain.

All plants were irrigated with a drip irrigation system. Two drippers with a drip discharge of 2.3 L/h with a pressure of 0.1 MPa were deployed in each bucket for irrigation application. From the sowing to elongation stage (around late June), all plants were fully irrigated for growth. Thereafter, the plants were irrigated following the experimental design. The controlled upper soil water content for irrigation was approximately 90% FC. Additionally, the irrigation amount for each treatment was calculated using the measured soil water content and the controlled upper limit soil water content. The real irrigation amount was measured with a water meter deployed in the main pipe of this drip irrigation system. The irrigation water was pumped from a well in the experimental station.

2.3 Measurements and calculation

2.3.1 Soil water

The soil water content was measured using the ECH₂O system (Decagon Devices, Inc., USA). Each ECH₂O system has three probes, separately installed at 10 cm, 20 cm and 40 cm depths in the soil. The mean data of these three probes were used as the soil water content in the measured bucket. In each measurement, 12 sets of ECH₂O systems were installed in 12 buckets, with one set in

a bucket. The soil water content was only measured for plants during the water stress period. For plants in T1, the soil water content was measured in all growth seasons.

2.3.2 Stomatal conductivity

Stomatal conductivity was measured at the second or third full-grown leaf from the top down at approximately 12:00 using a Leaf Porometer (Model SC-1, Decagon Devices, Inc., USA). On the measured leaf, three points which were 1/4, 2/4 and 3/4 in leaf length were selected for stomatal conductivity measurement. The mean value of the three measurements for the same leaf was used for data analysis. Stomatal conductivity was measured in each replicated plant during the set water stress period.

2.3.3 Canopy temperature

The canopy temperatures of the three replicated plants in each treatment were measured at approximately 12:00 using a Thermal Imager (Model Ti200, Fluke Corp., USA). Only the plant canopy area in the image was selected, and the mean canopy temperature was then calculated.

2.3.4 Crop evapotranspiration

Twelve electrical balances, three for each treatment, were prepared to measure the mass change of each bucket with maize plant. The mass change was used to calculate the plant evapotranspiration (ET) and irrigation amount. The rain amount was not considered because a rain shelter was used to prevent rain from falling into the buckets. The data were sampled at 15 min and stored in a data logger. These data were downloaded to a laptop computer for crop ET analysis.

2.3.5 Climate measurement

In the two experimental seasons (i.e., from May to September in 2014 and 2015), climate factors, including air temperature, relative humidity, solar radiation, and wind speed at a 2-m height above the ground surface, were measured at an automatic weather station (HOBO, Campbell Scientific Inc., USA) located approximately 50 m away from the experimental site. The data were sampled at 1-minute intervals and stored at 15-minute intervals and were then downloaded periodically to obtain the daily mean values.

2.3.6 Crop Water Stress Index

The crop water stress index (CWSI) was computed from the measured canopy temperatures and air temperatures using the following equation[26,27,35-37]:

$$\text{CWSI} = \frac{\Delta T_m - \Delta T_{LL}}{\Delta T_{UL} - \Delta T_{LL}} \tag{1}$$

where, ΔT_m is the difference between the measured canopy temperature (T_c, ℃) and air temperature (T_a, ℃), ℃; ΔT_{LL} is the lower limit difference between the canopy temperature and air temperature when plants grow in well-watered and non-water-stress conditions, ℃; and ΔT_{UL} is the upper limit difference between the canopy temperature and air temperature when plants suffer from severe water stress with transpiration reaching zero, ℃. In this study, the values of ΔT_{LL} was determined using data from T1 where maize was controlled under non-water stress condition, and ΔT_{UL} using the data measured in T4 where plant was always suffering great water stress condition, and results are shown in Figure 1. ΔT_{UL} varied from 3.54 ℃ to 6.25 ℃ with an average of 4.79 ℃, and ΔT_{LL} decreased linearly with VPD with a regressed line: $\Delta T_{LL} = -0.91VPD + 3.74$.

