Carbon Dioxide Enrichment and Irrigation Effects on Wheat Evapotranspiration and Water Use Efficiency

D. J. Hunsaker, B. A. Kimball, P. J. Pinter Jr., R. L. LaMorte, G. W. Wall

Abstract. *Evapotranspiration (ET) and water use efficiency were evaluated for two spring wheat crops, grown in a drip-irrigated field under ambient (about 370 μmol mol^{-1}) and enriched (550 μmol mol^{-1}) carbon dioxide (CO_2) concentrations during the 1992-1993, and 1993-1994, Free-Air CO_2 Enrichment (FACE) experiments in central Arizona. CO_2-enriched (FACE) and ambient CO_2 (CONTROL) treatments were replicated in four circular plots, 25 m in diameter, and well-watered (WET) and water-stressed (DRY) irrigation treatments were imposed on one-half of each plot. Wheat ET, measured over discrete time periods of several days by a soil water balance, was significantly higher for WET than DRY irrigation treatments after the first week in March in both years. Differences in ET between CO_2 treatments during the season were generally small, although there was a consistent trend towards decreased ET for the FACE over CONTROL under the well-watered irrigation regime.*

The two-year average reduction in seasonal ET owing to the FACE treatment was about 5% under WET irrigation and was consistent with the results from two parallel investigations that used an energy balance and sap flow measurements. Under the DRY irrigation treatment, seasonal ET was 5 and 0.9% higher for the FACE treatment in the first and second years, respectively. Water use efficiency (grain yield per unit seasonal ET) was significantly higher for FACE treatments; 15 and 24% higher than CONTROL under DRY irrigation, and 13 and 18% higher than CONTROL under WET irrigation. The results indicate that irrigation requirements for fully irrigated wheat may be slightly lower in the future high-CO_2 environment. ***Keywords.** Carbon dioxide, Global change, Soil water depletion.*

Historical and modern records show that the atmospheric carbon dioxide (CO_2) concentration increased from approximately 280 μmol mol^{-1} in preindustrial times to about 315 μmol mol^{-1} in 1958, and to over 350 μmol mol^{-1} in 1988 (Boden et al., 1994). The accelerated trend in the global CO_2 growth rate during the first 30 years of modern records led to various scenarios for the future CO_2 concentrations of the atmosphere. A number of studies have estimated a doubling of atmospheric CO_2 over the preindustrial value could possibly occur before the end of the next century (Hoffman and Wells, 1987; Watson et al., 1990; Trenberth, 1991). However, there was a significant and unexpected decline in the atmospheric CO_2 rate of increase from 1989 to 1993 (Boden et al., 1994). Environmental factors such as an enhanced biospheric or oceanic carbon sink during that period, perhaps induced by the Pinatubo volcanic eruption in 1991, and the El Niño events of 1992 and 1993, or a reduced natural source of carbon, may have been the primary cause rather than reduced fossil fuel combustion rates (Keeling et al., 1995). Although the sudden downturn in CO_2 has not been fully explained, it appears that the sustained decrease in the atmospheric CO_2 growth rate was a temporary climate-induced anomaly, which effectively ended by late 1993 (Keeling et al., 1995). However, as pointed out by Keeling et al., both the beginning and ending of the anomaly were entirely unpredictable. Thus, projections of when a doubling of CO_2 will occur are generally regarded as uncertain (Hendrey and Kimball, 1994).

If the atmospheric CO_2 concentration does continue to rise during the next century, we can expect the growth and yield of many important agricultural crops to be significantly increased (Kimball, 1983). One natural concern for future irrigated agriculture is how higher CO_2 concentrations will affect crop evapotranspiration (ET) and, hence, the management of irrigation water. Larger and more vigorous plants from a CO_2-enriched environment may be associated with increased crop ET. However, CO_2 enrichment may slow plant transpiration by partially closing stomata (Morrison 1985; Allen, 1990), and some investigations have reported a decrease in leaf transpiration per unit leaf area at higher atmospheric CO_2 concentrations (Kimball and Idso, 1983; Goudriaan and Unsworth, 1990).

Previous experimental studies to assess the effects of CO_2 enrichment on crop water use were almost exclusively conducted in environments significantly altered from natural agricultural field conditions by the use of enclosures to confine the CO_2 around plants (Kimball et al., 1994a). Some of the earlier investigations utilizing growth chambers or greenhouses indicated changes in water use (either ET or transpiration) owing to increased CO_2 levels, although in general the effects have been small and inconsistent. Kimball et al. (1983), using

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lysimeters in open-top chamber studies in Arizona, indicated that a doubling of CO_2 concentration reduced seasonal ET for cotton by 5 to 10%. However, in a second study (Kimball et al., 1984), they reported inconsistent effects on cotton ET for a doubling of CO_2. Controlled, chamber experiments with soybean (Jones et al., 1985a) did not indicate significant differences in whole canopy transpiration between CO_2 levels of 330 and 800 μmol mol^{-1}. However, in a similar experiment (Jones et al., 1985b), soybean transpiration was reduced 10% at a CO_2 level of 660 μmol mol^{-1}. Chaudhuri et al. (1990) reported little effect of CO_2 on the ET of winter wheat grown in greenhouses during two out of the three years of study.

Recognizing the need to eliminate the effects imposed by walled chambers in CO_2 enrichment experiments, a Free-Air CO_2 Enrichment (FACE) system was developed to evaluate the effects of increased CO_2 on crop response in a typical agricultural environment (Hendrey and Kimball, 1994). Experiments were conducted in 1989, 1990, and 1991 using the FACE system in a large, irrigated cotton field in central Arizona. During the FACE cotton experiments, cotton ET was measured using three independent approaches; stem flow gauges (Dugas et al., 1994), energy balance (Kimball et al., 1994a), and soil water balance (Hunsaker et al., 1994). All three investigations were in agreement, and the conclusion was that any effects of CO_2 enrichment to 550 μmol mol^{-1} were too small to be detected.

Experiments to investigate the responses of wheat to CO_2 and irrigation were conducted at the FACE system site during the 1992-1993 and 1993-1994 spring wheat seasons. The objective of this work was to evaluate ET, using a soil water balance approach, and water use efficiency for wheat exposed to ambient (about 370 μmol mol^{-1}) and elevated (550 μmol mol^{-1}) CO_2 concentrations under limited and nonlimited irrigation. Parallel investigations by Senock et al. (1995), using a sap flow heat balance approach, and Kimball et al. (1994b), using an energy balance approach, also sought to determine any impact of CO_2 on the water use for wheat in the same FACE experiments.

