Effects of increased atmospheric CO_2 concentrations on photosynthetic characteristics of spring wheat in semiarid areas of Northwest China

Zhang K.[1,2,*] , Wang R.Y.[1] , Wang H.L.[1], Zhao F.N.[1], Qi Y.[1] And Chen F.[1]

[1]Gansu Key Laboratory of Arid Climatic Change and Reducing Disaster, Key Laboratory of Arid Climatic Change and Disaster Reduction of CMA, Institute of Arid Meteorology, China Meteorological Administration, Lanzhou, China 730020.

[2]Dingxi Arid Meteorology and Ecological Environment Experimental Station, Dingxi, Gansu, China 743000.

*corresponding author:

e-mail: lanzhouzhk@163.com

Abstract To provide a theoretical basis for the high-yield cultivation of spring wheat under increased CO_2 concentrations, an open-top chamber (OTC) experiment with the spring wheat variety Dingxi 24 was conducted during 2013 in Dingxi, Gansu, China. The photosynthetic characteristics of spring wheat under different CO_2 concentrations were analyzed. The results showed significant midday depressions of photosynthesis under both control and elevated CO_2 levels. The variation of intercellular CO_2 concentration in the spring wheat leaves presented a "V" shape, while the diurnal variation of transpiration rate (Tr) possessed a two-peak curve. Compared with the control concentration of 370 μmol/mol, under the CO_2 concentrations of 460 and 550 μmol/mol, the net photosynthetic rate (Pn) increased by an average of 14.68% and 28.20% over the whole growth period, respectively, the stomatal conductance (Cs) decreased by an average of 15.29% and 24.83%, respectively, the intercellular CO_2 concentration (Ci) increased by an average of 10.38% and 26.14%, respectively, and the transpiration rate decreased by an average of 6.63% and 12.41%, respectively. The increases of Pn and Ci, as well as the decreases of stomatal conductance and transpiration rate, were different at different growth stages under the increased CO_2 concentrations.

Keywords: Increased CO_2 concentration, Photosynthetic Characteristics, Spring wheat, Semiarid areas, Northwest China

1. Introduction

Along with the rapid development of modern agriculture and industry and the intensification of human activity, atmospheric CO_2 concentration has increased at an annual rate of 0.45%. This concentration has already risen from 270 μmol/mol in 1860 to 391 μmol/mol in 2011(IPCC, 2013). As estimated, the atmospheric CO_2 concentration by 2050 may reach 550 μmol/mol. By 2100, the atmospheric CO_2 concentration will further climb to 750 μmol/mol (Lin *et al*., 2005; IPCC, 2007). CO_2 is an important factor in crop habitats and also serves as the substrate for photosynthesis in green plants. The increase of atmospheric CO_2 concentration will have a profound influence on crop ecosystems. Therefore, the increase of atmospheric CO_2 concentration and its effects have become a focus of global research in the fields of ecology and agriculture (Yang *et al*., 2006).

Since the 1970s, many studies have examined the responses of plants to increased CO_2 concentrations (Kimball and Idso, 1983; Morison, 1985; Kang *et al*., 1996). In terms of photosynthetic characteristics, research has indicated that long-term growth under high concentrations of CO_2

decreases the photosynthetic rate of crops, indicating that the adaptation or downregulation of photosynthesis is a response to high CO_2 levels. A mild increase of CO_2 can promote the photosynthesis of plants, including crops, but to the extent of the impact, the results differed greatly. Wheat is a widely planted crop throughout the world. Semi-arid regions of Loess plateau in central Gansu Province are the main wheat planting areas in Northwest China, and some research has examined the effects of increased CO_2 concentrations on spring wheat in this area, however, the related research on spring wheat by using open-top chambers (OTC) test platform was still rather poor. In this study, the atmospheric CO_2 was controlled at different concentrations, and the effects of increased CO_2 concentrations on the photosynthetic characteristics of spring wheat were analyzed. The variation and regulation of photosynthetic rate, stomatal conductance, intercellular CO_2 concentration and transpiration rate under different CO_2 concentrations were examined. The findings provide a theoretical and technical basis for the cultivation of high-quality and high-yielding spring wheat by promoting the sufficient utilization of light energy and water resources under the elevated CO_2 conditions of the future.