2.4 Statistical analysis

The measured data, including canopy temperature, stomatal conductivity and plant evapotranspiration were statistically analyzed using the IBM SPSS Statistics software package (version 20.0, IBM Corp., USA). The means' differences among treatments were tested using the least significant difference (LSD) at the 5% level. Excel 2013 (Version: Microsoft Office 2013, Microsoft Corp., USA) was used to prepare the figures.
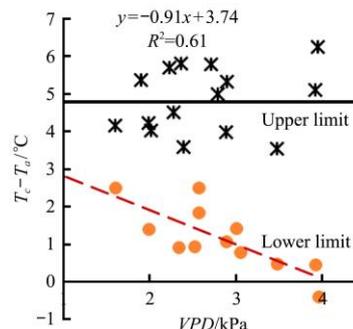
Note: Data in the upper line was achieved from T4 where maize suffered severe water stress, and data in the lower limit was from T1 where maize was grown under non-water stress conditions.

Figure 1   Relationships between measured temperature difference between canopy and air (T_c-T_a) and vapor pressure deficit (VPD) of maize from elongation to grain-milking stages in 2015 season

3   Results

3.1   Stomatal conductivity

Stomatal conductivity represents the opening condition of stomas. High stomatal conductivity means full opening stomas and high evapotranspiration and photosynthesis rates. Under water-sufficient conditions, stomatal conductivity varies with climate conditions and is especially controlled by radiation[38,39]. In the study region, stomatal conductivity increased from 6:00 to 12:00, after that point decreases gradually and reached approximately zero when radiation also reached zero at 18:00. Therefore, stomatal conductivity was measured at its maximum value, approximately 12:00 for each plant in this study.

Figure 2 shows stomatal conductivity changes at each treatment in the elongation stage and heading stage in the 2015 season. Generally, stomatal conductivity was significantly ($p<0.05$) lower when plants suffered from soil water stress and then increased to or reached its maximum values when the plant was re-irrigated. At times, stomatal conductivity after re-irrigation for extreme water stressed treatments (for example, T3 and T4) was greater than those for fully irrigated plants (for example, T1). This may be due to the plant's water compensation effect[40,41]. Yu[42] reported a significant compensatory elevation of stomatal conductance of the maize plants after water recovery in the mild and severe water stress conditions. The maize plants in the T4 treatment suffered from the greatest water stress with the longest non-irrigation period and consequently has the lowest stomatal conductivity before re-irrigation.

Water stress was the main reason for the stoma closing and the subsequent stomatal conductivity decrease. Therefore, the relationship between stomatal conductivity and soil water content was analyzed. In this analysis, only data on clear days were used because cloudy days may reduce solar radiation and thus stomatal conductivity. It can be seen in Figure 3 that in both seasons, stomatal conductivity generally increased with soil water content increases. Their relationship has three statuses based on soil water content. When the soil water content was greater than 0.22 cm³/cm³, stomatal conductivity was generally approximately 300 mmol/(m² s), indicating full growth and well-watered conditions. When the soil water content ranged from 0.15 to 0.22 cm³/cm³, stomatal conductivity varied greatly from 50 to

300 mmol/(m² s). When the soil water content was lower than 0.15 cm³/cm³, stomatal conductivity was generally smaller than 50 mmol/(m² s), indicating great water stress conditions. Han[19] reported stomatal conductance greater than 500 mmol/(m² s) under no water stress and less than 200 mmol/(m² s) under severe water stress conditions. Yu[42] reported a stomatal conductivity range of 250-300 mmol/(m² s) under water-sufficient conditions. The differences in stomatal conductance between this study and other studies may be due to plant species variation, climate conditions and the designated water stress category.
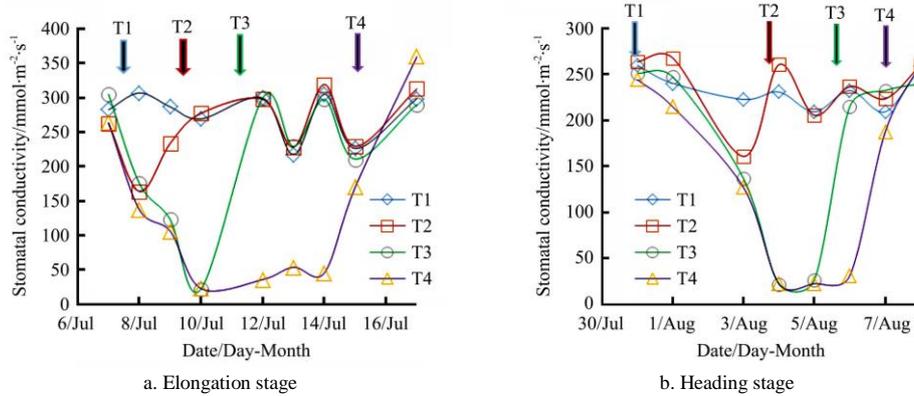

