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Impact of soil conditions on the physiological characteristics of maize plants in an arid region, Northwest China

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ABSTRACT

Overuse of irrigation water to ensure the crop yield of maize plants has caused serious water shortage problems in the middle reach of Heihe River, China. Thus, further research on the physiological characteristics, *i.e.*, photosynthetic rate and leaf transpiration rate, are urgently needed to develop an efficient irrigation management system. In this paper, we selected two common soil textures (sandy loam, sand) and three one-time irrigation volumes (60 mm, 20 mm, 0 mm) in order to analyze the impact of soil conditions on the physiological characteristics of maize plants. Physiological and meteorological factors, soil water content and plant growing parameters were synchronously monitored on Jun. 30, Jul. 25 and Aug. 27 of 2012. The results indicate that sandy loam is better than sand for the growth of maize plants and single irrigation may provide limited influence on the physiological characteristics. Thus, increasing irrigation times and decreasing one-time volume is suggested for an efficient irrigation system.

Keywords: photosynthesis; leaf transpiration; water use efficiency; maize plant; soil water content

1 Introduction

Maize (*Zea mays* L.) is the main crop in the middle reach of Heihe River, China. According to the local Bureau of Seed Management, Zhangye City supplies maize seeds for more than 40% of maize planting areas of China (Yang and Chen, 2014). Due to limited precipitation, large amounts of groundwater or Heihe river water was required for farmland irrigation over the past few decades, leading to serious water shortage problems (Kang, 2004). In particular, environmental problems such as water and vegetation degradation, soil salinization, and desertification has occurred (Ji *et al*., 2005; Ren, 2005). Water shortages caused by agricultural development has become a key restriction factor in economic development in this region (Cheng, 2002). Thus, further research on photosynthetic characteristics, leaf transpiration rates, and water use efficiency of maize plants may benefit a reasonable planting scheme for water resources.

Photosynthesis is the most important physical process in plants (Xu *et al*., 1995), which greatly affects growth and crop yield (Hui *et al*., 2003). Photosynthetic rate is usually influenced by various environmental factors (Huang *et al*., 2008). Numerous studies have been conducted on these environmental factors. For instance, Meng *et al*. (2015) investigated the impact of CO_2 concentration and irrigation amount on photosynthetic characteristics. Yu *et al*. (2015) analyzed photosynthetic characteristics and water use efficiency of maize leaves during different growth stages. Zhang *et al*. (2015) discussed photosynthetic characteristics under different planting densities of maize plants.

Leaf transpiration is often measured by diffusion porometer (Katerji *et al*., 2003), steady-state porometer (Horwitz *et al*., 2008), Li-6400/Li-6400XT portable photosynthesis systems (Wullschleger *et al*., 2000; Peng *et al*., 2009) or CIRAS-2 portable photosynthesis (Uehlei *et al*., 2008). Leaf transpiration rate can be up-scaled to individual plants or canopy, important in providing a reasonable irrigation measure, especially in regions facing water shortages (Zhao L and Zhao W, 2015). In addition, leaf transpiration will not only be influenced by environmental factors but also by plant physiology (Tyree and Sperry, 1988).

Water use efficiency is a comprehensive index indicating the ratio between productivity and water consumed. Water use efficiency can be calculated by three different scales, *i.e*., leaf, colony and field, and leaf-level water use efficiency is the basis for analyzing the other two (Wang and Liu, 2000). Water use efficiency at the leaf scale refers to the ratio between photosynthetic rate and leaf transpiration rate, which has been widely researched for water-saving agriculture. Zhang *et al*. (2015) discussed the relationships between water-use efficiency and carbon isotope composition. The constraints on water use efficiency of maize grown in a semi-arid environment were extensively investigated by Tolk *et al*. (2016). The coupling effects of plastic film mulching and urea types on water use efficiency in the Loess Plateau of China were analyzed by Liu *et al*. (2016). The impact of saline water irrigation and adapting cultivars on water use efficiency of maize were respectively analyzed by Wang *et al*. (2016) and Bu *et al*. (2015). In addition, an optimal method to increase water use efficiency and maize productivity was put forward by adjusting plant density and plastic film mulch (Liu *et al*., 2014).

