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Effects of Doubled Atmospheric CO_2 Concentration on Apple Trees IV. Water Consumption

Auswirkungen einer Verdoppelung der atmosphärischen CO_2-Konzentration auf Apfel IV. Wasserverbrauch

K. Chen, G. Q. Hu, and F. Lenz
(Institut für Obstbau und Gemüsebau, Universität Bonn)

Summary

Two year old apple (*Malus domestica* Borkh. cv. 'Golden Delicious') trees on 'M9' were exposed to ambient (350 ± 10 ppm) and doubled (700 ± 10 ppm) atmospheric CO_2 for 120 d in growth chambers situated in an apple orchard. Atmospheric CO_2 enrichment accelerated new leaf appearance, total leaf area increment, and total shoot length of the trees due to the increase of carbohydrate production of the plants. As a result of dry mass accumulation in the plant tissues, water content in all organs of the trees tended to decline during the long-term atmospheric CO_2 enrichment. Cumulative water consumption, however, was higher in trees exposed to 700 than 350 ppm CO_2 concentration throughout the experiment. The differences in cumulative water consumption between the two sets of trees developed with the duration of the CO_2 treatments. In June, July, August, September, and October, the mean of daily water consumption per tree was recorded 174.4, 297.2, 308.3, 231.3, and 135.7 ml for trees grown under the 350 ppm CO_2 condition, and 206.7, 334.5, 346.2, 277.4, and 173.4 ml for those at 700 ppm CO_2, respectively. In comparison with trees grown at 350 ppm CO_2 concentration, those treated by 700 ppm CO_2 were characterised by an increase of total water consumption by 13 – 16 % and water-use efficiency by 98 – 130 %, whereas leaf transpiration rate and water-uptake efficiency of the plant roots decreased by 27 – 33 % and 39 – 41 %. Linear regression and bivariate correlation analyses revealed very significantly positive relationships among cumulative sunshine duration, natural evaporation, air temperature, total leaf number as well as total shoot length per tree, and total water consumption of the trees at both 350 and 700 ppm CO_2 concentrations. The physiological mechanisms to enhance the canopy development and foliage transpiration, and to raise water-consumption efficiency of the plants are associated with the altered water status and improved growth turgor of the trial apple trees treated by the long-term doubled atmospheric CO_2 concentration. A continuous increase in CO_2 concentration of the global atmosphere in the future will not significantly change the pattern for water consumption of apple trees. However, it will enable the plants to utilize available soil water for dry mass production more efficiency, and thus improve apple productivity.

Zusammenfassung

Zweijährige Apfelbäume (*Malus domestica* Borkh. cv. 'Golden Delicious') auf 'M9' wurden 120 Tage in Pflanzenkammern, die in einer Apfelplantage aufgestellt waren, der gegenwärtigen (350 ± 10 ppm) und der doppelten atmosphärischen CO_2-Konzentration (700 ± 10 ppm) ausgesetzt. Infolge der erhöhten CO_2-Konzentration wurde die Bildung neuer Blätter, die Zunahme der gesamten Blattfläche sowie die der Gesamtlänge der Triebe pro Baum beschleunigt. Der Wassergehalt sämtlicher Organe nahm im Behandlungszeitraum tendenziell ab. Während des gesamten Experimentes war der kumulative Wasserverbrauch von Bäumen, die 700 ppm CO_2 ausgesetzt waren, größer. Die Unterschiede im kumulativen Wasserverbrauch zwischen den beiden CO_2-Ansätzen wurden um so deutlicher, je länger das Experiment dauerte. Im Juni, Juli, August, September und Oktober betrug der mittlere tägliche Wasserverbrauch pro Baum bei 350 ppm CO_2 174.4, 297.2, 308.3, 231.3 und 135.7 *ml*, und bei 700 ppm CO_2 206.7, 334.5, 346.2, 277.4 und 173.4 *ml*. Im Vergleich zu Bäumen, die bei 350 ppm CO_2 wuchsen, zeichneten sich die bei 700 ppm gehaltenen durch einen Anstieg des gesamten Wasserverbrauchs um 13 – 16 % und der Effizienz der Wasserausnutzung um 98 – 130 % aus. Dagegen nahm die Transpirationsrate der Blätter um 27 – 33 % und die Effizienz der Wasseraufnahme über die Wurzel um 39 – 41 % ab. Lineare Regressions- und bivariate Korrelationsanalysen zeigten eine signifikante positive Korrelation zwischen der kumulativen Sonnenscheindauer, der natürlichen Evaporation, der Lufttemperatur, der Zahl aller Blätter sowie der Gesamtlänge aller Triebe pro Baum und dem Gesamt-Wasserverbrauch der Bäume sowohl bei 350 als auch bei 700 ppm CO_2.

