

Free-air CO₂ enrichment (FACE): blower effects on wheat canopy microclimate and plant development

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Abstract

Free-air carbon dioxide enrichment (FACE) provides a realistic, cost-effective method for evaluating the effects of supra-ambient CO₂ concentrations on growth, development, yield, and water use of agricultural crops and natural ecosystems with very few of the problems normally associated with glasshouse or chamber type research. There are no walls interfering with incident radiation and no artificial constraints on rooting depth. With current FACE technology, CO₂ enriched air is injected around the perimeter of circular plots and natural wind disperses the CO₂ across the experimental area. Under stable, nighttime wind conditions found in FACE wheat experiments at Maricopa, Arizona, the blowers used to inject CO₂ exerted subtle effects on the microclimate in a manner analogous to wind machines used for orchard frost protection. Plots equipped with blowers had nighttime foliage and air temperatures that averaged 0.6–1.0°C warmer than controls without blowers. A secondary effect of these elevated temperatures was that plots equipped with blowers displayed differences in dew duration (time that leaves were wet was reduced 30%), plant development (anthesis occurred 4 days earlier), and senescence [as measured with the normalized difference vegetation index (NDVI)]. Natural wind and turbulence appear to overcome the blower effect during daytime treatments and on some nights. Aerial thermal imagery (8–12 μm) acquired during the 1998 FACE experiment with grain sorghum provided additional evidence of the blower effect on canopy temperatures. Since increased plant tissue temperatures also occur when elevated CO₂ induces partial stomatal closure and reduces transpiration, not all instances of

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canopy temperature elevation in CO₂ enriched plots can be ascribed solely to the presence of blowers. It is concluded that proper controls for FACE facilities should have similar air flows to those used in the FACE plots. Advantages and disadvantages to nighttime CO₂ enrichment are discussed. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Wheat; *Triticum aestivum*; Carbon dioxide; Climate change; Microclimate; Canopy temperatures; Canopy reflectance; Leaf wetness

1. Introduction

Free-air carbon dioxide enrichment (FACE) was developed to expose plants to elevated levels of CO₂ under natural field conditions while minimizing the microenvironmental and climatic artifacts often associated with open-top chambers or glasshouse culture (Hendrey, 1993; Hendrey et al., 1993; Dugas and Pinter, 1994). This new technology has made it possible to make realistic assessments of the effects of anticipated, 21st century atmospheric CO₂ concentrations on yields of agricultural crops growing in large scale production fields (Pinter et al., 1996; Kimball et al., 1997a). Performance metrics have shown that the FACE facility provides very good temporal and spatial control of CO₂ concentrations and is a cost-effective means for large scale fumigation experiments (Kimball, 1992; Nagy et al., 1994). Carbon isotope studies have likewise confirmed that the plants actually 'see' the intended exposure concentrations over the entire season (S.W. Leavitt and H.B. Johnson, unpublished data).

Strategies for CO₂ exposure and the sophistication of ambient CO₂ control plots have evolved over the years as FACE was applied to different ecosystems and as experimental objectives changed. As is usually the case in application of any new technology, changes were also made as more was learned about system behavior under different environmental conditions. For example, in cotton experiments conducted from 1987 through 1991, the FACE plots had blowers to promote uniform mixing of the CO₂ with the air entering the plots, and enrichment was only done during daylight hours. Control plots were not equipped with blowers because studies had shown that the CO₂-rich air injected into the plots from the vertical standpipes was essentially dissipated within 2 m from the injection ports (Lipfert et al., 1992) and did not intrude upon experimental zones where plant observations were taken. Dummy plastic manifolds and standpipes (without blowers) were added to

Control plots in 1990 and 1991, to make early season microclimate (e.g. windbreak) and visual clues to migrating pests more similar to the FACE plots.

In 1992, when the focus of the agricultural FACE project shifted to spring wheat (Kimball et al., 1995, 1999; Pinter et al., 1996), emerging evidence that elevated CO₂ could inhibit plant respiration (e.g. Reuveni and Gale, 1985; Amthor, 1991; Bunce and Caulfield, 1991; Bunce, 1992) led to a decision to apply CO₂ enrichment on a 24-h basis. During the first 2 years of FACE experimentation in wheat (1992–1993 and 1993–1994), Control plots had dummy plastic manifolds and standpipes but were not equipped with blowers. However, with the new 24-h protocol, CO₂ levels of FACE plots remained near the intended 550 μmol mol⁻¹ set point while CO₂ in Control plots would occasionally soar to 800 or 1000 μmol mol⁻¹ during calm periods at night. Workers taking measurements in the field early in the morning and around sundown also noticed more dew in the Control plots than in FACE plots.

Thus, we began to suspect that the gas injection was inducing microturbulence into the boundary layer above the canopy at night in the FACE plots. If that were true, there would be a temperature perturbation that could explain the nighttime differences in CO₂ concentrations between FACE and Control plots and the crepuscular dew phenomena. Likewise, a temperature difference might provide an alternative explanation for a major portion of what appeared to be CO₂-related differences in wheat crop development and end-of-season maturity as reported by Kimball et al. (1995) and Pinter et al. (1996).

Wheat FACE studies were continued for another 2 years, through the 1995–1996 and 1996–1997 growing seasons (Kimball et al., 1999). For these experiments blowers were installed in the experimental control plots (hereafter called Blower plots) so that air movement would be similar to the FACE plots. During the 1995–1996 study, two additional plots were established in another portion of the field at a

distance from the FACE and Blower plots to better understand the ‘blower effects’. These plots were referred to as Ambient plots and were functionally equivalent to the Control plots from the two earlier wheat experiments. They were equipped with dummy plastic manifolds and vertical release pipes but received neither extra CO₂ nor forced air movement. The purpose of this paper is to compare microclimate and plant responses among the FACE, Control, Blower, and Ambient plots. This information should be useful when designing future FACE experiments.