a. Elongation stage   b. Heading stage

Figure 2   Stomatal conductivities at the elongation and heading stages for each water stress treatment in the 2015 season, symbol ⬇ represents the re-watering day for the corresponding treatment
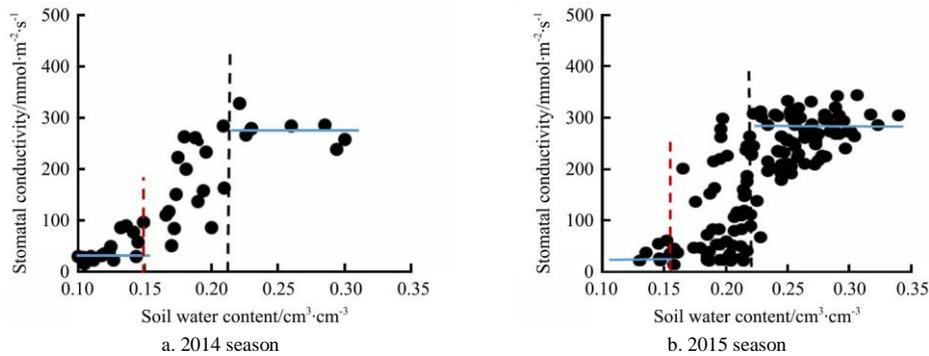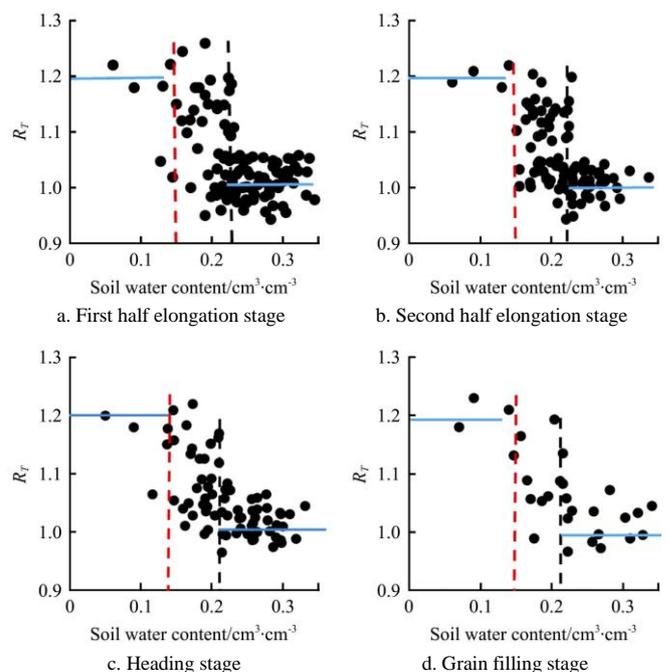

a. 2014 season   b. 2015 season

Figure 3   Relationship between stomatal conductivity measured at 12:00 and mean daily soil water content in the 2014 and 2015 seasons. Blue solid lines on the figures represent the mean values of the stomatal conductivity in the corresponding soil water content range

3.2 Canopy temperature

Canopy temperature is a sensitive factor used to evaluate crop water conditions[19,27]. Canopy temperature (T_c), the difference in canopy and air temperatures (ΔT_m) and the ratio of canopy to air temperatures (R_T) generally increased with the soil water content decreasing, indicating a greater increase in the degree of plant water stress. However, in the same soil water conditions, T_c and ΔT_m were lower on cloudy days than on sunny days, which means that the measured absolute values of T_c and ΔT_m are closely related to the environmental condition, especially air temperature. Therefore, R_T was used to eliminate the effects of the environment's effect on the canopy temperature. The results show that R_T is closely related to the soil water content.