Introduction

The primary effects of an elevated atmospheric carbon dioxide (CO_2) concentration on C_3 plants are enhancement of photosynthetic CO_2 uptake (CHEN et al. 1997, STITT 1991) as well as reductions in stomatal conductance for water-vapour diffusion and transpiration rate per unit of leaf area (CEULEMANS and MOUSSEAU 1994, CHEN and LENZ 1997a). In response to atmospheric CO_2 enrichment, a combination of these effects may result in a decreased leaf transpiration index and an improved water-consumption efficiency of plants

(BAZZAZ 1990, CHEN et al. 1997). KIMBALL and IDSO (1983), based on 46 previous observations of 18 species, estimated that doubling the present atmospheric CO_2 concentration doubled water-use efficiency of plants. These secondary responses to elevated CO_2 are of ecological and physiological importance to drought tolerance of plants with regard to global climate changes, particularly in dry seasons as well as in water-deficient regions (MORISON 1993). Plant water-consumption is one of the most important processes closely related to plant growth and productivity (EAMUS and JARVIS 1989). Both atmospheric CO_2 concentration and water supply are the two key limitations for apple production, since most commercial apple orchards are established in hilly and arid areas (JONES et al. 1986, LENZ 1985). CHEN and LENZ (1997b) investigated seasonal fluctuations for water use of apple trees growing in field lysimeters as affected by training method, shading, and fruiting. However, water consumption of apple trees under elevated atmospheric CO_2 levels has rarely been studied yet. The objectives of the present work were

- to investigate the differences in leaf transpiration index and daily water consumption of apple trees under 350 and 700 ppm CO_2 conditions,
- to examine whether long-term atmospheric CO_2 enrichment affects water-uptake efficiency of roots and water-consumption efficiency of the trees, and
- to evaluate the effects of most important internal and external factors, such as total leaf number and total shoot length per tree, cumulative sunshine duration, natural evaporation as well as air temperature, on total water consumption of apple trees at both ambient and doubled CO_2 concentration.

Materials and Methods

From June 18 to October 16 in 1996, 16 two year old 'Golden Delicious' apple (*Malus domestica* Borkh.) trees on 'M9' rootstocks were exposed to ambient (350 ± 10 ppm) and doubled (700 ± 10 ppm) CO_2 in growth chambers situated in an apple orchard as described before (CHEN et al. 2001). Each chamber was connected to a closed air-circuit and microclimate-control system (UKG 4000, Kälte-Klimatechnik, K. H. Spitzl GmbH, Bonn, Germany) with an air flow rate of 100 $m^3 h^{-1}$. Except of the CO_2 concentration, the other environmental parameters in the chambers were maintained similar to orchard-conditions. Meteorological data (Fig. 1) were obtained from the local meteorological station approximately 1000 m away from the plant growth chambers.

The trees were individually grown in 10 l plastic pots filled with 0.7 – 1.2 mm Ø quartz sand. Pots were covered by 1 – 2 cm Ø pebbles to prevent the surface sand from crusting and to minimize evaporation of the culture medium. Each pot was placed in a 20 l lysimeter which was connected to a 10 l plastic bottle with daily additions of tap water. The trees were supplied with sufficient Hoagland nutrient solution (HOAGLAND and ARNON 1938) twice a week, irrigated and drained every 2 hours from 10:00 to 18:00 by raising and lowering the position of bottles relative to the lysimeters as described by WERNER and LENZ (1980). Daily water consumption of each tree was calculated on the basis of the differences of water volume in the bottle before and after flooding by each day.

Total leaf number and total shoot length per tree were investigated in the middle of each month during the experiment. Destructive harvests of four trees for each treatment were performed at a two-months-interval. The trees were fractionated into their different organs to investigate dry weight of each component. Leaf area was measured with a LI-COR 3100 area meter (LI-COR, INC., Lincoln, Nebraska, USA). Leaf transpiration index was defined as water consumption per unit of leaf area per tree. Water-uptake efficiency of roots represented the ratio of total water consumption per tree to its total root dry weight at harvest (CHEN et al. 2000, 2002a). Water-use efficiency of the tree was expressed as total dry mass increment of the whole plant divided by its total water consumption during the CO_2 treatment.

All measurements were conducted as randomized block designs. The experimental data were tested for normal distribution. Levene tests were adopted to examine variance homogeneity. Student t-tests were used for comparison of means between 350 and 700 ppm CO_2 treatments by SPSS commercial software (SPSS INC., Chicago, USA). Linear regression and bivariate correlation analyses were carried out to evaluate the relationships of cumulative sunshine duration, natural evaporation, air temperature, total leaf number as well as total shoot length per tree and total water consumption of the trees under both ambient and doubled atmospheric CO_2 conditions.

