

Free-air CO₂ enrichment and soil nitrogen effects on energy balance and evapotranspiration of wheat

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Abstract. In order to determine the likely effects of the increasing atmospheric CO₂ concentration on future evapotranspiration, ET, plots of field-grown wheat were exposed to concentrations of 550 $\mu\text{mol/mol}$ CO₂ (or 200 $\mu\text{mol/mol}$ above current ambient levels of about 360 $\mu\text{mol/mol}$) using a free-air CO₂ enrichment (FACE) facility. Data were collected for four growing seasons at ample water and fertilizer (high N) and for two seasons when soil nitrogen was limited (low N). Measurements were made of net radiation, R_n ; soil heat flux; air and soil temperatures; canopy temperature, T_s ; and wind speed. Sensible heat flux was calculated from the wind and temperature measurements. ET, that is, latent heat flux, was determined as a residual in the energy balance. The FACE treatment increased daytime T_s about 0.6° and 1.1°C at high and low N, respectively. Daily total R_n was reduced by 1.3% at both levels of N. Daily ET was consistently lower in the FACE plots, by about 6.7% and 19.5% for high and low N, respectively.

1. Introduction

The CO₂ concentration of the atmosphere is increasing, and climate modelers have predicted a consequent global warming as well as changes in precipitation patterns. The report of the IPCC [Intergovernmental Panel on Climate Change, 1996] projects CO₂ increasing from present day concentrations of about 360 $\mu\text{mol/mol}$ to about 500 $\mu\text{mol/mol}$ by the end of the next century if emissions are maintained at 1994 levels. They further project that the increase in CO₂ plus that of other radiatively active “greenhouse” gases (methane, nitrous oxide, chlorofluorocarbons (CFCs), ozone) will cause an increase in global mean temperature of 0.9° to 3.5°C depending on future emission rates. Some regions might receive increases in precipitation, while others might receive less. However, these projected changes in climate are very uncertain.

Increasing CO₂ concentration has been shown to cause partial closure of plant leaf stomata, which reduces the conductance of water vapor from inside the leaf stomatal cavities to the outside air [Morison, 1987]. The decrease in conductance reduces transpiration per unit of leaf area, as has been observed many times [Kimball and Idso, 1983]. Such a decrease in the rate of leaf water loss suggests the possibility that reductions in evapotranspiration (ET) and plant water requirements may be forthcoming in the future high-CO₂ world. On the other hand, as the elevated CO₂ causes the partial stomatal closure, the resultant decrease in transpirational cooling in-

creases the foliage temperature [Kimball *et al.*, 1992a]. The increased foliage temperature increases the partial pressure of water vapor inside the leaves and increases leaf transpiration, thereby partially counteracting the CO₂-induced stomatal closure. At the same time, the CO₂ stimulation of growth leads to larger leaf areas, which would also tend to increase whole-plant transpiration [Rosenberg *et al.*, 1990].

Allen [1990] and Kimball *et al.* [1994] have reviewed the few early attempts utilizing chamber techniques to measure the effects of elevated CO₂ on ET. More recently, Samarakoon and Gifford [1995] conducted an interspecific comparison among cotton, wheat, and maize using glasshouses that illustrated the importance of the relative changes in leaf area and stomatal conductance in determining the relative effects of CO₂ on water use, as mentioned in the previous paragraph. Cotton had a large increase in leaf area and small change in conductance, so that water use per pot actually increased. Maize had very little photosynthetic or leaf area response, so that the reduction in conductance resulted in significant water conservation. Wheat was intermediate between the other two species. Dugas *et al.* [1997] measured sap flow (i.e., transpiration, T) in open-top chambers at near-doubled CO₂ concentrations and found that there was little effect of CO₂ on leaf area of sorghum or soybean, yet T was reduced by a surprisingly large 31% and 43%, respectively. Fredeen *et al.* [1997] exposed grassland to elevated CO₂ using open-top chambers and attempted to measure ET with smaller gas-exchange chambers. They found reductions of ET of 12–39% due to elevated CO₂ on sandstone-derived soil, but on serpentine-derived soil, ET actually increased from –1% to +14%. They believe that the latter increase is because the serpentine canopy was sparse, so there was more E (evaporation from soil) than T , and E would not be affected by CO₂. Thus the prior experimental work using chambers has been somewhat variable but explainable based on leaf area growth, canopy, and stomatal effects. Except for the results of Dugas *et al.* [1997], however, generally the effects of CO₂ on ET have been small.

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At the same time, the changes in growth due to CO₂ enrichment have been substantial, which coupled with the little change in water use, implies that water use efficiency increases in direct proportion to the increase in growth.

Thus there are counteracting reasons why the increasing CO₂ concentration might either increase or decrease ET under open field conditions, and such changes have the potential to cause changes in streamflow and water resources. At the same time, the changes in canopy temperature and ET imply changes in the energy balance at Earth's surface that could feed back on climate processes. Moreover, the changes in plant water balance and especially in plant water use efficiency suggest the possibility of shifts in the geographic location of whole biomes, which in turn could have large effects on the climate system [Melillo *et al.*, 1996]. Therefore energy balance studies under elevated CO₂, such as described herein, are needed to determine the effects of elevated CO₂ on plant canopy energy balance and ET. In addition, because the growth of plants is often limited by low soil nitrogen, especially in natural ecosystems and in the agricultural crops of developing countries, the studies need to be conducted over a range of soil nutrient conditions.

Although the earlier chamber studies provide clues about how elevated CO₂ affects ET, the walls of the chambers alter the transfer of water vapor from the plants, and the chambers shade the plants. Therefore the free-air CO₂ enrichment (FACE) approach as utilized in this study provided an opportunity to observe the effects of elevated CO₂ on ET and other components of the energy balance under conditions as representative of future fields as it is possible to create them today.

In the first FACE experiments on cotton, from 1989 to 1991, we determined ET using sap flow gauges [Dugas *et al.*, 1994], as a residual in the soil water balance, [Hunsaker *et al.*, 1994], and as a residual in the energy balance [Kimball *et al.*, 1994]. The growth response of the cotton in those experiments was large: about a 40% increase in biomass with enrichment to 550 $\mu\text{mol/mol}$ [Mauney *et al.*, 1994; Pinter *et al.*, 1996a]. Although the elevated CO₂ decreased stomatal conductance [Hileman *et al.*, 1994] and increased canopy temperatures about 0.8°C [Kimball *et al.*, 1992a], the counteracting factors were almost exactly compensatory because we found no detectable effects of the CO₂ on the ET of the amply watered cotton by the any of the three approaches.

We conducted additional FACE experiments on wheat from December through May of the 1992–1993, 1993–1994, 1995–1996, and 1996–1997 growing seasons. Hunsaker *et al.* [1996a] reported the results of soil water content determinations of ET for the first two of these experiments when there was an additional water stress variable. They report that with ample irrigation, the ET of the wheat was reduced about 5% at CO₂ concentrations of 550 $\mu\text{mol/mol}$. Under water stress conditions the ET actually increased 5.0% and 0.9% for the 2 years, respectively, indicating greater mining of initial soil water at the elevated CO₂. Senock *et al.* [1996] installed sap flow gauges on main wheat stems during the initial experiment. Using this second approach, they reported that under the ample water treatment, the reduction in *T* due to elevated CO₂ ranged from 7% to 23%, but variability was high and differences were often statistically insignificant.

Kimball *et al.* [1995] reported initial results of energy balance measurements from the first (1992–1993) wheat experiment for the ample water treatment. The purpose of this paper is to present a combined analysis of the energy balance measure-

ments from all four seasons of the well-watered wheat at ample nitrogen and also from two seasons of well-watered wheat when soil nitrogen was limited.

2. Methods

Two experiments were conducted during the 1992–1993 and 1993–1994 growing seasons to determine the interactive effects of elevated CO₂ and limited soil water on spring wheat (*Triticum aestivum* L. cv. Yecora Rojo) at the University of Arizona Maricopa Agricultural Center (MAC), Maricopa, Arizona. Two additional experiments were similarly conducted to determine the interactive effects of elevated CO₂ and limited soil nitrogen during the 1995–1996 and 1996–1997 growing seasons. A field plot plan for the 1992–1993 and 1993–1994 experiments is presented by Wall and Kimball [1993], while that for the 1995–1996 and 1996–1997 experiments is Figure 1 of this paper.