2. Methods

2.1. Location and general description of experiment

Experiments were conducted during four growing seasons in a 10-ha field located at the University of Arizona Maricopa Agricultural Center (MAC), Maricopa, Arizona, USA. A hard red spring wheat, *Triticum aestivum* L cv Yecora Rojo, which is photoperiod insensitive and does not require vernalization, was sown in mid-December, emerged between 1 and 3 January, and was harvested in late May or early June of each year. The soil was classified as a reclaimed Trix clay loam (fine-loamy, mixed (calcareous), hyperthermic Typic Torrifuvents). Application of water and fertilizer was accomplished via subsurface drip irrigation.

2.2. FACE plot hardware and operational control of CO₂

The FACE technique was used to enrich the air in circular plots within a wheat field similar to prior experiments in cotton (Hendrey, 1993; Hendrey et al., 1993; Wall and Kimball, 1993; Mauney et al., 1994; Dugas and Pinter, 1994; Wechsung et al., 1995; Kimball et al., 1995, 1999; Pinter et al., 1996; Hunsaker et al., 1996). Briefly, four replicate, 25 m diameter toroidal plenums (rings) constructed from 0.305 m diameter plastic pipe were placed in the field shortly after planting. The center-to-center spacing between rings was ~90 m (Wall and Kimball, 1993). Each ring had 2.5-m-high vertical stand pipes with individual valves spaced about every 2.5 m around the periphery (Wall and Kimball, 1993; Lewin et al.,

1994). Air enriched with CO₂ was blown at a rate of 40 m³ air min⁻¹ into the plenum and exited through tri-directional jets in the stand pipes at elevations near the top of the crop canopy.

The amount of CO₂ released into the FACE plots was based on feedback from CO₂ concentrations and wind speeds measured near the center of each plenum. Wind direction was used to open valves on stand pipes on the upwind side, so that CO₂-enriched air flowed across the plots no matter which way the wind blew. At wind speeds below the 0.4 m s⁻¹ detection threshold of the anemometers, CO₂-enriched air was released from alternate standpipes around the rings. The CO₂ flow rates were updated every second, and the choice of which vertical pipes to release from was updated every 4 s. Analysis of daytime data from the FACE cotton experiments showed the 1-min-average CO₂ concentrations remained within 10% of the desired set point 90% of the time (Nagy et al., 1994).

2.3. FACE (elevated CO₂) plots

The FACE treatment was applied continuously from emergence to maturity during all four experimental years. During the first two seasons (1992–1993 and 1993–1994), the target CO₂ set point was a constant 550 μmol mol⁻¹ both day and night. For the second two seasons (1995–1996 and 1996–1997) the FACE plots were enriched to a nominal 200 μmol mol⁻¹ above ambient levels.¹ This resulted in average CO₂ concentrations for the FACE plots of ca. 548 μmol mol⁻¹ during daylight hours and ca. 598 μmol mol⁻¹ at night.

¹ Ambient CO₂ concentrations averaged 360 μmol mol⁻¹ during daylight hours but varied widely based on time of day, wind-speed, soil moisture, and other environmental factors. A separate sequential sampling system was used to measure CO₂ concentration in each FACE and Blower plot as well as from the two Ambient plots. The minimum value from among the most recent observations of the four Blower and two Ambient plots was selected as the background ambient level against which to reference the 200 μmol mol⁻¹ enrichment in the FACE plots. Selecting the minimum value, generally resulted in choosing the signal from the most upwind plot, thereby avoiding signal contamination by the supplemental CO₂ added to the FACE plots. However, since the mixing of the air layers during calm nighttime conditions had the effect of reducing CO₂ concentrations at the canopy level in the blower plots, this practice probably underestimated the actual ambient concentrations during these periods.

2.4. Control plots (1992–1993 & 1993–1994)

For the initial two seasons of the FACE wheat project, the control treatments (i.e. background or ambient CO₂ plots) were equipped with dummy plastic manifolds and standpipes. There were no blowers and no attempt to mimic the air flow conditions associated with the FACE plots.

2.5. Blower plots (1995–1996 & 1996–1997)

During the second 2 years of the experiments, an air injection system was installed in the control plots (hereafter called ‘Blower’ plots) to provide air movement similar to that of the FACE plots (Kimball et al., 1999). The Blower plots had toroidal plenums like the FACE plots, but they only had half the number of stand pipes. There were no valves on the pipes. Thus, the blower supplied air continuously to all the pipes, and the release locations were not changed in response to changing wind direction as was done in the FACE treatment plots. This strategy was justified because the air flow from the blower appeared to be affecting microclimate and CO₂ concentrations under low wind speed conditions when the FACE plots were being operated in the mode of releasing CO₂-enriched air from every other vertical pipe.