Methods and Materials

Field Layout and Experimental Design

A Free-Air CO_2 Enrichment (FACE) system was installed in a 9-ha field located within The University of Arizona, Maricopa Agricultural Central, in central Arizona. The soil is classified as Trix clay loam [fine-loamy, mixed (calcareous), hyperthermic Typic Torrifluvents]. Volumetric water contents within the top 0.7-m soil profile are approximately 0.30 and 0.20 m^3 m^{-3} at soil water matric potentials of –33 and –1 500 kPa, respectively (Post et al., 1988), and about 0.22 and 0.12 m^3 m^{-3} for the soil profile between 0.7 to 2.0 m, respectively (F. D. Whisler, personal communication, 1992). The estimated plant available water capacity within a potential root zone of 1.3 m was 130 mm.

The FACE system was used during the 1992-1993 and 1993-1994, spring wheat seasons to enrich the CO_2 concentration of the atmosphere above four circular plots, 25 m in diameter, to 550 μmol mol^{-1}. The four circular plots comprised what was termed the FACE treatment. Four matching circular plots without CO_2 enrichment (ambient CO_2 concentration was about 370 μmol mol^{-1}) were also installed in the field, each positioned 90 to 100 m directly east or west from one of the FACE plots. The ambient CO_2 plots were denoted as the CONTROL treatment. A complete description of the design, construction, and algorithms of the FACE exposure and monitoring system are provided by Lewin et al. (1994) and Nagy et al. (1994). In both studies, wheat plants in the FACE plots were exposed to elevated CO_2 concentrations beginning in January, shortly after crop emergence, through late May, shortly before harvest. The plants were exposed 24 h a day, except for the last two weeks of January 1993 when exposure was limited to daylight hours to conserve CO_2 when heavy rainstorms curtailed CO_2 deliveries during that period.

The experimental design was a strip-split-plot (G. V. Richardson, personal communication, 1994), with two levels of the main treatment, CO_2 concentration, replicated four times. Each of the eight circular main plots was split into two semicircular subplots, one northern and one southern, to test the effect of two different irrigation amounts on wheat response to CO_2. One of the subplots was assigned to a well-watered (WET) irrigation treatment and the other to a water-stressed (DRY) irrigation treatment. Irrigation water was delivered to the subplots through a subsurface drip system. The drip-irrigation tape was installed 0.18 to 0.25 m below the soil surface at a spacing of 0.5 m, parallel to the east-west plant rows. Emitter outlets were spaced every 0.30 m along the tape. The subplots were irrigated in strips that extended across a main plot replicate. Thus, it was necessary to impose the same irrigation treatment on the same subplot side for each replicate. However, the WET and DRY irrigation treatments were alternated over the four main plot replicates, such that two replicates had a WET and DRY treatment on the northern side of the main plot, while the other two had a WET and DRY treatment on the southern side.

Crop Culture and Management

Hard red spring wheat (*Triticum aestivum* L., cv. Yecora Rojo) was planted in rows spaced 0.25 m apart in an unbedded soil surface on 15 December 1992, and on 7 and 8 December 1993. Plant densities, determined at harvest, were 1.1 and 1.5 million plants per hectare during the first and second years, respectively.

Immediately following planting in 1992, approximately 300 mm of water was applied by the drip system to allow adequate moisture to "sub-up" to the seed line for germination. In 1993, a portable sprinkler system was installed temporarily and used to "irrigate-up" the wheat with two water applications totaling 30 mm.

A computer-based irrigation scheduling program, AZSCHED, developed by The University of Arizona (Fox et al., 1993), was used to schedule the times and amounts of irrigation for the WET treatments during the two growing seasons. Irrigations were applied when a specified allowable depletion of the plant available water in the crop root zone had been reached. The irrigation depth applied was the depth required to replenish the root zone to field capacity (0% depletion), as predicted by AZSCHED. The program calculated soil water depletion and the irrigation requirement by a water budgeting procedure. Crop water use was estimated from a crop coefficient curve developed for wheat from historical data, which expressed the ratio of daily wheat ET to daily potential ET for a grass-reference crop. The grass-reference ET was calculated with the modified Penman equation using the method of Doorenbos and Pruitt (1977). Meteorological data for the modified Penman calculation was provided by The University of Arizona, AZMET weather station (Brown, 1987), located about 2 km from the field site.

During both seasons, WET treatments were irrigated when AZSCHED predicted ≈30% of the available water in the root zone was depleted. During 1992-1993, DRY treatments were irrigated on the same days as the WET treatments, but received only 50% of the WET application depth. During 1993-1994, DRY treatments were given the same application depth as the WET, but were irrigated only every other time the WET treatments were irrigated. Cumulative irrigation totals between crop emergence and harvest were 600 and 620 mm for the WET treatments of 1992-1993, and 1993-1994, respectively, and 275 and 257 mm for the DRY treatments, respectively. Cumulative rainfall during the same periods was 76 and 61 mm for the first and second years, respectively.

Plant nutrients, as well as insect and weed control, were managed according to recommendations of The University of Arizona Cooperative Extension Service and research staff. All treatments received the same amounts of fertilizer during the growing seasons. A total of 271 and 44 kg P/ha was applied during 1992-1993; and a total of 261 and 29 kg P/ha was applied during 1993-1994 (Pinter et al., 1995).

Wheat plants were sampled every 7 to 10 days during the two seasons. Information on the plant sampling methodology used is provided by Pinter et al. (1995). Final grain yields were determined by machine harvesting 20 m^2 of undisturbed areas within each subplot on 25 to 27 May 1993, and 1 June 1994. After harvest, the grain was oven-dried at 70°C for a total of 14 days, and the yields were expressed on a dry weight basis (Pinter et al., 1995).

Soil Water Content Measurements

Volumetric soil water contents were measured in each subplot using Time-Domain-Reflectometry (TDR) and neutron scattering equipment installed at the start of the first year's experiment on 18 December 1992. The multi-dimensional distribution patterns of applied water with subsurface drip irrigation require soil moisture sampling at a number of locations to quantify average soil water content conditions (Mahrer and Rytwo, 1991). However, because there were numerous co-investigations conducted during the FACE experiments, and each generally required an area set apart from other research activities, soil water content measurements were confined to a small area within each subplot. Consequently, water content measurements were only made at one location within each subplot during the experiments. The approach was to install the measurement equipment in each subplot at the same location relative to drip emitters and plant rows. Thus, the measurements of water content were made uniformly in subplots with respect to field position, although the position selected may not have represented the average soil moisture condition of the subplot. The equipment was installed near the center of each semicircular subplot, 7 m from the outside perimeter of the plot. A TDR probe (fig. 1) was installed in the soil to a depth of 0.3 m in a plant row, equidistant between two drip emitters and 0.125 m from the nearest line of drip emitters. The TDR was used to measure the integrated volumetric water content of the soil from 0 to 0.3 m below the soil surface at the probe location. Once installed, the TDR probes remained at the same location throughout the season.