2.1. CO₂ Treatments

The FACE technique was used to enrich the air in circular plots within a wheat field similar to prior experiments [Hendrey, 1993; Wall and Kimball, 1993; Dugas and Pinter, 1994; Kimball *et al.*, 1995; Pinter *et al.*, 1996a; Hunsaker *et al.*, 1996a]. Briefly, four replicate 25-m-diameter toroidal plenum rings constructed from 0.305-m-diameter pipe were placed in the field shortly after planting (Figure 1). The rings had 2.5-m-high vertical stand pipes with individual valves spaced about every 2.4 m around the periphery. Air enriched with CO₂ was blown into the rings, and it exited near the canopy top through tridirectional jets in the vertical pipes. Wind direction, wind speed, and CO₂ concentration were measured at the center of each ring. A computer-controlled system used the wind speed and CO₂ concentration information to adjust the CO₂ flow rates to maintain the desired CO₂ concentrations at the centers of the FACE rings. The system used the wind direction information to turn on only those stand pipes upwind of the plots, so that CO₂-enriched air flowed across the plots no matter which way the wind blew. When wind speeds were low (<0.4 m/s), and it was difficult to detect direction, the CO₂-enriched air was released from every other vertical pipe around the rings.

Starting with the 1995–1996 season, air blowers were installed in the non-CO₂-enriched ambient control plots, hereafter called "blower" plots, to provide air movement similar to that of the FACE plots (Figure 1). The blower plots had toroidal plenums like the FACE plots, but their vertical pipes were spaced about every 5 m around the periphery, and there were no valves on the vertical pipes. Thus the air flowed all the time, and it was not changed in response to changing wind speed or direction. This strategy was justified because we believe the air flow in the blower plots was important only under calm conditions (wind <0.4 m/s) when the FACE plots were operated in the mode of releasing CO₂-enriched air from every other vertical pipe.

Also starting in 1995–1996, unlike the prior experiments which had a constant set-point of 550 $\mu\text{mol/mol}$ CO₂ concentration, the FACE plots were enriched by 200 $\mu\text{mol/mol}$ above ambient (~360 $\mu\text{mol/mol}$). A separate sequential sampling system was used to measure the concentration in all of the FACE and blower plots, as well as from two additional ambient sampling points north of replicate 1 (Figure 1). Twenty seconds were required to measure the concentration in each plot, and 3 min for all of them. The minimum value from

1995 - 1997 FACE FIELD LAYOUT

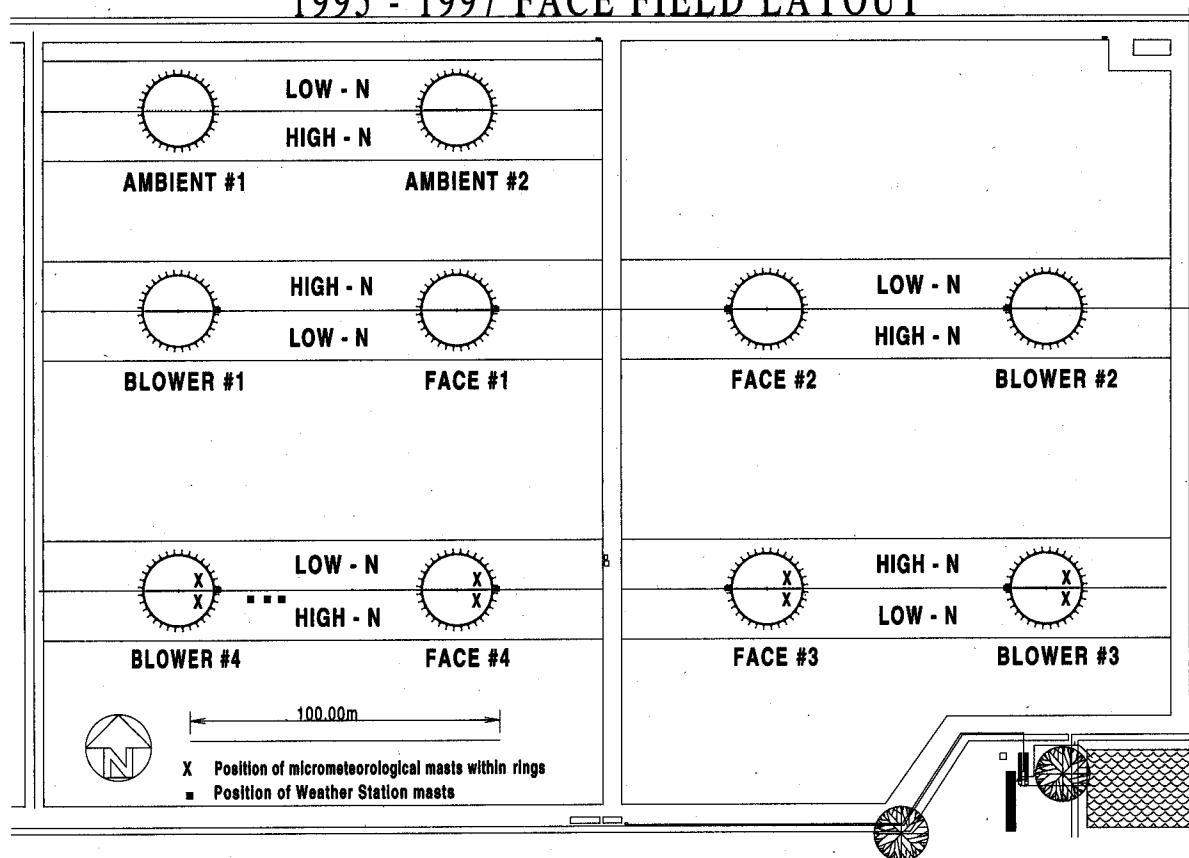


Figure 1. Field plot plan for the 1995–1997 FACE experiments showing four replicate circular FACE plots and four corresponding blower plots that had similar air flow but no added CO₂. Also shown are two ambient plots that had no forced air movement and no added CO₂. All of the circular main plots were split into semicircular high-N and low-N plots. These nitrogen treatments were applied via a subsurface drip irrigation system in strips across the field as indicated.

among the most recent observations of the four blower plots and the two ambient points was selected to provide a standard ambient value for the next 20 s against which to reference the 200 $\mu\text{mol/mol}$ enrichment in the FACE plots. By selecting the minimum value, we generally were choosing the values from the most upwind plots, thereby avoiding contamination of the ambient value by CO₂ from the FACE plots.

The FACE treatment was applied continuously from emergence to harvest. For 1995–1996 the average daytime CO₂ concentrations in the FACE and blower plots were 548 and 363 $\mu\text{mol/mol}$, respectively, while the nighttime values were 598 and 412 $\mu\text{mol/mol}$. Thus the daytime elevation of CO₂ concentration in the FACE plots above the blower plots was 185 $\mu\text{mol/mol}$, and these data also indicate the average contamination of the blower plots with CO₂ from the FACE plots was 15 $\mu\text{mol/mol}$ above the upwind ambient concentration.

2.2. Soil Nitrogen Treatments

During 1995–1996 and 1996–1997 each of the main circular FACE and blower plots was split into semicircular halves, with each half receiving either an ample (high-N) or a limiting (low-N) level of nitrogen fertilizer (Figure 1; Table 1). The high-N plots received a total of 350 kg N/ha from ammonium nitrate in four applications during both seasons. The low-N plots received 70 and 15 kg N/ha during 1995–1996 and 1996–

1997, respectively (Table 1). An additional 33 and 30 kg/ha of N were added to the high- and low-N plots, respectively, from the irrigation water itself.

An unfortunate oversight during the 1996–1997 season resulted in the nitrogen applications being switched between the high- and low-N sides of the blower-replicate 3 plots (Figure 1) on March 5, 1997 (DOY 64). The mistake was discovered about a week later, and the high-N plot was salvaged by applying additional nitrogen to it. This switch is important to this report because the instrumentation for the energy balance measurements had been installed in replicates 3 and 4. After discovery of the switch, the instruments were moved from replicate 3 to replicate 2.

The irrigations were accomplished using a subsurface drip system with a tube depth of about 0.23 m, a tube spacing of 0.50 m, and an emitter spacing of 0.30 m. The irrigation scheduling methodology and soil water content data are presented in detail for the 1992–1993 and 1993–1994 seasons by Hunsaker *et al.* [1996a]. They also describe a dry treatment which will not be discussed further here because we did not have adequate instrumentation in the dry plots to determine ET from the energy balance. Briefly, however, the tubing of the irrigation system extended across whole replicates. Thus in 1995–1996 and 1996–1997 the high-N sides of both the FACE and blower plots shared the same tubes and likewise for the low-N sides.