2.6. Ambient plots (1995–1996)

In addition to the four Blower and the four FACE plots, two ‘Ambient’ plots were established in the field for the 1995–1996 experiment. They had no mechanical air movement and no CO₂ enrichment, and thus were very similar to the Control plots in years 1992–1993 and 1993–1994 (e.g. Wall and Kimball, 1993). Both Ambient plots were intentionally positioned in the far northwest corner of the field, as far as possible (~90 m) from microclimatic disturbances that might result from the regular Blower and FACE plots of Replicate 1 (see Fig. 1 of Kimball et al., 1999). They had similar plastic pipes and walkways, and except for having no CO₂ enrichment or blowers, they were treated the same as the Blower and FACE plots. In retrospect, we discovered that the Ambient plots were positioned in an area of the field where overall conditions (perhaps initial soil fertility or

water holding characteristics) were more favorable and yield potentials were higher. In the following analysis, we present air and canopy temperatures and dew durations from the Ambient plots. We exclude supporting data on plant phenology, grain yield, and senescence because those data may have been biased by the field’s inherent spatial variability.

2.7. Micrometeorological observations

Foliage temperatures were measured using stationary infrared thermometers (IRTs, Model 4000a, 15° field-of-view, 8–14 μm waveband, Everest Interscience, Tustin, CA) that were deployed in two replicates during each year (Kimball et al., 1999). Here we include 2 years of data obtained from treatment plots that received adequate fertilizer and water throughout the season, e.g. the wet irrigation treatment in Control and FACE plots during 1993–1994, and the high nitrogen fertilizer treatment in Ambient, Blower, and FACE plots during 1995–1996. The IRTs were mounted ca. 1 m above the crop and oriented northward at an angle of 45° below horizontal. All were carefully calibrated before and after each season using an extended-area, black-body source (Model EABB-250, Advanced Kinetics, Huntington Beach, CA) and a 5–45°C range of instrument body temperatures. The latter were measured using copper–constantan thermocouples attached to the metal housing both during calibration and while deployed in the field. Non-linear equations were fitted to these calibration data and used to correct the field data for changes in ambient temperature. In order to further remove possible instrument biases that might affect comparisons between treatments, IRTs were rotated weekly between FACE and Control or FACE, Blower, and Ambient plots. One-minute voltage readings were recorded, and the corrected crop foliage temperatures (T_f) were calculated from the non-linear calibration equations before 15-min averages were computed. The apparent IRT temperatures were then adjusted for canopy emittance (assumed=0.98) and reflected sky radiation. The latter was calculated from weather mast air temperature and vapor pressure (determined from wet bulb measurements made with aspirated psychrometers) data using the 8–14 μm equation of Idso (1981). A foliage temperature degree-day index (T_fDD) was also computed by accumulating the 24-h

mean T_f in a method analogous to a growing degree day computation.

Presence or absence of dew ('leaf wetness duration') was measured during the 1995–1996 season with printed circuit card sensors (Model 237-L, Campbell Scientific, Logan, UT) in plots equipped with IRTs. The sensors were painted with a gray latex paint (Gillespie and Kidd, 1978) to improve their performance. They were mounted at an angle of 45° below horizontal and oriented toward the northwest. For the first 3 months they were close to the soil surface, but then it was realized that dirt and insect deposits were affecting their output. Beginning on 4 April 1996, they were raised to the top of the canopy and cleaned weekly with distilled water. Spurious data and observations acquired when the sensors were obviously contaminated were excluded from the analysis.

Air temperatures were measured with a single, shielded fine-wire (0.12 mm diameter) copper–constantan thermocouple at 10 cm above the wheat canopies (as well as other heights) near the center of each IRT-equipped plot. Thermocouple height was adjusted weekly. All sensor outputs were scanned every minute using data logging systems (Models CR7 and CR21X, Campbell Scientific, Logan, UT), and 15-min averages were recorded, as well as the 1-min observations for the IRTs.

2.8. Maize plant survival

As part of a separate carbon isotope discrimination study, 20 dwarf maize plants (*Zea mays* ssp. *mays* L. cv Gaspé and Morden) were transplanted into 1.1 m × 0.3 m mini-plots in each of the main experiment subplots during late January in 1994. Several cold nights followed, killing many of the frost sensitive maize plants. Counts comparing survival of maize plants in Control and FACE plots were made on 10 February 1994.

2.9. Wheat plant phenology

The developmental age of the wheat canopy was determined from plants sampled from each subplot at 7–10 day intervals throughout each season. Main stems were assigned growth stages according to the

Zadoks' scale of plant development (Zadoks et al., 1974; Bauer et al., 1983). Dates when plants reached the midpoint of select stages (tillering, stem elongation, booting, heading, anthesis, milk development, soft dough, and ripening) were computed via linear interpolation and then averaged for all replicates within a treatment combination.

2.10. NDVI of wheat canopies

Frequent measurements of canopy reflectance factors provided a continuous record of green biomass accumulation and a practical method for quantifying end-of-season senescence (viz. Idso et al., 1980) associated with crop maturity. Data were acquired in red (0.61–0.68 μm) and near-infrared (NIR, 0.79–0.89 μm) wavelengths using a handheld radiometer (Model 100BX, Exotech, Gaithersburg, MD) equipped with 15° field-of-view optics. Twenty-four nadir measurements were taken along a transect in a 6 m × 3 m area that was later harvested for final yield. Reflectance factors were computed as ratios of directional canopy radiances to time interpolated, hemispheric irradiances inferred from frequent measurements of a BaSO₄ reference panel that was calibrated in terms of its bidirectional reflectance properties (Jackson et al., 1992). Data were obtained 2–5 times per week at a morning time period corresponding to a solar zenith angle of 57°. ² The normalized difference vegetation index was computed as: $\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$. Comparisons of NDVI were made between FACE and Control plots during the first 2 years of the experiment and between FACE and Blower plots in the second 2 years.