Results

Total leaf number and leaf area increment

Total leaf number per tree increased linearly during the experiment both at 350 and 700 ppm CO_2 concentrations (Fig. 2). However, the differences between the two treatments became more distinct the longer the experiment continued, mainly because doubled CO_2 promoted the appearance of new leaves. When compared with trees grown under 350 ppm CO_2, those grown under 700 ppm CO_2 developed additional 9, 20, 28, and 34 leaves per tree in July, August, September, and October, respectively (Fig. 2).

On the other hand, atmospheric CO_2 enrichment significantly promoted single leaf area development (data not shown). As a consequence, doubled CO_2 concentration increased total leaf area per tree by 55 % and 73 % in the first and the second 60 d of the CO_2 treatments when compared with trees grown under 350 ppm CO_2 (Tab. 1).

Increment of total shoot length

Similarly, total shoot length of the trial apple trees continuously increased during the experiment (Fig. 3). The doubled atmospheric CO_2 concentration accelerated the appearance and prolongation of new shoots. Nevertheless, the increase rate in total shoot length of the trees grown under 700 ppm CO_2 slightly declined in September and October as the effects of developmental stage and growth rhythm of the shoots. In comparison

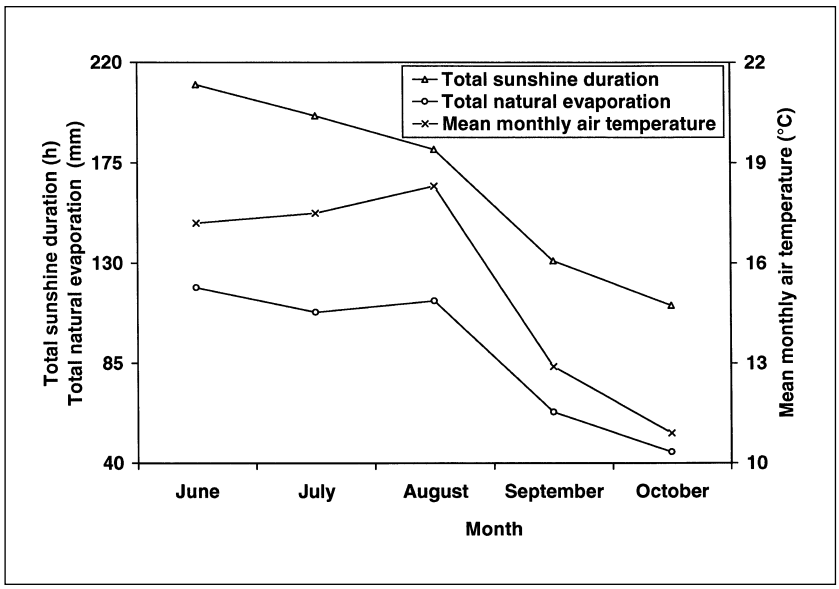


Fig. 1. Total sunshine duration, total natural evaporation, and mean monthly air temperature during the experiment.
Gesamt-Sonnenscheindauer, gesamte natürliche Evaporation und mittlere monatliche Lufttemperatur während des Experimentes.

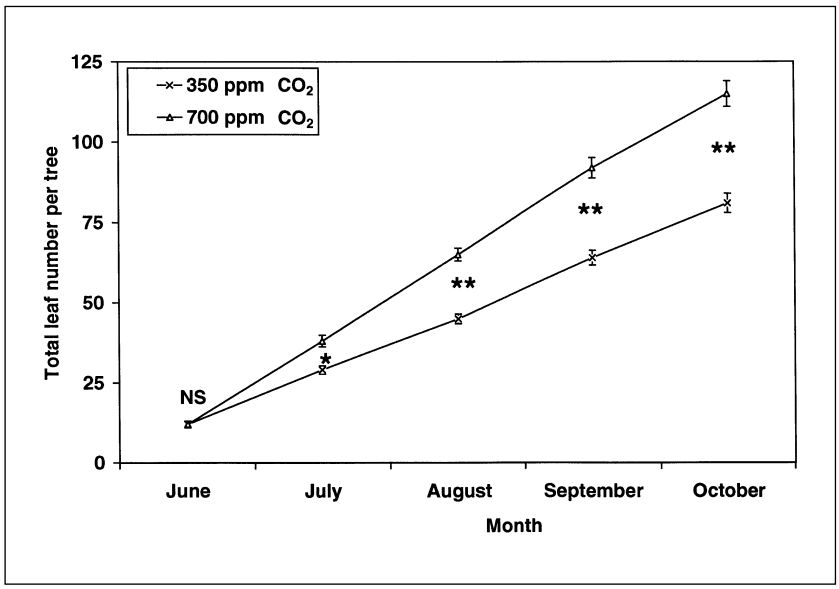


Fig. 2. Total leaf number of apple trees as affected by doubled CO_2 (**, *, and NS denote the significance of t-tests at $P<0.01$, $P<0.05$, and $P>0.05$, respectively).
*Auswirkungen einer Verdoppelung der atmosphärischen CO_2-Konzentration auf die Zahl aller Blätter bei Apfel (**, * und NS geben die Signifikanzen der T-Tests an; $P<0.01$, $P<0.05$ und $P>0.05$).*

