Impact of elevated CO_2 concentration on growth and water use efficiency of spring wheat under free-air conditions at semi-arid rain-fed area of northwest China

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Abstract: Spring wheat (*Triticum aestivum* L. 'New Dingxi 24') was grown at ambient (370 μl l^{-1}) and elevated (620 μl l^{-1}) concentrations of CO_2 in a mini free-air CO_2 enrichment (FACE) facility to study the impact of CO_2 enrichment on growth, yield, and water use efficiency (WUE) in a semi-arid area in northwest China. The results showed that at the elevated CO_2 concentration the plant height (20.1%), leaf area index (18.8%), average number of grains in a spike (22.5%), and thousand-kernel weight (17.2%) were higher than that of ambient CO_2 concentration(CK), whereas the proportion of sterile spikes was 41.5% lower in the CO_2-enriched plots. The period from sowing to harvesting was 5 days longer (within which the filling–milking stage was significantly longer) in the CO_2-enriched plots. Consequently, the yield (15.4%) and water use efficiency (WUE) (15.4%) was significantly higher in the CO_2-enriched plots. Overall, the results suggest that the higher yield was mainly attributable to the greater average number of grains in a spike and higher thousand-kernel weight. Moreover, the improved WUE helped to counteract the negative effects of moisture stress.

Key words: *Triticum aestivum*; CO_2 enrichment; grain yield; yield components; water use efficiency

1. Introduction

The concentration of CO_2 in the atmosphere has risen by about over 40% since the Industrial Revolution, and is currently 391 μl·L^{-1} *(IPCC, 2013)*. Free-air CO_2 enrichment (FACE) systems has been facilitated since 1990s, which can expose plants to higher CO_2 concentrations at open-air conditions (Bunce *et al*., 2017; O'Leary *et al*., 2015; Iker *et al*., 2013; Ainsworth *et al*., 2011; 2007). Extensive research on the impact of elevated CO_2 concentration has been conducted on many field crops including wheat, sorghum, rice, soybean, clover, and cotton etc (Bunce *et al*., 2017; Chai *et al*., 2011; Kimball *et al*., 2006). If any of the adverse effects of climate change are not considered, increased levels of CO_2 have a positive impact on plant growth (IPCC, 2013), at a CO_2 concentration of 550 μl·L^{-1}, yields of C_3 plants are estimated to increase by 10–20% (Long *et al*., 2010; Yang *et al*., 2009) and those of C_4 plants by up to 10% (Gifford, 2004).

Elevated CO_2 concentration increases available effective carbon, stimulates dark respiration through transcriptional reprogramming of metabolism (Leakey *et al*., 2009), accelerates flag leaf senescence in wheat (Zhu *et al*., 2009), and restricts, chlorophyll content, and photosynthetic electron transport in PSⅡ (Gokhale *et al*., 2011). Elevated CO_2 concentration can lower the contents of protein, gliadin, gluteinin, and glutein in the grain and the sedimentation value of flour (Cui *et al*., 2011), together with the content of most of the amino acids in wheat grains (Högy and Fangmeier, 2008), but raise the contents of starch and organic acids in wheat grains and the capacity of chloroplasts to absorb light energy and the regulative capability of excitation energy distribution between PSⅡ and PSⅠ (Zuo *et al*., 2002). Elevated CO_2 concentration can increase grain yield and N accumulation through promoting the accumulation of dry matter and nitrogen in vegetative organs before anthesis and their translocation from vegetative organs into grains after anthesis (Xu *et al*., 2011). As CO_2 concentrations increase, the quantity, density, and morphological structure of roots change(Guo *et al*., 2002). Elevated CO_2 concentration increases the intrinsic water use efficiency (WUE) by lowering the ratio of CO_2 internal the leaves to that in atmospheric air (Erbs *et al*., 2009) and thus alleviates drought stress (Varga *et al*., 2010). Thus the impact of elevated CO_2 on plant water relations probably results in a positive feedback, leading in turn to higher availability of soil water (Erbs *et al*., 2009).