3. Results

3.1. Foliage and air temperatures

Daytime T_f in the FACE plots averaged 0.6°C warmer than the Blower plots for much of the growing season [a CO₂-induced stomatal closure effect

² Canopy reflectance factors are directional, being dependent on sensor viewing and solar illumination angles. This source of variation was minimized by choosing a constant zenith angle that could be accommodated throughout the season.

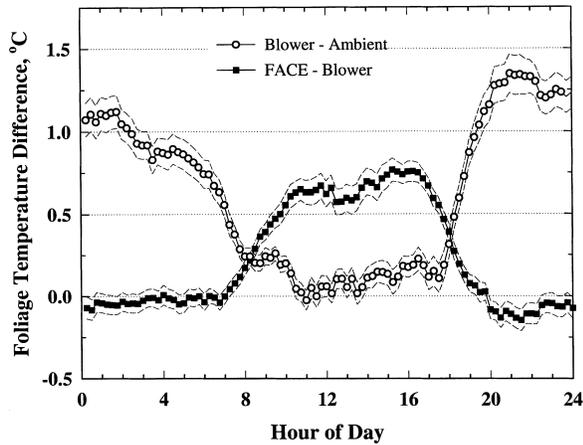


Fig. 1. Diurnal trajectory of foliage temperature differences ($^{\circ}\text{C}$) measured with stationary IRTs during the FACE Wheat experiment in 1995–1996. Data are average differences (± 1 S.E.) observed at 15-m intervals over 71 days for which good data were available from 6 February 1996 (tillering) through 29 April 1996 (~soft dough). Contrasts are shown between plots equipped with blowers but having different CO_2 treatments (FACE minus Blower) and between plots at the same CO_2 concentration with and without blowers (Blower minus Ambient).

(see Garcia et al., 1998)], while nighttime differences between FACE and Blower were small (Fig. 1). By contrast, T_f in the Ambient plots remained ca. 1°C cooler than the Blower plots during the night with only a small difference during the day. Long term differences in T_a at +10 cm (Fig. 2) displayed trends that were similar to T_f although the absolute differences were slightly less. In a separate, short-term study (results not shown here), T_a was also measured along a transect crossing the boundary between a blower-equipped FACE plot and the surrounding wheat canopy. During calm periods, we observed a discontinuity in T_a at the edge of the plots, adding to the evidence that blowers altered microclimate.

3.2. Leaf wetness

Not unexpectedly, we observed striking differences in the leaf wetness parameter measured in each of the treatments (Fig. 3). Slightly lower temperatures in plots without blowers resulted in earlier evening dew formation and longer persistence in the morning. At night the Ambient plots were wet 30% longer than the Blower plots, while there was little difference between

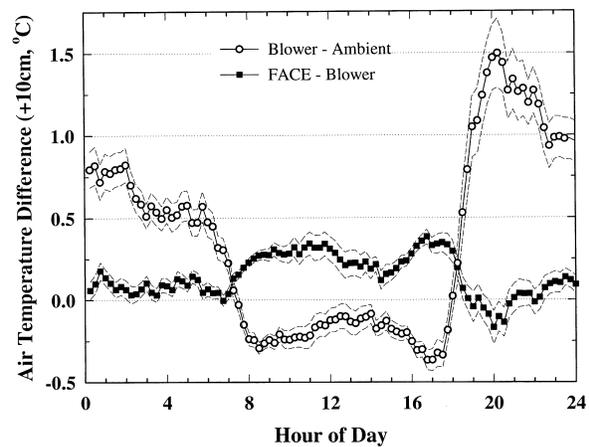


Fig. 2. Diurnal trajectory of air temperature differences ($^{\circ}\text{C}$, mean ± 1 S.E.) measured at +10 cm above the canopy using shaded, fine-wire thermocouples from late January until late April during the FACE Wheat experiment in 1995–1996. Contrasts are shown between plots equipped with blowers but having different CO_2 treatments (FACE minus Blower) and between plots at the same CO_2 concentration with and without blowers (Blower minus Ambient).

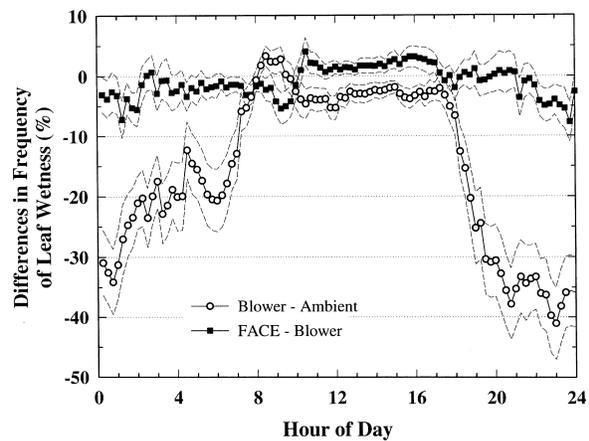


Fig. 3. Differences in the frequency of leaf wetness measured with Campbell Scientific, Inc. printed circuit card sensors during 15 min intervals over 73 days for which good data were available from 6 February 1996 (tillering) through 7 May 1996 (soft dough). Data are average percentage differences of the time when leaves were wet (± 1 S.E.). Contrasts are shown between plots equipped with blowers but having different CO_2 treatments (FACE minus Blower) and between plots at the same CO_2 concentration with and without blowers (Blower minus Ambient). A value of -20% , as an example, for the Blower minus Ambient comparison at 0600 h, indicates that the sensors in the Blower plots were wet for an average 20% less of the 15-min interval ending at 0600 h than those in the Ambient plots.