2. Materials and methods

2.1. Test platform

The experiment was conducted in 2013 in open-top chambers (OTC), at the Dingxi Arid Meteorology and Ecological Experimental Station of the Lanzhou Institute of Arid Meteorology. The experimental station is located in the middle of Gansu Province (104°37′E, 35°35′N, altitude 1896.7 m), and represents a typical semiarid region of the Loess Plateau. The annual average temperature is 6.7°C, and the annual precipitation is 386.6 mm.

The OTC test platform consisted of a CO_2 supply device, control system and delivery system. Three OTCs were used in the experiment, consisting of two treatment chambers and one control chamber. Each OTC was equipped with a CO_2 gas monitor to collect the CO_2 samples. The control system analyzed the distribution of CO_2 concentration inside the OTC. A temperature-humidity sensor was also installed inside each OTC to collect the related real-time data. CO_2 was delivered to the OTCs from the beginning of May (tillering stage) to the end of July (harvest stage). From the baseline local average natural atmospheric CO_2 concentration (370 μmol/mol), 0, 90 and 180 μmol/mol of CO_2 were added to the three OTC, yielding final concentrations in OTC1, OTC2 and OTC3 of 370, 460 and 550 μmol/mol, respectively.

2.2. Experimental design

The spring wheat variety chosen for the experiment was Dingxi 24, which has narrow, grayish-green leaves. The stalk of the variety is slender and flexible, and its growth period is approximately 120 days. Dingxi 24 is commonly planted in the area. The seed was sown on April 1, 2013, at a row spacing of 0.15 m, and the total amount of seed was 225 kg/ha. Farmyard manure (56000 kg/ha), diammonium phosphate (228 kg/ha) and urea (138 kg/ha) were applied as basal fertilizer during sowing.

2.3. Observation indicators and methods

A LI-6400 portable photosynthesis system (LI-COR, USA) was used in the present study. At the jointing, booting, blooming, grain filling and milk ripe stages, 10 wheat leaves of identical growth status and illumination direction were collected on sunny days under stable climatic conditions. The gas exchange parameters of the plant samples in the treatment and control groups were measured, including net photosynthetic rate (Pn), stomatal conductance (Cs), transpiration rate (Tr), intercellular CO_2 concentration (Ci) and leaf temperature (T_l).

3. Results and analysis

3.1. Effects of CO_2 concentration on Pn of spring wheat leaves

Atmospheric CO_2 is a key ingredient of photosynthesis in wheat. The results showed that as CO_2 concentration increased, the net photosynthetic rate (Pn) of wheat leaves showed a significant increase (Figure 1a). In both the control and treatment groups, the diurnal variations of Pn in the wheat leaves exhibited a "two-peak" pattern. Pn increased gradually after sunrise, reaching its daily peak at 12:00. Pn then presented a declining tendency, with a second peak appearing at 16:00. An obvious “midday depression of photosynthesis” was exhibited. As shown in Figure 1a, Pn was much higher in the morning than in the afternoon, mainly because the accumulation of photosynthetic products in the leaves in the morning inhibited photosynthesis by negative feedback. The diurnal variations of Pn in wheat leaves under the different CO_2 concentrations were further analyzed. The results showed that, under the concentration of 460 μmol/mol, Pn was increased by a daily average of 17.34% compared with its value under 370 μmol/mol; under 550 μmol/mol, Pn was increased by a daily average of 33.61%. The Pn of the wheat leaves was therefore enhanced under both increased CO_2 concentrations. The increase was most significant at noon and much less significant in the morning and evening.

Figure 1b shows the responses of Pn in spring wheat leaves to the increases of atmospheric CO_2 concentration at different growth stages. Under the three different CO_2 concentrations, Pn was greatest at the blooming stage and smallest at the milk ripe stage. As atmospheric CO_2 concentration increased, the extent of the leaf Pn increase also varied. This increase was largest at the jointing stage (21.59% and 47.19%, respectively) and smallest at the blooming stage (7.91% and 13.83%, respectively).