The present experiment sought to (a) test whether the soil of CO_2-elevated plots were wetter or drier than those in plots with normal levels of CO_2, (b) ascertain whether elevated CO_2 concentration can increase the yield of spring wheat, and (c) assess the beneficial effect of elevated CO_2 concentration on yield and WUE of spring wheat in semi-arid in northwestern China.

2. Materials and methods

2.1 Experimental site

The FACE experiments were carried out in 2010 at the Dingxi Arid Meteorology and Ecological Environment Experimental Station of the Institute of Arid Meteorology of China Meteorological Administration in Lanzhou (IAM, CMA). The station (35°33′ N, 104°35′ E, and 1896.7 m asl) lies in Dingxi county of Gansu, north-western China. The climate is medium temperate with mean annual air temperature of 7.1 °C, annual precipitation of 382 mm. Annual pan evaporation is 1500 mm, and the frost-free period is about 140 d. The soil at the experimental site is a loess-like loam, with average bulk density of 1.38 $g \cdot cm^{-3}$ before sowing, and a field water holding capacity of 25.6%. The permanent wilting point of the upper 180 cm layer of the soil profile is 6.7% (Zhao *et al*., 2012). There is no irrigation and regarded as a typical rain-fed agriculture region.

2.2 FACE facility and experiment design

The experiment was conducted in a mini-FACE facility consisting of a CO_2 supply device, a control system, a release system and a data collection system. Three FACE rings and three control rings were set up, each of which had a diameter of 4m. The actual experimental area within a ring was about $14m^2$ (Zhao *et al*, 2011).

Spring wheat (*Triticum aestivum* L. 'New Dingxi 24') was grown at ambient and elevated CO_2 concentrations in 2010. The experiment lasted from 18 March (the date of sowing) to 5 August (the date of harvest). From tillering to maturity, CO_2 concentration above the wheat canopy in the FACE plots was consistently maintained at a 250 $\mu l \cdot L^{-1}$ higher than the ambient level in the control plots (14-h average of 6:00-20:00 each day) by releasing pure CO_2 into the plant canopy. The release system regulated the flow to maintain the set concentration by taking into account wind direction and speed. The CO_2 concentrations at canopy height were monitored by a probe (VASALA, GMP343) at the centre of each FACE ring. The ambient air CO_2 concentration within the control rings was 370 $\mu l \cdot L^{-1}$.

Meteorological data including air temperature and relative humidity above canopy of spring wheat, as well as soil temperature and soil water content at depths of 10 cm, 20 cm were obtained from the weather station at the experimental site. All the data were monitored and recorded by a HOBO weather station (U30, USA). In order to increase the gradient, we also intensive observation soil temperature and soil water content at depths of 5 cm, 30 cm except for depths of 10 cm, 20 cm in the FACE rings.

In each plot, growth was recorded at different stages. Three wheat plants were chosen at random for the purpose and marked. Plant height was measured manually and leaf area index (LAI) was measured using a portable leaf area meter (LI-3000, Licor). After harvest, ten plants in each plot were sampled for determining the yield components and actual yield of each plot was also recorded.

2.3 Statistical analyses

The ANOVA procedure in SAS (1999) was used to conduct the analysis of variance. Mean values of the treatments were compared using the least significant difference (LSD) at $P \leq 0.05$. The values reported in the tables and figures are mean values.

3. Results

3.1 Meteorological condition during growth period

The air temperature (including mean, maximum and minimum air temperature), rainfall, relative humidity (RH) was showed in Table 1 during the whole growth period and every month during the growth of spring wheat.

Table 1. Temperature, rainfall during the growth period of spring wheat at Dingxi, China

Month	Tmean (°C)	Tmax (°C)	Tmin (°C)	Rainfall (mm)	RH (%)
March (3.18-3.31)	4.6	12.4	-2.5	3.5	42.1
April (4.1-4.30)	7.2	14.4	0.4	43.2	49.6
May (5.1-5.31)	13.6	19.7	7.6	60.2	56.4
June (6.1-6.30)	17.1	23.4	11.2	39.5	61.1
July (7.1-7.31)	20.2	26.8	14.6	30.2	67.7
August (8.1)	24.5	32.4	18.1	0.0	64.3
Average (3.18-8.1)	13.6	19.9	7.1	-	57.0
Total (3.18-8.1)	-	-	-	176.6	-