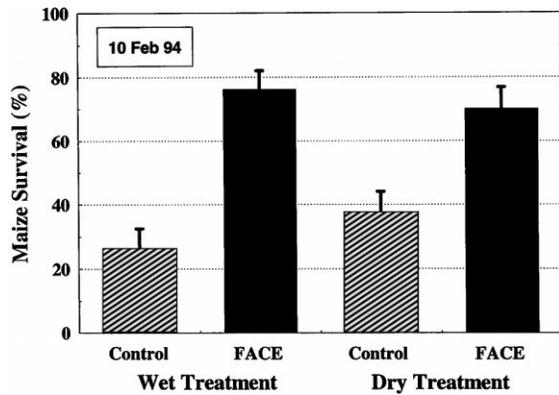


Fig. 4. Percent survival of dwarf maize plants (*Z. mays* ssp. *mays* cv Gaspe and cv Morden) ≈ 2 weeks after transplanting into Control (ambient CO_2 , no blower) and FACE plots ($550 \mu\text{mol CO}_2 \text{ mol}^{-1}$, with blower) during the 1993–1994 FACE Wheat experiment. Data are mean survival of plants (± 1 S.E.). There were four replicates of 20 plants in each treatment combination.

Blower and FACE plots. Although not observed in our experiments, we believe that such differences in the time that leaves are wet have the potential to influence the incidence of plant diseases and affect arthropod infestations.

3.3. Maize plant survival

We observed a significant ($p \leq 0.05$) difference in survival of maize plants that was dependent on presence or absence of blowers (Fig. 4). In Control plots (without blowers), 68% of the plants were killed by cold temperatures that occurred shortly after they were transplanted. Mortality was only 22% among maize transplanted into the FACE plots. The difference in survival between plants in wet and dry irrigation treatments was not statistically different.

3.4. Wheat plant phenology

Developmental differences between plants that were grown under different blower configurations were apparent to researchers and project visitors alike, especially at times of heading, anthesis, and maturity. Seeking to quantify these differences, we interpolated the phenological data from the frequent plant samples and estimated the date when the plants in each plot reached the midpoint of each of eight princi-

pal growth stages from tillering to ripening (Zadoks et al., 1974; Bauer et al., 1983). We then computed the difference in chronological time required to reach a specific growth stage between plots with and without blowers (i.e. Control minus FACE for 1992–1993 and 1993–1994) and also between plots having blowers but exposed to either ambient or elevated CO_2 levels (i.e. Blower minus FACE for 1995–1996 and 1996–1997). This comparison revealed that amply watered and fertilized plants reached each growth stage from 2 to 5 days sooner when grown in a blower-equipped plot, while the CO_2 treatment by itself appeared to have minimal effect on developmental rates (Fig. 5). Paired ‘*t*’ tests showed the average differences in phenology between FACE and Control during 1992–1993 and 1993–1994 were relatively large and highly significant ($p \leq 0.001$) under both irrigation regimes (Table 1). Developmental differences between FACE and Blower treatments during 1995–1996 and 1996–1997 were < 0.5 days and only under deficit

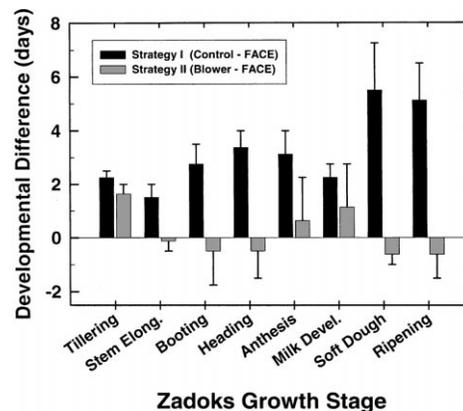


Fig. 5. Differences in time (days ± 1 S.E.) required for plants to reach specified growth stages when exposed to different ‘control’ strategies during the FACE wheat experiment. Strategy I, employed during the first two seasons (1992–1993 and 1993–1994), shows the difference between Control and FACE response when controls were not equipped with blowers. A positive value for Strategy I indicates that plants in CO_2 -enriched, blower-equipped plots had an accelerated development compared with plots having neither CO_2 enrichment nor blowers. Strategy II, used during the 1995–1996 and 1996–1997 seasons, shows the time difference between response of plants in Blower and those in FACE when both treatments were equipped with blowers. Small values for Strategy II suggest little effect of CO_2 by itself on plant development. Only data for optimum management (i.e. ample water and N treatments) are shown.

Table 1

Mean differences in the time required to reach each of eight primary growth stages (tillering→ripening) between different Blower and CO₂ configurations used during the FACE Wheat experiments at Maricopa, AZ

Comparison ^a	Is blower present?		<i>n</i> ^b	Mean time difference days±1 S.E.	Value from paired <i>t</i> -test
	Ambient CO ₂ treatment	Elevated CO ₂ treatment			
<i>CO₂ by Water Experiment (1992–1993 and 1993–1994)</i>					
CW minus FW	No	Yes	64	3.2±0.33	9.80***
CD minus FD	No	Yes	64	2.3±0.23	10.10***
<i>CO₂ by Nitrogen Experiment (1995–1996 and 1996–1997)</i>					
BH minus FH	Yes	Yes	57	0.4±0.31	1.25 NS
BL minus FL	Yes	Yes	57	0.4±0.18	2.20*

*, ***Significant at the 0.05 or 0.001 probability levels, respectively.

^a Treatment abbreviations: C, Control; B, Blower; F, FACE; W, Wet (ample) irrigation; D, Dry (deficit) irrigation; H, High (ample) nitrogen; L, Low (deficit) nitrogen.