Table 1. List of Significant Dates, Climatic Conditions, and Amounts of Nitrogen and Water Applied to the Crops During the Various Growing Seasons

Item	Season/N Treatment					
	1992–1993, Ample	1993–1994, Ample	1995–1996		1996–1997	
			High N	Low N	High N	Low N
CO ₂ treatment, $\mu\text{mol/mol}$	550	550	+200	+200	+200	+200
Planting date	Dec. 15, 1992	Dec. 8, 1993	Dec. 15, 1995	Dec. 15, 1995	Dec. 15, 1996	Dec. 15, 1996
Emergence date	Jan. 1, 1993	Dec. 28, 1993	Jan. 1, 1996	Jan. 1, 1996	Jan. 3, 1997	Jan. 3, 1997
25% fAPAR date ^a	May 11, 1993	May 18, 1994	May 10, 1996	April 29, 1996	May 10, 1997	April 29, 1997
Harvest date	May 24, 1993	June 1, 1994	May 30, 1996	May 30, 1996	May 28, 1997	May 28, 1997
Plant density, ^b plants/m ²	130	186	189	189	194	194
Growing-degree days ^c	1911	2053	1988	1728	1882	1637
Minimum temperature, °C	−1.1	−4.5	−3.8	−3.8	−3.9	−3.9
Maximum temperature, °C	37.7	39.2	41.4	41.4	41.5	41.5
Total N applied, kg/ha	277	261	350	70	350	15
Total irrigation plus rain, mm	676	681	731	670	650	577

^aDate at which the fraction of absorbed photosynthetically active radiation had declined to 25% of the midseason maximum.

^bAt emergence.

^cComputed as $(\text{max} + \text{min})/2$ of the 2-m-height air temperature (i.e., base of 0°C) at the weather mast from emergence date through 25% fAPAR date.

Therefore the experimental design was strip-split-plot, such as used previously with the differential irrigation treatments [e.g., Pinter *et al.*, 1996a; Hunsaker *et al.*, 1996a]. All plots were irrigated after about 30% of the available water in the rooted zone was depleted; they were irrigated with an amount calculated to replace 100% of the potential evapotranspiration since the last irrigation (adjusted for rainfall), as determined by an irrigation scheduling program (AZSCHED) [Fox *et al.*, 1992]. In 1995–1996, the cumulative seasonal irrigation amounts were 692 and 631 mm in the high- and low-N treatments, respectively, and in 1996–1997 they were 621 and 548 mm (Table 1). The amounts of high N and low N would have been nearly identical each year except that the last irrigations in the low-N treatments were curtailed due to the earlier maturity of the N-stressed plants. The seasonal rainfall amounted to 39 and 29 mm for the 2 years, respectively. Similar cumulative irrigation (plus rainfall) amounts were applied in the other seasons (Table 1).

2.3. Crop Culture

In 1992 FACE and control arrays were moved to new areas within the same field where the FACE cotton experiments had been conducted. Then in 1995, between the FACE–water stress and FACE–nitrogen stress experiments, the FACE and blower arrays were moved again within the same field to virgin areas where extensive soil sampling had not been done. The soil is classified as a reclaimed, Trix clay loam (fine-loamy, mixed (calcareous), hyperthermic Typic Torrifluvents); additional details about the soil properties are given by Post *et al.* [1988] and Kimball *et al.* [1992b]. During the 1994–1995 winter growing season (between the FACE experiments), domestic oats (*Avena sp.*) were grown as an N-removal crop and cut several times as green forage. Following the oat crop, the soils were deeply ripped in two directions and disked. Then new drip irrigation tubing was installed, as described above. A large preplant irrigation (about 150 mm) was applied with sprinklers between November 30 and December 2, 1995, in order to leach as much initial soil nitrogen as possible and germinate remaining oat seeds which were suppressed with Roundup on December 12, 1995. (Note: Trade names and company names are

included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors, the U.S. Department of Agriculture, or the University of Arizona.) Despite these efforts, a substantial number of volunteer oat plants appeared in the later wheat crops, and they had to be rogued by hand from experimental plots.

Certified Yecora Rojo wheat seed was planted at mid-December in all seasons (Table 1) in east-west rows that were spaced 0.25 m apart (parallel to the drip irrigation tubing). In 1992–1993 a large initial irrigation was applied with the drip irrigation system for germination, but in the subsequent seasons, germination was accomplished with smaller irrigation amounts applied using sprinklers. Fifty percent emergence of seedlings was observed about January 1 in all seasons (Table 1), and FACE treatments commenced at that time. A combination of biological and chemical methods were used for control of oat bird cherry aphids and broadleaf weeds; losses caused by these pests were judged to be minimal. Air temperatures (2-m height) typically ranged from -5° to 42°C . Growing-degree-days amounted to about 2000, except for the low-N treatments which matured earlier as evidenced by an accelerated decline in the fraction of absorbed photosynthetically active radiation (fAPAR; Table 1). Final harvests of grain occurred at the end of May for each season.

2.4. Evapotranspiration From Residual in Energy Balance

The methodology used for determining components of the energy balance was similar to that used by Kimball *et al.* [1994] for cotton but with improvements as described by Kimball *et al.* [1995]. Briefly, ET (actually latent heat flux, λET) was calculated as the difference between net radiation, R_n ; soil surface heat flux, G_0 ; and sensible heat flux, H [e.g., Huband and Monteith, 1986a, b]:

$$\lambda\text{ET} = R_n - G_0 - H \quad (1)$$

where λ is the latent heat of vaporization. Each term on the right side of (1) was evaluated from instruments installed in the four individual semicircular wet plots of replicates 3 and 4 for both the control and FACE CO₂ treatments during the 1992–

1993 and 1993–1994 experiments. In 1995–1996 and 1996–1997 they were installed in eight plots: the high- and low-N sides of the blower and FACE plots of replicates 4 and 3 (Figure 1), the latter being moved to replicate 2 after the N treatment mixup occurred in 1996–1997, as described earlier. Micrometeorological masts were erected on the east edge of the designated “no traffic” areas about 4 m from the center walkways of the plots (Figure 1), where plant sampling was forbidden until the end of the season. The noncontact remote sensing instruments used in this study were positioned to view these no traffic areas. Additional “weather station” instruments were installed to the east of the replicate 4 control or blower plots, wet or high N (Figure 1). Most sensors were scanned every minute, and hourly (1992–1993 and 1993–1994) or 15-min (1995–1996 and 1996–1997) averages were recorded.

Net radiation, R_n , was measured using net radiometers [Kimball *et al.*, 1995] mounted over the no-traffic areas above (0.4 m in 1992–1993 and 1993–1994; 1.0 m in 1995–1996 and 1996–1997) the top of the crop. Duplicate pairs were deployed in each of the four plots in 1992–1993 and 1993–1994, but in 1995–1996 and 1996–1997 single instruments were mounted in each of the eight plots. All the net radiometers were raised, cleaned, and leveled weekly. Corresponding instruments were switched between the FACE and control (or blower) plots weekly in order to remove instrument biases from the season-long averages of comparisons between FACE and control (or blower) plots. Before and after each season, they were calibrated using the shading technique. In addition, before and after the 1995–1996 and 1996–1997 seasons, the net radiometers (model Q6, Radiation Energy Balance Systems, Seattle, Washington) were comparison-calibrated against a factory-calibrated model Q7 net radiometer (also from Radiation Energy Balance Systems), which had separate plus (daytime) and negative (nighttime) factors. For the latter two seasons all radiometers had the factory-made ventilators, and therefore no wind corrections were made. The plus (daytime) factors were similar to those from the shading technique, so the Q7-derived factors were used for computation of the 1995–1996 and 1996–1997 fluxes.

Soil surface heat flux, G_o , was determined from measurements of soil heat flux using soil heat flux plates positioned at the 10-mm depth plus estimates of changes in heat storage above the plates, as described by Kimball *et al.* [1994]. Four plates were installed in each plot near the micrometeorological masts. In 1992–1993 and 1993–1994 they were installed in both replicates 3 and 4, but after it was realized that they required considerable effort for a very minor component, they were installed only in replicate 4 in 1995–1996 and 1996–1997. Two plates were installed in the wheat rows, and the other two were installed midway between the rows.

Sensible heat flux, H , was calculated from

$$H = \rho_a c_p (T_s - T_a) / r_a \quad (2)$$

where ρ_a is air density, c_p is air heat capacity, T_s is temperature of the “surface,” T_a is air temperature, and r_a is aerodynamic resistance. Air dry bulb, T_a , as well as wet bulb temperatures were measured with aspirated psychrometers at the 2-m height in the wet or high-N sides of the FACE and the control or blower plots as described by Kimball *et al.* [1994, 1995]. The surface temperature, T_s , was measured using stationary infrared thermometers (IRTs), also as described by Kimball *et al.* [1994, 1995]. Duplicate pairs were deployed in each of the four

plots in 1992–1993 and 1993–1994, and the pairs were switched between the corresponding FACE and control plots weekly in order to remove instrument biases from the season-long averages of comparisons between FACE and control. They were mounted about 0.5 m above the crop and pointed northward at an oblique viewing angle of 20° below horizontal. White metal shields were mounted above each IRT to shade them from the sun. In 1995–1996 and 1996–1997, single IRTs were deployed in each of 10 plots (high- and low-N sides of both FACE and blower plots, replicates 3 and 4, plus two “ambient” plots at high-N positioned away from the FACE and blower plots; Figure 1). Following the tallgrass prairie results of Vining and Blad [1992], who found that for wind speeds of less than 4 m/s, the best estimates of H using radiometric temperatures were obtained with view zenith angles of 40° to 60°, the IRTs were mounted about 1 m above the crop and viewed northward at a 45° zenith angle. Again, the corresponding instruments were switched weekly between FACE and blower plots, although in the case of the high-N plots, the corresponding IRTs were rotated weekly among the FACE, blower, and ambient plots.