Table 2. Soil temperature and soil water content at different depths during the growth period of spring wheat under elevated and ambient CO2 concentrations

Month	Treatments	Soil temperature at the depth of 10 cm (°C)	Soil temperature at the depth of 20 cm (°C)	Soil water content at the depth of 10 cm (%)	Soil water content at the depth of 20 cm (%)
May (5.24-5.31)	+250	16.79	16.34	18.09	11.81
	CK	15.94	16.19	17.12	19.70
Jun(6.1-6.30)	+250	18.49	17.81	14.88	11.56
	CK	20.05	16.76	13.48	17.98
Jul(7.1-7.20)	+250	21.23	20.42	13.52	11.13
	CK	23.74	20.01	10.89	16.25
May-Jul(5.24-7.31)	+250	19.52	18.81	14.64	11.39
	CK	21.23	17.95	12.74	17.40

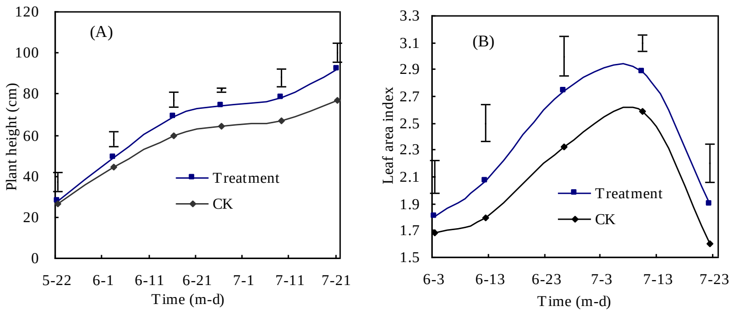

Figure 1. Differences in plant height (A) and leaf area index (B) of spring wheat under elevated and ambient CO2 concentrations. Bars show the LSD at P ≤ 0.05.

3.2 Growth and the micro-environment

3.2.1 Soil temperature and water content

Soil water content at a depth of 10 cm was higher 1.90% *in* CO_2-enriched *plots* during the later growth stages. At a depth of 20 cm, however, the patterns were just the opposite, with the treated plots recording lower levels of water by differences of 7.9%, 6.43%, and 5.12% in May, June, and July, respectively. The extent of difference was reduced during the later stages of the experiment. The mean soil water content for the entire experiment was 6.01% higher in the CO_2-enriched plots. The greater moisture content in the shallower layer must have benefitted crop growth (Table 2).

However, the difference of soil temperatures at the depth of 10cm, as well as 20cm, were not significant between the CO_2-enriched and CK plots (Table 2).

3.3 Development, yield, and WUE

3.3.1 Duration of growth stages

The duration of each growth stage is shown in Figure 5. In the CO_2*-enriched plots, the period from the grain-filling stage to the milking stage was longer by 4 days and the entire growth period was longer by 5 days* (the differences were significant at $P \leq 0.01$) but the lengths of *other stages did not differ significantly*. Obviously, the increased CO_2 concentration was beneficial for the growth and reproduction of spring wheat at the semi-arid, rain-fed site *(Figure is not shown here).*

3.3.2 Plant height and LAI

At all growth stages except *the jointing stage*, plants in the treated plots were significantly ($P \leq 0.05$) higher. The differences were heading stage by higher of 14.7%, filling stage of 15.9%, milking stage of 17.7%, and maturing stage of 20.1% (Figure 1A).

The differences of Leaf area index(LAI) were significant ($P \leq 0.05$) after the jointing stage with plant height. The exact differences were as follows: heading stage, LAI greater by 15.6%; grouting stage by 18.1%; milking stage by 11.2 %; and maturing stage by 18.8% (Figure 1B). *3.3.3 Yield components and WUE*

The elevated CO_2 concentration increased the yield of spring wheat significantly ($P \leq 0.05$) (Table 3), by as much

Table 3. Yield and water use efficiency of spring wheat under elevated and ambient CO2 concentrations