From the above analyses, though soil texture and soil water content may highly influence plant physiology (Xie and Su, 2011), little work has been done on the impact of soil conditions on photosynthetic characteristics, leaf transpiration rate, and water use efficiency. It is of great importance for selecting profitable planting area as well as for water resource saving.

In this paper, two common soil textures were selected in the middle stream of Heihe River. Different irrigation volumes were applied, while concrete tanks were built for avoiding lateral and downward water-percolation. The same variety of maize was planted in the concrete tanks. Factors such as plant physiological parameters, meteorological factors, and soil water content were monitored during three days on Jun. 30, Jul. 25 and Aug. 27, 2012. Based on the monitored data, the impact of soil conditions (soil texture and soil water content) on photosynthetic rate, leaf transpiration rate, and water use efficiency were analyzed.

2 Materials and methods

2.1 Location

Figure 1 shows the observation field (Linze Research Station of the Chinese Academy of Science), located in Zhangye City, Gansu Province, China. Maize plant is the main crop in the middle reaches of Heihe River, where the average annual air temperature is about 7.6 °C; average daily net radiation is less than 200 W/m^2; annual precipitation is about 117 mm. Other meteorological information can be referred in Ji *et al*. (2007) and Liu *et al*. (2011). Since the annual rainfall is very limited, large amounts of underground water are often consumed by irrigation.

2.2 Monitoring program

2.2.1 Soil conditions and concrete tanks

In order to investigate the impact of soil conditions on photosynthetic characteristics and water use efficiencies of maize plants, two common soil textures were selected. The soils were collected around the study area and filled within five concrete tanks, sandy loam within three tanks and sand within two tanks. Concrete walls and bottoms were built to prevent water and nutrition exchanges with the surrounding soils. The schematic diagram is presented in Figure 2. The soil properties, *i.e*., soil texture, organic content, some key chemical ionic contents, and cation exchange capacity, are summarized in Table 1. The soil textures are defined by the averaged sand/silt/clay contents according to Lal and Shukla (2004). Since more than 80% of the irrigation water are often consumed during the two growing stages, jointing-tasseling and tasseling-filling, three dates, Jun. 30, Jul. 25 and Aug. 27 of 2012, were selected during the two stages. Different irrigation volumes were applied in the five concrete tanks (see Table 1). Due to the relatively higher water retention capability of sandy loam than sand, three different volumes of irrigation were applied for the former soil while two different volumes for the latter one. The watering time was the day before the second monitoring date, *i.e*., Jul. 25, 2012. Other detailed information is described below.

2.2.2 Plant physiological and meteorological factors

A Li-6400XT portable photosynthesis system (Li-COR, Inc., USA) was adopted to measure plant physiological parameters (photosynthetic rate, and leaf transpiration rate) and meteorological factors (photosynthetically active radiation, relative air humidity, air temperature and CO_2 concentration). The physiological parameters were measured from 8:00 to 18:00 with 2-hour intervals during the three days. Four leaves from three maize plants for each concrete tank were repeatedly monitored.

2.2.3 Soil water contents and plant growing parameters

The soil water content up to 1 m was measured by the evaporation method. Three soil samples were taken by aluminum specimen cans at each depth for repeat measurements. Water was removed by a drying oven at a temperature of 105 °C. The mass water content was calculated by mass of wet and dry soils. More details about the procedure can be referred to in Lal and Shuka (2004). The measured data in the three days is illustrated in the following section. Some plant growing parameters were also measured on the same days, including plant height, leaf area, fresh weight, dry weight and mass water content of single maize plants. Measurements were in triplicates to reduce measuring errors. The measured data are summarized in Table 2. Deviations resulted from many influencing factors, *e.g.*, seed quality, sunlight and soil fertilizer.