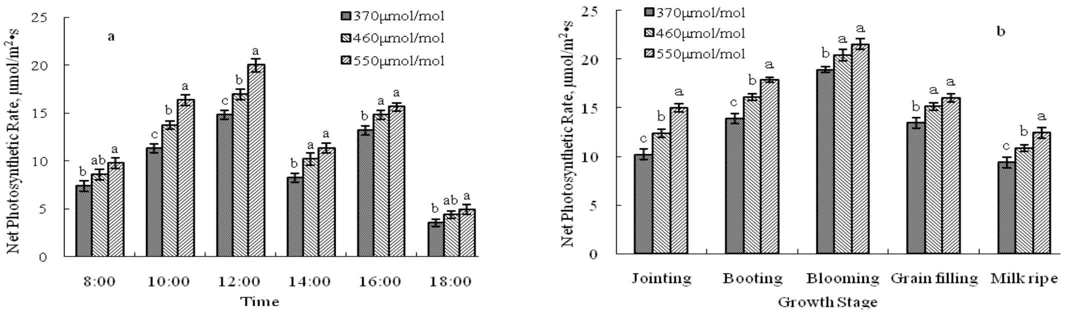

Figure 1. Diurnal variation (a) and growth stage variation (b) of net photosynthetic rate in leaves under different CO_2 concentrations.

.

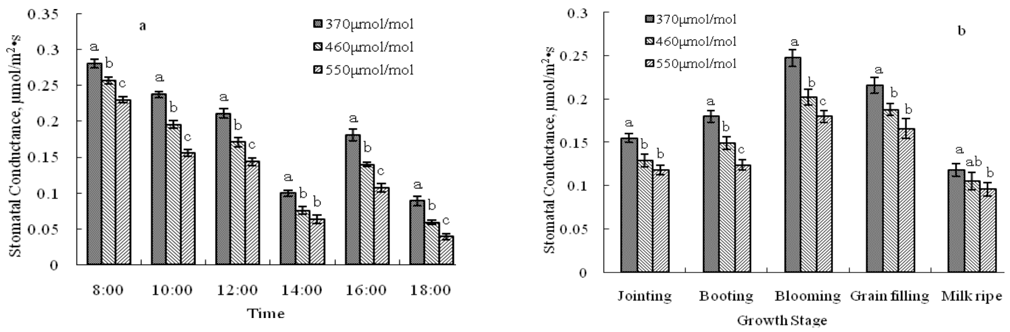

Figure 2. Diurnal variation (a) and growth stage variation(b) of stomatal conductance in leaves under different CO_2 concentrations

3.2. Effect of CO_2 concentration on Cs of spring wheat leaves

Stomata allow gas exchange between plant leaves and the environment and are also used for water evaporation and CO_2 exchange. Stomatal conductance (Cs) is used to measure the difficulty with which gas passes through the stomata. A higher Cs value indicates a larger stomatal aperture and smaller stomatal resistance, allowing water vapor and CO_2 to be smoothly exchanged (Zhao *et al.*, 2007). The diurnal variation of Cs in wheat leaves under different CO_2 concentrations is shown in Figure 2a. As illumination increased after sunrise, Cs increased and reached its maximum at 08:00. Cs then decreased gradually until 14:00, after which point it increased again and reached a second peak at 16:00. After this peak, Cs again declined and dropped to its minimum value. The diurnal variations of Cs in wheat under different CO_2 concentrations were further analyzed. Compared with the Cs value under the concentration of 370 μmol/mol, those under 460 and 550 μmol/mol decreased by a daily average of 18.37% and 32.73%, respectively.

Figure 2b shows the responses of Cs in spring wheat leaves to increased atmospheric CO_2 at different growth stages. In both the control and treatment groups, Cs was greatest at the blooming stage and smallest at the milk ripe stage. As atmospheric CO_2 concentration increased, the degree of Cs decrease differed between the two increased CO_2 treatments, and the greatest decreases occurred at the blooming stage (18.48%) and booting stage (31.11%) under 460 and 550 μmol/mol, respectively

3.3. Effects of CO_2 concentration on Ci in spring wheat leaves

Intercellular CO_2 concentration (Ci) is one of the major influencers of photosynthesis and is closely related to Pn. When Pn is higher, more CO_2 is fixed, which causes the reduction of Ci (Zhang *et al*., 2006). The variation of atmospheric CO_2 concentrations also affects the Ci of leaves, and increased CO_2 concentrations lead to increased concentration differences between the insides and outsides of leaves (Shen *et al*., 2009). As shown in Figure 3a, the diurnal variation of Ci in spring wheat leaves exhibited a slanted "V" curve. Ci declined rapidly from 08:00 to 12:00 and dropped to its minimum at 12:00, after which point it increased again. The diurnal variations of Ci in wheat leaves under different CO_2 concentrations were further analyzed. The results showed that the Ci values of both treatment groups were higher than those of the control group. Compared with Ci under the concentration of 370 μmol/mol, the Ci under 460 and 550 μmol/mol increased by 9.41% and 29.36% on average, respectively.