A 2-m-long neutron probe access tube was installed vertically in the plant row (fig. 1), 0.9 m from the TDR probe, and with the same placement as the TDR probe relative to the drip emitters. The neutron access probes remained at the same location for the duration of the two wheat seasons. A neutron moisture gauge, calibrated at the field site, was used to measure volumetric soil water contents in 0.2-m intervals from 0.4 to 2.0 m. Soil water content measurements were made in all subplots for 38 days during the 1992-1993 study (from 18 December 1992 to 20 May 1993), and for 46 days during the 1993-1994 study (from 9 December 1993 to 25 May 1994). Water contents were measured about once every week from crop emergence through the first regular irrigation. After that, water contents were measured every two to five days depending on the frequency of irrigation for the WET treatments.

Wheat Evapotranspiration Measurements

Wheat ET was determined in each subplot by measuring the change in soil water over a period of time and calculating the soil water balance equation (Jensen et al., 1990). The ET was calculated with the soil water balance equation only for those periods between soil water measurements where rainfall was small (less than 10 mm), irrigation water was not applied, and where deep percolation could be reasonably assumed negligible, i.e., waiting at least two days after irrigation or heavy rainfall before taking the water content measurement (Jensen et al., 1990). The ET for the periods when irrigation water was applied or when heavy rainfall occurred was estimated from the ET data before and after the period, as will be explained in more detail shortly. The active root zone depth for the computation of the soil water balance equation was estimated from the root growth model of the AZSCHED irrigation scheduling program. The maximum depth of the effective wheat root zone was assumed to be 1.3 m (Doorenbos and Kassam, 1979).

In the 1992-1993 study, the average daily ET was calculated with the soil water balance equation for 18 and 20 periods between 15 January (shortly after crop

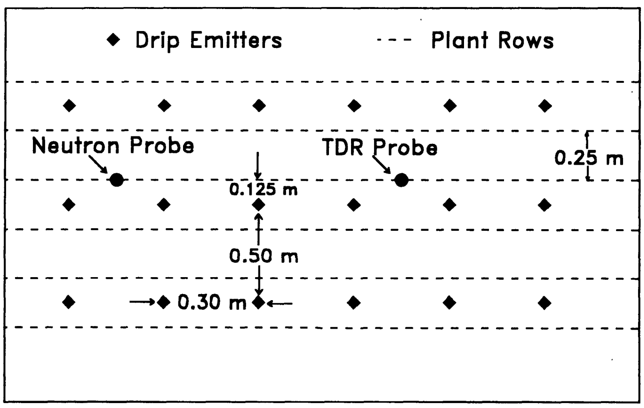

Figure 1–Location of TDR and neutron probes relative to drip tape, drip emitters, and plant rows.

emergence) to 20 May 1993 (shortly before harvest), for the WET and DRY treatments, respectively. The length of the periods varied from 2 to 12 days. In the 1993-1994 study, the average daily ET was calculated with the soil water balance equation for 22 and 31 periods between 10 January to 25 May 1994, for the WET and DRY treatments, respectively. The length of the periods in 1994 varied from two to seven days.

In order to calculate the total seasonal ET for the treatments, it was necessary to estimate ET for the periods that were not calculated with the soil water balance, namely those periods that included either irrigation or heavy rainfall. The ET values for those periods were estimated by, first calculating the ratio of the measured wheat ET from the soil water balance to the ET for the grass-reference crop (by the modified Penman equation from AZSCHED) for the measurement periods that were immediately before and after the estimation period. Next, the average of the two ratios was assumed to approximate the ratio between the actual wheat ET and the grass-reference ET during the estimation period. Finally, the average ratio was multiplied by the grass-reference ET during the estimation period to obtain the estimated wheat ET during the period. Total seasonal ET was then calculated as the cumulative ET, expressed in millimeters, taken over all periods (both the measurement periods calculated with the soil water balance and the estimation periods) from 15 January through 20 May in the 1992-1993 season; and from 10 January through 25 May in the 1993-1994 season.

Data Analysis

Analysis of variance (ANOVA) and related statistical procedures were performed using the ANOVA procedure of SAS (SAS Institute Inc., 1988). Statistical analyses of treatment effects on soil water contents, daily ET, total seasonal ET, and water use efficiency were made using a strip-split-plot ANOVA model, as described by Little and Hills (1978). The strip-split-plot model had three parts. Part 1 included the replication effect (ρ) and the CO_2 main effect (α); the error term used for evaluating the effect of CO_2 was $\rho\alpha$, which had three degrees of freedom. Part 2 included the irrigation effect (β), evaluated with the error term, $\rho\beta$, which had three degrees of freedom. Part 3 included the interaction term ($\alpha\beta$), evaluated with the residual mean-square error, which also had three degrees of freedom.

In this variation of the split-plot design, the subunit treatment (irrigation) was applied in strips across each main plot replicate. This arrangement facilitated the physical operations for irrigation, but sacrificed precision in comparing the effect of the irrigation treatment. Had the FACE experiment been designed as a traditional split-plot design, a pooled error term with six degrees of freedom would have been used for testing both irrigation and the CO_2 by irrigation interaction.

The least significant difference (LSD) criterion (Snedecor and Cochran, 1967) was used to compare treatment means for seasonal ET and water use efficiency. The formula for calculating the LSD between two means was: LSD = $t\rho\alpha$ with three degrees of freedom for the CO_2 means, and LSD = $t\rho\beta$ with three degrees of freedom for the irrigation means, where t is determined from the Student's t distribution table (Snedecor and Cochran, 1967).

Results

Soil Water Contents

1992-1993. Figure 2 shows the distribution of the average soil water contents within the 0- to 0.9-m soil profile with time for the four, CO_2 by irrigation treatment combinations, CONTROL DRY (CD), CONTROL WET (CW), FACE DRY (FD), and FACE WET (FW). Following the initial water application for crop establishment in late December 1992, soil water contents for all treatments were at or above 0.28 $m^3\ m^{-3}$, a value that approximates the average field capacity of soil. During January and the first two weeks of February 1993, water contents remained near field capacity. By late February, the water contents for all treatments had declined, reaching a soil water depletion of about 30 to 35%, which marked the beginning of regular seasonal irrigation.

A decision was made by the FACE investigators to increase the difference in soil water contents between WET and DRY treatments. Thus, when 12.5 mm and 60 mm of water were applied to the WET plots on 1 March (DOY 060) and 9 March (DOY 068) 1993, respectively, none was applied to the DRY plots. Following those irrigations, soil water content in the WET treatment was increased to about field capacity, while it declined in the DRY treatment, reaching about 80% soil water depletion before irrigation was eventually applied to the DRY treatment on 18 March (DOY 077). Through the remainder of the wheat season, the DRY treatment received 50% of the WET water application depth every time the WET treatment was irrigated. For the WET plots, average water contents in the 0.9-m soil profile varied during the season from about field capacity, following irrigations, to about 20 to 35% soil water depletion, just prior to irrigations. For the DRY plots, average water contents varied from about 60 to 90% soil water depletion from the middle of March through early May.