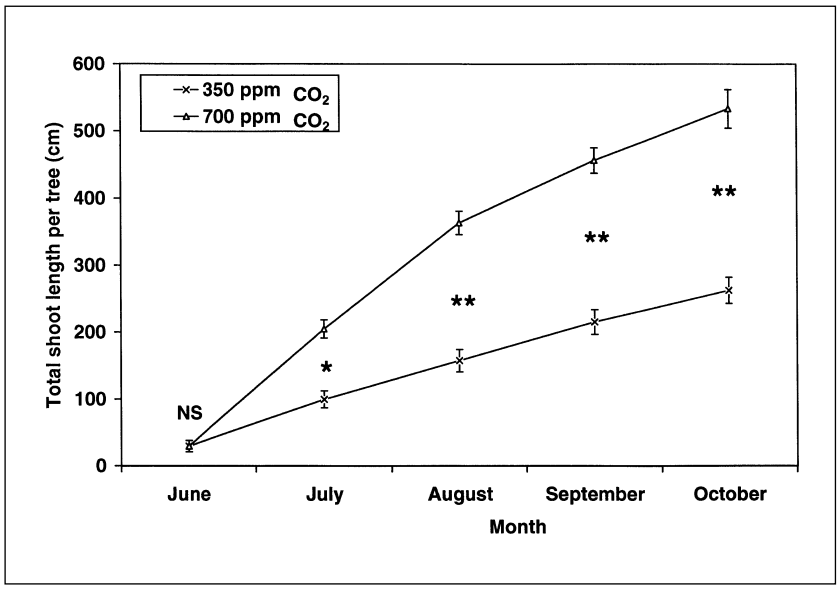


Fig. 3. Total shoot length of apple trees as affected by doubled CO_2 (**, *, and NS denote the significance of t-tests at $P<0.01$, $P<0.05$, and $P>0.05$, respectively).
*Auswirkungen einer Verdoppelung der atmosphärischen CO_2-Konzentration auf die Gesamtlänge aller Triebe bei Apfel (**, * und NS geben die Signifikanzen der T-Tests an; $P<0.01$, $P<0.05$ und $P>0.05$).*

Table 1. Total leaf area and water consumption of apple trees as affected by doubled CO_2.
Auswirkungen einer Verdoppelung der gegenwärtigen CO_2-Konzentration auf die gesamte Blattfläche und den Wasserverbrauch von Apfel.

Treatment CO_2 (ppm)	Duration (d)	Total leaf area (cm^2 $tree^{-1}$)	Total water consumption (l H_2O $plant^{-1}$)	Mean daily water consumption (ml H_2O $tree^{-1}$)	Leaf transpiration index (l H_2O m^{-2} leaf)
350	60	1283.6 ± 3.8	16.41 ± 0.45	273.6 ± 7.5	127.9 ± 3.9
700	60	1993.6 ± 36.4	18.60 ± 0.92	309.9 ± 15.3	93.3 ± 6.3
Significance		**	*	*	*
350	120	1680.0 ± 49.2	30.01 ± 0.84	250.1 ± 7.0	178.7 ± 2.0
700	120	2906.6 ± 12.0	34.71 ± 1.71	289.3 ± 14.3	119.4 ± 5.4
Significance		**	*	*	**

Values are means ± SD. ** and * denote significances of t-tests at $P<0.01$ and $P<0.05$, respectively.

Table 2. Water content (%) in different organs of apple trees as affected by doubled CO_2.
Auswirkungen einer Verdoppelung der gegenwärtigen CO_2-Konzentration auf den Wassergehalt in % von verschiedenen Organen bei Apfel.

CO_2 (ppm)	Duration (d)	Leaves	Shoots	Stems	Roots	Trees
350	60	67.7 ± 1.5	64.7 ± 1.8	50.1 ± 2.4	53.6 ± 0.4	58.0 ± 2.1
700	60	64.4 ± 3.7	62.7 ± 3.8	48.7 ± 2.4	51.4 ± 2.7	56.8 ± 3.0
Significance		NS	NS	NS	NS	NS
350	120	65.8 ± 0.9	54.4 ± 0.1	48.3 ± 1.1	61.4 ± 3.6	58.0 ± 0.5
700	120	53.6 ± 3.9	53.5 ± 0.2	45.5 ± 2.1	53.3 ± 3.2	51.7 ± 3.1
Significance		*	NS	NS	*	*

Values are means ± SD. * and NS denote significances of t-tests at $P<0.05$ and $P>0.05$, respectively.

with trees grown at 350 ppm CO_2, those grown at 700 ppm CO_2 increased total shoot length by 105.5, 205.7, 240.9, and 270.4 cm per tree in July, August, September, and October, respectively (Fig. 3).