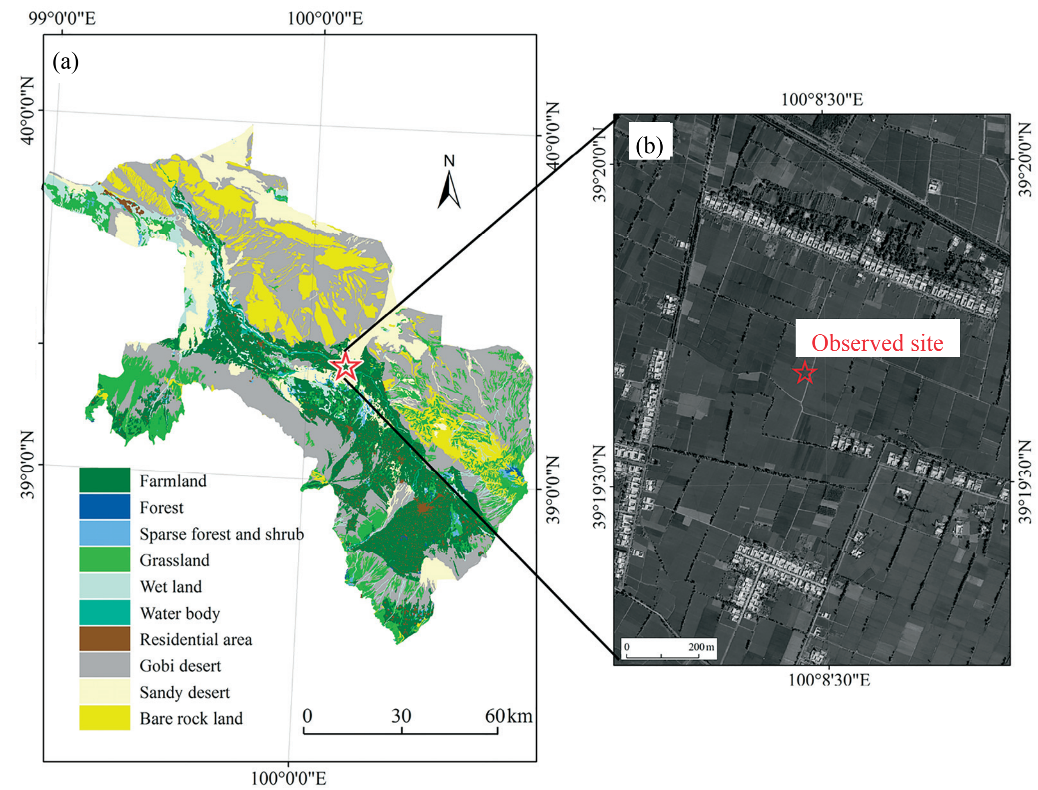

Figure 1 Location of the maize filed studied

2.2.4 Calculation method for water use efficiency

The leaf-level water use efficiency can be calculated by the ratio between photosynthetic rate and transpiration rate. The equation is shown in the following.

$$WUE = c \cdot \frac{P}{T} \qquad (1)$$

where WUE is the leaf-level water use efficiency (‰), P is the photosynthetic rate (μmol $CO_2/(m^2 \cdot s)$), T is the leaf transpiration rate (mmol $H_2O/(m^2 \cdot s)$) and c is a constant value for unit conversion, where the ratio between the molar masses of CO_2 and H_2O is 2.44.