ANOVA was performed on the profile water contents for each measurement date of figure 2. Differences in the water contents between the WET and DRY treatments were not significant on days prior to the WET irrigation on 9 March (DOY 068). However, water content differences between WET and DRY treatments from 10 March (DOY 069) to 21 May (DOY 141) were large and the differences were consistently significant ($P < 0.02$) during that period.

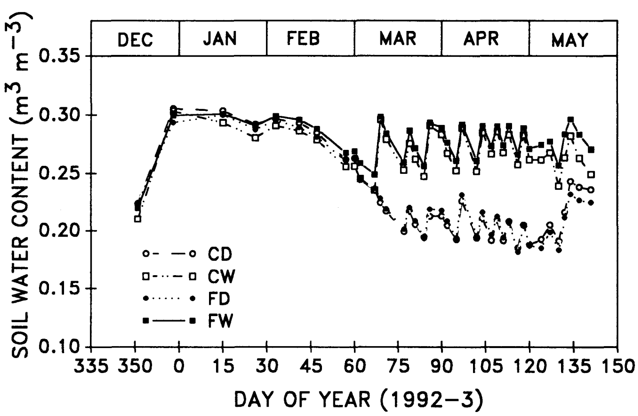

Figure 2–Distribution of volumetric water contents within a 0.9-m soil profile with time for the CD, CW, FD, and FW treatments in the 1992-1993 wheat season. Each data point is the average of four replicates.

The effect of CO_2 on water contents was not significant ($P < 0.36$ to 0.96) for any measurement date in the season, and there was no significant CO_2 by irrigation interaction except for several measurement dates in May. The interaction in May can be partially explained by differences in canopy maturity between the plants within the CO_2 treatments under WET and DRY irrigation conditions. As seen in figure 2, the water contents during May were considerably higher for the FACE than CONTROL in the WET irrigation treatment, although slightly lower for the FACE than CONTROL in the DRY treatment. Higher water contents for the FW over the CW treatment late in the season were attributed to one-week earlier maturity (Pinter et al., 1995) for wheat canopies exposed to elevated CO_2 than those within the CONTROL. Thus, while irrigation to all treatments continued through the middle of May, plants of the FW treatment were removing less water from the soil than were plants of the CW treatment because of the different canopy maturity. The rapid increase in water contents for the CD and FD treatments in mid-May coincided with the two- to three-week earlier maturity for the plants in the DRY than the WET treatments (Pinter et al., 1995).

In general, the FACE treatment had slightly higher water contents than the CONTROL counterparts throughout the season. Excluding the May data, water contents averaged over all measurements made from 28 December 1992 through 30 April 1993, were 0.229 and 0.230 m^3 m^{-3} for the CD and FD treatments, respectively, and 0.272 and 0.280 m^3 m^{-3} for the CW and FW treatments, respectively.

1993-1994. The distributions of the average soil water contents within the 0- to 0.9-m soil profile with time are shown for the CD, CW, FD, and FW treatments in figure 3. Following the water applications to establish the wheat crop in mid-December 1993, soil water contents were near field capacity for all treatments. Soil water depletion for the WET treatment reached ≈30% during the third week in January 1994, and the WET plots received their first scheduled irrigation on 21 January (DOY 021). The DRY plots received their first irrigation on 3 February (DOY 034). However, because there was significant rainfall (27 mm) in mid-February, the FACE investigators decided to withhold the next irrigation for the DRY treatment until 16 March (DOY 075). Consequently, the water content for DRY plots declined to about 80% soil water depletion prior to the irrigation on 16 March (DOY 075).

Average water contents for the WET treatment in the 1993-1994 study varied from about field capacity from 20 to 30% depletion during the season, similar to the WET treatment water content variation during 1992-1993. However, water content for the DRY treatment in 1993-1994, fluctuated more widely during the season than it had for the DRY treatment in 1992-1993, due to the different irrigation strategy employed for the DRY treatment in the 1993-1994 study (i.e., basically applying larger water applications to the DRY plots, but only every other time the WET plots were irrigated, rather than applying one-half the amount each time the WET plots were irrigated as was done in 1992-1993). Consequently, the water content for the DRY treatment in 1993-1994 varied from about 30 to nearly 100% soil water depletion between early-March through the end of May.

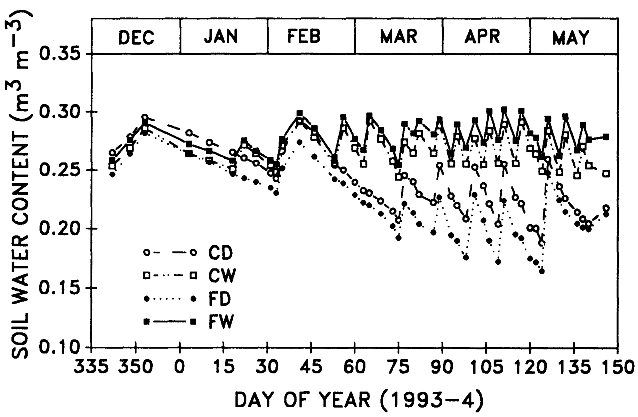

Figure 3–Distribution of volumetric water content within a 0.9-m soil profile with time for the CD, CW, FD, and FW treatments in the 1993-1994 wheat season. Each data point is the average of four replicates.

Following irrigation to the WET treatment on 23 February 1994 (DOY 054), water contents of the WET treatment were higher than those of the DRY treatment and the difference was significant at the 0.05 probability level for all measurements through the end of the season on 26 May (DOY 146). As in the 1992-1993 study, the effect of CO_2 on water content was not statistically significant ($P <$ 0.32 to 0.79) for any measurement date in the 1993-1994 study. However, significant CO_2 by irrigation interaction occurred on 18 March (DOY 077) and on most of the latter measurement dates. The CO_2 by irrigation interaction coincided with an abrupt difference in water contents levels between the CD and FD treatments that began on DOY 077. As seen in figure 3, water contents were slightly higher for the CD than FD treatment prior to DOY 077, but were considerably higher from DOY 077 though early-May (DOY 123). Water contents for the FW treatment were also higher than the CW treatment after DOY 077, although the differences between the WET CO_2 treatments were not as pronounced as those between DRY CO_2 treatments. However, none of the treatments experienced a marked change in the replicate variability of water contents after DOY 077. At present we are unable to explain the abrupt difference in water content levels between the FACE and CONTROL treatments, but expect that there were differences in the water depths applied to both the WET and DRY FACE plots than their CONTROL counterparts during the irrigations on 16 March (DOY 075).

