Agricultural Water Management 195 (2018) 71–83

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Research Paper

Deficit irrigation provokes more pronounced responses of maize photosynthesis and water productivity to elevated CO_2

Xiaojie Li[a], Shaozhong Kang[a,*], Xiaotao Zhang[a], Fusheng Li[b], Hongna Lu[a]

[a] Center for Agricultural Water Research in China, China Agricultural University, Beijing 100083, China
[b] College of Agriculture, Guangxi University, Nanning, Guangxi 530005, China

ARTICLE INFO

Article history:
Received 1 June 2017
Received in revised form
26 September 2017
Accepted 27 September 2017
Available online 12 October 2017

Keywords:
CO_2 concentration
Deficit irrigation
Photosynthesis
Growth
Yield
Water productivity

ABSTRACT

It is very significant to study the impact of deficit irrigation on crop growth and water use under the future scenarios with elevated CO_2 concentrations and reduced water availability. This study investigated the growth and yield differences of maize grown in a phytotron in response to elevated CO_2 concentrations under different irrigation treatments. Two irrigation treatments were carried out: regular irrigation (RI) and deficit irrigation (DI), in which the irrigation amounts were respectively 100 and 70% of evapotranspiration (*ET*), with four CO_2 concentrations (400, 550, 700, and 900 μmol mol^{-1}). Thus eight treatments, i.e. RI_{400}, RI_{550}, RI_{700}, RI_{900}, DI_{400}, DI_{550}, DI_{700}, and DI_{900} were included in this study. Results show that, the relative reductions of stomatal conductance (g_s) and transpiration rate (T_r) in response to elevated CO_2 concentrations were higher under DI than RI, thus causing leaf temperature (T_{leaf}) rose higher under DI due to the transpiration cooling effect. As photosynthetic rate (P_n) and its physiological process were positively correlated with T_{leaf}, the relative increases of P_n and the resulting maximum leaf area index (LAI_{max}), total dry matter weight (*TDW*), and grain yield (*GY*) react to elevated CO_2 concentrations were higher under DI than RI, as well as the leaf water use efficiency (WUE_L) and water productivity (*WP*). The DI_{900} treatment in which the irrigation amount was reduced by 30% only decreased the *TDW* and *GY* by 7 and 5% when compared with RI_{900}. The variation of *GY* was consistent with the variation of kernels per ear (*KPE*), but was not directly related to hundred-grain weight (*HGW*). The above results show that when atmospheric CO_2 concentrations rise in the future, deficit irrigation would be an effective way of saving water and would not only have a mitigating effect on water crises, but would also contribute to improving *WP*, which is more important in terms of actual production.

1. Introduction

It is estimated that, by the end of the 21st century, atmospheric CO_2 concentration will have reached 936 μmol mol^{-1} if we do not take measures to reduce emissions (IPCC, 2013). There have been researches about elevated CO_2 concentration effects on crops and vegetables since 1970s (Gifford, 1977, 1979; Ludlow and Wilson, 1971). The experimental equipment was mainly including enclosed chambers (Kang et al., 1996), open-top chambers (Meng et al., 2014), and free-air CO_2 enrichment technology (Leakey et al., 2006). The elevation of atmospheric CO_2 concentration would have a significant impact on crop growth (Oliver et al., 2009), because it increases net photosynthetic rate (P_n), which would likely increase plant height (*H*), leaf area index (*LAI*), total dry weight (*TDW*), and grain yield (*GY*) (Ainsworth and Rogers, 2007; Kang et al., 1996; Meng et al., 2014). It would also reduce stomatal conductance (g_s), leading to a smaller than proportional decrease in transpiration rate (T_r) and total evapotranspiration (*ET*) (Allen et al., 2003; Bernacchi et al., 2007; Bunce, 2004; Vanuytrecht et al., 2012). This would ultimately mean that there would be a significant increase in the importance of water productivity (*WP*) (Idso et al., 1987; Kang et al., 2002; Li et al., 2003; Vanuytrecht et al., 2012).

Together with CO_2 concentration, the controlled variables also covered water (Kang et al., 2002), nitrogen (Li et al., 2003), temperature (Cai et al., 2016), ozone (Ainsworth, 2008), transplanting density (Lai et al., 2014), etc., among which water stress was the top factor that considered. A number of current studies have emphasized the effects of the interaction of elevated CO_2 concentration

---

[*] Corresponding author.
E-mail address: kangsz@cau.edu.cn (S. Kang).

https://doi.org/10.1016/j.agwat.2017.09.017
0378-3774/

and water stress on crop growth, water consumption, and yield (Islam et al., 2012; Qiao et al., 2010; Saadi et al., 2015; Samarakoon and Gifford, 1996; Wall et al., 2011). The data of P_n, *GY*, irrigation amounts, and *WUE* in these references showed that elevated CO_2 concentration benefit crops more under drought conditions than well-watered conditions. A number of previous studies have also shown that elevated CO_2 concentration only affect photosynthesis and grain yield of maize, a C_4 crop, under drought conditions (Kim et al., 2007; Kimball, 2016; Leakey et al., 2006; Manderscheid et al., 2014; Rogers et al., 1983), while several other CO_2 enrichment studies with maize grown under controlled environment conditions showed an increase of C_4 photosynthesis and biomass production under sufficient water supply (Driscoll et al., 2006; Kang et al., 2002; King and Greer, 1986; Loomis and Lafitte, 1987; Morison and Gifford, 1984; Ziska and Bunce, 1997). The different results among these literatures may be due to the experimental equipments and some other experimental conditions that need further investigation.

The elevated CO_2 concentration will result in the intensity and frequency of climate extremes such as heat waves, heavy precipitation, and drought (Oliver et al., 2009), and the availability of water will rapidly decrease (IPCC, 2014). Water shortage is already a serious problem in Northwest China (Kang et al., 2002; Wang et al., 2012), and water availability will almost certainly decrease even further under climate change (IPCC, 2007; Zhao et al., 2010), posing a huge challenge for food security in the region (Kang et al., 2017). So applying water-saving irrigation method (e.g. deficit irrigation, or insufficient water supply) into that region is in urgent need in the future.

Deficit irrigation (DI) is an effective water-saving method by which to reduce water consumption used in irrigation while maintaining yield levels acceptable (Dorjia et al., 2005; Geerts and Raes, 2009; Kang et al., 2017). Although DI may reduce crop yield and total dry weight (Badr et al., 2012; Dorjia et al., 2005; Geerts and Raes, 2009; Rop et al., 2016), it also improves economic yield and fruit quality (Cantore et al., 2016; Dorjia et al., 2005), saves water, and increases *WUE* and *WP* (Badr et al., 2012; Geerts and Raes, 2009; Mitchell et al., 1991; Rop et al., 2016).

The local regular irrigation method (i.e. sufficient irrigation with 100% demand of evapotranspiration) may lead to some drought before re-irrigation. According to the above literatures it may benefit crops to some extent with elevated CO_2 concentrations in the future. But how about the deficit irrigation? The interactive impacts of elevated CO_2 concentrations (such as the projected concentration of 900 μmol mol^{-1} under RCP 8.5 by the end of this century (IPCC, 2013)) and deficit irrigation on growth and yield of C_4 plants like maize are not yet completely unraveled and deserve further investigation. Despite there are many researches about the interactive effects of CO_2 concentration and water stress on crops, there is still a lack of experimental studies addressing the response of crops to elevated CO_2 concentrations and irrigation methods. Whether deficit irrigation still makes positive effect along with elevated CO_2 concentration or not is needed to contribute to an in-depth understanding of the changing environment and therefore of great significance in arid and semi-arid areas (Aljazairi et al., 2015; Vu and Allen, 2009).

A commonly used cultivar of maize (*Zea mays* L. cultivar Qiangsheng 51) in Northwest China has been planted for this study. Two irrigation treatments and four CO_2 concentrations have been designed in order to analyze the effects of elevated CO_2 concentrations on stomatal response, growth characteristics, yield, evapotranspiration, water use efficiency, and water productivity under regular and deficit irrigation. Our objective is to explore whether the deficit irrigation method would save water and at the same time benefit maize more than regular irrigation, thus providing a fundamental research and a reference point for irrigation management decision in agriculture in semi-arid areas under elevated CO_2 concentrations in the future.

2. Materials and methods

2.1. Experimental conditions

The experiment was conducted from May to September 2015, in the climate phytotron at Shiyanghe Experimental Station of China Agricultural University, located in Wuwei City, Gansu Province in Northwest China (N 37°52′, E 102°50′, altitude 1581 m) (Fig. 1). The climate phytotron consisted of four separate chambers of 3-m length by 4-m width by 2.5-m height, and was supplied with natural light. Each chamber had the same indoor equipments. The different parameters set in the phytotron, and their range of variation, are shown in Table 1. Air temperature, relative humidity, and CO_2 concentration were set automatically through a digital program timer at different time periods in a closed control cabinet (Fig. 2a). Indoor temperature was controlled by an electric heating (warming) and a compressor (cooling); relative humidity was adjusted by an ultrasonic humidifier (humidifying) and a heat transfer valve (dehumidifying); both were controlled within the accuracy range (Table 1). A CO_2 sensor was used to measure indoor CO_2 concentration, and CO_2 gas was provided by a CO_2 gas cylinder, through a pipe (Fig. 2a). When the CO_2 concentration target was set, a control system automatically calculated aeration time according to the flow rate of the CO_2 gas cylinder and the difference between the target and current CO_2 concentrations. With the consumption of CO_2 in the chamber, the above control method was repeated to maintain the target CO_2 level. Fresh air was inhaled from outside the chamber by a blower, evenly distributed throughout the chamber, from the bottom, and then extracted through the upper wall to circulate the air. The indoor wind speed was less than 0.5 m s^{-1}.

2.2. Experimental design

The maize (*Zea mays* L. cultivar Qiangsheng 51) used in the experiment was planted in plastic pots of 26.5 cm height, 21 cm and 33 cm bottom and top diameter, respectively. Three seeds were sown in each plastic pot initially and one seedling retained after emergence. The experiment was conducted in climatic chambers during the whole growth period from the date of sowing (May 7) to harvest (September 16). The pots were filled with local sandy loam soil after being air-dried, crushed, and sieved. Each pot had 18 kg of soil with a dry bulk density of 1.38 g cm^{-3} and a field water capacity of 0.27 cm^3 cm^{-3}. Little stones were spread over the bottom of each pot with fine sand acting as a filtration layer. The surface of the soil was then covered with fine sand and nutritive soil to reduce the impact of irrigation on the topsoil structure. The same fertilization scheme was applied in each pot, which was 1.5 g urea and 1.5 g diammonium phosphate, on May 29, June 19, July 10, July 29, and August 27. In addition, a foliar spray of 250 ml potassium dihydrogen phosphate solution was used at a concentration of 2% on May 29, June 19, July 20, and August 5.