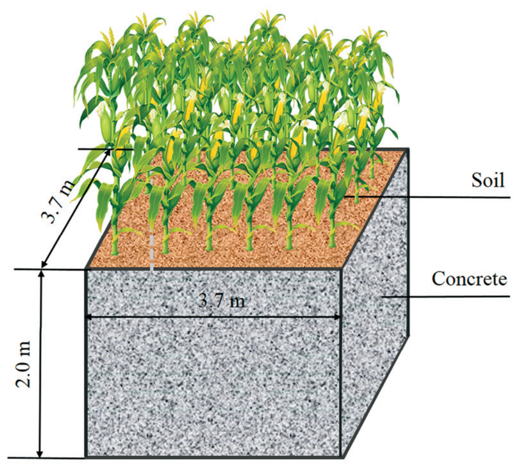

Figure 2 A schematic diagram of concrete tank with maize plants

Table 1 Five typical soil conditions

Soil texture	Irrigation (mm)	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	O (g/kg)	N (mg/kg)	P (mg/kg)	K (mg/kg)	CEC (cmol/kg)
Sandy loam	1#: 60	0–20	54.1	27.7	18.1	11.4	67.9	33.2	160	9.1
		20–40	50.6	27.6	21.6	8.8	62.0	15.6	150	7.8
		40–60	45.0	33.6	21.2	7.4	50.4	7.4	140	7.7
		60–80	76.4	11.5	12.0	–	–	–	–	–
		80–100	90.2	3.0	6.6	–	–	–	–	–
		Average	63.2	20.7	15.9					
	2#: 20	0–20	57.8	24.3	17.7	9.9	61.0	33.9	150	9.3
		20–40	55.4	26.2	18.3	8.1	48.7	9.5	130	7.6
		40–60	71.9	14.7	13.2	7.1	34.3	32.9	90	6.6
		60–80	85.1	5.5	9.4	–	–	–	–	–
		80–100	90.7	2.5	6.6	–	–	–	–	–
		Average	72.2	14.7	13.0					
	3#: 0	0–20	65.5	18.2	16.2	7.6	48.7	28.2	110	6.6
		20–40	76.6	11.4	11.8	5.7	36.3	30.9	100	5.2
		40–60	87.5	4.9	7.5	3.3	15.8	2.2	80	2.9
		60–80	91.8	2.3	5.8	–	–	–	–	–
		80–100	92.3	2.0	5.5	–	–	–	–	–
		Average	82.7	7.8	9.4					
Sand	4#: 20	0–20	83.0	7.3	9.5	5.0	29.2	33.5	100	4.8
		20–40	87.3	5.2	7.4	3.5	19.8	10.7	70	4.0
		40–60	89.7	3.7	6.4	2.4	17.1	3.7	60	3.4
		60–80	91.3	2.8	5.8	–	–	–	–	–
		80–100	91.6	2.6	5.7	–	–	–	–	–
		Average	88.6	4.3	7.0					
	5#: 0	0–20	80.1	8.9	10.9	5.8	31.8	39.8	90	5.3
		20–40	90.6	5.1	4.2	3.8	23.0	6.8	60	4.3
		40–60	91.6	2.4	5.9	1.7	17.2	2.0	60	3.3
		60–80	92.5	1.8	5.5	–	–	–	–	–
		80–100	91.9	2.2	5.7	–	–	–	–	–
		Average	89.3	4.1	6.4					

Table 2 Maize plant parameters

Date	Soil texture number	Plant height (m)	Leaf area (m^2)	Fresh weight (g)	Dry weight (g)	Mass water content (%)
Jun. 30	1#	2.03±0.19	0.66±0.04	836.48±143.32	112.30±13.82	86.4±0.7
	2#	2.07±0.14	0.62±0.06	653.03±31.03	79.98±7.21	87.7±1.0
	3#	1.95±0.13	0.55±0.04	581.89±82.98	77.69±13.34	86.6±0.4
	4#	1.94±0.08	0.63±0.03	691.79±119.81	95.35±16.44	86.2±0.0
	5#	2.00±0.16	0.57±0.08	580.14±124.80	81.10±20.82	86.0±1.2
Jul. 25	1#	2.13±0.19	0.68±0.08	1,193.20±96.45	252.10±45.77	78.9±3.8
	2#	2.23±0.17	0.69±0.02	1,134.71±70.21	295.08±72.11	73.9±6.1
	3#	2.21±0.04	0.62±0.02	969.53±200.61	206.45±66.56	78.9±2.4
	4#	2.22±0.07	0.64±0.05	1,118.03±178.85	298.64±72.06	72.9±6.7
	5#	2.24±0.11	0.66±0.04	1,059.92±152.64	291.20±105.94	72.9±5.1
Aug. 27	1#	2.25±0.04	0.62±0.09	945.43±96.36	318.32±19.24	66.1±2.0
	2#	2.47±0.05	0.52±0.06	920.95±262.81	303.26±101.79	67.1±2.9
	3#	2.25±0.13	0.42±0.04	782.80±229.47	221.12±64.21	71.2±9.1
	4#	2.29±0.10	0.71±0.20	923.18±215.33	280.30±70.74	69.8±2.7
	5#	2.40±0.06	0.44±0.15	948.90±150.41	356.24±62.01	62.3±3.8

3 Results

3.1 Plant physiological parameters

The monitored photosynthetic and leaf transpiration rates as well as calculated water use efficiencies are presented in Figure 3. The photosynthetic rate decreased from Jun. 30 to Aug. 27, which may be caused by the decrease of leaf physiological activity. The same variation trend was observed for the leaf transpiration rate. The lowest values of photosynthetic rate, leaf transpiration rate and water use efficiency occurred in the sand field with 20-mm irrigation (4# on Jun. 30, 2012), which may, to some extent, indicate that the sand field is unsuitable for maize production, compared with sandy loam. On Aug. 27, both photosynthetic rate and leaf transpiration rate were the highest in the sandy loam field. No obvious changes can be found in the water use efficiency.