Seasonal average water contents for the CW and FW treatments in 1993-1994 were similar to those in 1992-1993. Excluding the May data, water contents averaged over all measurements made from 20 December 1993 through 29 April 1994, were 0.269 and 0.279 m^3 m^{-3} for the CW and FW treatments, respectively. However, unlike the 1992-1993 study, the average water content for the CD treatment (0.242 m^3 m^{-3}) was considerably higher than that of the FD treatment (0.222 m^3 m^{-3}) during 1993-1994.

In 1993-1994, irrigation for the DRY treatment was terminated during the first week in May to more closely match the complete senescence of the DRY treatment plants in early May. Note that this was unlike 1992-1993 where irrigation to the DRY treatment was continued through the middle of May despite the complete senescence of the treatment in early May. Following the final irrigation to the DRY treatment (on DOY 124) in 1994, soil water contents declined through about the middle of May. Irrigation for the WET treatment continued through 16 May (DOY 136), shortly before the wheat canopies for WET treatment plants were completely senesced.

EVAPOTRANSPIRATION

1992-1993. Table 1 shows the 1992-1993 treatment means of average daily ET, as determined by the soil water balance equation, for periods from 15 January (DOY 015) through 20 May 1993 (DOY 140). The soil water balance ET was determined for the DRY but not the WET treatment during DOY 060 to 061 and DOY 067 to 070, since the WET treatment was irrigated during those periods. Analysis of variance (ANOVA) of daily ET was performed for each of the periods shown in the table, except for the periods of DOY 060 to 061 and DOY 067 to 070. The ANOVA results for each period are shown in table 1.

The effect of irrigation on average daily ET was significant ($P < 0.04$) starting the first week of March (DOY 062 to 066), shortly after the initiation of irrigation to the WET treatment. The ANOVA results also indicated a significant irrigation effect during the middle of March (DOY 071 to 076), as well as from the end of March (DOY 086 to 089) through the second week in April (DOY 097 to 101). However, differences in daily ET between WET and DRY treatments were not statistically significant during mid-to-late April (DOY 104 to 106 through DOY 113 to 115). This suggests that by mid-April the root systems for DRY treatment plants were sufficiently developed to extract soil water from deeper depths in the profile and, thereby, the plants in the DRY treatment were able to maintain water extraction at nearly the same rate as WET treatment plants. However, by late April (DOY 118 to 119), soil water reserves in the deeper soil profiles of the DRY treatment were exhausted and the ET rate of the DRY treatment was significantly decreased from that of the WET treatment. During May, ET more rapidly declined in the DRY treatment coinciding with the earlier maturity of the DRY than WET treatment plants, as previously indicated.

Table 1. Mean daily ET for treatments, as determined with the soil water balance equation, and the ANOVA results for periods in the 1992-1993 study

Period	Treatments*				Effects†		
Day of Year 1993	CD	CW	FD	FW	CO_2	I	$CO_2 \times I$
	(mm/d)				(P > F)		
015-027	1.1	1.2	1.2	1.1	0.85	0.31	0.01
033-040	1.6	1.6	1.8	1.5	0.74	0.16	0.12
041-046	2.2	2.0	2.1	2.0	0.91	0.18	0.66
047-056	2.1	2.0	1.8	1.8	0.42	0.93	0.94
057-059	2.6	2.7	2.1	2.6	0.49	0.31	0.58
060-061	3.5	—	3.3	—	—	—	—
062-066	3.9	4.7	3.7	4.5	0.18	0.04	0.99
067-070	4.3	—	4.4	—	—	—	—
071-076	3.4	4.3	3.1	4.3	0.66	0.03	0.81
079-083	3.8	4.5	4.4	4.8	0.08	0.26	0.49
086-089	3.2	4.4	3.3	4.3	0.77	0.02	0.55
090-094	4.6	6.3	5.0	6.1	0.85	0.09	0.40
097-101	6.2	7.7	7.2	7.4	0.46	0.03	0.19
104-106	6.6	7.5	7.3	7.4	0.72	0.69	0.34
109-110	8.2	9.4	8.7	8.9	0.98	0.55	0.08
113-115	7.9	8.6	8.0	8.5	0.97	0.57	0.92
118-119	8.2	10.9	8.5	10.1	0.79	0.08	0.53
127-129	4.1	9.7	4.4	7.7	0.09	0.02	0.16
134-136	1.6	6.6	1.6	7.8	0.31	0.00	0.25
137-140	0.6	4.1	0.4	3.9	0.66	0.00	0.74

* Treatments are CD, CW, FD, and FW. Evapotranspiration by the soil water balance was determined for the DRY, but not WET treatments for periods DOY 060 to 061 and DOY 067 to 070 during which the WET treatments were irrigated.

† The probability of a larger F statistic (P > F) for the CO_2, irrigation (I), and the $CO_2 \times I$ interaction effects from the ANOVA.

The ANOVA results indicated that the effect of CO_2 on ET was generally not significant, although the probability level of the F statistic was less than 0.18 for 3 of the 18 periods analyzed. The CO_2 by irrigation interaction effect was also generally not significant during any of the periods. Although the differences for ET between CO_2 treatments were small, there was a consistent tendency for the ET of FACE to be greater than that of the CONTROL for the DRY treatment from about the middle of March (DOY 079 to 083) through late April (DOY 118 to 119), while it was consistently greater in the CONTROL than FACE treatment for the WET treatment from late March (DOY 086 to 089) through late April. The seasonal effect of CO_2 on ET was evaluated by plotting the mean ET values given in table 1 for the FACE treatment with those of CONTROL for both the WET (fig. 4) and DRY (fig. 5) irrigation treatments. The FACE data were then linearly regressed against the CONTROL data with the regression forced through zero. Because there were observed differences in crop maturity between FACE and CONTROL, ET data for periods during the month of May were excluded from the regression, although the May data are shown in the figures.

For the WET treatment (fig. 4), the regression slope was below the 1:1 line indicating an overall seasonal tendency for the ET of FACE to be lower than that for the CONTROL. The resultant slope (0.964) from the regression was significantly different from 1.0 at the 0.01 probability level. Thus, the regression suggested that the daily ET of FACE was about 3.6% lower than CONTROL under the WET irrigation treatment. For the DRY treatment (fig. 5), the regression slope was above the 1:1 line indicating an overall seasonal tendency for the ET of FACE to be higher than that of the CONTROL. The value of the regression slope (1.045), which was significantly different from 1.0 at the 0.02 probability level, suggested that the daily ET of FACE was about 4.5% higher than CONTROL under the DRY irrigation treatment.