^b Refers to the total number of paired observations. Only three replicates were available for *t*-test comparisons during most of the 1996–1997 experiment.

nitrogen conditions were the differences between CO₂ treatments statistically significant ($p \leq 0.05$).

3.5. Rates of canopy senescence

Plant canopies in the FACE treatment changed from completely green to yellow and then brown ca. 1 week before plants in the Control treatments during the 1992–1993 and 1993–1994 experiments. This was apparent visually and was also evident in the temporal trends of NDVI, which in this case were used to quantify post-anthesis changes in whole canopy greenness (Fig. 6a and b). However, NDVI differences were not detected between Blower and FACE plots in 1995–1996 or 1996–1997 (Fig. 6c and d), suggesting that canopy senescence, like stage of growth, might be a microclimatic artifact associated with the presence of blowers rather than a developmental response to CO₂.

3.6. NDVI versus cumulative plant temperatures

Further evidence linking blowers to accelerated phenology comes from a set of graphs showing NDVI as a function of developmental time (i.e. accumulated temperatures instead of chronological time). The NDVI from FACE and Control treatments in 1993–1994 (Fig. 7a), and FACE and Blower treatments in 1995–1996 (Fig. 7b) are plotted versus the

traditional cumulative growing degree-day parameter (Σ GDD), computed as the average of maximum and minimum daily air temperatures (with a base temperature=0°C) from a nearby meteorological station (AZMET, Brown, 1989). The data of Fig. 7a show approximately a 100 GDD separation between plots with and without blowers which is roughly equivalent to the time separation shown earlier in Fig. 6a and b. When however, the ordinate axis was changed from Σ GDD to a cumulative thermal index derived from the IRT temperatures of plant tissues in each plot (i.e. the foliage temperature degree-day index, ΣT_f DD), the once separate, NDVI senescence curves from Control and FACE (Fig. 7a) fused together into a single trend line (Fig. 7c). Because Blower and FACE treatments had similar foliage temperatures, their NDVI senescence curves remained coincident when plotted versus ΣT_f DD (Fig. 7d). In as much as temperature is generally conceded to have a dominant, controlling effect on wheat plant developmental rates, we interpret this as causal evidence that the blowers accelerated plant maturity indirectly by increasing plant tissue temperatures.

3.7. Thermal images from the 1998 FACE project in grain sorghum

Following completion of the FACE Wheat project, we have had a continued interest in understanding the micrometeorological phenomena associated with the

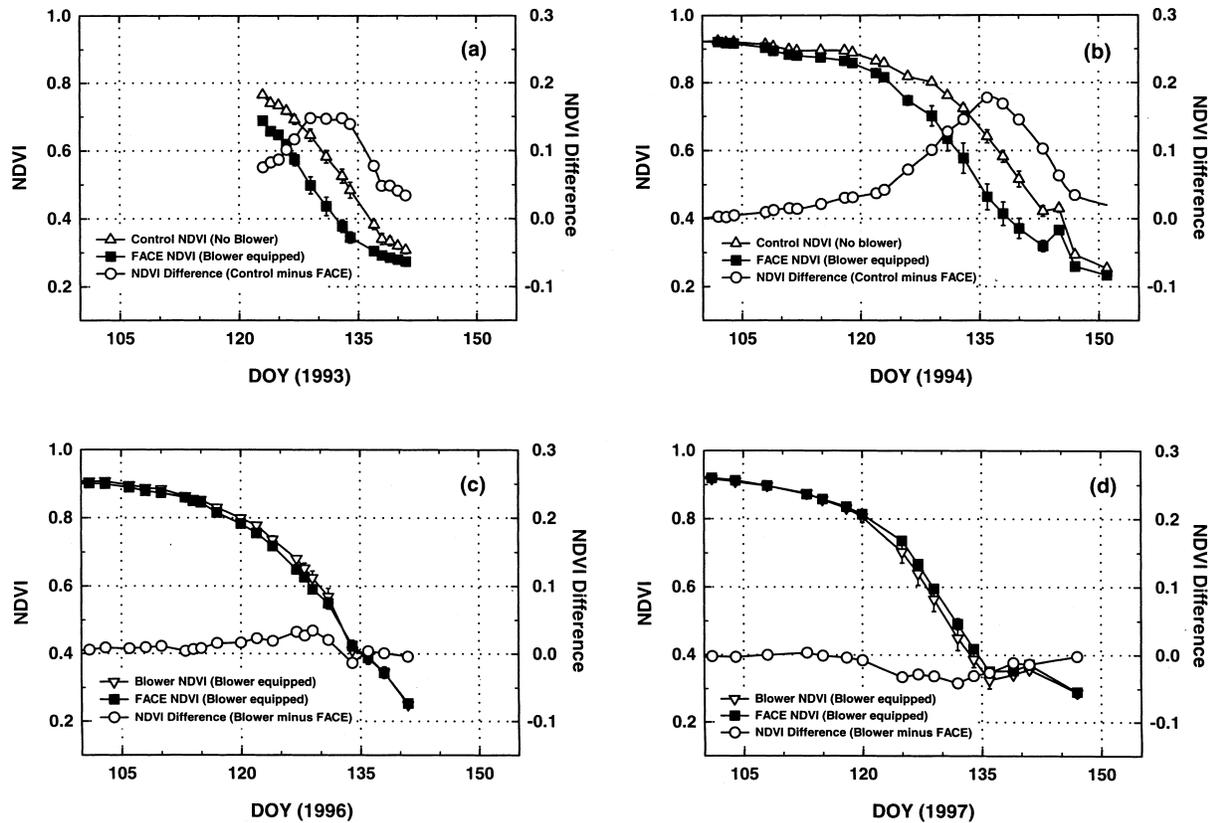


Fig. 6. Time-based trajectories of the normalized difference vegetation index (NDVI; mean \pm 1 S.E.) and NDVI difference measured throughout the grain filling period during 4 years of FACE Wheat experiments at Maricopa, AZ. Only data from plots with optimum management (i.e. ample water and N treatments) and also having IRTs are shown. Abbreviation: DOY, day of year.