The effects of increased atmospheric CO_2 concentrations on the Ci of spring wheat leaves at different growth stages were analyzed (Figure 3b). In both the control and treatment groups, Ci was at its greatest at the blooming stage and its smallest at the milk ripe stage. Under the concentration of 460 μmol/mol, the increase of Ci at the different growth stages ranged from 6.20% to 15.60%, with an average of 10.38%; under 550 μmol/mol, the increase of Ci at the different growth stages ranged from 20.44 to 31.71%, with an average of 26.15%.

3.3. Effect of CO_2 concentrations on Tr in spring wheat

The results indicated that the tendency of diurnal variation for transpiration rate (Tr) in spring wheat was consistent with that of Pn and showed the same "two-peak" pattern, indicating the occurrence of a "midday depression of transpiration" (Figure 4a). As light intensity increased after 08:00, Tr gradually increased and reached its maximum at 12:00. At noon, the higher temperature and lower RH caused excess water loss from the leaves, inducing stomatal closure to reduce transpiration and maintain water balance. Tr declined rapidly and dropped to its minimum at 14:00. Later, as temperature decreased and RH increased, the water stress was alleviated and Tr rose again. The second peak appeared at 16:00, and as light intensity subsequently decreased, Tr declined rapidly. As shown in Figure 4a, the Tr of spring wheat leaves exhibited a declining tendency as atmospheric CO_2 concentrations increased. Under increased CO_2 concentrations, the Cs of spring wheat declined, increasing the resistance to vapor emission from the leaves and thereby decreasing Tr.

The effects of increased atmospheric CO_2 concentrations on the Tr of spring wheat leaves at different growth stages were analyzed (Figure 4b). In the control and treatment groups, the Tr of spring wheat was largest at the blooming stage and smallest at the jointing stage. Under the concentration of 460 μmol/mol, the decrease of Tr in spring wheat at different growth stages ranged from 4.17% to 9.92%, with an average of 6.63%. Under the concentration of 550 μmol/mol, the decrease of Tr in spring wheat at different growth stages ranged from 6.15% to 20.87%, with an average of 12.41%.

4. Conclusion

CO_2 is an important ingredient in the production of organic matter by photosynthesis. an open-top chamber (OTC) experiment was conducted to study the effects of increased atmospheric CO_2 concentrations (370, 460 and 550 μmol/mol) on photosynthetic characteristics of spring wheat in semiarid areas. The paper analyzed the variation and regulation of net photosynthetic rate, stomatal conductance, intercellular CO_2 concentration and transpiration rate under different CO_2 concentrations, and discussed the mechanism of the effects of increased atmospheric CO_2 concentrations on photosynthetic characteristics of spring wheat. The research results would provide a theoretical and technical basis for the cultivation of high-quality and high-yielding spring wheat by promoting the sufficient utilization of light energy and water resources under the elevated CO_2 conditions of the future. and had great significance for understanding the environmental adaptability of wheat to future climate changes.

Acknowledgements

This research was supported by the China Special Fund for Meteorological Research in the Public Interest (GYHY201106029, GYHY201506001-2), National Natural Science Foundation of China (41575149, 41505098), the Drought Meteorological Research Fund Project (IAM201505).