The total seasonal ET was expressed as the cumulative depth of ET from 15 January (DOY 015) through 20 May (DOY 140) 1993, and included both the ET determined with the soil water balance equation plus the estimated ET for all other periods, as described in the Methods section. The treatment means for seasonal ET were 457, 625, 479, and 598 mm for the CD, CW, FD, and FW treatments, respectively. Thus, when the entire growing season was considered, total seasonal ET was 4.5% lower for FACE than CONTROL in the WET irrigation treatment, but was 4.8% greater for FACE than CONTROL in the DRY irrigation treatment. As expected, the ANOVA for seasonal ET indicated that the irrigation effect was highly significant ($P < 0.02$). Although the main effect of CO_2 was not significant ($P < 0.37$), the CO_2 by irrigation interaction was

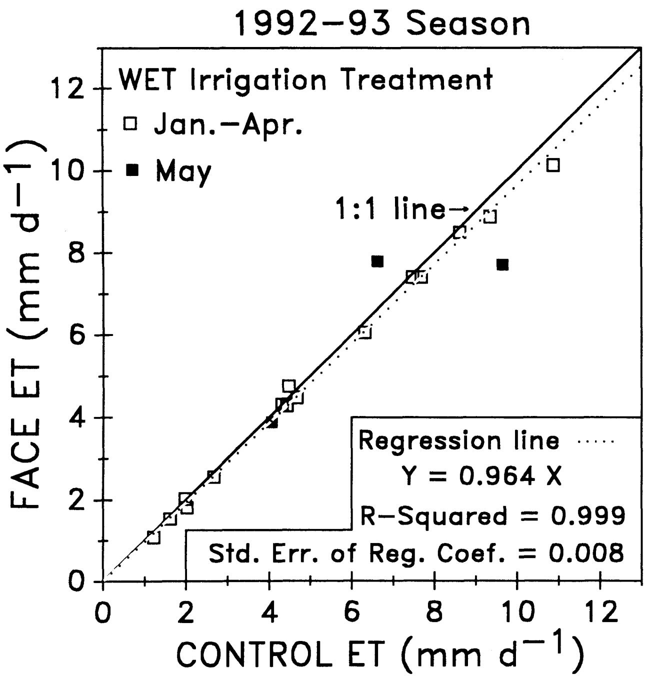

Figure 4–Daily FACE ET vs. the corresponding CONTROL ET for the WET irrigation treatment in 1992-1993. The regression excludes the May data.

highly significant ($P < 0.01$). Consequently, the interaction was analyzed by comparing the seasonal ET means for CO_2 treatments within irrigation treatments with the least significant difference (LSD) criterion. The error term for the analysis was obtained by pooling the error term for the CO_2 effect, i.e., Rep × CO_2, with the error term for the CO_2 by irrigation effect, i.e., the residual mean-square error (G.V.

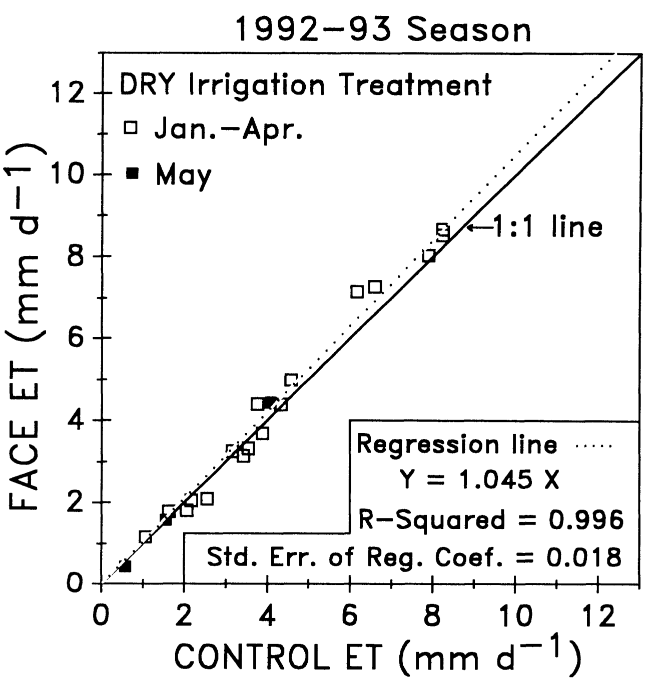

Figure 5–Daily FACE ET vs. the corresponding CONTROL ET for the DRY irrigation treatment in 1992-1993. The regression excludes the May data.

Richardson, personal communication, 1994). The resultant LSD was 20.0 mm at the 0.05 probability level. Thus, for both the WET and DRY irrigation treatments, the differences for total seasonal ET between FACE and CONTROL were significant at the 0.05 level of probability.

1993-1994. Table 2 shows the 1993-1994 treatment means of average daily ET, as determined by the soil water balance equation, for periods from 10 January (DOY 010) through 25 May (DOY 145) 1994. The ANOVA for daily ET was conducted separately for all periods in table 2 except for nine periods in which the daily ET was determined with the soil water balance equation for the DRY but not the WET treatment, i.e., periods when only the WET treatment was irrigated.

The effect of irrigation on daily ET was significant ($P < 0.02$) starting the last week of February (DOY 055 to 059), immediately after the irrigation to the WET (but not DRY) plots on 23 February (DOY 054). Except for two periods after February, daily ET was significantly different between WET and DRY treatments. During May 1994, as in the 1992-1993 study, the differences in ET between WET and DRY treatments increased, reflecting the earlier maturity of the DRY treatment wheat crops.

The effect of CO_2 on ET was not significant, although the probability of the F statistic was less than 0.20 during 5 of the 22 periods evaluated with the ANOVA. The CO_2 by irrigation interaction effect was also generally not significant.

The regression procedure that was used with the 1992-1993 data to evaluate the seasonal effect of CO_2 on daily ET, was also applied to the 1993-1994 data, again omitting ET data from periods in May from the regression. For the WET treatment (fig. 6), the slope of the regression was 0.967 and was significantly different from 1.0 at the 0.05 probability level. Thus, the daily ET for the FACE treatment in the 1993-1994 study was decreased about 3.3% from that of CONTROL in the WET irrigation treatment, similar to the 3.6% decrease from the 1992-1993 analysis. For the DRY treatment in 1993-1994, the regression slope (0.978) was below the 1:1 line (fig. 7). However, statistical evaluation of the slope indicated that it was not significantly different from 1.0 ($P < 0.46$), and, therefore, it was concluded that there was no effect on daily ET due to FACE under the DRY irrigation treatment in 1993-1994.

The total seasonal ET between 10 January (DOY 010) and 25 May (DOY 145) 1994, was 435, 659, 439, and 623 mm for the CD, CW, FD, and FW treatments, respectively. Thus, the total seasonal ET was 5.8% lower for FACE under the WET irrigation treatment, and 0.9% higher for FACE under the DRY irrigation treatment. Just as in 1992-1993, the irrigation effect on seasonal ET was highly significant ($P < 0.001$) in 1993-1994, but unlike the previous year, CO_2 by irrigation interaction was not highly significant ($P < 0.26$). The effect on seasonal ET due to CO_2 in 1993-1994 was significant at $P < 0.18$.