FACE apparatus and present those findings here because of their relevance to documenting the spatial extent of the blower perturbation in an agricultural crop. The image shown in Fig. 8 was obtained just before dawn on 19 November during the 1998 FACE Sorghum experiment. It was acquired using a thermal scanner (Model 760, Inframetrics, Billerica, MA) deployed on a helicopter flown at ≈ 150 m above the canopy. This oblique view of the east half of the experimental field (~ 5 ha in size) shows relative plant canopy temperatures ($8\text{--}12\ \mu\text{m}$, uncorrected for surface emissivity) with warmer values represented as lighter shades of gray. The image includes four experimental rings (2 FACE and 2 blower-equipped Control plots) within the field of view of the scanner. Three

rings had fully functional blowers that were operating in the every other standpipe release mode because wind speeds were below $0.4\ \text{m s}^{-1}$. The position of these plots is obvious due to the warmer canopy temperatures. We had intentionally turned off the blower in the Control treatment located in the lower left corner of the image (arrows). Shortly after this image was obtained, we turned the blower back on and within several minutes the imagery showed warmer temperatures in this ring also. Additional imagery captured during midday (not shown) revealed warmer canopy temperatures associated with stomatal closure caused by elevated CO_2 and also water stress, but there was no effect of the blowers themselves on canopy temperature.

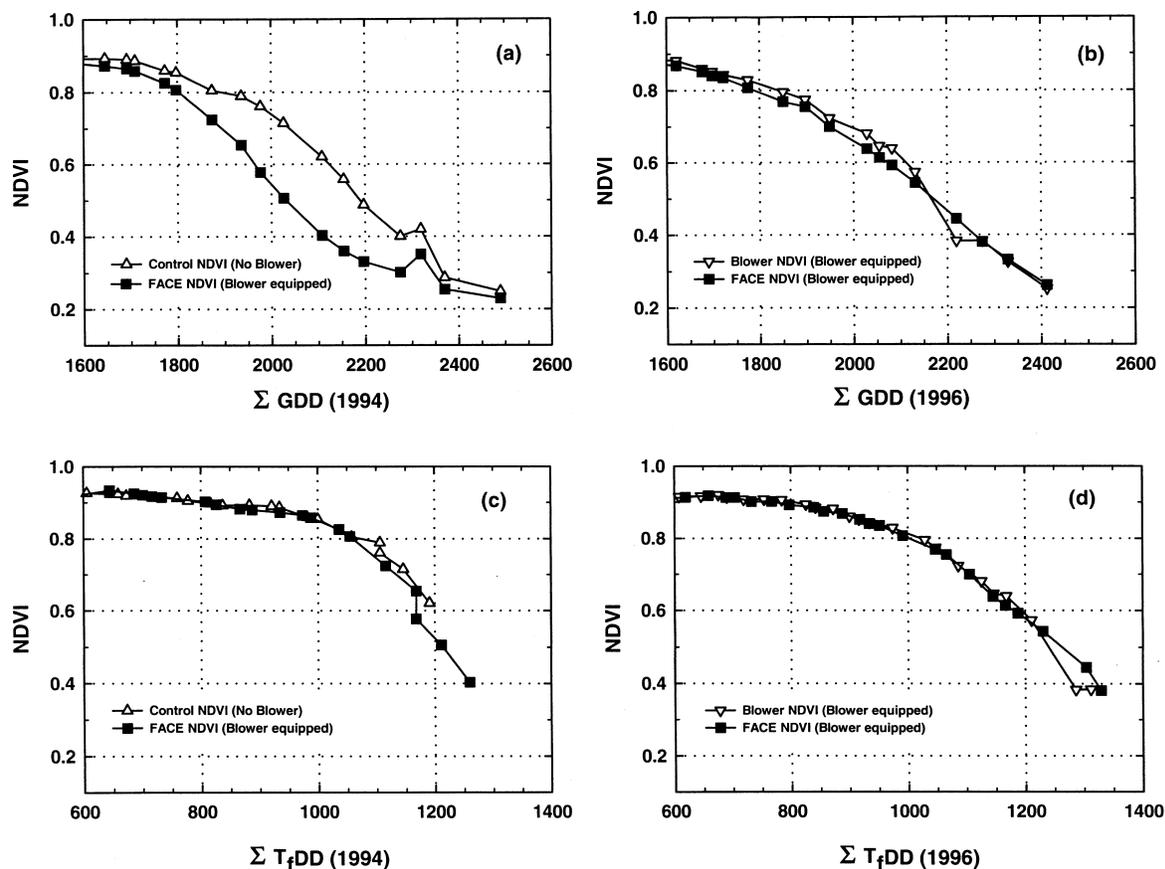


Fig. 7. Temperature-based trajectories of the normalized difference vegetation index (NDVI; mean \pm 1 S.E.) measured throughout the grain filling period during the 1993–1994 and 1995–1996 FACE Wheat experiments at Maricopa, AZ. (a) and (b) show NDVI as a function of growing degree-days (Σ GDD) based on air temperature ($^{\circ}$ C) measured at a nearby agricultural meteorological station and accumulated from emergence. (c) and (d) show NDVI as a function of a foliage temperature ($^{\circ}$ C) degree-day index (ΣT_f DD) measured using stationary IRTs within each plot and accumulated from late January through the end of the growing season. As soon as the FACE plots matured, CO_2 enrichment was halted and the IRT data loggers were turned off. As a result, the NDVI of (c) and (d) does not fall to the low values seen in (a) and (b). Direct comparisons between Σ GDD and ΣT_f DD are not valid due to different starting dates for the accumulation and the fact that IRTs were out of service 1 day each week while they were rotated to new field locations. Only data from plots with optimum management (i.e. ample water and N treatments) are shown.