Experimental meteorological conditions were set according to the 10-day averages of observed meteorological data from May to September of the previous six years at the experimental station; their adjustment frequencies are shown in Table 1. Natural light was utilized. The experiment consisted of two irrigation treatments, namely, regular irrigation (RI, which was similar to the local water management) and deficit irrigation (DI) in which the irrigation amounts were 100 and 70% of evapotranspiration (*ET*), and four CO_2 concentrations of 400 (current atmospheric CO_2 concentration), 550, 700, and 900 μmol mol^{-1}. Both regular and deficit irrigation were carried out at the same time and with the same fre-

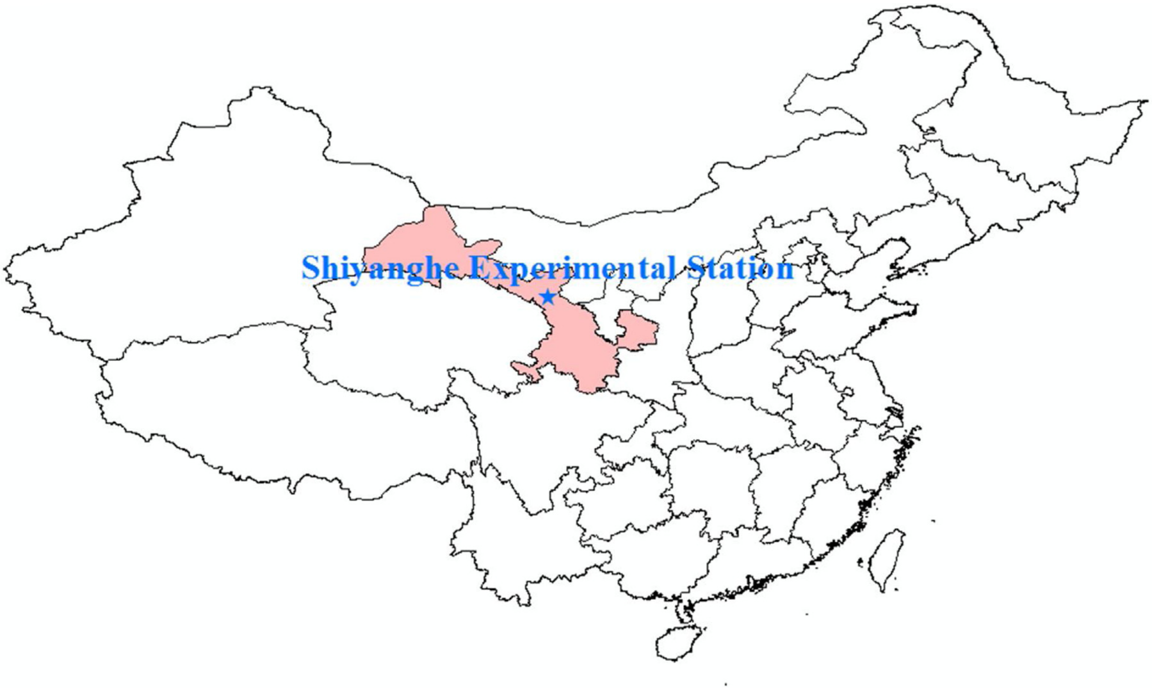


Fig. 1. Map with Shiyanghe Experimental Station in China (The map shows only China's land area).

Table 1
The different parameters set in the phytotron, their range of variation and accuracy, and frequency of adjustment.

Parameters (unit)	Range of variation ± accuracy	Frequency of adjustment
Temperature (°C)	–5 ~ 40 ± 0.1	every 2 h from 8:00 to 20:00 each day; changed every 10 days
Relative humidity (%)	30 ~ 95 ± 5	the same as temperature
CO_2 concentration (μmol mol^{-1})	400 ~ 2000 ± 50	consistent from 8:00 to 20:00 each day in each chamber

Table 2
Irrigation water amounts for each growth stage of maize under different CO_2 concentrations and irrigation treatments. RI denotes regular irrigation, and DI denotes deficit irrigation.

CO_2 (μmol mol^{-1})	Irrigation regime	Irrigation amount (mm)					
		Seeding stage	Jointing stage	Heading stage	Filling stage	Maturity stage	Entire growing season
		5.7–6.25	6.26–7.18	7.19–8.7	8.8–8.26	8.27–9.16	5.7–9.16
400	RI	60	102	147	112	107	528
	DI	60	72	103	78	75	388
550	RI	60	86	124	91	94	455
	DI	60	60	87	64	66	337
700	RI	60	79	129	86	91	445
	DI	60	55	90	61	64	330
900	RI	60	85	130	98	91	464
	DI	60	60	91	69	64	344

quency in the four chambers. The crops and the corresponding CO_2 concentrations were interchanged once randomly within the four chambers in the later half maize period. There were eight treatments altogether: RI_{400}, RI_{550}, RI_{700}, RI_{900}, DI_{400}, DI_{550}, DI_{700}, and DI_{900}. Each treatment had six pot replicates placed in a row (Fig. 2b) and the two rows were switched position after each weighing. To ensure the regular emergence and growth of maize, there was no water deficit during the seedling stage, after which the deficit treatment was implemented. The experimental pots were weighed every three to four days by high precision weighing scales for the basis of the irrigation amount, and measuring cylinders were used for measuring the irrigation water manually. The irrigation amount of each growth stage is shown in Table 2.

2.3. Measurements

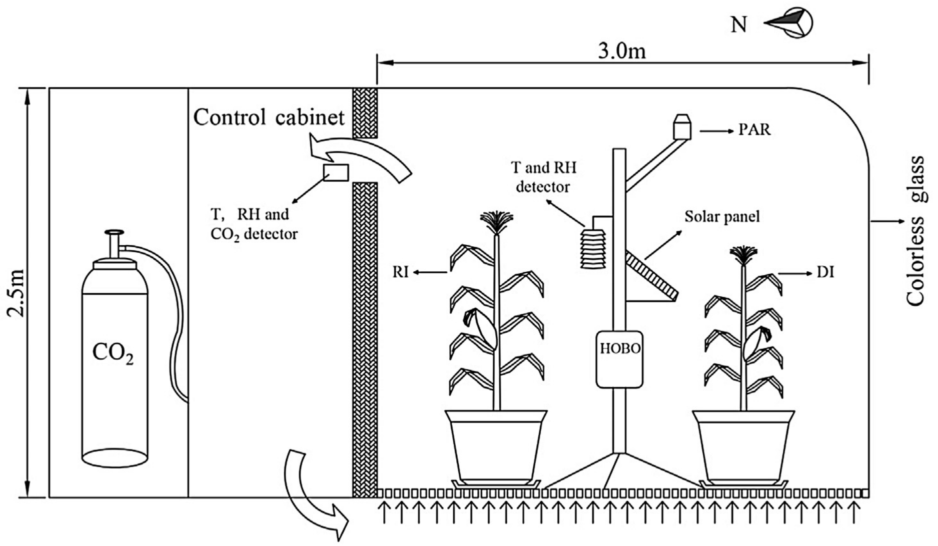
2.3.1. CO_2 concentrations

CO_2 concentrations in the chambers were monitored and recorded at 1 s intervals using the CO_2 gas sensors in the phytotron. The daily variations of the average values of four CO_2 concentrations from 8:00 to 20:00 are shown in Fig. 3a.

2.3.2. Meteorological data

Conventional meteorological data in each chamber, including photosynthetic active radiation (*PAR*), air temperature (*T*), relative humidity (*RH*), and wind speed (*u*), were continuously observed by a portable automatic weather station (HOBO U30, Onset Com-

(a) Schematic drawing of the phytotron



(b) Experimental design

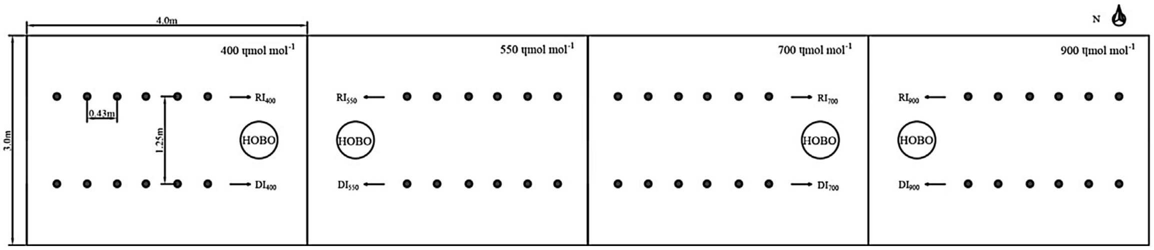


Fig. 2. Schematic drawing of the phytotron (a) and Experimental design (b) (*T*, daily average temperature; *RH*, relative humidity; *PAR*, photosynthetic active radiation; RI, regular irrigation; DI, deficit irrigation; HOBO, portable automatic weather station; •, maize plant).

puter Corp., USA) and a multi-functional automatic anemometer (VELOCICALC 9565, TSI Inc., USA). The data were sampled every 5 s interval, and 15 min averages were calculated and recorded using a data logger. The daily average meteorological data in the chamber during the experimental period are shown in Fig. 3b.

2.3.3. Photosynthetic parameters

Stomatal conductance of water vapor diffusion (g_s), transpiration rate (T_r), leaf temperature (T_{leaf}), and net photosynthetic rate (P_n) of maize leaves were measured using a LI-6400 type photosynthesis system (Li-Cor Inc., USA). The second leaves of three representative plants undergoing the same treatment were randomly selected for measurement. The daily variations of the photosynthetic parameters of each treatment were recorded at two-hourly intervals from 8:00 to 18:00 on July 10, July 17, and August 15.

2.3.4. Crop growth and yield parameters

Three plants representative of each treatment were randomly selected to measure leaf length, maximum leaf width, and plant height using steel tapes every seven to ten days after the emergence of maize. The leaf area was calculated by summing the leaf length multiplied by the maximum leaf width and then multiplied by a conversion factor of 0.74 (Li et al., 2008). The leaf area index (*LAI*, $m^2\ m^{-2}$) was defined as the ratio of leaf area to the soil surface area in the plastic pots. The stem dry weight (*SDW*), leaf dry weight (*LDW*), root dry weight (*RDW*), hundred-grain weight (*HGW*), kernels per ear (*KPE*), and grain yield (*GY*) of maize were measured using the oven-drying method on September 16 when harvesting, and four plants representative of each treatment were selected. Specific leaf area (*SLA*, $cm^2\ g^{-1}$) was defined as the ratio of *LAI* to *LDW*. The harvest index (*HI*) was defined as the ratio of *GY* to total dry weight (*TDW*).