3.2 Meteorological factors

Since the five concrete tanks were built very close together, the meteorological factors were averaged to show only one series in one day. Figure 4 illustrates the monitored data. It can be seen that small changes were observed for the meteorological factors within the three days. Air temperatures firstly increased to a maximum value of about 40 °C, and then decreased to a minimum value of about 25 °C. The same variation trend was observed for active radiation. The value of active radiation on Jun. 30 was obviously larger than that on Jul. 25 or Aug. 25. In contrast, both CO_2 concentration and relative humidity reached the minimum value at 14:00. In addition, relatively high values of CO_2 concentration were observed on Aug. 27.

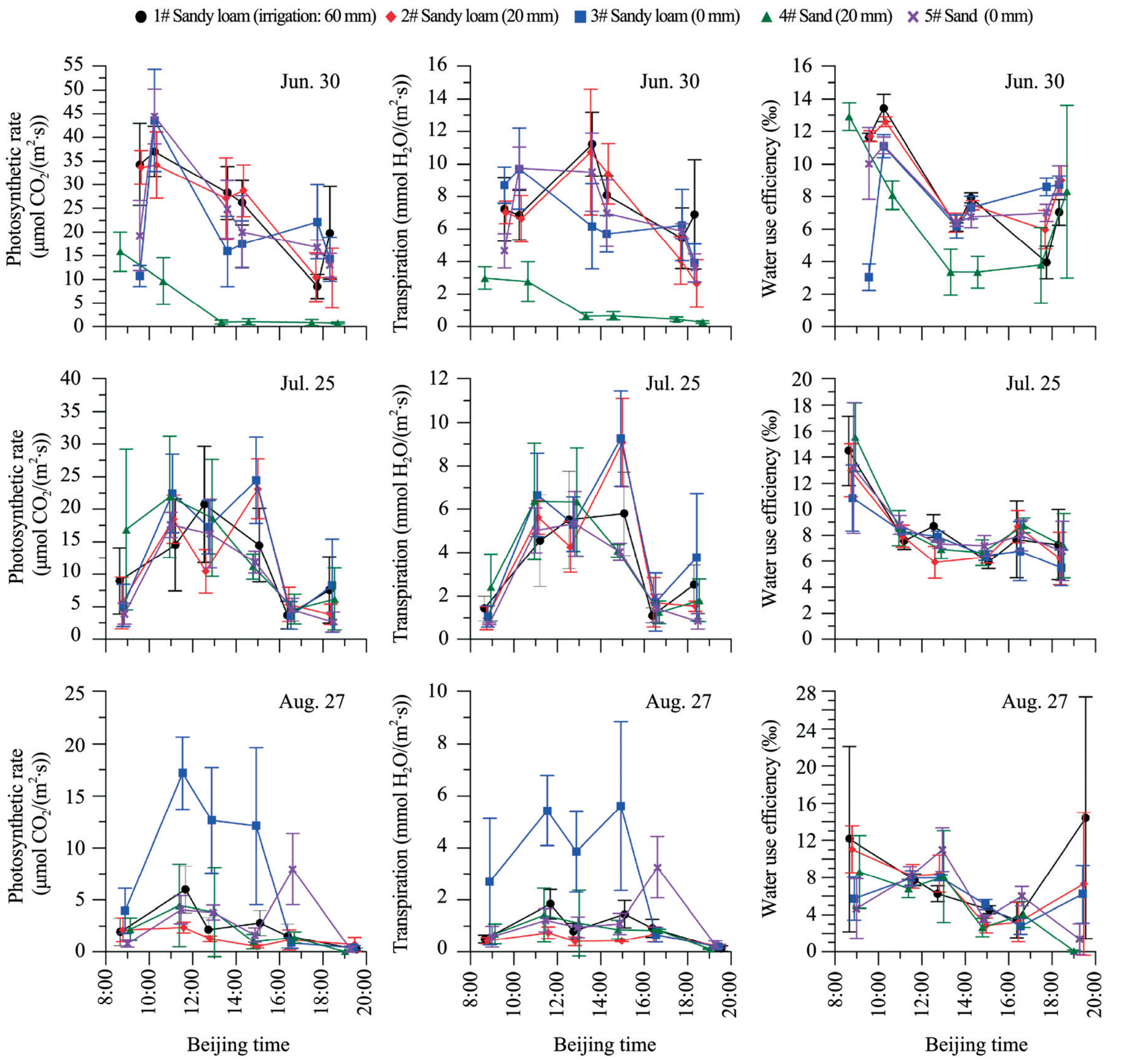

Figure 3 The average diurnal values of photosynthetic rate, stomatal conductance, and leaf transpiration of the maize plants in the five concrete tanks within the three days