Water content of organs

Water content was always highest in leaves, medium in shoots and roots, and lowest in stems (Tab. 2). As shown in Tab. 2, atmospheric CO_2 enrichment tended to reduce water content in all organs of the plants. When compared with the trees grown under 350 ppm CO_2, no significant differences of water content in all organs of the plants were observed in those grown under 700 ppm CO_2 during the first 60 d, but water content in leaves, roots, and the whole plant level significantly decreased in trees exposed to 700 ppm CO_2 by the end of the experiment (Tab. 2). As a result, average water content was 6.3 % lower in trees grown under 700 than 350 ppm CO_2 after 120 d of the CO_2 treatment.

Water consumption

Long-term atmospheric CO_2 enrichment promoted total water consumption of the trees as well as mean daily water consumption per tree, but decreased leaf transpiration indexes of the trees (Tab. 1). When compared with the 350 ppm CO_2 treatment, 700 ppm CO_2 increased both total water consumption and mean daily water consumption per tree by 13 – 16 %, and reduced leaf transpiration index by 27 – 33 % throughout the experiment.

Cumulative water consumption of the trees was always higher in trees grown under 700 than 350 ppm CO_2 concentration (Fig. 4). The difference was not statistically significant until July, but it became more and more prominent from August to October. In comparison with the 350 ppm CO_2 treatment, 700 ppm CO_2 increased cumulative water consumption by 0.4, 1.6, 2.8, 4.1, and 4.7 l per tree in June, July, August, September, and October, respectively (Fig. 4).

The mean of daily water consumption of the trial trees depended on the season (Fig. 5). It was highest in August, next in July, then in September, very low in June, and lowest in October. As indicated in Fig. 5, daily water consumption was also higher for trees grown under 700 than 350 ppm CO_2 throughout the experiment. The difference was larger by the end of the CO_2 treatment than at the early stage of the experiment. When compared with trees grown at 350 ppm CO_2, 700 ppm CO_2, on average, increased the monthly mean of daily water consumption by 32, 37, 38, 46, and 38 ml per tree in June, July, August, September, and October, respectively (Fig. 5).

Water-uptake efficiency and water-consumption efficiency

Doubled CO_2 reduced water-uptake efficiency of the plant roots, but improved water-consumption efficiency of the trees (Fig. 6). These effects were more prominent in the second 60 d than the first 60 d of the CO_2 experiment. By comparison, water-uptake efficiency of plant roots decreased by 39 – 41 %, whereas water-consumption efficiency of the trees increased by 98 – 130 % due to the long-term atmospheric CO_2-enrichment (Fig. 6).

Discussion

Organic solutes in plant cells, especially soluble carbohydrates of photosynthetic origin, constitute a major fraction of osmotic substance in cells (PEARCY and BJÖRKMAN 1985). Increases in dry mass and carbohydrate production of the trees and their accumulation in