2.3.5. Evapotranspiration

Evapotranspiration (*ET*) was calculated using the following water balance method, and the average of three replications.

$$ET = I + P + W - D - R - \Delta S \quad (1)$$

where *ET* is the crop evapotranspiration (mm), *I* the irrigation amount (mm), *P* the precipitation (mm), *W* the capillary rise to the root zone (mm), *D* the drainage from the root zone (mm), *R* the surface runoff (mm), and ΔS the change in soil water storage (mm).

Since the maize was grown in pots and irrigation was applied carefully, there was no surface runoff and groundwater supply. A tray was put below every pot to collect drainage or water leakage. However, there was no overly saturated water and leakage observed from the trays because the water supplements were controlled by the *ET* between two irrigations, and there was no rain in the chambers either. Therefore Eq. (1) can be simplified as follows:

$$ET = I - \Delta S \quad (2)$$

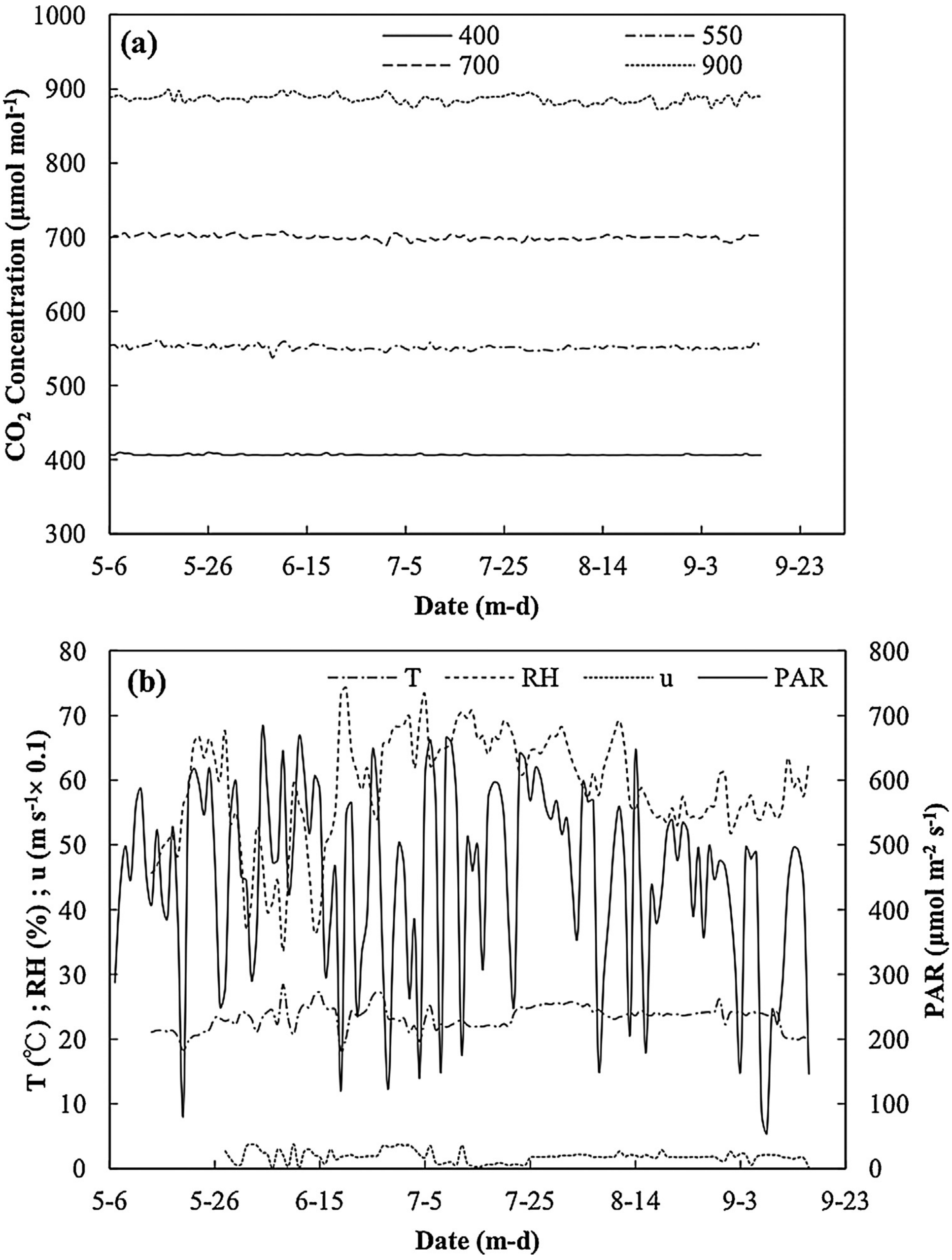


Fig. 3. Variation in the daily average of the four CO_2 concentrations from 8:00 to 20:00 (a), daily average temperature (*T*), relative humidity (*RH*), photosynthetic active radiation (*PAR*), and wind speed (*u*) in the climate chamber during the entire growth period of maize (b).

2.3.6. Leaf water use efficiency

Leaf water use efficiency (WUE_L) was calculated using the following formula:

$$WUE_L = \frac{P_n}{T_r} \quad (3)$$

where WUE_L is the leaf water use efficiency ($\mathrm{mmolCO_2\ mol^{-1}H_2O}$), P_n the net photosynthetic rate ($\mathrm{\mu molCO_2\ m^{-2}\ s^{-1}}$), T_r the transpiration rate ($\mathrm{\mu molH_2O\ m^{-2}\ s^{-1}}$).

2.3.7. Water productivity

(*WP*) was calculated using the following formula:

$$WP = \frac{TDW}{ET} \quad (4)$$

where *WP* is the water productivity ($\mathrm{g\,mm^{-1}}$), *TDW* the total dry weight (g), and *ET* the crop evapotranspiration (mm).

2.4. Data analysis

Microsoft Excel was used to analyze all the observed data. SPSS 21.0 software (SPSS 21.0, SPSS Inc., USA) was applied for the statistical analysis, ANOVA analysis, and the significant test of the average values of each parameter under different treatments. Although there was only one chamber of each CO_2 concentration and the pots of the same treatment were placed in a row, we interchanged the chambers at the later growth stage and switched the crop rows after each weighing, and also the observation parameters were measured randomly, so the variables can be treated as random factors. The significance level was set at 0.05.

Table 3
The effect of CO_2 concentrations on leaf temperature (T_{leaf}) under different irrigation treatments. Data in the table are the mean ± standard error.

CO_2 (μmol mol^{-1})	T_{leaf} (°C)	
	RI	DI
400	30.49 ± 0.61a	30.59 ± 0.60b
550	31.07 ± 0.25a	31.33 ± 0.23ab
700	31.56 ± 0.37a	31.81 ± 0.30ab
900	32.01 ± 0.56a	32.32 ± 0.44a

Means followed by the different letters (a, b, c) are significantly different at the level of $P < 0.05$, and by the same letter are not significantly different at the level of $P < 0.05$. RI denotes regular irrigation, and DI denotes deficit irrigation.

3. Results and discussion

3.1. More pronounced effects of elevated CO_2 concentrations on photosynthetic parameters of maize under deficit irrigation

The effects of different irrigation treatments and CO_2 concentrations on the stomatal conductance (g_s) and transpiration rate (T_r) of maize are shown in Fig. 4a–d. The figure shows that g_s and T_r decreased with the enrichment of CO_2 concentrations under both RI and DI. Compared with RI_{400}, g_s and T_r were 27 and 23% lower under DI_{400}; for the elevated CO_2 concentrations, g_s and T_r were 22–36 and 25–26% lower under DI when compared with RI. Relative reductions in g_s and T_r due to the DI treatment were therefore more pronounced along with elevated CO_2 concentrations.

Compared with RI_{400}, RI_{550}-RI_{700}-RI_{900} decreased g_s by 13, 22, and 33%, and T_r by 12, 23, and 38%, respectively. Compared with DI_{400}, DI_{550}-DI_{700}-DI_{900} decreased g_s by 8, 27, and 41%, and T_r by 16, 27, and 41%, respectively. Therefore, the relative reductions in g_s and T_r caused by elevated CO_2 concentrations were mostly higher under DI than under RI. This was because, under DI, the crop suffered from water stress, which affected the leaves and roots, so the guard cells reduced the solute in the cells by regulating their own metabolic processes to increase water potential, thus causing stomata closure (Stalfelt, 1959; Yu and Wang, 2010). Water deficit was also able to change the intracellular CO_2 concentrations (C_i) by affecting photosynthesis, plant hormones, and *pH*, etc., which also caused stomata closure (Schulze, 1986, 1993; Sharkey, 1984; Yu and Wang, 2010). The stomata reduction was therefore aggravated by the combined effect of deficit irrigation and elevated CO_2 concentrations. So the elevated CO_2 concentration effect on stomatal closure was higher under DI. Since stomata control is the most important way to regulate T_r (Yu and Wang, 2010), T_r had the same variation patterns as g_s.

The effect of different irrigation treatments and CO_2 concentrations on the leaf temperature (T_{leaf}) is shown in Table 3. It shows that T_{leaf} was increased along with the elevated CO_2 concentrations, but it was only significant under DI. Compared with RI_{400}, RI_{550}-RI_{700}-RI_{900} increased T_{leaf} by 1.9, 3.5, and 5.0%, respectively. While compared with DI_{400}, DI_{550}-DI_{700}-DI_{900} increased T_{leaf} by 2.4, 4.0, and 5.7%, respectively. Hence the relative increase in T_{leaf} caused by elevated CO_2 concentrations was higher under DI than under RI. Leaf temperature was highly correlated with T_r under most conditions (Pallas et al., 1967). And it was obvious to see that the higher T_r was shown in the markedly lower T_{leaf}, and vice versa, namely the so called transpiration cooling effect (Pallas et al., 1967). So when the elevated CO_2 concentration reduced T_r, the T_{leaf} increased. Also with the decrease in soil water in DI condition, T_r was decreasing; meanwhile, T_{leaf} rose more remarkable than that only under elevated CO_2 conditions. As T_r cannot be ignored in the changes of T_{leaf} (Cook et al., 1964; Gates, 1964) and T_r changes were more pronounced under DI, so as to the changes of T_{leaf}.