The aerodynamic resistance, r_a , was determined from the 2-m windspeed measured using a cup anemometer as described by Kimball *et al.* [1994, 1995], again using the stability corrections of Mahrt and Ek [1984]. Zero plane displacement, d , and roughness length, z_0 , were calculated from the measurements of crop height, h_c , using equations from Monteith [1973]: $d = 0.63h_c$ and $z_0 = 0.13h_c$. However, measurements of wind speed profiles inside and outside the FACE and control rings (A. Frumau and H. Vugts, personal communication, 1995) in January 1993, when the wheat plants were tiny, indicated that the plenum rings of 0.3-m diameter were disturbing the profiles inside the rings. Therefore for the calculations of aerodynamic resistance, a minimum plant height of 0.3 m was used.

3. Results

3.1. Diurnal Patterns

The diurnal patterns of solar radiation, air dry bulb and dew point temperatures, wind speed, and wheat foliage temperatures from the FACE and blower plots (averaged over replicates) are shown in Figure 2 for a fairly typical clear day at midseason, March 27, 1996. Foliage temperatures were about 3°C cooler than the 2-m air temperature for most of the day except for a period from about dawn until midafternoon, when they rose slightly above air temperature.

The differences in foliage temperature among the various plots were computed for each 15-min period during the 1995–1996 season for which there were valid data. They were sorted by time-of-day and averaged over days during the season (Figure 3). At high N, the FACE foliage was 0.6° warmer and 0.1°C cooler than the blower foliage during daytime and nighttime, respectively (Figure 3a); at low N, it was 1.1° and 0.1°C warmer. These data show the effects on foliage temperatures of the partial closing of the leaf stomata due to the elevated CO₂. (Garcia *et al.* [1998] report that midday leaf conductances were reduced 36% because of FACE in the wet plots of our 1992–1993 experiment.) At night, when the stomata were closed in both FACE and blower plots, temperature differences were small, whereas during the daytime the effects of the differential closing were maximal. Such increases in canopy temperature due to elevated CO₂ imply that the climate ranges over which crops, particularly wheat, can be grown could shift

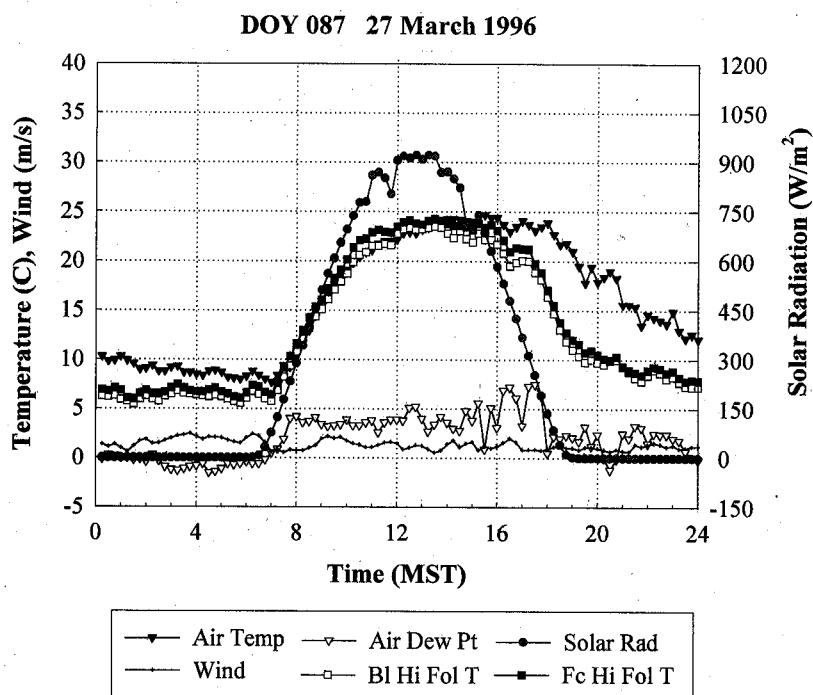


Figure 2. Solar radiation, air dry bulb and dew point temperatures (at a 2-m height), wind speed (at a 2-m height), and wheat foliage temperatures in blower and FACE high-N plots versus time of day for March 27, 1996.

in the future, even in the absence of any change in global air temperature.

Figure 3b illustrates that at ambient (blower) concentrations of CO₂, the foliage in the high-N plots tended to be cooler than that in the low-N ones, amounting to about -1.5°C at midday. At elevated (FACE) concentrations of CO₂, the differences are even greater, about -2.0°C at midday. These data suggest there was a greater resistance to water loss in the low-N plots and that this change in resistance was larger at elevated CO₂. Preliminary data reported by Wall *et al.* [1997] from the 1995–1996 and 1996–1997 experiments show that elevated CO₂ caused marked reductions in leaf conductance at both high N and low N, but no such interactive effect between CO₂ and N is detectable within the scatter of their leaf data. Changes in canopy architecture may also have been a factor. Brooks *et al.* [1997] determined mean leaf tip angles and found that the FACE low-N canopy was more erectophile, while the FACE high-N one was more planar.

R_n was the largest component of the energy budget, generally much larger in magnitude than G_0 or H , as illustrated in Figures 4 and 5 for high N and low N, respectively, for March 27, 1996. Consequently, λET followed R_n . The differences in R_n between FACE and blower were small, amounting to 3.5% and 3.8% reductions in the daily totals of R_n at both high N and low N, respectively, on this particular March day. The effects of FACE on daily total λET amounted to 13% and 14% reductions, respectively.

3.2. Seasonal Patterns of Net Radiation, Sensible Heat, and Latent Heat Fluxes

There were small but consistent differences between the FACE and blower treatments at both high N and low N in the daily total fluxes of net radiation, R_n ; sensible heat flux, H ; and latent heat flux, λET (Figure 6). As can be inferred from

Figures 4 and 5, daily totals of soil heat flux, G_0 , were very small, (generally $<1 \text{ MJ}^{-2} \text{ day}^{-1}$), as expected so they are not shown. Daily FACE H tended to be about $0.7 \text{ MJ}^{-2} \text{ day}^{-1}$ higher than Blower H , which meant it was less negative on many of the days. This tendency was because the FACE plants were slightly warmer than the blower plants during most of the daytime, and both FACE and blower plants generally were cooler than the air except from about dawn until shortly after noon (Figure 2; equation (2)).

The slope of the regression line in Figure 7a indicates that the FACE treatment decreased net radiation, R_n , by about 1.3% [$(1.000 - 0.987) \times 100 = 1.3\%$; $\pm \text{S.E. of } 0.6\%$] under wet, high-N conditions. Under low-N conditions the reduction in R_n was similar (Figure 7b). A decrease in R_n was expected because of the warmer temperatures in the FACE compared to the blower or control plots (Figure 3a). However, at a surface temperature of 20°C , a 0.6°C canopy temperature increase (Figure 3a for daytime at high N) would be expected to decrease R_n by 3.4 W m^{-2} , and such a decrease would only be about 0.5% of typical midday R_n values (Figure 4a). Also under low N, the temperature increase was greater (1.1°C during daytime; Figure 3a), yet the R_n change was about the same (Figures 7a and 7b). Therefore canopy structure and/or leaf reflectance properties for shortwave radiation must have also been altered by the FACE treatment, and the amount of alteration was more in the low-N plots than in the high-N plots. Moreover, such changes were observed. As already mentioned, Brooks *et al.* [1997] determined mean leaf tip angles and found that the FACE low-N canopy was more erectophile while the FACE high-N canopy was more planar. In 1992–1993 and 1993–1994 the FACE plots had a larger albedo from grain filling onwards (although at heading the FACE plots were lower), which would have decreased R_n relative to the control

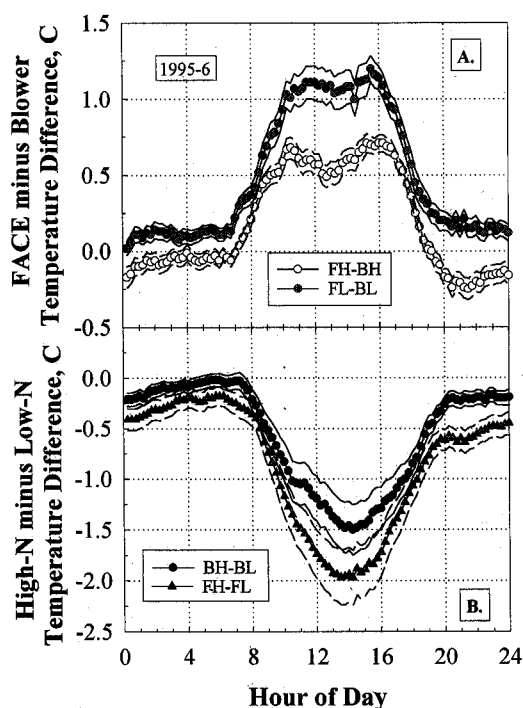


Figure 3. Near-season-long average foliage temperature differences for the 1995–1996 season. (a) between the FACE high-N (FH) and the blower high-N (BH) plots and between the FACE low-N (FL) and the blower low-N (BL) plots and (b) between the FACE high-N (FH) and the FACE low-N (FL) plots and between the blower high-N (BH) and the blower low-N (BL) versus time of day. The data are the mean differences for each particular 15-min period averaged over 73 days for which good data were available between February 6 and May 7 for the high-N plots and for 65 days between February 6 and April 27 for the low-N plots. This selection of data excluded early season data when the instruments viewed soil and late season data when the crop senesced. The standard errors were computed from the standard deviation of the differences over the 73 or 65 days.

plots (A. Frumau and H. Vugts, personal communication, 1998).