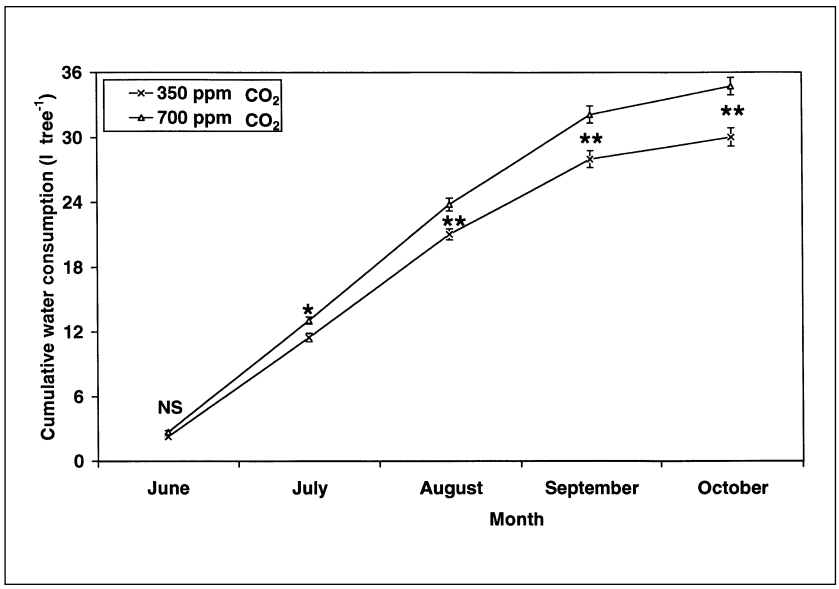


Fig. 4. Cumulative water consumption of apple trees as affected by doubled CO_2 (**, *, and NS denote the significance of t-tests at $P<0.01$, $P<0.05$, and $P>0.05$, respectively).
*Auswirkungen einer Verdoppelung der atmosphärischen CO_2-Konzentration auf den kumulativen Wasserverbrauch bei Apfel (**, * und NS geben die Signifikanzen der T-Tests an; $P<0.01$, $P<0.05$ und $P>0.05$).*

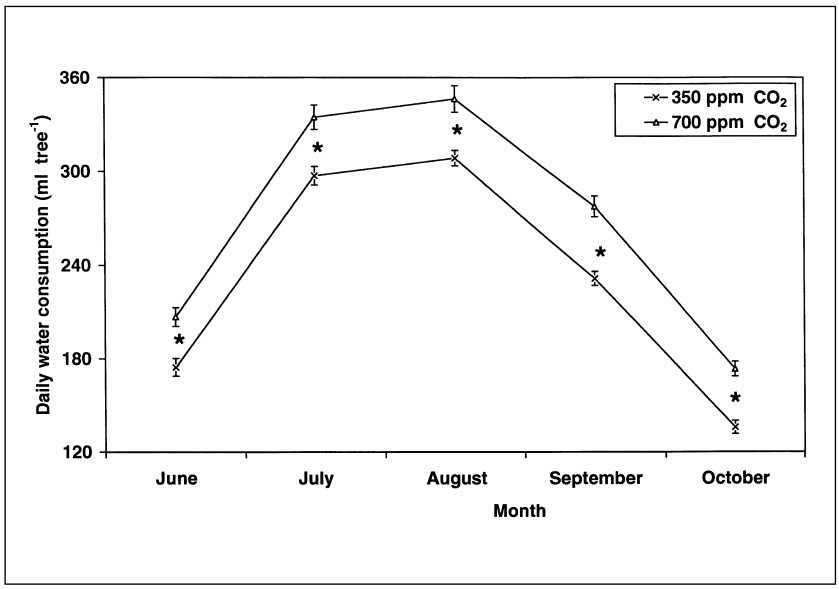


Fig. 5. Daily water consumption of apple trees in different months as affected by doubled CO_2 (* denotes the significance of t-tests at $P<0.05$).
Auswirkungen einer Verdoppelung der atmosphärischen CO_2-Konzentration auf den täglichen Wasserverbrauch von Apfel in den verschiedenen Monaten (gibt einen signifikanten Unterschied der T-Tests bei $P<0.05$ an).*

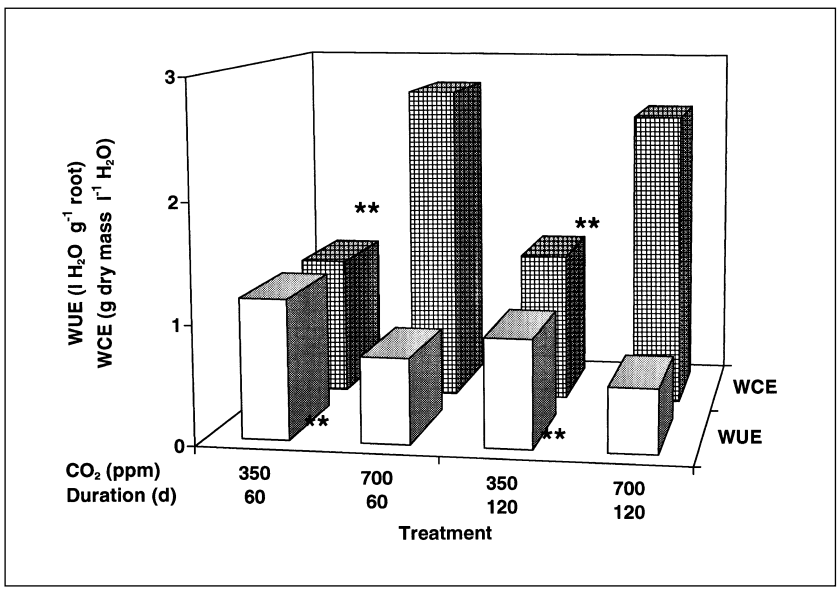


Fig. 6. Water-uptake efficiency (WUE) and water-consumption efficiency (WCE) of apple trees as affected by doubled CO_2 (** denotes the significance of t-tests at $P<0.01$).
*Auswirkungen einer Verdoppelung der atmosphärischen CO_2-Konzentration auf die Effizienz der Wasseraufnahme (WUE) und des Wasserverbrauchs (WCE) bei Apfel (** gibt einen signifikanten Unterschied der T-Tests bei $P<0.01$ an).*