Fig. 4e and f show the effect of different irrigation treatments and CO_2 concentrations on net photosynthetic rate (P_n). Net photosynthetic rate increased with the enrichment of CO_2 concentration. Compared with RI_{400}, P_n was 24% lower under DI_{400}; for the elevated CO_2 concentrations, P_n was 15–20% lower under DI when compared with RI. Relative reductions in P_n due to the DI treatment were therefore weakened along with elevated CO_2 concentrations.

Compared with RI_{400}, RI_{550}-RI_{700}-RI_{900} increased P_n by 30, 45, and 59%, respectively, while compared with DI_{400}, DI_{550}-DI_{700}-DI_{900} increased P_n by 37, 51, and 77%, respectively. Therefore, the increased percentage of P_n caused by elevated CO_2 concentrations was higher under DI than under RI. The result was the same with those in many studies (Kang et al., 2002; Robredo et al., 2007; van der Kooi et al., 2016). This was because both water deficit and elevated CO_2 concentrations reduced the Rubisco enzyme content and activity (Vu et al., 1998), thus weakening the Calvin cycle and increasing the C_i in bundle sheath cells. At the same time, the reduced g_s caused by the two factors also increased C_i by 86 (DI_{400}), 94 (DI_{550}), 75 (DI_{700}), and 15 (DI_{900}) μmol mol^{-1} when compared with that under RI condition with the same CO_2 concentrations (data were measured in our experiment but not shown in the tables). On the other hand, the leaf temperature rose higher under DI. It was 0.10 (DI_{400}), 0.26 (DI_{550}), 0.25 (DI_{700}), and 0.31 (DI_{900}) °C higher than under RI when CO_2 concentrations were the same (Table 3). Since P_n was positive correlated with C_i (Robredo et al., 2007), and within the optimum temperature ranges for photosynthesis at 30–40 °C (Berry and Björkman, 1980; Long, 1999; Ludlow and Wilson, 1971; Mjwara and Botha, 1993; Wardlaw, 1979), a slight increase in leaf temperature resulted in a substantial increase in the P_n of maize due to the positive effect on the photosynthetic biochemical reactions and physical processes (Ghannoum et al., 2000; Yu and Wang, 2010), the relative increase of P_n caused by elevated CO_2 concentrations was higher under DI than under RI.

3.2. More pronounced effects of elevated CO_2 concentrations on the growth and yield of maize under deficit irrigation

The effects of elevated CO_2 concentrations on the maximum leaf area index (LAI_{max}), maximum height (H_{max}), maximum stem diameter (SD_{max}), and specific leaf area (*SLA*) under different irrigation treatments are shown in Table 4. DI_{400} decreased LAI_{max}, H_{max}, and SD_{max} by 18, 21, and 5%, respectively, but increased

Table 4
The effects of CO_2 concentrations on maximum leaf area index (LAI_{max}), maximum height (H_{max}), maximum stem diameter (SD_{max}), and specific leaf area (*SLA*) under different irrigation treatments. Data in the table are the mean ± standard error.

CO_2 (μmol mol^{-1})	LAI_{max} (cm^2 cm^{-2})		H_{max} (cm)		SD_{max} (mm)		SLA (cm^2 g^{-1})	
	RI	DI	RI	DI	RI	DI	RI	DI
400	6.35 ± 0.09a	5.19 ± 0.14c	233.70 ± 3.75c	184.90 ± 7.74b	20.11 ± 0.26b	19.01 ± 0.08b	111.83 ± 12.33a	116.01 ± 7.10ab
550	6.43 ± 0.20a	5.60 ± 0.18bc	244.85 ± 3.33b	226.23 ± 0.74a	20.35 ± 0.38b	19.46 ± 0.49b	102.20 ± 7.47ab	118.59 ± 2.70a
700	6.47 ± 0.32a	6.08 ± 0.05b	250.80 ± 2.31ab	233.15 ± 7.85a	20.38 ± 0.47b	19.81 ± 0.76b	90.32 ± 14.19bc	98.20 ± 9.09bc
900	6.73 ± 0.23a	6.71 ± 0.16a	257.23 ± 2.62a	237.93 ± 4.60a	22.39 ± 0.71a	22.13 ± 0.59a	71.70 ± 5.86c	76.32 ± 5.97c

Means followed by the different letters (a, b, c) are significantly different at the level of $P < 0.05$, and by the same letter are not significantly different at the level of $P < 0.05$. RI denotes regular irrigation, and DI denotes deficit irrigation.

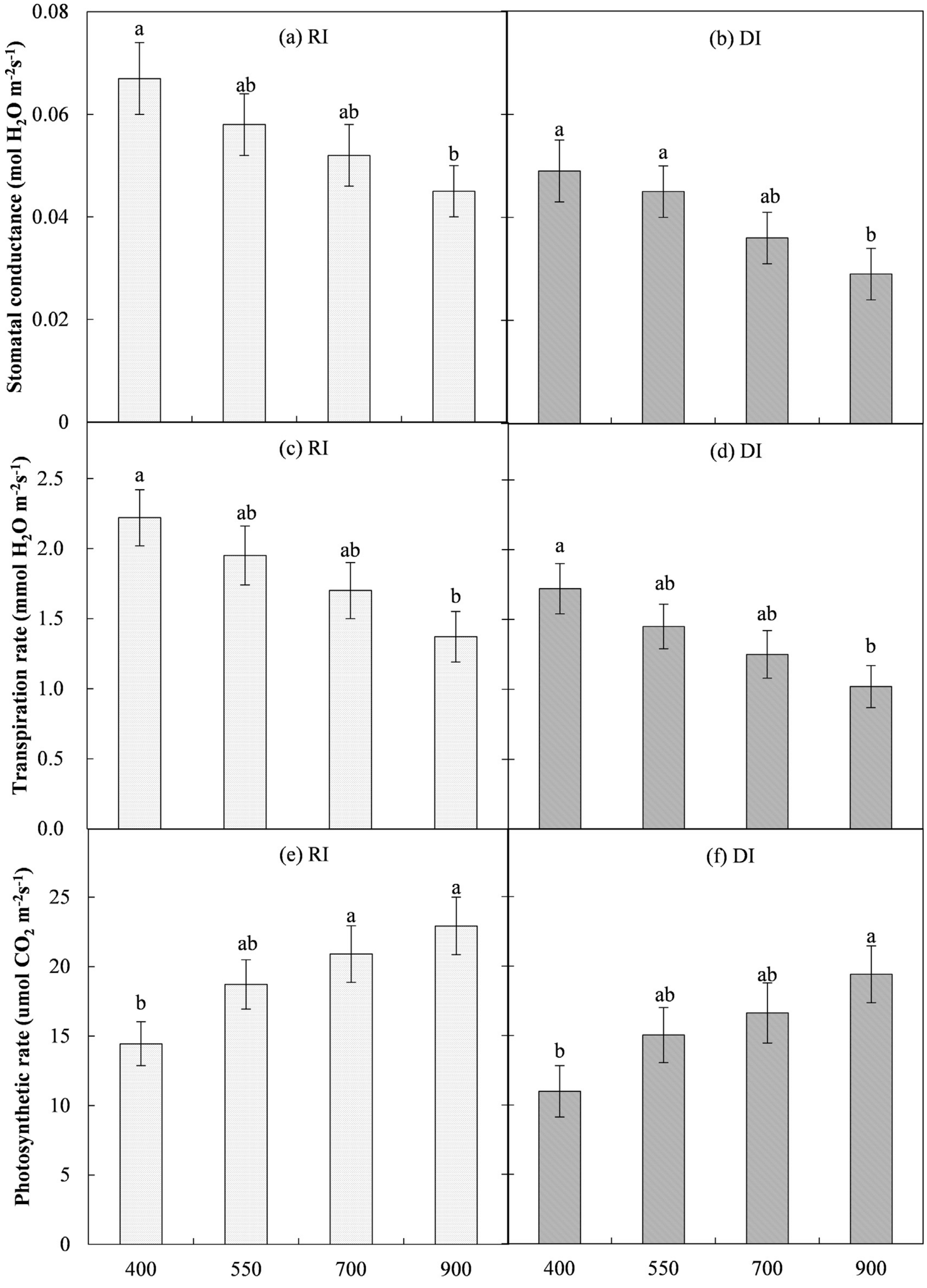


Fig. 4. The effects of CO_2 concentrations on stomatal conductance (g_s), transpiration rate (T_r), and net photosynthetic rate (P_n) under different irrigation treatments. (Data in the figure are the mean ± standard error. Means followed by the different letters (a, b, c) are significantly different at the level of $P < 0.05$, and by the same letter are not significantly different at the level of $P < 0.05$. RI denotes regular irrigation, and DI denotes deficit irrigation).

SLA by 4% when compared with RI_{400}. For elevated CO_2 concentrations, DI decreased LAI_{max}, H_{max}, and SD_{max} by 0–13, 7–8, and 1–4%, but increased *SLA* by 6–16% when compared with RI. Relative reductions in LAI_{max}, H_{max}, and SD_{max} caused by DI were therefore weakened, while relative increases in *SLA* caused by DI were enhanced along with elevated CO_2 concentrations.

Compared with RI_{400}, RI_{550}-RI_{700}-RI_{900} increased LAI_{max} by 1, 2, and 6%, H_{max} by 5, 7, and 10%, and SD_{max} by 1, 1, and 11%, respectively. Compared with DI_{400}, DI_{550}-DI_{700}-DI_{900} increased LAI_{max} by

8, 17, and 29%, H_{max} by 22, 26, and 29%, and SD_{max} by 2, 4, and 16%, respectively. Hence, the relative increases in LAI_{max}, H_{max}, and SD_{max} caused by elevated CO_2 concentrations were higher under DI than under RI. This was because the increased percentages of P_n and T_{leaf} caused by elevated CO_2 concentrations were higher under DI than under RI (see Section 3.1). Since the photosynthesis can form 90–95% of biomass (Zelitch, 1982), and a slight increase in leaf temperature between 30–35 °C was good for crop growth (Wardlaw, 1979; Watts, 1971), the relative increases in LAI_{max}, H_{max}, and SD_{max} were higher under DI.