Like Figures 4c, 5c, 6c, and 6d, Figures 7e and 7f also show that generally the sensible heat flux, H , in the FACE plots was higher (sometimes less negative) than that in the blower or control plots, as a result of the warmer temperatures in the FACE plots (Figures 2 and 3; equation (3)). Comparing Figure 7e to Figure 7f, H in the low-N plots was higher than that in the high-N plots. One possible reason for this result is that the elevated CO₂ in the FACE plots caused relatively more stomatal closure under low N compared to high N, resulting in relatively higher stomatal resistances and canopy temperatures (Figure 3a). However, the CO₂-induced and especially the N-induced changes in crop canopy architecture [Brooks *et al.*, 1997] might also have changed the surface emissivity and the degree of difference between the radiative and aerodynamic surface temperatures [Huband and Monteith, 1986a].

The FACE treatment decreased latent heat flux or evapotranspiration, λET , by an average 6.7% ($\pm 1.2\%$) for the four seasons under wet, high-N conditions, as indicated by the slope of the regression line in Figure 7c, confirming the previous results reported for the 1992–1993 season by Kimball *et al.* [1995]. Under low N the reduction was 19.5% ($\pm 2.5\%$; Figure 7d). Regressions for all the individual seasons for the data in Figures 7c and 7d (not shown) were in good agreement, which gives confidence in these results.

4. Discussion

Because the plots were semicircular with a useable radius of only about 10 m (Figure 1), the fetch was rather short to evaluate the effects of CO₂ on ET using micrometeorological methods which rely on measurement of profiles of windspeed, temperature, and water vapor above the crop. However, the residual energy balance technique (equation (1)) was reasoned to be less sensitive to the fetch constraints and could be used to determine the relative differences in ET between the FACE and control or blower plots. The first reason is that all of the plots were in fields of wheat where, to a first approximation,

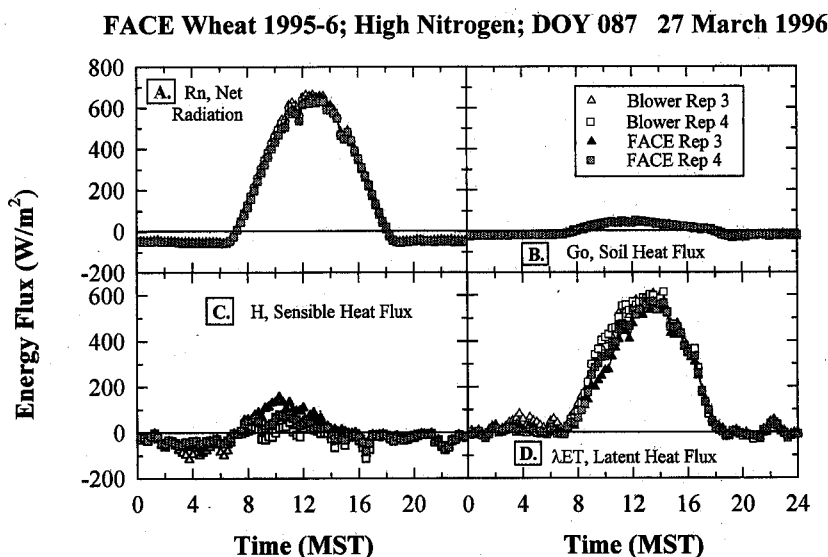


Figure 4. (a) Net radiation, R_n ; (b) soil heat flux, G_o ; (c) sensible heat flux, H ; and (d) latent heat flux, λET , in blower and FACE plots versus time of day on March 27, 1996 in the high-N plots for replicates 3 and 4.

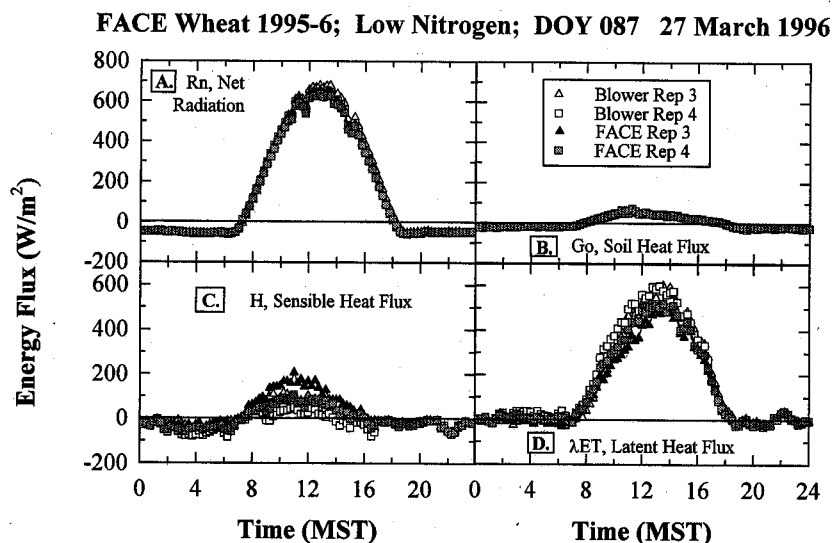


Figure 5. (a) Net radiation, R_n ; (b) soil heat flux, G_o ; (c) sensible heat flux, H ; and (d) latent heat flux, λET , in blower and FACE plots versus time of day on March 27, 1996 in the low-N plots for replicates 3 and 4.

the structural elements were close to the same size and geometry everywhere. Therefore the aerodynamic resistance used in the calculation of H and determined from wind speed at a single mast would not be expected to vary much among plots. A second reason is that turbulent transfer processes are a logarithmic function of height above the surface, so that the gradients close to the crop are largest and most important in determining the rates of transfer. In this case actual crop surface temperatures were measured with infrared thermometers, thereby minimizing fetch requirements. Air temperatures were measured at the 2-m height (approximately 1 m above the crop), which is high compared to the fetch.

The consequences of such limited fetch have been addressed by Grant *et al.* [1999] in a modeling paper with some of the same data reported herein. Using the geometry of our wheat field and following the work of Brunet *et al.* [1994], they estimated that more than 0.67 of the change in radiative surface temperature would have been observed compared to semi-infinite fetch conditions. Similarly, following the companion work of Itier *et al.* [1994], the 2-m air temperature was estimated to change about 0.2 of the amount for a semi-infinite case. Focusing on 2 April days when large upward values of H were observed and adjusting the FACE minus control surface and 2-m air temperatures with these ratios, Grant *et al.* calculated that H would be reduced by as much as 50 W m^{-2} when wind speeds were lowest or increased by a similar amount when wind speeds were highest. Over the 2-day period such an adjustment caused an average reduction in calculated H of 12.5 W m^{-2} , which is less than 0.3 of the increase in H over these 2 days under elevated compared to ambient CO₂.

The ET reduction of 6.7% due to the FACE treatment under wet, high-N conditions, as determined by the residual energy balance approach used here, is close to the 5% reduction reported for the 1992–1993 and 1993–1994 seasons by Hunsaker *et al.* [1996a], who used a residual soil water balance approach. However, Hunsaker *et al.* [1996b, 1997], again using the soil water method, did not detect any reductions in ET at either high N or low N during the 1995–1996 and 1996–1997 seasons. Considering that ET was calculated as a residual in both the energy balance and soil water balance techniques,

both suffer from the accumulation of errors made in the measurements of other terms. Soil water is notoriously inhomogeneous, so it is difficult to detect small differences amid large variability. The soil water content measurements needed to be made just after and just before irrigations and rainfall, as well as frequently between, and such was not always possible. Water fluxes at the bottom of the rooting zone were assumed zero, which may not have been true. However, although it is difficult to detect small differences among the plots with the soil water balance method, the cumulative absolute values should be fairly accurate.