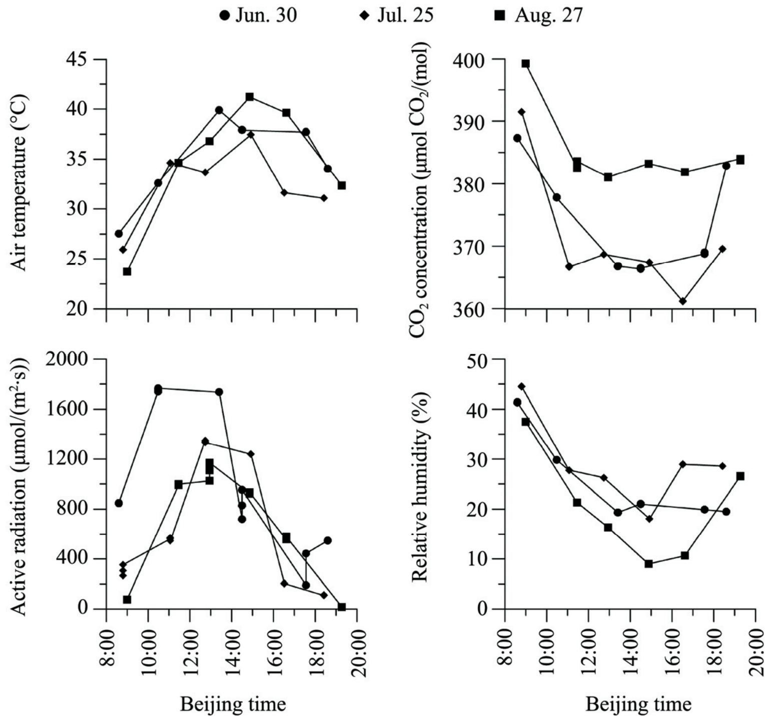

Figure 4 The average diurnal values of air temperature, CO_2 concentration, active radiation and relative humidity of the maize plants within the three days

3.3 Soil water contents

In order to analyze the influence of soil water content on plant physiological factors, different volumes of irrigation water were applied in the five concrete tanks, three volumes for sandy loam and two values for sand. The monitored soil water contents for the five soil textures are presented in Figure 5. For soils with irrigation water (1#, 2# and 4#), soil contents firstly increased and then decreased during the three days, since the irrigation waters were applied on Jul. 24. For soils without irrigation water (3# and 5#), soil water contents where nearly constant at different depths. The mass soil water contents were approximately 6% without irrigation, which were supposed to be lower than the wilting points (Zhao L and Zhao W, 2014).