Compared with RI_{400}, RI_{550}-RI_{700}-RI_{900} decreased *SLA* by 9, 19, and 36%, respectively, while compared with DI_{400}, DI_{550}-DI_{700}-DI_{900} decreased *SLA* by 2, 15, and 34%, respectively. The reduced percentage of *SLA* caused by elevated CO_2 concentrations was therefore lower under DI than under RI. Elevated CO_2 concentrations reduced *SLA* which was the leaf area per leaf weight, possibly because they increased P_n so that dry matter accumulation was first stored in the leaves rather than in the leaf extension within per unit leaf weight (Mamatha et al., 2014; Yelle et al., 1990). Moreover, the redistribution of excess carbohydrates into older leaves under high CO_2 concentrations contributes more to leaf weight than to leaf area, thus reducing *SLA* (Kimball et al., 2002). The reduced percentage of *SLA* caused by elevated CO_2 concentrations was lower under DI than under RI. This might have been because the absolute P_n, dry matter accumulation, and leaf area were small under DI conditions, and photosynthate was used for leaf expansion first of all rather than for storage in the per unit leaf weight to receive more light by increasing the leaf area, which was good for increasing photosynthate under disadvantage conditions. That maybe the crop ability to survive from a bad soil water environment and gain the drought tolerance. So that the reduced percentage of *SLA* caused by elevated CO_2 concentrations was lower under DI.

The effects of different irrigation treatments and CO_2 concentrations on the dry matter in different plant parts and the grain yield of maize are shown in Table 5. The leaf dry weight (*LDW*), stem dry weight (*SDW*), root dry weight (*RDW*), grain yield per plant (*GY*), and total dry weight (*TDW*) at harvest time increased under elevated CO_2 concentrations. The dry matter under DI was lower than under RI. Compared with RI_{400}, the *LDW*, *SDW*, *RDW*, *GY*, and *TDW* under DI_{400} was 16, 34, 25, 21, and 26% lower, respectively. While under elevated CO_2 concentrations, the *LDW*, *SDW*, *RDW*, *GY*, and *TDW* under DI was 6–9, 10–20, 8–15, 5–20, and 7–19% lower, respectively, when compared with RI. Therefore, the reduced percentages of *GY* and *TDW* caused by DI were weakened along with the elevated CO_2 concentrations. That was because the increased percentage of P_n caused by elevated CO_2 concentrations was higher under DI, and the fertilization effect of CO_2 concentration was more significant under DI (Leakey et al., 2006), which offset the negative effect of DI. The interesting thing was that under the CO_2 concentration of 900 μmol mol^{-1}, the reduced percentages of *GY* and *TDW* caused by DI were at their lowest and not significantly different at 5 and 7%, respectively. That may because the higher the CO_2 concentration, the greater the fertilization effect was under DI conditions. So when the irrigation amount was reduced by 30%, the DI did not significantly affect the growth of maize under elevated CO_2 concentrations. Recent studies have suggested that, in the future, as CO_2 concentrations and temperatures increase, extreme rainfall events will be more frequent in spring in Northwest China, but in summer and autumn the precipitation frequency will be reduced (Gao et al., 2015; Guo et al., 2016). Changes in precipitation patterns could lead to a mismatch between natural precipitation and the demand for water of crops, causing frequent seasonal droughts, and seriously restricting the improvement of productivity (Wang et al., 2015). In this case, applying moderate deficit irrigation to crops during the planting season could save irrigation water and decrease *GY*

Table 5
The effects of CO_2 concentrations on leaf dry weight (*LDW*), stem dry weight (*SDW*), root dry weight (*RDW*), grain yield per plant (*GY*), and total dry weight (*TDW*) when maize was harvested under different irrigation treatments. Data in the table are the mean ± standard error.

CO_2 (μmol mol^{-1})	LDW (g)		SDW (g)		RDW (g)		GY (g plant^{-1})		TDW (g)	
	RI	DI	RI	DI	RI	DI	RI	DI	RI	DI
400	25.71 ± 0.52c	21.55 ± 0.28c	52.73 ± 8.84b	34.63 ± 2.48b	17.50 ± 3.28b	13.10 ± 1.05c	110.52 ± 9.16b	86.98 ± 9.19c	247.00 ± 16.90c	182.83 ± 6.00c
550	28.12 ± 0.85bc	25.49 ± 1.74bc	55.57 ± 6.96ab	45.45 ± 5.64ab	21.88 ± 2.26ab	18.58 ± 2.82bc	135.95 ± 10.99ab	108.53 ± 4.46bc	292.60 ± 11.03bc	237.10 ± 14.69bc
700	30.54 ± 1.28b	28.16 ± 2.01b	63.87 ± 3.09ab	57.73 ± 8.39a	23.80 ± 2.47ab	21.45 ± 2.32b	144.61 ± 18.46a	125.27 ± 19.02ab	329.50 ± 22.53ab	287.13 ± 34.01ab
900	35.42 ± 1.03a	33.35 ± 0.66a	73.95 ± 3.58a	59.16 ± 4.05a	28.83 ± 3.29a	31.10 ± 2.89a	159.28 ± 4.82a	151.45 ± 1.77a	359.45 ± 14.61a	332.79 ± 20.83a

Means followed by the different letters (a, b, c) are significantly different at the level of $P < 0.05$, and by the same letter are not significantly different at the level of $P < 0.05$. RI denotes regular irrigation, and DI denotes deficit irrigation.

slightly. This could mitigate food reduction and water crises as CO_2 concentrations increase in the future.

Table 5 also shows that, compared with RI_{400}, RI_{550}-RI_{700}-RI_{900} increased *LDW* by 5, 21, and 40%, *SDW* by 9, 19, and 38%, *RDW* by 25, 36, and 65%, *GY* by 23, 31, and 44%, and *TDW* by 18, 33, and 46%, respectively. However, compared with DI_{400}, DI_{550}-DI_{700}-DI_{90} increased *LDW* by 31, 67, and 71%, *SDW* by 18, 31, and 55%, *RDW* by 42, 64, and 137%, *GY* by 25, 44, and 74%, and *TDW* by 30, 57, and 82%, respectively. Accordingly, the increased percentage of dry matter caused by elevated CO_2 concentrations was higher under DI than under RI. This was due to the fact that the increased percentage of P_n caused by elevated CO_2 concentrations was greater under DI than under RI, resulting in a greater increase in the percentage of dry matter accumulation.

In this study, elevated CO_2 concentrations increased *GY* and *TDW* by 24–59 and 24–64%, respectively, which was close to the results obtained with the same or similar CO_2 concentrations (Cure and Acock, 1986; Guo, 2003; Long et al., 2006; Meng et al., 2014). The changed percentages of *GY* and *TDW* were similar in the reports compiled by many researchers (Ainsworth et al., 2008; van der Kooi et al., 2016). However, the increased effects on *GY* and *TDW* caused by CO_2 enrichment differ slightly in this study when compared with the results obtained in some of the other literature on the subject. For example, the results obtained by Ziska and Bunce (1997) and Samarakoon and Gifford (1996) show that elevated CO_2 concentrations can increase the total biomass of maize in wet soil, but the effect was not significant, which differed from our conclusions. However, in a dry soil environment, *TDW* increased by 54% due to elevated CO_2 levels, which was a similar result to that given in this study. The response of *TDW* to elevated CO_2 concentrations in a dry environment or under DI treatment was very clear. The reasons for the different results in a wet environment may include the followings: (1) Our regular irrigation (RI) was conducted every three to four day according to the *ET* that consumed by the crops, it was not an absolute non-drought soil environment when compared with other literature. The crops may suffer from some slight drought periods before renewed access to irrigation, which may cause the significant results; (2) The irrigation frequency for the crops was performed more or less on a daily basis in previous studies, which was more frequent than in our study where it was carried out every three to four days. And studies have shown that *GY* and *TDW* decrease significantly with increased irrigation frequency (Tian et al., 2016); (3) This study was conducted in arid and semi-arid areas where the crop was highly dependent on water, which led to a more sensitive response to increased CO_2 concentrations; (4) Most previous studies set two constant temperatures, day and night, but we set a sine curve for the temperature during the daytime and a natural temperature at night according to the average temperature calculated at the experimental station over many years. According to the study of Hu (1963), increasing the temperature differential between day and night is beneficial to the growth and development of maize; (5) The experimental period in previous studies was short (about 30-60 days), but in this study it covered the entire growth season (about 133 days), which also resulted in a difference in biomass or yield at the final harvest. All the above explanations may cause the different result from other studies in a wet soil environment. But the increased percentages of *GY* and *TDW* caused by CO_2 enrichment under DI (or drought) are higher than under RI (or wet) is beyond doubt.

The effects of different irrigation treatments and CO_2 concentrations on hundred-grain weight (*HGW*), kernels per ear (*KPE*), and harvest index (*HI*) are shown in Table 6, in which, elevated CO_2 concentrations had no significant effects on *HGW* and *HI*, but *KPE* increased with a rise in CO_2 concentrations. There was no significant difference in terms of *HGW* between DI and RI under the same CO_2 concentration. DI_{400}, DI_{550}, DI_{700}, and DI_{900} decreased *KPE* by 21, 20, 13, and 5% respectively, however, when compared with RI under the same CO_2 concentration. The higher the CO_2 concentration, the lower the reduced percentage of *KPE* caused by DI. Compared with RI_{400}, RI_{550}-RI_{700}-RI_{900} increased *KPE* by 23, 31, and 44%, respectively, but compared with DI_{400}, DI_{550}-DI_{700}-DI_{900} increased it by 25, 44, and 74%. The increased percentage of *KPE* caused by elevated CO_2 concentrations was higher under DI than under RI. This accorded with the variation in *GY*, which would indicate that the variety in terms of *GY* was mainly determined by the variety in *KPE* under different irrigation and CO_2 concentration treatments, but that there was no direct relation to variations in *HGW*.

There were no significant effects in terms of elevated CO_2 concentrations on the *HI*. But DI increased *HI* by 5–15% when compared with RI, which means that DI can improve *HI*. This is consistent with many previous studies (Kang et al., 2000; Zhang et al., 1998; Zhang et al., 2008), although other studies have shown that *HI* decreases with increasing water stress (Bolaños and Edmeades, 1993; Farré and Faci, 2006; Muchow, 1989). The different results may be due to the fact that, in our experiment, the level of DI did not reach a level that could significantly reduce *HI*. This might also be due to the different dependence of *HI* on irrigation levels in different studies, where the experimental areas have different climate conditions (drought or wet). Further research is, therefore, needed on this.