On the other hand, the residual energy balance approach suffers from possible errors in the calibration of the net radiometers, infrared thermometers, and the other instruments. There are also questions about the assumptions associated with determination of the aerodynamic resistance, r_a , especially the fetch constraints discussed previously. The agreement of aerodynamic and radiative surface temperatures may not be exact [Huband and Monteith, 1986a, b]. Thus the energy balance method may be less accurate than the soil water balance for determining the absolute level of ET, especially for cumulative ET over several days. However, because the residual energy balance method is most sensitive to the net radiation and surface temperature measurements [Kimball *et al.*, 1994] and because these instruments were switched weekly between FACE and blower or control plots, the residual energy balance technique as implemented here should be accurate for determining relative differences among the plots.

Compared to the 40% increase in cotton biomass with CO₂ enrichment to $550 \mu\text{mol/mol}$ in our prior FACE experiments [Mauney *et al.*, 1994; Pinter *et al.*, 1996a], the wheat growth response was only about 20% at midseason [Kimball *et al.*, 1995; Pinter *et al.*, 1996a, b]. Thus it appears that for wheat, the increase in growth did not fully counteract the increase in leaf stomatal resistance, so that a net savings in water use per unit of land area resulted, whereas the large increase in cotton growth fully compensated the resistance increase, resulting in no change in water use per unit of land area.

The degree to which these plot-scale measurements pertain to larger regional-scale ET also needs to be addressed. A

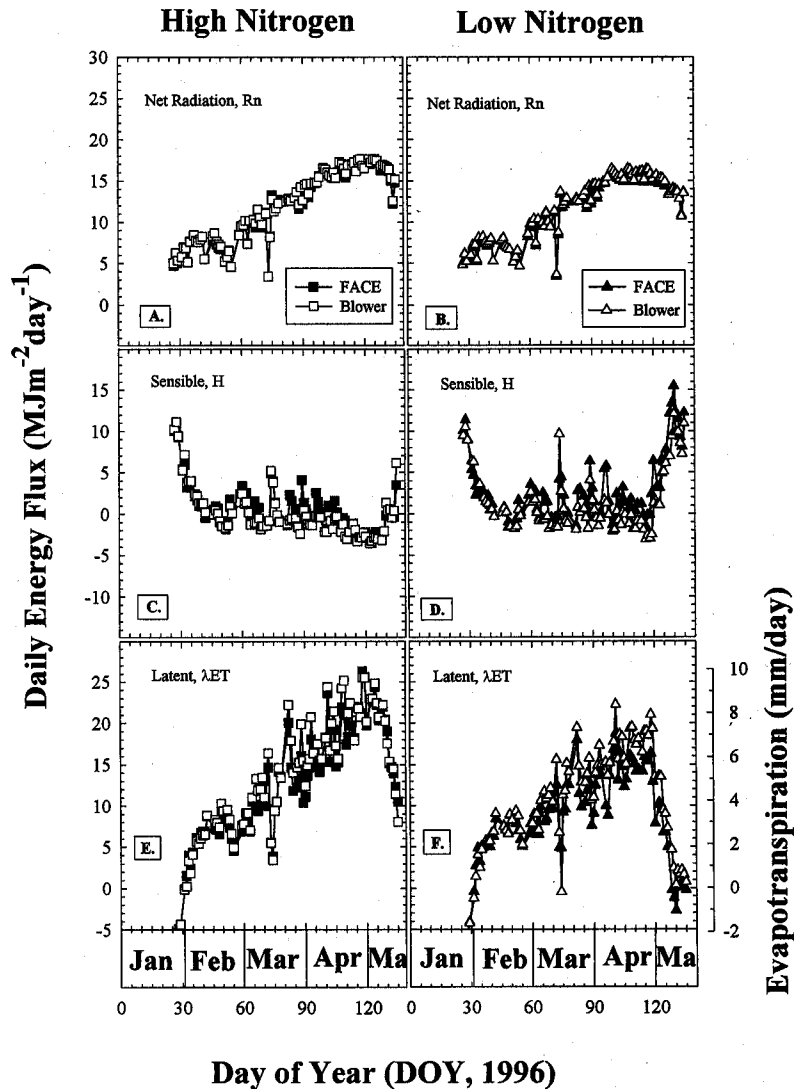


Figure 6. (a, b) Daily total net radiation, R_n ; (c, d) sensible heat flux, H ; and (e, f) latent heat flux, λET , in blower and FACE plots for the high- and low-N treatments versus day of year in 1996. Each data point is an average from two replicate plots.

well-known theory by *Jarvis and McNaughton* [1986] postulates that on a regional scale, there is no control of stomatal resistance on evapotranspiration. They argue that if CO₂ or some other factor alters stomatal resistance, then humidity profiles adjust within the planetary boundary layer (PBL), which is a negative feedback that counters the stomatal closure. In other words, if the stomata partially close so that there is more resistance to water loss, then the PBL becomes drier and increases the water vapor concentration gradient from inside the leaves to the upper atmosphere, thereby negating any effect of changing the stomata. They also argue that stomatal resistance is only one of a series of resistances to water loss from vegetation, and changing CO₂ will not affect the other resistances. The architecture of the plant canopy affects the relative sizes of the resistances, and therefore it is important for regulating the coupling from the leaves to the PBL, with smooth vegetation such as grassland being poorly coupled, while rough vegetation like a forest is more tightly coupled. Therefore stomatal effects would be more important in forest than in grassland. In contrast, the simulations by *Martin et al.* [1989] indicate that sto-

matal control of transpiration in grasslands is similar or even greater than that of forests. However, recent simulations by *Carlson and Bunce* [1996] and *Bunce et al.* [1997] are consistent with the postulate of Jarvis and McNaughton.

If the theory of *Jarvis and McNaughton* [1986] is true, then plot-scale manipulations of stomatal resistance via elevated CO₂ from FACE rings are largely irrelevant for predicting the consequences of global change on regional evapotranspiration and water resources (except perhaps in a relatively small irrigated area surrounded by desert, such as the irrigation district where this work was done). However, at least seven papers [*Jacobs and de Bruin*, 1992; *de Bruin and Jacobs*, 1993; *Jacobs*, 1994; *Pollard and Thompson*, 1995; *Sellers et al.*, 1997; *Dickinson et al.*, 1997; *Raupach*, 1998] have recently appeared that consider several additional feedbacks, and their simulations suggest that stomata have far more control on regional and global evapotranspiration than as postulated by Jarvis and McNaughton.

Following *Jacobs and de Bruin* [1992], *de Bruin and Jacobs* [1993], and *Jacobs* [1994], if the canopy or surface resistance,

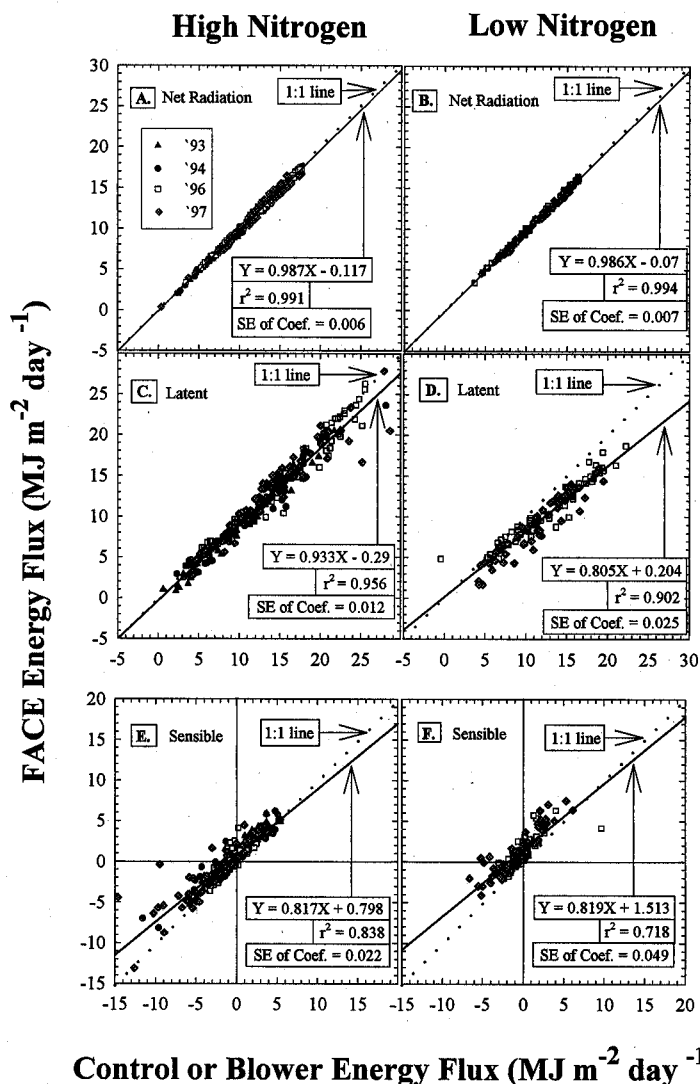


Figure 7. Daily total FACE (a, b) net radiation, R_n ; (c, d) latent heat flux, λET ; and (e, f) sensible heat flux, H , versus the corresponding blower or control values. Figures 7a, 7c, and 7e include data from wet, high-N plots from all four seasons (1992–1993, 1993–1994, 1995–1996, and 1996–1997). Figures 7b, 7d, and 7f include data from low-N plots from the last two seasons (1995–1996 and 1996–1997). Each data point from 1992–1993 and 1993–1994 is an average over dual sets of instruments per plot and over two replicate plots, and each point from 1995–1996 and 1996–1997 is an average over two replicate plots. About 60 data points per season are plotted about from mid-February until early May (high N) or late April (low N). This selection of data excluded early season data when the instruments viewed soil and late season data when the crop senesced. Also shown are the overall regression lines.