Figure 4 shows the relationships between R_T and soil water content at the four growth periods in the 2015 season. The data in the 2014 season showed a similar result and is therefore not presented in the figures. Figure 4 shows that the responses of canopy temperatures to the soil water content in the four stages showed a similar relationship, and their relationships can be classified into three stages according to the soil water content. In the first stage, the soil water content was greater than 0.22 cm³/cm³ and the canopy temperature was close to the air temperature. This means that R_T is approximately 1.0 under well soil water condition, in which the maize is growing healthily. In the third stage, the soil water content was lower than 0.15 cm³/cm³, and R_T is approximately 1.2. On sunny days, the canopy temperature reached

a. First half elongation stage   b. Second half elongation stage

c. Heading stage   d. Grain filling stage

Note: Blue solid lines on the figures represent the mean values of the ratio of canopy to air temperatures in the corresponding soil water content range.

Figure 4   Relationship between ratio of canopy to air temperatures (R_T) and soil water contents in the four growth stages of maize in the 2015 season

35°C when the air temperature was approximately 30°C. This indicates the plants suffered from severe water stress and required a timely water application. Between the first and third stages is the second stage, in which the soil water content ranged from 0.15 to 0.22 cm³/cm³, and R_T mostly ranged from 1.0 to 1.2. The great variation of canopy temperatures in this soil water range may be due to the plants' adjustment in coping with water stress. When soil water continued to decrease and reached the third stage, the plants could lose their adjustment ability and demonstrated an extremely high canopy temperature.

3.3 Crop evapotranspiration

In Figure 5, the relative evapotranspiration, the ratio of daily evapotranspiration of each treatment to the T1 treatment — referred to as R_{ET} hereafter — was used to eliminate the impact of climate on crop *ET*. It was found that plants during

non-irrigation periods had very low crop *ET*. However, after re-irrigation, crop ET in the T2 and T3 treatments increased quickly and reached the values in T1 treatment. It should be noted that although plants in the T4 treatment were irrigated, their ET was still lower by 20%-30% compared to those at T1. This ET pattern is different from the stomatal conductivity response in Figure 3, where stomatal conductivity increased to values reflecting water sufficient conditions. The reason is that after a long period of water stress, a few leaves near the ground surface became withered; therefore, actual transpiration in the leaf area was reduced and ultimately resulted in a small crop ET for the whole plant. Therefore, a short period of water stress may have a slight effect on maize plant *ET*, while a long period of water stress may negatively impact maize plant growth and evapotranspiration.