3.3. More pronounced effects of elevated CO_2 concentrations on maize evapotranspiration under deficit irrigation

The effects of CO_2 concentrations on maize evapotranspiration (*ET*) under RI and DI are shown in Fig. 5. It shows that when the amount of irrigation was reduced by 30% under DI, *ET* was 30% lower than that under RI. Under both RI and DI, *ET* decreased first to a minimum value at 700 μmol mol^{-1} and then increased with an elevation in CO_2 concentrations. This was because, although elevated CO_2 concentrations reduced g_s and T_r, they increased *LAI*, offsetting the reduction in canopy conductance caused by reduced g_s and T_r (Hileman et al., 1994; Kang et al., 1996). Wullschleger et al. (2002) also reported that the canopy conductance only decreased by 14% when g_s decreased by 44% due to the elevation of CO_2 concentration from 394 μmol mol^{-1} to 538 μmol mol^{-1}. The impact of an elevated CO_2 concentration on *ET* was therefore small and, even when the CO_2 concentration reached a certain high value, *ET* increased. Oliver et al. (2009) also note that the effects of elevated CO_2 concentrations on *ET* are wide ranging and can remain at a reduced level (Cech et al., 2003; Owensby et al., 1997), or remain unchanged (Ellsworth, 1999; Qiao et al., 2010), or even increase (Tricker et al., 2009; Uddling et al., 2008).

Compared with RI_{400}, RI_{550}-RI_{700}-RI_{900} decreased *ET* by 15, 18, and 13%, respectively, while compared with DI_{400}, DI_{550}-DI_{700}-DI_{900} decreased *ET* by 10, 14, and 10%, respectively. Accordingly, the reduced percentage of *ET* caused by elevated CO_2 concentrations was less under DI than under RI. The result was similar to the findings of Samarakoon and Gifford (1996) and Kang et al. (2002). As mentioned previously, although the decrease in T_r caused by elevated CO_2 concentrations was 2–4% higher under DI than under RI, the increased percentage of *LAI* was higher (7–23%). So the offset effect of the increased *LAI* on the decreased T_r was more obvious. Thus, the impact of elevated CO_2 concentrations on *ET* was smaller under DI than under RI.

3.4. More pronounced effects of elevated CO_2 concentrations on water use efficiency and water productivity of maize under deficit irrigation

The effects of different irrigation treatments and elevated CO_2 concentrations on leaf water use efficiency (WUE_L) and water pro-

Table 6
The effects of CO_2 concentrations on hundred-grain weight (*HGW*), kernels per ear (*KPE*), and harvest index (*HI*) under different irrigation treatments. Data in the table are the mean ± standard error.

CO_2 (μmol mol^{-1})	HGW (g)		KPE (n)		HI	
	RI	DI	RI	DI	RI	DI
400	29.28 ± 1.90a	29.72 ± 0.81a	346.13 ± 28.68b	272.42 ± 28.79c	0.41 ± 0.03a	0.47 ± 0.04a
550	31.57 ± 0.58a	32.91 ± 0.93a	425.77 ± 17.21ab	339.88 ± 13.95bc	0.43 ± 0.02a	0.46 ± 0.03a
700	32.43 ± 2.36a	32.80 ± 1.33a	452.89 ± 57.81a	392.33 ± 59.56ab	0.42 ± 0.02a	0.48 ± 0.04a
900	31.98 ± 0.54a	31.47 ± 0.98a	498.83 ± 15.10a	474.33 ± 5.55a	0.44 ± 0.02a	0.46 ± 0.02a

Means followed by the different letters (a, b, c) are significantly different at the level of $P < 0.05$, and by the same letter are not significantly different at the level of $P < 0.05$. RI denotes regular irrigation, and DI denotes deficit irrigation.

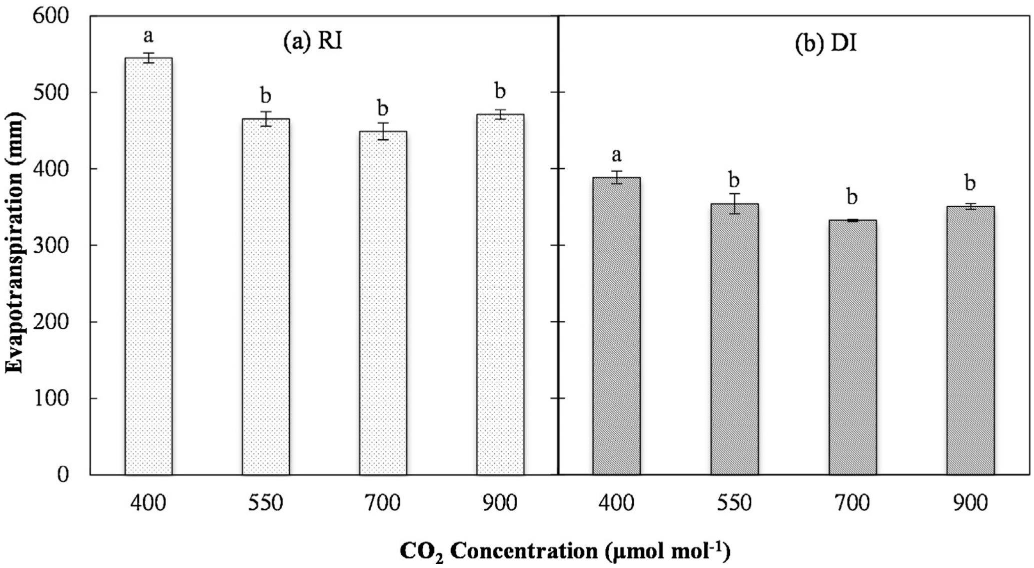


Fig. 5. The effect of CO_2 concentrations on maize evapotranspiration (*ET*) under different irrigation treatments. (Data in the figure are the mean ± standard error. Means followed by the different letters (a, b, c) are significantly different at the level of $P < 0.05$, and by the same letter are not significantly different at the level of $P < 0.05$. RI denotes regular irrigation, and DI denotes deficit irrigation).

Table 7
The effects of CO_2 concentrations on leaf water use efficiency (WUE_L) and water productivity (*WP*) of maize under different irrigation treatments. Data in the table are the mean ± standard error.

CO_2 (μmol mol^{-1})	WUE_L (mmolCO_2 mol^{-1}H_2O)		WP (g mm^{-1})	
	RI	DI	RI	DI
400	6.56 ± 0.49c	6.05 ± 0.64c	0.42 ± 0.00c	0.46 ± 0.03c
550	9.94 ± 0.80b	10.39 ± 1.09b	0.62 ± 0.04b	0.69 ± 0.05b
700	12.56 ± 0.97b	13.34 ± 1.28b	0.69 ± 0.08ab	0.80 ± 0.05b
900	18.72 ± 1.60a	21.23 ± 1.94a	0.79 ± 0.02a	0.93 ± 0.06a

Means followed by the different letters (a, b, c) are significantly different at the level of $P < 0.05$, and by the same letter are not significantly different at the level of $P < 0.05$. RI denotes regular irrigation, and DI denotes deficit irrigation.

ductivity (*WP*) are shown in Table 7. It shows that WUE_L and *WP* increased with the elevation of CO_2 concentrations in both irrigation treatments, so that the results were the same as the results obtained in previous studies (Idso et al., 1987; Kang et al., 2002; Leakey et al., 2006; Li et al., 2003; Meng et al., 2014; Oliver et al., 2009). Compared with RI_{400}, WUE_L was 8% lower with DI_{400}, but *WP* was 10% higher. As far as the elevated CO_2 concentrations were concerned, DI increased WUE_L and *WP* by 4–12 and 10–15%. Therefore, the increased percentages of WUE_L and *WP* caused by DI grew along with the elevated CO_2 concentrations.

Compared with RI_{400}, RI_{550}-RI_{700}-RI_{900} increased WUE_L by 52, 91, and 185%, and *WP* by 48, 64, and 88%, respectively, while compared with DI_{400}, DI_{550}-DI_{700}-DI_{900} increased WUE_L by 72, 120, and 251%, and *WP* by 50, 74, and 102%, respectively. Accordingly, the increased percentages of WUE_L and *WP* caused by elevated CO_2 concentrations were higher under DI than under RI. That was because at the leaf level, according to Eq. (3), when the numerator (P_n) increased and the denominator (T_r) decreased, the result (WUE_L) came out to increase. And since the increased percentage of P_n and the reduced percentage of T_r were both higher under DI than under RI (see Section 3.1), the increased percentage of WUE_L caused by elevated CO_2 concentrations was higher under DI than under RI. At the canopy level, there was a similar situation of *WP* to WUE_L, i.e. when the numerator (*TDW*) increased and the denominator (*ET*) decreased, the result (*WP*) came out to increase according to Eq. (4). The increased percentage of *TDW* (11–36%) was much higher than the decreased percentage of *ET* (3–5%) under DI than under RI, thus the increased percentage of *WP* caused by elevated CO_2 concentrations was higher under DI than under RI. This was the same as the result obtained by Allen et al. (2011) using a similar CO_2 concentration.

The improvement of water use efficiency and water productivity was more significant than the improvement of P_n and yield (Chaves and Pereira, 1992), especially in the case of water deficit conditions. Water deficit reduced crop production, while increased CO_2 concentrations not only reduced water consumption, but also increased yield. The results of this study show that the increased proportion of *WP* caused by CO_2 enrichment was more under DI. This would provide a strong theoretical basis for conducting irrigation water management under elevated CO_2 concentrations in the future.

4. Conclusions

In this study, we explored the different effects of elevated CO_2 concentration on stomatal conductance, transpiration rate, leaf temperature, photosynthetic rate, evapotranspiration, crop growth, biomass parameters, yield parameters, leaf water use efficiency, and water productivity, among which the effect on leaf temperature was only discussed in this study, under two different irrigation methods. And the results show that the elevated CO_2 concentration would benefit maize crops more under deficit irrigation (which can save a lot of water) than regular irrigation method (which was similar to the local water management). Although the elevated CO_2 concentration and deficit irrigation decreased the absolute value of stomatal conductance and transpiration rate, but the leaf temperature increased more due to the transpiration cooling effect, then promoted the photosynthetic rate, the crop growth, and the yield, weakening the disadvantages of deficit irrigation on maize plants.

Some of our results under regular irrigation were different from those of other literature in wet soil conditions. That was because the maize grown in regular irrigation conditions may suffer from slight drought before re-irrigation and the environment was not absolutely non-water stressed. Also the irrigation frequency was quite different from other references, which may cause different results and need to be considered in the future. Whatever, our study revealed that under future climate change, deficit irrigation is not only an efficient water saving method, but also can benefit crops more with lowest yield reduction and highest water productivity.