the plant tissues under high CO_2 (CHEN et al. 2002a, 2002b) may lead to a more concentrated cell sap, and hence to a lower water content of the plant organs (Tab. 2). The altered water status and improved turgor of the trees grown at 700 ppm CO_2 in this experiment (Tab. 2) may be one of the most important mechanisms to accelerate new leaf appearance (Fig. 2) and total leaf area development, resulting in a larger single leaf area (data not shown) and therefore, ultimately promoting leaf growth and canopy development (CHEN et al. 2001). In addition, high CO_2 may change growth rates both in above- and below-ground organs of the trees (CHEN et al. 2001), which substantially affects water-use and turgor properties of the plants. On one hand, the trees grown under high CO_2 conditions can develop a larger canopy surface, which may enhance water loss via foliage transpiration, thus, tending to increase total water consumption per tree. KIMBALL and IDSO (1983) also observed that the long-term atmospheric CO_2 enrichment increased water consumption in many annual crops as a result of a higher foliage transpiration rate. On the other hand, a larger and more vigorous root system of the tree grown at a high CO_2-atmosphere enables the plant to extract more water from the culture medium (CHEN et al. 2002a, ROGERS et al. 1994). Whereas a decline in water-uptake efficiency of the plant roots grown at 700 ppm CO_2 concentration (Fig. 6) mainly resulted from an increase in dry mass allocation to the roots, which agreed well with our previous observations on doubled atmospheric CO_2 effects on water consumption of strawberry plants (CHEN et al. 1997), pepino and citrus (unpublished data). Besides, the elevated atmospheric CO_2 concentration tended to reduce the stomatal conductance of plant leaves (BAZZAZ 1990, EAMUS and JARVIS 1989), which might limit total water use by decreasing leaf transpiration index of the trees (Tab. 1). The reduced leaf transpiration index just partly offset the enhanced total water consumption of the plants due to the increased dry mass production. Thus, water-consumption efficiency of the trees rose with the atmospheric CO_2 enrichment. A 98 – 130 % increase in water-consumption efficiency of trees grown under 700 ppm CO_2 in comparison to those grown under 350 ppm CO_2 was observed in this experiment, which was consistent with the evaluation of KIMBALL and IDSO (1983). The increased plant growth maintain a higher turgor pressure of the trees under elevated atmospheric CO_2 concentration, but under water-deficiency condition, drought stress may less affect the plants grown in a high CO_2-atmosphere because of their improved water-consumption efficiency. In the present experiment, water-use efficiency of the tree was expressed as dry mass increment per unit of water consumption over the whole period of the CO_2 treatment. It may therefore represent a long-term effect of the doubled atmospheric CO_2 concentration on the real efficiency in water consumption of the tree with regard to its dry mass productivity. The positive response of water-consumption efficiency of apple trees to the elevated atmospheric CO_2 concentration indicates that the predicted future increase of the global atmospheric CO_2 level will increase the amount of dry mass production per water expended. It suggests that the trees will use the available soil water more efficiently to produce more dry mass under high CO_2 conditions. Thus, the predicted elevated global atmospheric CO_2 concentration in the future should substantially improve apple productivity, wherever water supply exerts an important limitation on apple tree growth, especially in arid and hilly regions.

The relationships between atmospheric CO_2 enrichment and water consumption of apple trees are complex. Firstly, water-vapour diffusion and CO_2 exchange through the stomata on the leaf surface are interrelated and may also interact with each other (CEULEMANS and MOUSSEAU 1994, EAMUS and JARVIS 1989). In contrast to annual crops, secondly, apple trees have a relatively large canopy and root system. Their development needs more time and, consequently, the distance and time delay from water uptake by the roots to transpiration by leaves is larger in apple trees than in annual crops. The metabolic activity of the above- and below-ground organs of the trees and the regulation of their activity may influence both water uptake and water loss of the trees (LENZ 1985, MORISON 1983). Finally, water consumption of apple trees depends not only on plant physiological, but also on environmental factors (JONES et al. 1986). Total leaf number (Fig. 2), leaf area (Tab. 1) and total shoot length (Fig. 3) of the trees, as well as cumulative sunshine duration, natural evaporation, and air temperature (Fig. 1) are most important physiological and environmental factors directly affecting the amount of leaf transpiration (Tab. 1), water uptake of the plant roots and water consumption of the trees. Foliage development and shoot growth are the key factors determining water loss of the trees (CHEN and LENZ 1997b, JONES et al. 1986). In the present experiment, simultaneous increases were observed not just in total leaf number (Fig. 2), total leaf area (Tab.1) and total shoot length (Fig. 3) of the trees, but still in cumulative water consumption of the trees during the CO_2 treatment (Fig. 4). The mean of daily water consumption per tree, however, increased from June to July, maintained a high level during July and August, and sharply declined after August (Fig. 5). This fluctuation might mainly result from growth rhythm of both leaves and shoots (Fig. 2 and 3). Similar patterns of leaf and shoot development as well as daily water consumption of apple trees were observed by CHEN and LENZ (1997b) in a field lysimeter experiment lasting for several growing seasons.