r_s , increases because of elevated CO₂, then λET decreases and H and T_s increase. However, then the vapor pressure deficit, VPD, increases, which increases λET , that is, a negative surface layer feedback. However, the energy balance is coupled to plant physiological processes, and secondary effects on r_s can become important. As VPD increases, the lower humidity causes r_s to increase and λET to decrease, which is a positive feedback. At the same time stomatal resistance is also coupled to assimilation, so that increased T_s (as long as it is below the optimum temperature for assimilation) will increase assimilation, decrease r_s , and thereby increase λET , that is, another negative feedback. Increased leaf area with elevated CO₂ would also decrease r_s and increase λET . When PBL feedback is considered as well, the increase of H increases the T at reference height, thereby increasing T_s and VPD. The latter

increases λET directly, but it also increases r_s which indirectly decreases λET . Besides neglecting several surface layer feedbacks, another defect of the *Jarvis and McNaughton* [1986] theory is that the upper edge of the PBL is really rather convective according to *Dickinson et al.* [1997], so that it does not present a hermetic barrier to the transfer of water upward out of the PBL as assumed by Jarvis and McNaughton.

Jarvis and McNaughton [1986] and more-recent papers postulate several indirect negative and positive feedbacks that affect the sensitivity of ET to changes in stomatal or surface conductance. Thus one cannot presume that a reduction of ET of about 6.7% due to elevated CO₂ under ample water and N, such as observed in our plots, would be observed at a regional scale. Nevertheless, the recent papers suggest that the reduction is likely to be significant.

A reduction of ET by 6.7% due to the 200 $\mu\text{mol/mol}$ increase in CO₂ concentration from the FACE treatment under high N (Figure 7c) is smaller than some of the other plant responses caused by elevated CO₂ such as growth or biomass, which increased about 20% in our wheat experiments [Kimball et al., 1995; Pinter et al., 1996a, b]. Such a growth increase, however, coupled with the reduction in water use represents an increase in water use efficiency of about 29%. Thus the reductions in ET are fairly small and probably would not be expected to have significant impacts on streamflow. On the other hand, the increases in water use efficiency, assuming other grasses will behave like wheat, are substantial. Moreover, such increases in the efficiency with which plants use water and are likely to be important in determining the optimal production areas in managed agriculture. They may also cause major areal shifts of whole biomes in unmanaged ecosystems [Melillo et al., 1996]. Such shifts in vegetation areas are likely to have important feedbacks to the climate system and global change.

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References

- Allen, L. H., Jr., Effects of increasing carbon dioxide levels and climate change on plant growth, evapotranspiration, and water resources, in *Managing Water Resources in the West Under Conditions of Climate Uncertainty*, pp. 101–147, Natl. Acad. Press, Washington, D. C., 1990.
- Brooks, T. J., G. W. Wall, P. J. Pinter Jr., N. Adam, B. A. Kimball, R. L. LaMorte, F. J. Adamsen, and D. J. Hunsaker, Effects of nitrogen and CO₂ on wheat canopy architecture and gas exchange, in *Annual Research Report*, pp. 78–81, U.S. Water Conserv. Lab., U.S. Dep. of Agric., Phoenix, Ariz., 1997.
- Brunet, Y., B. Itier, J. McAneney, and J. P. Lagouarde, Downwind evolution of scalar fluxes and surface resistance under conditions of local convection, II, Measurements over barley, *Agric. For. Meteorol.*, **71**, 227–245, 1994.
- Bunce, J. A., K. B. Wilson, and T. N. Carlson, The effect of doubled CO₂ on water use by alfalfa and orchard grass: Simulating evapotranspiration using canopy conductance measurements, *Global Change Biol.*, **3**, 81–87, 1997.
- Carlson, T. N., and J. A. Bunce, Will a doubling of atmospheric carbon dioxide concentration lead to an increase or a decrease in water consumption by crops?, *Ecol. Modell.*, **88**, 241–246, 1996.
- De Bruin, H. A. R., and C. M. J. Jacobs, Impact of CO₂ enrichment on the regional evapotranspiration of agro-ecosystems, a theoretical and numerical modelling study, *Vegetatio*, **104/105**, 307–318, 1993.
- Dickinson, R. E., A. N. Hahmann, and Q. Shao, Commentary on Mecca sensitivity studies, in *Assessing Climate Change*, edited by W. Howe and A. Henderson-Sellers, pp. 195–206, Gordon and Breach, Sidney, Australia, 1997.
- Dugas, W. A., and P. J. Pinter Jr. (Eds.), The free-air carbon dioxide enrichment (FACE) cotton project: A new field approach to assess the biological consequences of global change, *Agric. For. Meteorol.*, **70**, 1–342, 1994.
- Dugas, W. A., M. L. Heuer, D. J. Hunsaker, B. A. Kimball, K. F. Lewin, J. Nagy, and M. Johnson, Sap flow measurements of transpiration in open-field-grown cotton under ambient and enriched CO₂ concentrations, *Agric. For. Meteorol.*, **70**, 231–245, 1994.
- Dugas, W. A., S. A. Prior, and H. H. Rogers, Transpiration from sorghum and soybean growing in ambient and elevated CO₂ concentrations, *Agric. For. Meteorol.*, **83**, 37–48, 1997.
- Fox, F. A., Jr., T. Scherer, D. C. Slack, and L. J. Clark, *Arizona Irrigation Scheduling User's Manual*, 36 pp., Coop. Ext., Agric. and Biosyst. Eng., Univ. of Ariz., Tucson, Ariz., 1992.
- Fredeen, A. L., J. T. Randerson, N. M. Holbrook, and C. B. Field, Elevated atmospheric CO₂ increases water availability in a water-limited grassland ecosystem, *J. Am. Water Resour. Assn.*, **33**, 1033–1039, 1997.
- Garcia, R. L., S. P. Long, G. W. Wall, C. P. Osborne, B. A. Kimball, G.-Y. Nie, P. J. Pinter Jr., R. L. LaMorte, and F. Wechsung, Photosynthesis and conductance of spring wheat leaves: Field response to continuous free-air atmospheric CO₂ enrichment, *Plant, Cell Environ.*, **21**, 659–669, 1998.
- Grant, R. F., G. W. Wall, B. A. Kimball, K. F. A. Frumau, P. J. Pinter Jr., D. J. Hunsaker, and R. L. LaMorte, Crop water relations under different CO₂ and irrigation: Testing *ecosys* with the free-air CO₂ enrichment (FACE) experiment, *Agric. For. Meteorol.*, in press, 1999.
- Hendrey, G. R. (Ed.), *FACE: Free-Air CO₂ Enrichment for Plant Research in the Field*, 308 pp., C. K. Smoley, Boca Raton, Fla., 1993.
- Hileman, D. R., G. Huluka, P. K. Kenjige, N. Sinha, N. C. Bhattacharya, P. K. Biswas, K. F. Lewin, J. Nagy, and G. R. Hendrey, Canopy photosynthesis and transpiration of field-grown cotton exposed to free-air CO₂ enrichment (FACE) and differential irrigation, *Agric. For. Meteorol.*, **70**, 189–207, 1994.
- Huband, N. D. S., and J. L. Monteith, Radiative surface temperature and energy balance of a wheat canopy, I, Comparison of radiative and aerodynamic canopy temperature, *Boundary Layer Meteorol.*, **36**, 1–17, 1986a.
- Huband, N. D. S., and J. L. Monteith, Radiative surface temperature and energy balance of a wheat canopy, II, Estimating fluxes of sensible and latent heat, *Boundary Layer Meteorol.*, **36**, 107–116, 1986b.
- Hunsaker, D. J., G. R. Hendrey, B. A. Kimball, K. F. Lewin, J. R. Mauney, and J. Nagy, Cotton evapotranspiration under field conditions with CO₂ enrichment and variable soil moisture regimes, *Agric. For. Meteorol.*, **70**, 247–258, 1994.
- Hunsaker, D. J., B. A. Kimball, P. J. Pinter Jr., R. L. LaMorte, and G. W. Wall, CO₂ enrichment and irrigation effects on wheat evapotranspiration in a free-air environment, *Trans. ASAE* **39**, 1345–1355, 1996a.
- Hunsaker, D. J., B. A. Kimball, P. J. Pinter Jr., G. W. Wall, and R. L. LaMorte, Wheat evapotranspiration as affected by elevated CO₂ and variable soil nitrogen, in *Annual Research Report*, pp. 79–82, U.S. Water Conserv. Lab., U.S. Dep. of Agric., Phoenix, Ariz., 1996b.
- Hunsaker, D. J., B. A. Kimball, P. J. Pinter Jr., G. W. Wall, and R. L. LaMorte, Soil water balance and wheat evapotranspiration as affected by elevated CO₂ and variable soil nitrogen, in *Annual Research Report*, pp. 67–70, U.S. Water Conserv. Lab., U.S. Dep. of Agric., Phoenix, Ariz., 1997.
- Intergovernmental Panel on Climate Change, *Climate Change 1995: Summary for Policy Makers*, edited by J. T. Houghton et al., pp. 1–7, Cambridge Univ. Press, New York, 1996.
- Itier, B., Y. Brunet, K. J. McAneney, and J. P. Lagouarde, Downwind evolution of scalar fluxes and surface resistance under conditions of local advection, I, A reappraisal of boundary conditions, *Agric. For. Meteorol.*, **71**, 211–225, 1994.
- Jacobs, C. M. J., Direct impact of atmospheric CO₂ enrichment on regional transpiration, Ph.D. dissertation, Dep. of Meteorol., Wageningen Agric. Univ., Wageningen, Netherlands, 1994.
- Jacobs, C. M. J., and H. A. R. de Bruin, The sensitivity of regional transpiration to land-surface characteristics: Significance of feedback, *J. Clim.*, **5**, 683–698, 1992.
- Jarvis, P. G., and K. G. McNaughton, Stomatal control of transpiration: scaling up from leaf to region, *Adv. Ecol. Res.*, **15**, 1–49, 1986.