However, the irrigation amount of this study only considered two gradients, i.e. the regular irrigation and deficit irrigation in which the irrigation amounts were 100 and 70% of evapotranspiration, respectively, which would create some limitations of the research. Also, there were no irrigation frequency, planting density, and nitrogen treatments taking into account, which are also very important factors in the crop growth periods and may cause different results when considering the CO_2 concentration effect. More consideration is needed in the future's research.

Acknowledgement

We are grateful for the support from the National Natural Science Fund in China (51621061, 91425302), the Government Public Research Funds for Projects of the Ministry of Agriculture (201503125), the 111 Program of Introducing Talents of Discipline to Universities (B14002), and the Ministry of Water Resources of China (201327).

References

Ainsworth, E.A., Rogers, A., 2007. The response of photosynthesis and stomatal conductance to rising [CO_2]: mechanisms and environmental interactions. Plant Cell Environ. 30 (3), 258–270.

Ainsworth, E.A., Leakey, A.D.B., Ort, D.R., Long, S.P., 2008. FACE-ing the facts: inconsistencies and interdependence among field, chamber and modeling studies of elevated [CO_2] impacts on crop yield and food supply. New Phytol. 179 (1), 5–9.

Ainsworth, E.A., 2008. Rice production in a changing climate: a meta-analysis of responses to elevated carbon dioxide and elevated ozone concentration. Global Change Biol. 14 (7), 1642–1650.

Aljazairi, S., Arias, C., Nogués, S., 2015. Carbon and nitrogen allocation and partitioning in traditional and modern wheat genotypes under pre-industrial and future CO_2 conditions. Plant Biol. 17 (3), 647–659.

Allen, L.H., Pan, D., Boote, K.J., Pickering, N.B., Jones, J.W., 2003. Carbon dioxide and temperature effects on evapotranspiration and water use efficiency of soybean. Agron. J. 95 (4), 1071–1081.

Allen, L.H., Kakani, V.G., Vu, J.C.V., Boote, K.J., 2011. Elevated CO_2 increases water use efficiency by sustaining photosynthesis of water-limited maize and sorghum. J. Plant Physiol. 168 (16), 1909–1918.

Badr, M.A., El-Tohamy, W.A., Zaghloul, A.M., 2012. Yield and water use efficiency of potato grown under different irrigation and nitrogen levels in an arid region. Agric. Water Manage. 110, 9–15.

Bernacchi, C.J., Kimball, B.A., Quarles, D.R., Long, S.P., Ort, D.R., 2007. Decreases in stomatal conductance of soybean under open-air elevation of [CO_2] are closely coupled with decreases in ecosystem evapotranspiration. Plant Physiol. 143 (1), 134–144.

Berry, J., Björkman, O., 1980. Photosynthetic response and adaptation to temperature in higher plants. Annu. Rev. Plant Physiol. 31, 491–543.

Bolaños, J., Edmeades, G.O., 1993. Eight cycles of selection for drought tolerance in lowland tropical maize. I. Responses in grain yield, biomass, and radiation utilization. Field Crops Res. 31 (3-4), 233–252.

Bunce, J.A., 2004. Carbon dioxide effects on stomatal responses to the environment and water use by crops under field conditions. Oecologia 140 (1), 1–10.

Cai, C., Yin, X.Y., He, S.Q., Jiang, W.Y., Si, C.F., Struik, P.C., Luo, W.H., Li, G., Xie, Y.T., Xiong, Y., Pan, G.X., 2016. Reponses of wheat and rice to factorial combinations of ambient and elevated CO_2 and temperature in FACE experiments. Global Change Biol. 22 (2), 856–874.

Cantore, V., Lechkar, O., Karabulut, E., Sellami, M.H., Albrizio, R., Boari, F., Stellacci, A.M., Todorovic, M., 2016. Combined effect of deficit irrigation and strobilurin application on yield, fruit quality and water use efficiency of "cherry" tomato (*Solanum lycopersicum* L.). Agric. Water Manage. 167, 53–61.

Cech, P.G., Pepin, S., Körner, C., 2003. Elevated CO_2 reduces sap flux in mature deciduous forest trees. Oecologia 137 (2), 258–268.

Chaves, M.M., Pereira, J.S., 1992. Water stress, CO_2 and climate change. J. Exp. Bot. 43 (8), 1131–1139.

Cook, G.D., Dixon, J.R., Leopold, A.C., 1964. Transpiration: its effect on plant leaf temperature. Science 144 (3618), 546–547.

Cure, J.D., Acock, B., 1986. Crop responses to carbon dioxide doubling: a literature survey. Agric. Forest Meteorol. 38 (1–3), 127–145.

Dorji, K., Behboudian, M.H., Zegbe-Domínguez, J.A., 2005. Water relations, growth, yield, and fruit quality of hot pepper under deficit irrigation and partial rootzone drying. Sci. Hort. 104 (2), 137–149.

Driscoll, S.P., Prins, A., Olmos, E., Kunert, K.J., Foyer, C.H., 2006. Specification of adaxial and abaxial stomata, epidermal structure and photosynthesis to CO_2 enrichment in maize leaves. J. Exp. Bot. 57 (2), 381–390.

Ellsworth, D.S., 1999. CO_2 enrichment in a maturing pine forest: are CO_2 exchange and water status in the canopy affected? Plant Cell Environ. 22 (5), 461–472.

Farré, I., Faci, J.M., 2006. Comparative response of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) to deficit irrigation in a Mediterranean environment. Agric. Water Manage. 83 (1-2), 135–143.

Gao, J.Q., Yang, X.G., Dong, C.Y., Li, K.N., 2015. Precipitation resource changed characteristics in arid and humid regions in Northern China with climate changes. Trans. CSAE 31 (12), 99–110 (In Chinese with English abstract).

Gates, D.M., 1964. Leaf temperature and transpiration. Agron. J. 56 (3), 273–277.

Geerts, S., Raes, D., 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agric. Water Manage. 96 (9), 1275–1284.

Ghannoum, O., von Caemmerer, S., Ziska, L.H., Conroy, J.P., 2000. The growth response of C_4 plants to rising atmospheric CO_2 partial pressure: a reassessment. Plant Cell Environ. 23 (9), 931–942.

Gifford, R.M., 1977. Growth pattern, carbon dioxide exchange and dry weight distribution in wheat growing under differing photosynthetic environments. Aust. J. Plant Physiol. 4 (1), 99–110.

Gifford, R.M., 1979. Growth and yield of CO_2-enriched wheat under water-limited conditions. Aust. J. Plant Physiol. 6 (3), 367–378.

Guo, X.J., Huang, J.B., Luo, Y., Zhao, Z.C., Xu, Y., 2016. Projection of precipitation extremes for eight global warming targets by 17 CMIP5 models. Nat. Hazards 84 (3), 2299–2319.

Guo, J.P., 2003. Responses of Mainly Plants in Northern China to CO_2 Enrichment and Soil Drought. China Meteorological Press, Beijing, pp. 114, (In Chinese).

Hileman, D.R., Huluka, G., Kenjige, P.K., Sinha, N., Bhattacharya, N.C., Biswas, P.K., Lewin, K.F., Nagy, J., Hendrey, G.R., 1994. Canopy photosynthesis and transpiration of field-grown cotton exposed to free-air CO_2 enrichment (FACE) and differential irrigation. Agric. Forest Meteorol. 70 (1–4), 189–207.

Hu, D.J., 1963. Effects of meteorological conditions on maize growth and development. J. Northeast Agric. Univ. 1, 1–12 (In Chinese).

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 996.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1535.

IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Idso, S.B., Kimball, B.A., Mauney, J.R., 1987. Atmospheric carbon dioxide enrichment effects on cotton midday foliage temperature: implications for plant water use and crop yield. Agron. J. 79 (4), 667–672.

Islam, A., Ahuja, L.R., Garcia, L.A., Ma, L., Saseendran, A.S., Trout, T.J., 2012. Modeling the impacts of climate change on irrigated corn production in the Central Great Plains. Agric. Water Manage. 110, 94–108.

Kang, S.Z., Cai, H.J., Liu, X.M., Zhang, F.C., Liang, Y.L., Huang, M.B., 1996. The effect of climate changes in the future on crop evapotranspiration and water use efficiency. J. Hydraul. Eng. (4), 18–26 (In Chinese with English abstract).

Kang, S.Z., Shi, W.J., Zhang, J.H., 2000. An improved water-use efficiency for maize grown under regulated deficit irrigation. Field Crops Res. 67 (3), 207–214.

Kang, S.Z., Zhang, F.C., Hu, X.T., Zhang, J.H., 2002. Benefits of CO_2 enrichment on crop plants are modified by soil water status. Plant Soil 238 (1), 69–77.

Kang, S.Z., Hao, X.M., Du, T.S., Tong, L., Su, X.L., Lu, H.N., Li, X.L., Huo, Z.L., Li, S.E., Ding, R.S., 2017. Improving agricultural water productivity to ensure food security in China under changing environment: From research to practice. Agric. Water Manage. 179, 5–17.

Kim, S.H., Gitz, D.C., Sicher, R.C., Baker, J.T., Timlin, D.J., Reddy, V.R., 2007. Temperature dependence of growth, development, and photosynthesis in maize under elevated CO_2. Environ. Exp. Bot. 61 (3), 224–236.

Kimball, B.A., Kobayashi, K., Bindi, M., 2002. Responses of agricultural crops to free-air CO_2 enrichment. Adv. Agron. 77, 293–368.

Kimball, B.A., 2016. Crop responses to elevated CO_2 and interactions with H_2O, N, and temperature. Curr. Opin. Plant Biol. 31, 36–43.

King, K.M., Greer, D.H., 1986. Effects of carbon dioxide enrichment and soil water on maize. Agron. J. 78 (3, 515–521.

Lai, S.K., Zhou, S.N., Gu, W.F., Zhuang, S.T., Zhou, J., Zhu, J.G., Yang, L.X., Wang, Y.L., 2014. Effects of CO_2 concentration, nitrogen supply and transplanting density on yield formation of hybrid rice Shanyou 63: a FACE study. J. Agro-Environ. Sci. 33 (5), 836–843 (In Chinese with English abstract).

Leakey, A.D.B., Uribelarrea, M., Ainsworth, E.A., Naidu, S.L., Rogers, A., Ort, D.R., Long, S.P., 2006. Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO_2 concentration in the absence of drought. Plant Physiol. 140 (2), 779–790.

Li, F.S., Kang, S.Z., Zhang, J.H., Cohen, S., 2003. Effects of atmospheric CO_2 enrichment, water status and applied nitrogen on water- and nitrogen-use efficiencies of wheat. Plant Soil 254 (2), 279–289.