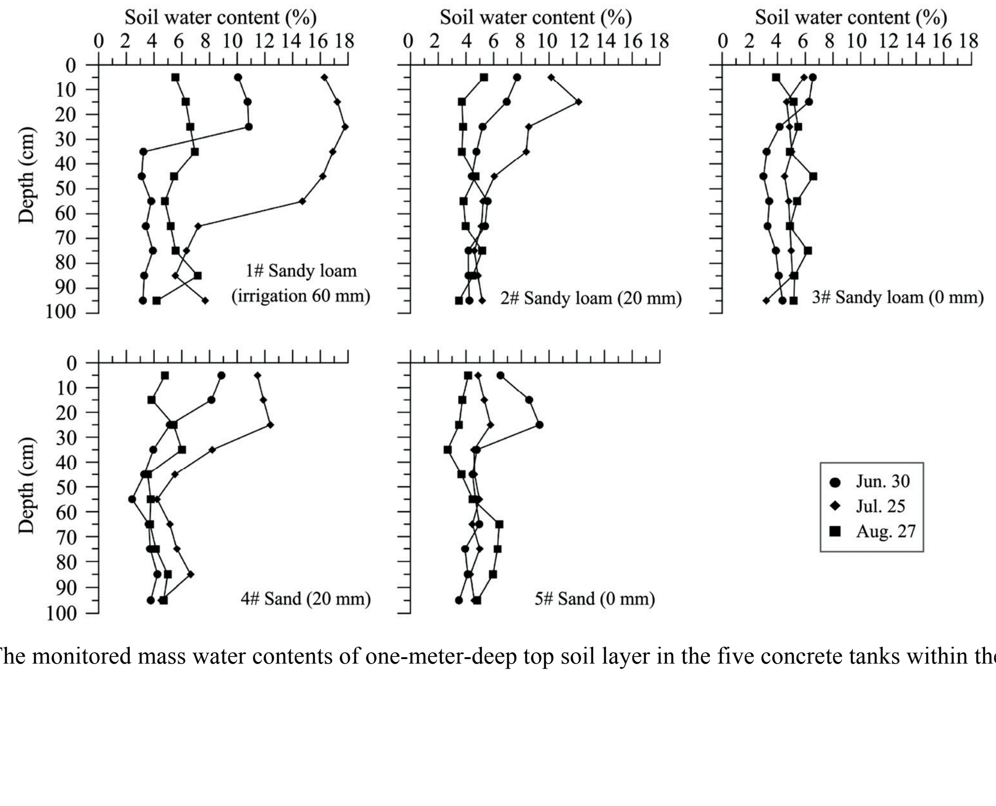

Figure 5 The monitored mass water contents of one-meter-deep top soil layer in the five concrete tanks within the three days

4 Discussion

Figure 6 illustrates the average values of photosynthetic rates, leaf transpiration rates, water use efficiencies and mass soil water contents. It can be seen that soil water content was almost the same for soils on Jun. 30 and Aug. 27, and then the water content differed on Jul. 25 due to different irrigation volumes. Finally, the soil water contents returned to the original levels on Aug. 27. Thus, in the following, the impact of soil texture on photosynthetic rate, leaf transpiration rate and water use efficiency will be discussed based on Jun. 30 and Aug. 27 data, while the impact of soil water content will be discussed based on Jul. 25 data.

4.1 The impact of soil texture

It can be seen from Figure 6 that both photosynthetic rate and leaf transpiration rate decreased from Jun. 30 to Aug. 27, probably caused by recession of the maize plants. On Jun. 30, the average photosynthetic rate and leaf transpiration rate for sandy loam (1#–3#) were nearly twice of that for sand (4# and 5#). On the other hand, the differences of soil water content and plant parameters were rather small on that day (Table 2 and Figure 5). This may, to some extent, indicate that sandy loam is a better soil than sand for maize production. The possible reason was that the ability in water and nutrition retention of sand texture was relatively weak. As presented in Table 1, available Nitrogen and Phosphorus in sand (4# and 5#) were lower than those in sandy loam (1#–3#). On Aug. 27, both photosynthetic rate and leaf transpiration rate of maize plants in concrete tank 3# were larger than those in the others. This may be caused by the delay of recession of the maize plants in concrete tank 3#, since the average water content of the maize plants was the highest (Table 2). As for water use efficiency, the lowest value in concrete tank 3# on Jun. 30 may be associated with the smallest leaf area (Table 2).