- Kimball, B. A., and S. B. Idso, Increasing atmospheric CO₂: Effects on crop yield, water use, and climate, *Agric. Water Manage.*, 7, 55–72, 1983.
- Kimball, B. A., P. J. Pinter Jr., and J. R. Mauney, Cotton leaf and boll temperatures in the 1989 FACE experiment, *Crit. Rev. Plant Sci.*, 11, 233–240, 1992a.
- Kimball, B. A., R. L. LaMorte, G. J. Peresta, J. R. Mauney, K. F. Lewin, and G. R. Hendrey, Appendices: Weather, soils, cultural practices, and cotton growth data from the 1989 FACE experiment in IBSNAT format, *Crit. Rev. Plant Sci.*, 11, 271–308, 1992b.
- Kimball, B. A., et al., Effects of free-air CO₂ enrichment on energy balance and evapotranspiration of cotton, *Agric. For. Meteorol.*, 70, 259–278, 1994.
- Kimball, B. A., P. J. Pinter Jr., R. L. Garcia, R. L. LaMorte, G. W. Wall, D. J. Hunsaker, G. Wechsung, F. Wechsung, and T. Kartschall, Productivity and water use of wheat under free-air CO₂ enrichment, *Global Change Biol.*, 1, 429–442, 1995.
- Mahrt, L., and M. Ek, The influence of atmospheric stability on potential evaporation, *J. Clim. Appl. Meteorol.*, 23, 222–234, 1984.
- Martin, P., N. J. Rosenberg, and M. S. Mc Kenney, Sensitivity of evapotranspiration in a wheat field, a forest, and a grassland to changes in climate and direct effects of carbon dioxide, *Clim. Change*, 14, 117–151, 1989.
- Mauney, J. R., B. A. Kimball, P. J. Pinter Jr., R. L. LaMorte, K. F. Lewin, J. Nagy, and G. R. Hendrey, Growth and yield of cotton in response to a free-air carbon dioxide enrichment (FACE) environment, *Agric. For. Meteorol.*, 70, 49–68, 1994.
- Melillo, J. M., I. C. Prentice, G. D. Farquhar, E.-D. Schulze, and O. E. Sala, Terrestrial biotic responses to environmental change and feedbacks to climate, in *Climate Change 1995*, edited by J. T. Houghton, pp. 445–481, Cambridge Univ. Press, New York, 1996.
- Monteith, J. L., *Principles of Environmental Physics*, 241 pp., Edward Arnold, London, 1973.
- Morison, J. I. L., Intercellular CO₂ concentration and stomatal response to CO₂, in *Stomatal Function*, edited by E. Zeiger and G. D. Farquhar, pp. 229–251, Stanford Univ. Press, Stanford, Calif., 1987.
- Pinter, P. J., Jr., B. A. Kimball, R. L. Garcia, G. W. Wall, D. J. Hunsaker, and R. L. LaMorte, Free-air CO₂ enrichment: Responses of cotton and wheat crops, in *Carbon Dioxide and Terrestrial Ecosystems*, edited by G. W. Koch and H. A. Mooney, pp. 215–248, Academic, San Diego, Calif., 1996a.
- Pinter, P. J., Jr., B. A. Kimball, G. W. Wall, R. L. LaMorte, F. Adamsen, and D. J. Hunsaker, FACE 1995–96: Effects of elevated CO₂ and soil nitrogen on growth and yield parameters of spring wheat, in *Annual Research Report*, pp. 75–78, U.S. Water Conserv. Lab., U.S. Dep. of Agric., Phoenix, Ariz., 1996b.
- Pollard, D., and S. L. Thompson, Use of a land-surface transfer scheme (LSX) in a global climate model: The response to doubling stomatal conductance, *Global Planet. Change*, 10, 129–161, 1995.
- Post, D. F., C. Mack, P. D. Camp, and A. S. Suliman, Mapping and characterization of the soils on the University of Arizona Maricopa Agricultural Center, *Proc. Hydrol. Water Resour. Southwest*, 18, 49–60, 1988.
- Raupach, M. R., Influences of local feedbacks on land-air exchanges of energy and carbon, *Global Change Biol.*, 4, 477–494, 1998.
- Rosenberg, N. J., B. A. Kimball, P. Martin, and C. F. Cooper, From climate and CO₂ enrichment to evapotranspiration, in P. E. Waggoner (ed.), *Climate and U.S. Water Resources*, edited by P. E. Waggoner, pp. 151–175, John Wiley, New York, 1990.
- Samerakoon, A. B., and R. M. Gifford, Soil water content under plants at high CO₂ concentration and interactions with direct CO₂ effects: A species comparison, *J. Biogeogr.*, 22, 193–202, 1995.
- Sellers, P. J., et al., Modeling the exchanges of energy, water, and carbon between continents and the atmosphere, *Science*, 275, 502–509, 1997.
- Senock, R. S., J. M. Ham, T. M. Loughin, B. A. Kimball, D. J. Hunsaker, P. J. Pinter, G. W. Wall, R. L. Garcia, and R. L. LaMorte, Sap flow in wheat under free-air CO₂ enrichment, *Plant Cell Environ.*, 19, 147–158, 1996.
- Vining, R. C., and B. L. Blad, Estimation of sensible heat flux from remotely sensed canopy temperatures, *J. Geophys. Res.*, 97(D17), 18,951–18,954, 1992.
- Wall, G. W., and B. A. Kimball, Biological databases derived from free air carbon dioxide enrichment experiments, in *Design and Execution of Experiments on CO₂ Enrichment*, edited by E. D. Schulze and H. A. Mooney, pp. 329–351, Comm. of the Eur. Communities, Brussels, Belgium, 1993.
- Wall, G. W., N. R. Adam, T. J. Brooks, B. A. Kimball, F. J. Adamsen, P. J. Pinter Jr., and R. L. LaMorte, Acclimation of the photosynthetic apparatus of spring wheat grown under free-air CO₂ enrichment (FACE) and two soil nitrogen regimes, in *Annual Research Report*, pp. 61–64, U.S. Water Conserv. Lab., U.S. Dep. of Agric., Phoenix, Ariz., 1997.
- F. J. Adamsen, D. J. Hunsaker, B. A. Kimball, R. L. LaMorte, P. J. Pinter Jr., and G. W. Wall, U.S. Water Conservation Laboratory, ARS, USDA, 4331 E. Broadway Rd., Phoenix, AZ 85040-8832. (bkimball@uswcl.ars.ag.gov)
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