Li, S.E., Kang, S.Z., Li, F.S., Zhang, L., 2008. Evapotranspiration and crop coefficient of spring maize with plastic mulch using eddy covariance in northwest China. Agric. Water Manage. 95 (11), 1214–1222.

Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nösberger, J., Ort, D.R., 2006. Food for thought: lower-than-expected crop yield stimulation with rising CO_2 concentrations. Science 312 (5782), 1918–1921.

Long, S.P., 1999. Environmental responses. In: Sage, R.F., Monson, R.K. (Eds.), C4 Plant Biology. Academic Press, San Diego, CA, pp. 215–249.

Loomis, R.S., Lafitte, H.R., 1987. The carbon economy of a maize crop exposed to elevated CO_2 concentrations and water stress, as determined from elemental analyses. Field Crops Res. 17 (1), 63–74.

Ludlow, M.M., Wilson, G.L., 1971. Photosynthesis of tropical pasture plants I. Illuminance, carbon dioxide concentration, leaf temperature, and leaf-air vapour pressure difference. Aust. J. Biol. Sci. 24 (3), 449–470.

Mamatha, H., Rao, N.K.S., Laxman, R.H., Shivashankara, K.S., Bhatt, R.M., Pavithra, K.C., 2014. Impact of elevated CO_2 on growth, physiology, yield, and quality of tomato (*Lycopersicon esculentum* Mill) cv. Arka Ashish. Photosynthetica 52 (4), 519–528.

Manderscheid, R., Erbs, M., Weigel, H., 2014. Interactive effects of free-air CO_2 enrichment and drought stress on maize growth. Eur. J. Agron. 52, 11–21.

Meng, F.C., Zhang, J.H., Yao, F.M., Hao, C., 2014. Interactive effects of elevated CO_2 concentration and irrigation on photosynthetic parameters and yield of maize in Northeast China. PLoS One 9 (5), e98318.

Mitchell, J.P., Shennan, C., Crattan, S.R., May, D.M., 1991. Tomato fruit yields and quality under water deficit and salinity. J. Am. Soc. Hortic. Sci. 116 (2), 215–221.

Mjwara, J.M., Botha, C.E.J., 1993. The interactive effects of light, temperature and CO_2/O_2 ratios on photosynthesis of *Coix lachryma-jobi* L. S. Afr. J. Bot. 59 (4), 377–384.

Morison, J.I.L., Gifford, R.M., 1984. Plant growth and water use with limited water supply in high CO_2 concentrations. II. Plant dry weight, partitioning and water use efficiency. Aust. J. Plant Physiol. 11 (5), 375–384.

Muchow, R.C., 1989. Comparative productivity of maize, sorghum and pearl millet in a semi-arid tropical environment II. Effect of water deficits. Field Crops Res. 20 (3), 207–219.

Oliver, R.J., Finch, J.W., Taylor, G., 2009. Second generation bioenergy crops and climate change: a review of the effects of elevated atmospheric CO_2 and drought on water use and the implications for yield. Global Change Biol. Bioenergy 1 (2), 97–114.

Owensby, C., Ham, J., Knapp, A., Bremer, D., Auen, L., 1997. Water vapour fluxes and their impact under elevated CO_2 in a C4-tallgrass prairie. Global Change Biol. 3 (3), 189–195.

Pallas, J.E., Michel, J.B.E., Harris, D.G., 1967. Photosynthesis, transpiration, leaf temperature, and stomatal activity of cotton plants under varying water potentials. Plant Physiol. 42 (1), 76–88.

Qiao, Y.Z., Zhang, H.Z., Dong, B.D., Shi, C.H., Li, Y.X., Zhai, H.M., 2010. Effects of elevated CO_2 concentration on growth and water use efficiency of winter wheat under two soil water regimes. Agric. Water Manage. 97 (11), 1742–1748.

Robredo, A., Pérez-López, U., de la Maza, H.S., González-Moro, B., Lacuesta, M., Mena-Petite, A., Mu˜noz-Rueda, A., 2007. Elevated CO_2 alleviates the impact of drought on barley improving water status by lowering stomatal conductance and delaying its effects on photosynthesis. Environ. Exp. Bot. 59 (3), 252–263.

Rogers, H.H., Bingham, G.E., Cure, J.D., Smith, J.M., Surano, K.A., 1983. Responses of selected plant species to elevated carbon dioxide in the field. J. Environ. Qual. 12 (4), 569–574.

Rop, D.K., Kipkorir, E.C., Taragon, J.K., 2016. Effects of deficit irrigation on yield and quality of onion crop. J. Agric. Sci. 8 (3), 112–126.

Saadi, S., Todorovic, M., Tanasijevic, L., Pereira, L.S., Pizzigalli, C., Lionello, P., 2015. Climate change and Mediterranean agriculture: Impacts on winter wheat and tomato crop evapotranspiration, irrigation requirements and yield. Agric. Water Manage. 147, 103–115.

Samarakoon, A.B., Gifford, R.M., 1996. Elevated CO_2 effects on water use and growth of maize in wet and drying soil. Aust. J. Plant Physiol. 23 (1), 53–62.

Schulze, E.D., 1986. Carbon dioxide and water vapor exchange in response to drought in the atmosphere and in the soil. Annu. Rev. Plant Physiol. 37, 247–274.

Schulze, E.D., 1993. Soil water deficits and atmospheric humidity as environmental signals. In: Smith, J.A.C., Griffiths, H. (Eds.), Water deficits: Plant Response from Cell to Community. Bios Scientific Publishers, Oxford UK, pp. 129–145.

Sharkey, T.D., 1984. Transpiration-induced changes in the photosynthetic capacity of leaves. Planta 160 (2), 143–150.

Stalfelt, M.G., 1959. The effect of carbon dioxide on hydroactive closure of the stomatal cells. Physiol. Plant. 12 (4), 691–705.

Tian, J.K., Zhang, F.C., Qiang, S.C., Zou, H.Y., Wu, Y., Yan, S.C., 2016. Effects of irrigation level and frequency on growth and water use efficiency of maize. J. Drain. Irrig. Mach. Eng. 34 (9), 815–822 (In Chinese with English abstract).

Tricker, P.J., Pecchiari, M., Bunn, S.M., Vaccari, F.P., Peressotti, A., Miglietta, F., Taylor, G., 2009. Water use of a bioenergy plantation increases in a future high CO_2 world. Biomass Bioenergy 33 (2), 200–208.

Uddling, J., Teclaw, R.M., Kubiske, M.E., Pregitzer, K.S., Ellsworth, D.S., 2008. Sap flux in pure aspen and mixed aspen–birch forests exposed to elevated concentrations of carbon dioxide and ozone. Tree Physiol. 28 (8), 1231–1243.

van der Kooi, C.J., Reich, M., Löw, M., De Kok, L.J., Tausz, M., 2016. Growth and yield stimulation under elevated CO2 and drought: a meta-analysis on crops. Environ. Exp. Bot. 122, 150–157.

Vanuytrecht, E., Raes, D., Willems, P., Geerts, S., 2012. Quantifying field-scale effects of elevated carbon dioxide concentration on crops. Clim. Res. 54, 35–47.

Vu, J.C.V., Allen Jr., L.H., 2009. Growth at elevated CO_2 delays the adverse effects of drought stress on leaf photosynthesis of the C_4 sugarcane. J. Plant Physiol. 166 (2), 107–116.

Vu, J.C.V., Baker, J.T., Pennanen, A.H., Allen Jr., L.H., Bowes, G., Boote, K.J., 1998. Elevated CO_2 and water deficit effects on photosynthesis, ribulose bisphosphate carboxylase-oxygenase, and carbohydrate metabolism in rice. Physiol. Plant. 103 (3), 327–339.

Wall, G.W., Garcia, R.L., Wechsung, F., Kimball, B.A., 2011. Elevated atmospheric CO_2 and drought effects on leaf gas exchange properties of barley. Agric. Ecosyst. Environ. 144 (1), 390–404.

Wang, H.Q., Zhang, M.S., Dang, X.Y., Zhu, H., 2012. The response of agricultural water demand to climate change in Shiyang River basin, in Northwest China. Adv. Mater. Res. 347–353, 1964–1972.

Wang, H.L., Zhang, X.C., Wei, S.W., 2015. Impact of climate change on rain-fed farming and response solutions in semiarid area of Northwest China. J. Agric. Resour. Environ. 32 (6), 517–524 (In Chinese with English abstract).

Wardlaw, I.F., 1979. The physiological effects of temperature on plant growth. Proceedings of the Agronomy Society of New Zealand 9, 39–48.

Watts, W.R., 1971. Role of temperature in the regulation of leaf extension in Zea mays. Nature 229 (5279), 46–47.

Wullschleger, S.D., Gunderson, C.A., Hanson, P.J., Wilson, K.B., Norby, R.J., 2002. Sensitivity of stomatal and canopy conductance to elevated CO_2 concentration – interacting variables and perspectives of scale. New Phytol. 153 (3), 485–496.

Yelle, S., Beeson Jr., R.C., Trudel, M.J., Gosselin, A., 1990. Duration of CO_2 enrichment influences growth, yield, and gas exchange of two tomato species. J. Am. Soc. Hortic. Sci. 115 (1), 52–57.

Yu, G.R., Wang, Q.F., 2010. Ecophysiology of Plant Photosynthesis, Transpiration, and Water Use. Science Press, Beijing, pp. 586, (In Chinese).

Zelitch, I., 1982. The close relationship between net photosynthesis and crop yield. Bioscience 32 (10), 796–802.

Zhang, J.H., Sui, X.Z., Li, B., Su, B.L., Li, J.M., Zhou, D.X., 1998. An improved water-use efficiency for winter wheat grown under reduced irrigation. Field Crops Res. 59 (2), 91–98.

Zhang, X.Y., Chen, S.Y., Sun, H.Y., Pei, D., Wang, Y.M., 2008. Dry matter, harvest index, grain yield and water use efficiency as affected by water supply in winter wheat. Irrig. Sci. 27 (1), 1–10.

Zhao, H.Y., Zhang, Q., Gao, G., Lu, E., 2010. Characteristic analysis of agricultural drought disaster in China during 1951–2007. J. Nat. Disasters 19 (4), 201–206 (In Chinese with English abstract).

Ziska, L.H., Bunce, J.A., 1997. Influence of increasing carbon dioxide concentration on the photosynthetic and growth stimulation of selected C_4 crops and weeds. Photosynth. Res. 54 (3), 199–208.