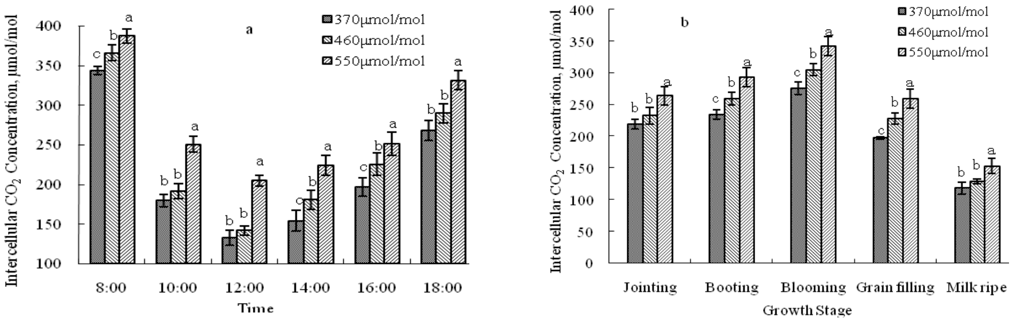

Figure 3. Diurnal variation (a) and growth stage variation (b) of intercellular CO_2 concentration in spring wheat leaves under different CO_2 concentrations

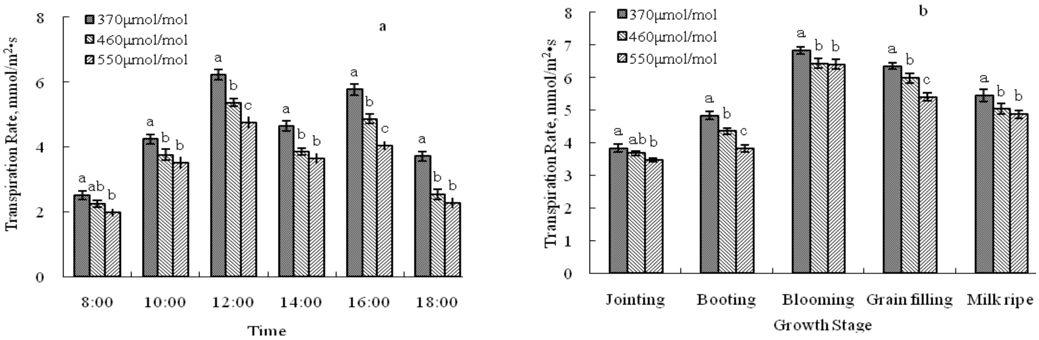

Figure 4. Diurnal variation (a) and growth stage variation (b) of transpiration rate in spring wheat leaves under different CO_2 concentrations

References

IPCC. (2013) Summary for Policymakers. In: T.F. Stocker et al. (Editors), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment REport of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York. NY. USA.

IPCC.(2007) Climate Change 2007: Impacts, Adaptation and Vulnerability.Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York. NY. USA.

Kang S. Z., Cai H. J., Liu X. M., Zhang F. C., liang Y. L. and Huang M. B. (1996) The effect of climate changes in the future on crop evapotranspiration and water use efficiency, *Journal of Hydraulic Engineering*, **4**,18-26.

Kimball B. A. and Idso S. B. (1983) Increasing atmospheric CO_2: Effects on crop yield, water use, and climate, *Agricultural Water Management*, **7**, 55-72.

Lin E. D., Xiong W., Ju H., Xu Y. L., Li Y., Bai L. P. and Xie L. Y. (2005) Climate change impacts on crop yield and quality with CO_2 fertilization in China, *Philos Trans R Soc London, Ser B*., **360**, 2149-2154.

Morison J. I. L. (1985) Sensitivity of stomata and water use efficiency to high CO_2, *Plant Cell Environ*, **8**,467-474.

Shen S. H., Zhang X. S., Deng A. J., Li Y. X. and Xie Y. S. (2009) Responses of leaf-level water use efficiency of winter wheat to CO_2 enrichment in different canopy layers, *Chinese Journal of Agrometeorology*, **30**, 547-552.

Yang L. X., Wang Y. L., Huang J. Y., Yang H. J. and Liu H. J. (2006) Responses of rice growth and development to free-air CO_2 enrichment(FACE): A research review, *Chinese Journal of Applied Ecology*, **17**, 1331-1337.

Zhang Z .A., Yang F., Chen Z .Y. and Xu K. Z. (2006) Relationship between diurnal changes of net photosynthetic rate and environmental factors in leaves of Zizania latifolia, *Chinese Journal of Ecology*, **3**, 502-509.

Zhao H., Yang Q. G., Deng Z. Y.and Liu H. Y. (2007) Characteristics of photosynthesis, transpiration and water use efficiency of wheat leaf in semi-arid rain feed region, *Agricultural Research in the Arid Area*, **1**,125-130.