a. First half elongation stage

b. Second half elongation stage

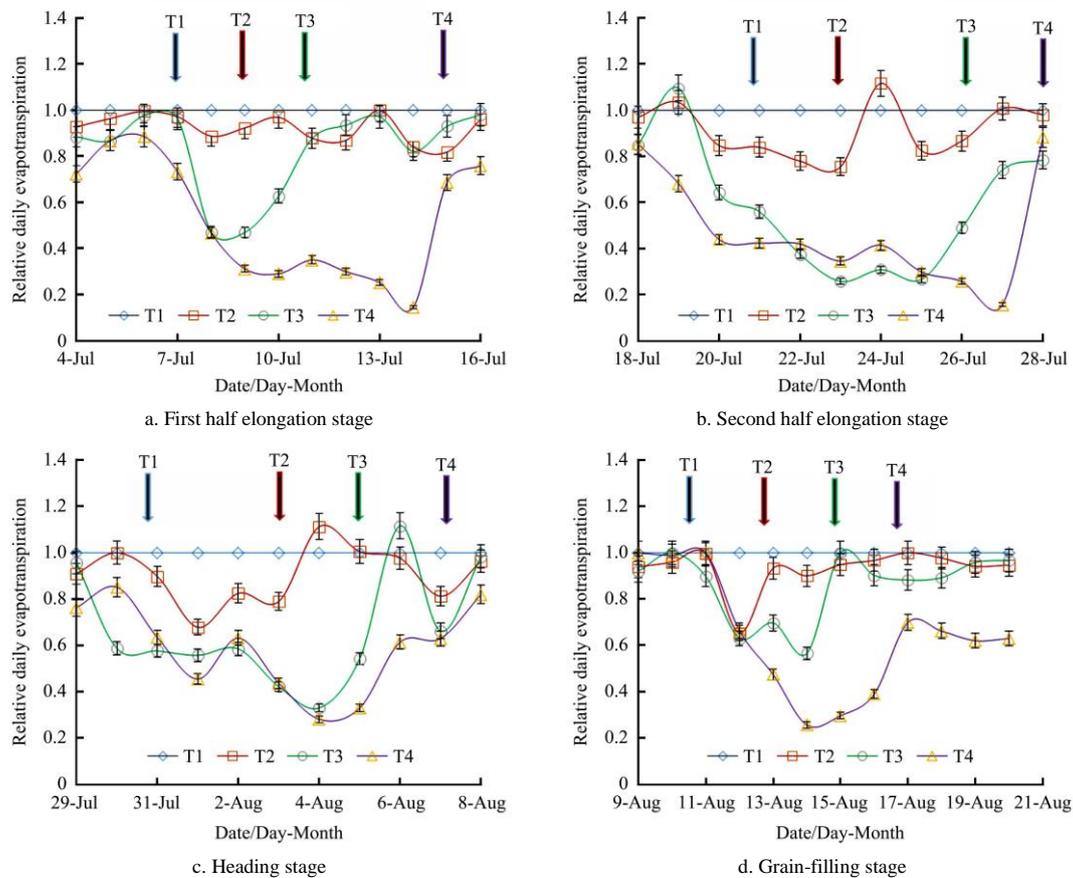c. Heading stage

d. Grain-filling stage

Figure 5   Relative daily evapotranspiration (the ratio of daily evapotranspiration of maize plants for each treatment to T1 treatment) in the four experimental periods in the 2015 season, symbol ⬇ represents the re-watering day for the corresponding treatment

Soil water was the only water resource for crop evapotranspiration in this experiment. Therefore, the relationship between crop R_{ET} and soil water content was analyzed, as shown in Figure 6. Generally, crop R_{ET} decreased with a decrease in soil water content, but their relationships varied among different soil water ranges. When the soil water content was greater than 0.20 cm³/cm³, the maize R_{ET} mostly ranged within 0.9-1.0 with a mean value of 0.92, indicating that water content in this range may have a slight effect on maize *ET*. When the soil water content ranged from 0.10 to 0.20 cm³/cm³, crop R_{ET} decreased with a decrease in the soil water content. When the two-year data were pooled together, the relationship between R_{ET} and soil water content was regressed as $R_{ET}=6.23SWC-0.32$ ($n=209$, $R^2=0.58$, $F<0.001$). When the soil water content was less than 0.10 cm³/cm³, the crop R_{ET} was reduced to approximately 0.1. This
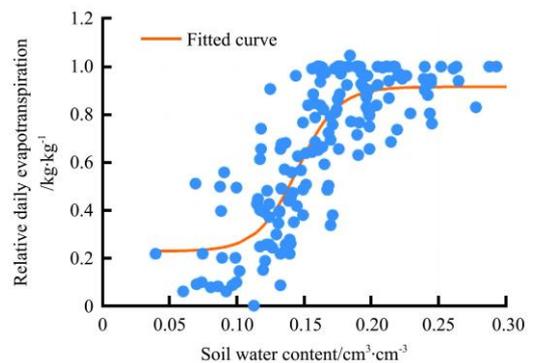

Figure 6   Relationship between soil water content and relative daily evapotranspiration when all data in the 2014 and 2015 seasons were pooled together. The regressed curves were fitted for sigmoid model

means that plant suffered greatly from severe water stress and its growth system was largely destroyed. We observed that only 2-3 active leaves remained and that the other leaves withered in the T4 treatment at the end of the experimental period at the grain-filling stage in 2015.