Treatments	Spikelet number	1000-grain weight (g)	Grain number per spike	Sterility spike rate (%)	Yield ($kg \cdot 667m^{-2}$)	Water use effiency (WUE) ($g \cdot m^{-3}$)
+250	16.27 [a]	48.06 [a]	36.50 [a]	6.98 [a]	208.0 [a]	1.50 [a]
CK	15.80 [a]	41.01 [b]	29.80 [b]	11.93[b]	180.3 [b]	1.30 [b]

Note: Means within columns followed by different letters are significantly different at P≤0.05.

as 15.4%. Values of different components of yield including thousand-kernel weight and average number of grains in a spike were also significantly ($P \leq 0.05$) higher. On average, each spike in the treated plots contained 6.7 more grains (the number greater by 22.5%) and samples of 1000-kernels were on average 7.07g heavier (heavier by 17.2%). The proportion of sterile spikes was significantly ($P \leq 0.05$) lower, by as much as 41.5%—all these differences resulted in significantly higher grain yield (208.0 $kg \cdot 667\ m^{-2}$ versus 180.3 $kg \cdot 667\ m^{-2}$). However, the number of spikelets did not increase significantly.

Water use efficiency (based on yield level) was also significantly ($P \leq 0.05$) higher by 15.4% in the CO_2-enriched plot. Thus, elevated CO_2 concentration improved yield and WUE of spring wheat at the semi-arid, rain-fed site. The yield increase resulted mainly from the greater number of grains in each spike and the higher weight of 1000 kernels (Table 3).

4. Discussion and conclusion

At the semi-arid rain-fed site, elevated CO2 concentration increased relative humidity above the canopy and soil water content of the surface layer (up to a depth of 10 cm), which is benefical to counteract drought and prolonged the grain-filling stage, thereby increasing both grain number and grain weight and, ultimately, grain yield. The increase may be the elevated CO2 concentration lowered the activity of photosystem Ⅰ (PSI) and (PSII) in leaves (Gokhale *et al*., 2011), delayed the heading and flowering stages, and changed the composition and transport of carbohydrates (Gokhale *et al*., 2011). The increased rate of photosynthesis and lowered stomatal conductance due to the elevated CO2 concentration decreased transpirational water loss. Consequently, soil water uptake by leaf area also declined although water was available in adequate quantities, which proved it is beneficial to dry matter transformation, transport, and partition, and thus increased WUE of leaves (Wall *et al*., 2001). Therefore, we propose that elevated CO2 concentration can promote the growth of spring wheat in water-deficient areas, enables plants to use the scarce water more efficiently in times of drought, and also favours the conversion of dry matter, a hypothesis consistent with the report by Wall (2001).

Present experiment was carried out at a semi-arid rain-fed site (Dingxi), the yield of spring wheat increased by 15.4%. Domestic research has shown that when atmospheric CO2 concentration was increased by 200 $\mu l \cdot L^{-1}$, the yield of winter wheat increased by 24.6% in a rice–wheat rotation mini-FACE system at a humid site (Wuxi) (Yang *et al*., 2009), and by 24.7% in a wheat–soybean rotation FACE system at a semi-humid site (Changping) (Han *et al*., 2009). Clearly, the increase is less marked in semi-arid rain-fed areas than that in humid and semi-humid areas, probably because wheat in humid and semi-humid areas is free from water stress and can thus derive greater benefit from the increased CO2 concentration; in semi-arid rain-fed areas, wheat usually suffers from water stress given the low precipitation throughout the year, and yields are often lower in drought years (Zhao *et al*., 1995). However, crops in these areas will benefit if atmospheric CO2 concentration is increased, because the increased CO2 will counter the adverse effect of water stress to some extent (Li *et al*., 2008), although the benefits will be smaller than those in humid and semi-humid areas. Higher concentration of CO2 can also increase the rate of photosynthesis and thus enable a plant to allocate more carbohydrates to its underground parts, thus promoting root growth. The better-developed root systems, in turn, ensures more efficient use of scarce water in times of drought, thereby promoting drought resistance or drought avoidance (Wall, 2001). Overall, it can be seen that elevated CO2 concentration has a complex impact on WUE of crops, and more experiments and further analysis are required to understand the impact in greater detail.

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