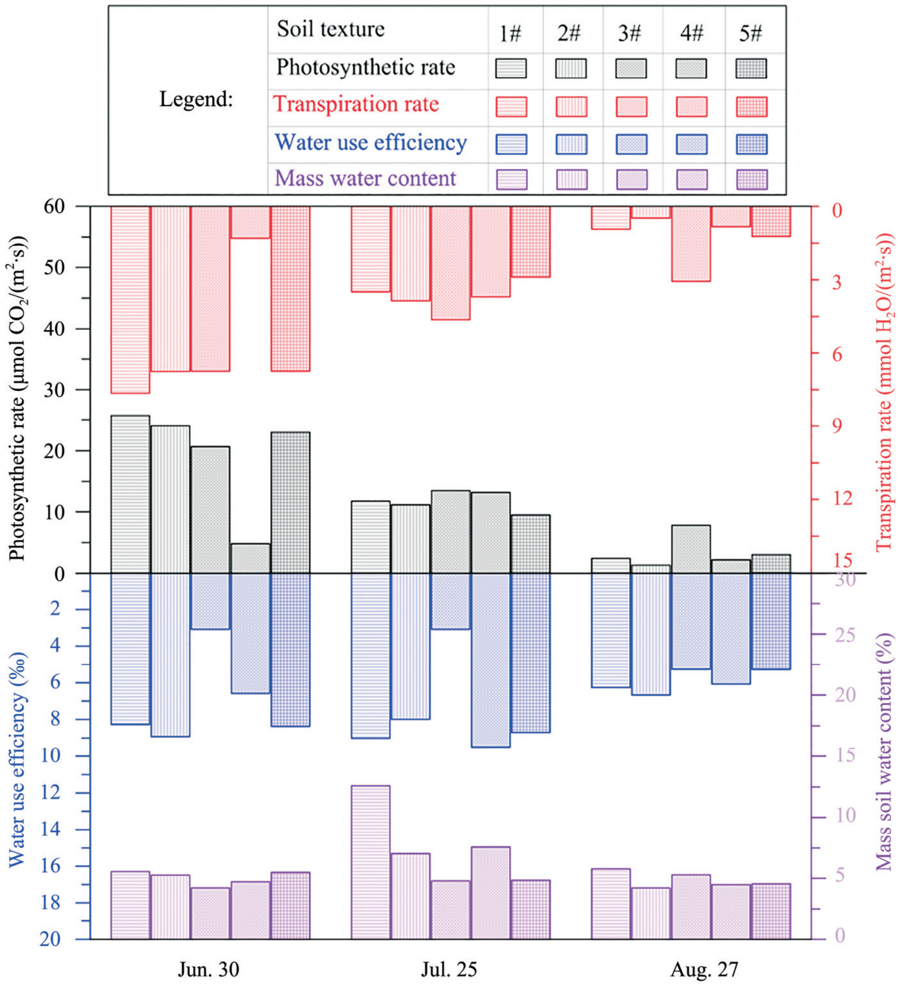

Figure 6 Photosynthetic rates, leaf transpiration rates, water use efficiencies and mass soil water contents for the five soils in the three days

4.2 The impact of water content

As presented in Figure 6, soil water content in concrete tanks 1#, 2# and 4# on Jul. 25 increased by different irrigation volumes (Table 1). The average soil water content in the concrete tanks was 12.5% in 1#, 7.0% in 2#, 7.5% in 4#, 4.8% in 3#, and 4.9% in 5#. Although the soil water contents were different, the monitored photosynthetic rate and leaf transpiration rate were almost the same. It seems that photosynthetic rate and leaf transpiration rate does not increase in the short term after irrigation. In other words, single irrigation may be insufficient, and thus a frequent irrigation measure with relatively low one-time volume may be required to increase the photosynthetic and leaf transpiration rate, and consequently the crop yield. In addition, the smallest leaf area (Table 2) may be the reason of the lowest water use efficiency in concrete tank 3# on Jul. 25, showing similar characteristics on Jun. 30. This may indicate that single irrigation would not increase water use efficiency.

5 Summary

In order to analyze the impact of soil conditions on the physiological characteristics of maize plants, a comprehensive monitoring program was initiated in the middle reach of Heihe River, China in 2012. The observations included photosynthetic rate, leaf transpiration rate, soil water content, plant growing parameters, and meteorological factors. Based on monitored data, leaf-level water use efficiency was calculated. Two common soils and three different irrigation volumes were designed.

The soil water content before irrigation and plant growing parameters were very similar for maize plants growing in the two soils, however both the photosynthetic and leaf transpiration rates in concrete tanks 4# and 5# were much lower than the other three. This indicates that sand is worse than sandy loam for maize production, since sand texture provided relatively weak ability in water and nutrition retention. After single irrigation, soil water content increased to about three times the soils without irrigation, however both photosynthetic rate and leaf transpiration rate did not increase in the short term after irrigation. This indicates a frequent irrigation measure with relatively low one-time volume is required. As for the water use efficiency, the leaf area may be the priority to be considered.

These results may be considered preliminary, since we monitored only three days. Physiological characteristics of maize plants can be influenced by various factors, not just soil conditions. Thus, long-term monitoring programs, taking more influencing factors into consideration, should be initiated to further reveal the physiological characteristics of maize plants. This would provide a good reference for the development of an efficient irrigation management plan.

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