4 Discussion

4.1 Stomatal conductivity and canopy temperature

High canopy temperature under water stress is mainly due to part of the stoma closing. Therefore, the relationship between stomatal conductivity and R_T was analyzed, seeing Figure 7. It can be seen that stomatal conductivity was negatively related to R_T and that stomatal conductivity linearly decreased as R_T increased. The slope rates of the regressed lines between stomatal conductivity and R_T are close in the 2014 and 2015 seasons. When all data were pooled together, the relationship can be regressed as $g_s=979R_T-1225$ ($R^2=0.61$, $F<0.001$), where g_s is the stomatal conductivity measured at approximately 12:00, mmol/(m^2 s), and R_T is the ratio of the canopy to air temperatures measured at approximately 12:00. Similar results were reported by Han[19] and Yu[42]. They reported that g_s decreased with T_c and ΔT increasing.
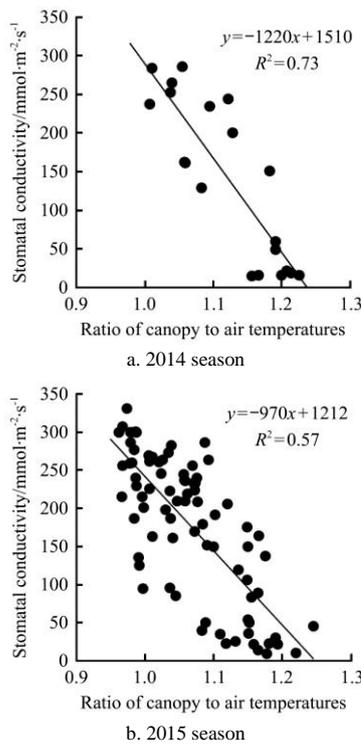

a. 2014 season

b. 2015 season

Figure 7   Relationship between stomatal conductivity to the ratio of canopy to air temperatures in the 2014 and 2015 seasons

The data in Figures 3 and 4 showed that when the soil water content was greater than 0.22 cm^3/cm^3, stomatal conductivity was approximately 300 mmol/(m^2 s) and R_T was approximately 1.0, while when the soil water content was lower than 0.15 cm^3/cm^3, stomatal conductivity was lower than 50 mmol/(m^2 s) and R_T was approximately 1.2. Similarly, in Figure 6, the crop ET begins to decrease when the soil water is lower than 0.2 cm^3/cm^3 and decreases by approximately 40% when the soil water is lower than 0.15 cm^3/cm^3. It is reported that the net photosynthesis rate of maize leave during the period from elongation to heading stage reached the maximum when soil water content is higher 60% FC, however, they decreased to approximately zero when soil water content reached 40% FC[43,44]. These findings are the same as the

results of this study. The findings are also in agreement with the data in the "Grades of Meteorological Drought" and "Grade of Agricultural Drought", in which 60% FC and 40% FC are the limits to identify the good water and severe water stress condition[33,34]. Therefore, the soil water content of 40% FC and 60% FC, correspondingly referring to the R_T values of 1.2 and 1.0, can be used to discriminate severe water stress and well-watered conditions, respectively.

4.2 Ratio of canopy to air temperatures and CWSI

The crop water stress index (CWSI) is widely used to evaluate crop water conditions[27,35]. In this study, the CWSI was calculated using the data measured in the heading and grain-filling stages in the 2014 and 2015 seasons in Equation (1). The lower limit temperature difference (ΔT_{LL}) represents the canopy temperature status under well-watered, non-stress conditions and generally relates to VPD[36]. The measured data in this study were used to develop the relationship between ΔT_{LL} and VPD, and the results are shown in Figure 1. The slope coefficient and interception of this regressed line were –0.913 and 3.74, respectively. The linear relationship between ΔT_{LL} and VPD for maize in Antalya of Turkey was $\Delta T_{LL}=1.39-0.86VPD$ by Irmak et al.[36], and $\Delta T_{LL}=2.14-1.97VPD$ in North Dakota of the USA by Steele et al.[45] and $\Delta T_{LL}=2.73-1.90VPD$ in Northeastern Colorado of the USA by Taghvaeian et al.[46] There are differences in intercept and slope coefficient among these researches, mainly because of the variation of climate, soil type, and plant variety[36].