Water Use Efficiency

1992-1993. Final grain yield of spring wheat in 1992-1993 increased an average of 21 and 8% under CO_2 enrichment for the DRY and WET irrigation treatments, respectively, and was an average of 24% higher for WET than DRY treatments (Pinter et al., 1995). Water use

Table 2. Mean daily ET for treatments, as determined with the soil water balance equation, and the ANOVA results for periods in the 1993-1994 study

Period	Treatments*				Effects†		
Day of Year 1994	CD	CW	FD	FW	CO_2	I	$CO_2 \times I$
	(mm/d)				(P > F)		
010-017	0.7	0.5	0.7	0.7	0.59	0.45	0.66
018-021	1.0	——	0.8	——	——	——	——
022-025	1.1	1.1	0.9	1.3	0.98	0.64	0.04
026-032	1.5	1.8	1.3	1.4	0.32	0.67	0.71
041-045	1.9	2.5	2.2	2.4	0.44	0.15	0.15
046-052	2.2	2.2	1.9	2.4	0.74	0.32	0.22
053-055	2.0	——	1.8	——	——	——	——
056-059	2.1	3.4	2.0	3.5	0.86	0.02	0.58
060-062	2.2	4.2	2.2	3.0	0.19	0.08	0.33
063-064	2.5	——	2.8	——	——	——	——
065-068	2.6	4.2	2.7	3.9	0.62	0.01	0.77
069-074	3.1	5.1	3.4	4.9	0.94	0.00	0.06
077-079	1.6	2.6	2.3	2.4	0.53	0.36	0.30
080-081	5.4	——	5.0	——	——	——	——
082-086	4.3	5.8	4.2	5.8	0.76	0.08	0.95
089-092	5.3	6.0	5.9	6.3	0.36	0.31	0.74
093-094	6.9	——	5.4	——	——	——	——
095-097	4.0	7.4	4.8	7.0	0.66	0.01	0.15
101-103	5.0	7.0	6.3	6.9	0.18	0.09	0.40
104-105	7.3	——	7.8	——	——	——	——
106-108	5.8	9.6	5.6	9.3	0.43	0.01	0.95
111-114	6.7	8.2	6.6	7.7	0.84	0.08	0.83
115-116	7.1	——	6.2	——	——	——	——
117-119	7.2	8.1	5.9	8.0	0.13	0.04	0.23
120-123	5.0	7.0	5.2	6.8	0.97	0.07	0.85
126-129	5.8	9.5	5.4	8.5	0.13	0.04	0.76
130-131	5.2	——	4.9	——	——	——	——
132-135	2.8	8.8	2.4	8.3	0.29	0.01	0.95
136-137	2.6	——	2.1	——	——	——	——
138-139	1.0	7.9	1.0	6.6	0.43	0.00	0.19
140-145	0.3	3.3	0.2	2.1	0.10	0.01	0.15

* Treatments are CD, CW, FD, AND FW). Evapotranspiration by the soil water balance was determined for the DRY, but not WET treatments for nine periods during which the WET treatments were irrigated.

† The probability of a larger F statistic (P > F) for the CO_2, irrigation (I), and the $CO_2 \times I$ interaction effects from the ANOVA.

efficiency (WUE), expressed as final grain yield per unit of seasonal ET (kg/m^3), was calculated for each replicate of a treatment. Mean water use efficiencies for the treatments are presented in table 3.

The FACE treatment resulted in a 15% increase in WUE for the DRY and a 13% increase for the WET irrigation treatments compared to CONTROL (table 3). Thus, because total ET differed between FACE and CONTROL, albeit the differences were small, the change in WUE due to FACE was lower than that for the yield change in the DRY irrigation treatment, but higher than that for the yield change in the WET treatment. Although the statistical difference in WUE due to CO_2 was significant ($P < 0.02$), there was no effect due to irrigation ($P < 0.89$) nor interaction ($P < 0.41$).

1993-1994. Final grain yield of spring wheat in 1993-1994 increased an average of 25 and 12% under CO_2 enrichment for the DRY and WET irrigation treatments, respectively, and was an average of 32% greater for WET than DRY treatments (Pinter et al., 1995).

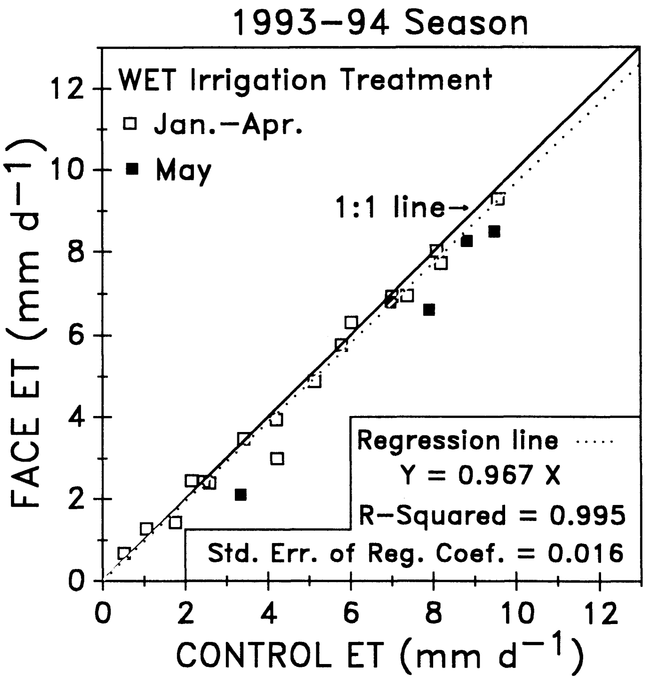

Figure 6–Daily FACE ET vs. the corresponding CONTROL ET for the WET irrigation treatment in 1993-1994. The regression excludes the May data.

In 1993-1994, the FACE treatment resulted in WUE 24% greater for the DRY, and 18% greater for the WET irrigation treatments compared to CONTROL (table 4). With little change in ET between the FACE and CONTROL DRY treatment, the increase in WUE due to FACE was essentially an increase in grain yield over CONTROL. The increase in WUE due to FACE for the

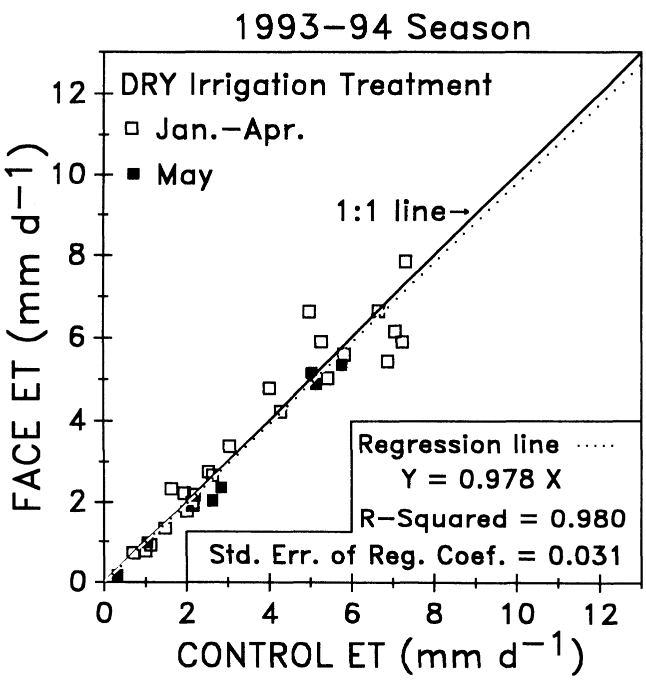

Figure 7–Daily FACE ET vs. the corresponding CONTROL ET for the DRY irrigation treatment in 1993-1994. The regression excludes the May data.