The present experiment, moreover, showed close interrelationships among water consumption of apple trees and physiological as well as environmental factors (Tab. 3), because these internal and external factors both interacted not only with water uptake of the plant roots but also with water loss of the canopy. Linear regression and bivariate correlation analyses showed that there were very significant positive relationships between total water consumption of the plants and the internal and external factors of the trees at both 350 and 700 ppm CO_2 (Tab. 3). Therefore, the experiment results are thought to provide valuable predictions of water-consumption by apple trees under an elevated atmospheric CO_2 concentration as predicted for the next century. When compared with the 350 ppm CO_2 treatment, furthermore, both the regression coefficient and the constant increased at 700 ppm CO_2 (Tab. 3). Thus, the present results suggest that the pattern for water consumption of apple trees will not be signifi-

Table 3. Linear regression and bivariate correlation relationships among cumulative sunshine duration (X_1, h), natural evaporation (X_2, mm), air temperature (X_3, °C), total leaf number (X_4, leaves tree^{-1}), total shoot length (X_5, cm tree^{-1}), and total water consumption (Y, l H_2O tree^{-1}) of apple trees under 350 and 700 ppm CO_2 conditions.
Lineare Regression und bivariate Korrelation zwischen der kumulativen Sonnenscheindauer (X_1, h), der natürlichen Evaporation (X_2, mm), der Lufttemperatur (X_3, °C), der Zahl aller Blätter (X_4, Blätter Baum^{-1}), der Gesamtlänge aller Triebe (X_5, cm Baum^{-1}) und dem Gesamt-Wasserverbrauch (Y, l H_2O Baum^{-1}) von Apfel bei 350 und 700 ppm CO_2.

Statistical parameter		X_1	X_2	X_3	X_4	X_5
			350 ppm CO_2			
Regression coefficient (B)		49.2	90.6	16.5	438.5	131.2
Constant (A)		–5139.3	–5921.9	–3053.2	1671.2	1868.9
Correlation coefficient						
	Y	0.999***	0.999***	0.999***	0.987**	0.996***
	X_1		0.998***	0.999***	0.990**	0.998***
	X_2			0.998***	0.980**	0.992**
	X_3				0.991**	0.998***
	X_4					0.997***
			700 ppm CO_2			
Regression coefficient (B)		57.0	104.8	19.1	340.4	69.5
Constant (A)		–6036.7	–6898.8	–3626.0	3381.7	3257.3
Correlation coefficient						
	Y	0.999***	0.998***	0.999***	0.994***	0.997***
	X_1		0.998***	0.999***	0.995***	0.998***
	X_2			0.998***	0.987**	0.999***
	X_3				0.996***	0.998***
	X_4					0.987**

Regression formula is $Y = A + B \times X_n$ (n=1, 2, …, 5). *** and ** denote significances of the correlation coefficient at $P<0.001$ and $P<0.01$, respectively.

cantly changed by the increase in global atmospheric CO_2 concentration in the future. However, the above physiological and environmental factors will play more important effects on water consumption of apple trees at the doubled than ambient CO_2 level.

Conclusion

The doubled atmospheric CO_2 concentration promoted apple trees to initiate more new leaves, to expand total leaf area, and to prolong total shoot length, which in turn enable the plants to increase their total water consumption. The atmospheric CO_2 enrichment, on the other hand, tended to reduce water content in the plant tissues, leaf transpiration index and water-uptake efficiency of the plant roots, as well as to improve water-consumption efficiency and turgor of the trees. The predicted increase of the global atmospheric CO_2 concentration in the future will likely enhance apple production by raising water-consumption efficiency of the trees.

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Anschrift der Verfasser: Dr. K. Chen, Dep. of Plant and Soil Sciences, Oklahoma State University, 368 Agric. Hall, Stillwater, OK 74078-6028, USA, e-mail: Chenkai6@yahoo.com; Dr. G. Q. Hu and Prof. Dr. F. Lenz, Institut für Obstbau und Gemüsebau der Universität Bonn, Auf dem Hügel 6, 53121 Bonn, Germany.