The upper limit temperature difference (ΔT_{UL}) represents the temperature of a severely stressed, non-transpiration plant. In this study, the ΔT_{UL} value was taken from a maize plant in the T4 treatment, where the maize suffered from severe water stress and transpiration reached zero for stomatal conductivity, being lower than 50 mmol/(m^2 s). The measured ΔT_{UL} varied from 3.54 ℃ to 6.25 ℃ with a mean value of 4.79℃ (Figure 1). This ΔT_{UL} value is close to 4.38 ℃ reported by Taghvaeian[35] and 4.0 ℃-5.1 ℃ by Irmak et al.[36].

The CWSI and R_T at the heading and grain-filling stages in 2015 were compared and the results are presented in Figure 8. It can be seen that CWSI was linearly related to R_T. The determination coefficients (R^2) of the regressed line in Figure 8 is 0.914, indicating that R_T accounted for 91.4% of variation in CWSI. Therefore, R_T can be used to evaluate crop water stress as CWSI does.
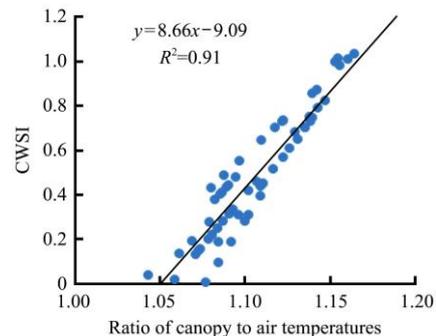

Figure 8   Relationship between crop water stress index (CWSI) and the ratio of canopy to air temperatures at the heading and grain-filling stages in 2015 season

CWSI ranges from 0 to 1, correspondingly representing non-water stress and severe water stress. Taghvaeian et al.[35] reported that for maize plants with full and high-frequency irrigation, the CWSI generally was lower than 0.3, while it was 0.3-0.7 under low-frequency irrigation conditions. Carroll et al.[27]

reported that the average CWSI values varied across irrigation treatments, with 0.37 and 0.54 for glasshouse well-watered and drought and 0.34, 0.47, and 0.51 for field well-watered, drought, and controlled deficit treatments, respectively. Möller et al.[29] reported a CWSI range of 0.4-0.6 for grapevine plants under moderate water stress conditions. These researches show that normally CWSI<0.3 can be used as indices of non-water stress conditions. When CWSI is 0.3, R_T is 1.08 from Figure 8, indicating a good water condition for maize growth based on Figures 3 and 4, in which R_T from 1.2 to 1.0 represent severely water-stressed and well-watered plants. R_T value of 1.08 is reaching 1.0, therefore, representing well-watered plants.

To calculate CWSI, the lower and upper limit temperature differences between the canopy and air are always estimated with empirically regressed curves using the vapor pressure deficit and air temperature[35,47-49]. These regressed curves may vary according to the climate, region and crops[35,48,49]. The indicator of R_T can reduce uncertainty from the parameters in these regressed models because all canopy and air temperatures are always directly and simultaneously measured. The consistency of the relationships among R_T, stomatal conductance, soil water content and CWSI (Figures 3, 4 and 7) also confirm that using the indices of R_T is an optional approach to evaluate maize water stress.

5   Conclusions

The main conclusions drawn from the two-year experiment were described as follows:

(1) The highest stomatal conductivity, approximately 300 mmol/(m^2 s), was measured under water sufficient conditions and decreased with the water stress duration. Soil water lower than 0.15 cm^3/cm^3 resulted in stomatal conductivity of less than 50 mmol/(m^2 s), indicating severe water stress condition.

(2) Canopy temperatures and the differences in the canopy and air temperatures increased with the soil water content decreasing but varied according to the environmental conditions. The ratio of the canopy to air temperatures was approximately 1.2 when the soil water content was lower than 0.15 cm^3/cm^3 and reached 1.0 under well-watered conditions. Therefore, the ratio value of 1.2 can be used to identify severe water conditions.

(3) Crop evapotranspiration was also decreased with soil water decreasing. ET after re-irrigation for severe water stress treatment further decreased by 20%-30% compared to T1. When the SWC is lower than 0.2 cm^3/cm^3, ET linearly decreased with SWC decreases.

(4) R_T is closely related to stomatal conductivity and soil water content, and especially linearly related to CWSI. Therefore, the indices of R_T are alternative to CWSI for evaluating maize water stress.

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