Table 3. Water use efficiency, expressed as final grain yield per unit of seasonal ET (kg/m³), for treatments of the 1992-1993 study*

Means†	Dry	Wet	Ratio of Dry/Wet
Control	1.31a	1.34a	0.98
Face	1.52b	1.52b	1.00
Ratio of face/control	1.15	1.13	

* Data are means of four replicates for each treatment combination.
† Means followed by different letters in a row or column are significantly different at the 0.05 probability level.

Table 4. Water use efficiency, expressed as final grain yield per unit of seasonal ET (kg/m³), for treatments of the 1993-1994 study*

Means†	Dry	Wet	Ratio of Dry/Wet
Control	1.09a	1.13a	0.97
Face	1.36b	1.34b	1.01
Ratio of face/control	1.24	1.18	

* Data are means of four replicates for each treatment combination.
† Means followed by different letters in a row or column are significantly different at the 0.05 probability level.

WET treatment was higher than that for yield, as it was in 1992-1993. The differences between FACE and CONTROL in WUE were significant ($P < 0.04$), but WUE was not affected by irrigation ($P < 0.92$) and there was little interaction ($P < 0.27$).

Discussion

The difference in daily ET between FACE and CONTROL treatments using the soil water balance for discrete periods during the season were generally small and not statistically significant. However, during both wheat seasons there was a consistent tendency for daily FACE ET to be lower than that for the CONTROL treatment when water was not limited. Total seasonal ET was also consistently lower for the FACE treatments under well-watered conditions, averaging about 5% less than CONTROL over both years.

Results from two parallel investigations on wheat water use, one using a residual energy balance approach to measure ET (Kimball et al., 1994b), the other using sap flow gauges to measure transpiration (Senock et al., 1995), in the same FACE wheat experiments were in general agreement with the soil water balance ET results under well-watered conditions. The energy balance approach indicated a two-year average reduction of 10% in plant water use for the FACE treatment under the well-watered treatments for the whole season, while the sap flow method indicated a cumulative reduction in water use of about 15%, during measurements made over a few days during the 1992-1993 study. Considering the three independent investigations together, it is apparent that when water was not limited wheat ET was lower for the FACE than the CONTROL. The precise magnitude of the reduction is still in question, however, since the results from the three measurement approaches were rather broad.

That the enriched CO_2 treatment decreased ET for wheat under well-watered conditions was different than the findings for cotton utilizing the same FACE system, which indicated no effect of CO_2 on the ET of fully irrigated cotton (Hunsaker et al., 1994; Dugas et al., 1994; Kimball et al., 1994a). However, unlike the cool-season wheat crop, the cotton's growth response over CONTROL when exposed to elevated CO_2 was substantially larger than the advantage realized by the FACE wheat (Pinter et al., 1995). Thus, a plausible explanation for the cotton ET findings was that the significantly larger leaf area produced for the FACE than CONTROL cotton plants compensated for reduced stomatal conductance so that changes in ET per unit area were negligible. In contrast, the leaf area advantage for FACE over CONTROL wheat plants was small during the first part of the season and then disappeared altogether during mid-season.

The effect of CO_2 enrichment on wheat ET under water-stress was less conclusive, since the energy balance investigation did not measure ET for the DRY plots in either study and sap flow measurements for DRY plots were only made during a few days of the 1992-1993 study. The soil water balance approach indicated a seasonal trend towards a small increase in the ET of FACE over CONTROL when water was limited during 1992-1993. The total seasonal ET for the FACE under water-stress was higher by about 5% for the CONTROL during the first study. Because the CO_2 effect on wheat growth caused larger plants and bigger root systems than those in the CONTROL, the FACE plants may have been able to more fully exploit the available moisture and thus transpire more water under water-stress than the CONTROL.

However, the soil water balance indicated no change in ET due to FACE in the water-stress treatment the second year. The inconsistent results between years may be related to the different irrigation strategies employed to achieve the DRY treatments. In the first study, irrigations to the DRY were applied frequently, but in light amounts. However, in the second study, longer irrigation intervals were used and available soil moisture was depleted for longer periods before irrigation was applied. During those excessively dry periods, the stimulatory effect that CO_2 apparently had on the ET of FACE plants in 1992-1993 may have been more limited by soil moisture in 1993-1994. The available water in FACE DRY plots may also have been lower than in the CONTROL DRY plots during 1993-1994.

Lower yields and higher evaporative conditions in 1993-1994 resulted in decreased water use efficiencies for all treatments from those in 1992-1993. Lower yields during the second season may have been related to less favorable weather conditions for growth, development, and grain production than during the first season. In 1993-1994, warmer and drier conditions, particularly during January through March, resulted in an increase in the cumulative seasonal reference-crop ET from 760 mm in 1992-1993, to 815 mm. The estimated seasonal wheat ET for the WET treatment was increased by about 30 mm in 1993-1994 over the previous season. The differences in plant densities between the two seasons may have also partially influenced the water use efficiencies. However, the effect of the FACE treatments on water use efficiencies was generally consistent over both seasons, although slightly more pronounced during the warmer, drier season of 1993-1994.

Conclusions

The effect of elevated CO_2 when water was not limiting resulted in a slight reduction in daily ET during the season and a total seasonal decrease in ET of about 5%. The different soil moisture regimes imposed for the water-stress treatments of the two studies apparently affected the ET response to elevated CO_2. Under frequent but limited irrigation, the total seasonal ET for plants exposed to elevated CO_2 increased about 5%. However, under infrequent and limited irrigation, the response was negligible. Water use efficiency (based on final grain yields and seasonal ET from the soil water balance) increased significantly due to elevated CO_2 for both well-watered and water-stress treatments.

The implications to irrigation water management suggested from these studies are that irrigation requirements for fully irrigated wheat may be slightly lower in the future high-CO_2 environment, provided that a concomitant change in climate warming does not occur. If water supplies for agricultural food production in the future high-CO_2 world decline and/or become more expensive, high wheat yields should be attainable even with limited irrigation due to the stimulatory effects of CO_2 on wheat water use efficiencies.

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