4. Discussion

4.1. Blower effects on microclimate

We observed a measurable effect of FACE blowers on canopy microclimate that was most evident at night when wind speeds were typically low and atmospheric stability near the ground was high. In our study, plants growing in blower-equipped plots were

slightly warmer at night and had less dew than those in plots without blowers. This suggested that the blowers were disrupting near-ground stability and, by entraining warmer air from above, were increasing air temperatures and vapor pressure deficits around the plants. It appears that this poses less of a problem during the day when solar heating of the exposed soil and vegetation causes more vertical mixing and microturbulence. However, such blower-induced changes

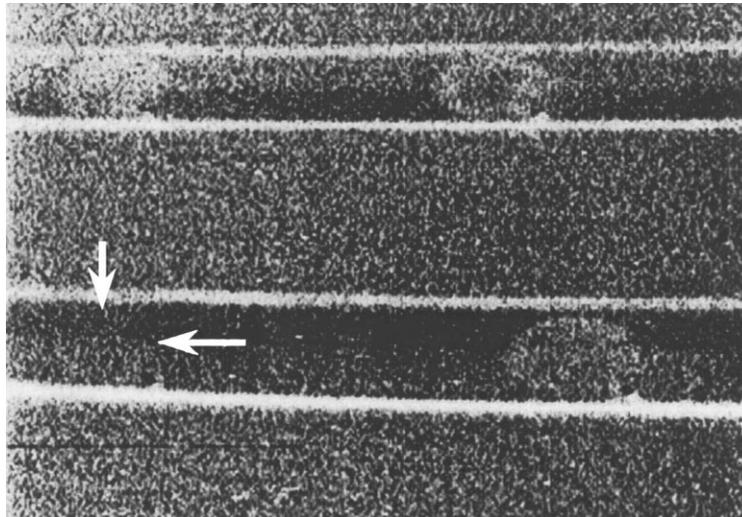


Fig. 8. Thermal image obtained at 0551 h on 19 November 1998 in the FACE Sorghum field. Canopy cover is $\sim 100\%$. Clockwise from the upper left corner are FACE rep 2, Control rep 2, and FACE rep 1. The blower fans were turned off in Control rep 1 which is located in the lower left corner but cannot be seen in this image (arrows). Lighter shades of gray represent warmer surfaces. Bold horizontal stripes are irrigation ditches.

in microclimate can have important biological consequences when a temperature threshold is crossed. This was illustrated by the differential survival of maize plants following the frost events of 1994 (Fig. 4). Of course, maize is more susceptible to low temperatures than wheat, and no overt effects of the cold were observed on survival of the wheat plants.

Researchers at the loblolly pine FACE site in the Duke Forest found a slight increase in mean wind speed within the tree canopy that was associated with the FACE apparatus, but were unable to detect any change in mean air temperatures (He et al., 1996). There are substantial differences in stand geometry and apparatus configuration (the ratio of FACE ring diameter to canopy height in the forest site was 3:1 compared to 10:1 for the FACE wheat site) as well as differences in nighttime wind and radiative cooling patterns that could possibly account for dissimilarities in micrometeorology between the two sites. The cup-type anemometers we used in our study precluded three-dimensional analysis of wind speeds in the FACE wheat project, but the foliage temperatures and other data presented in this report provide a definitive, season-long record of microclimate perturbation.

4.2. Blower effects on wheat development, maturity, and grain yields

Blower-related phenomena, albeit very slight, can also have subtle, cumulative effects on longer-term biological processes. As an example, one of the unique findings of the 1992–1993 and 1993–1994 FACE experiments was the apparent accelerating effect of elevated CO_2 on plant development and rates of canopy senescence (Photograph in Kimball et al., 1995; and Pinter et al., 1996). A re-examination of those data in light of the slight differences in temperature we now know to exist between the treatments and the new phenology results from the 1995–1996 and 1996–1997 FACE wheat experiments has led us to conclude that the blower effect was sufficient to explain most of the apparent developmental acceleration. Analysis of NDVI and IRT data showed that the apparent differences in end-of-season senescence rates were likely caused by the indirect effect that blowers had on plant tissue temperatures. We now believe that elevated CO_2 per se had very little effect on the rates of plant development in well-watered and amply-fertilized spring wheat.

What about CO₂ effects on grain yield of wheat? We originally reported only a 10% increase in yield for wheat exposed to CO₂ at 550 μmol mol⁻¹ and supplied with adequate water and nutrients, suggesting that plants in the Control treatment had additional opportunity to ‘catch up’ with the sink-limited FACE plants. We now believe that this figure was probably an *underestimate* of the true CO₂ effect that might have been observed during the first two seasons had the controls been properly equipped with blowers and the grain filling duration of both CO₂ treatments been similar. In fact, during the 1995–1996 and 1996–1997 experiments, grain yields for adequately fertilized and well-watered wheat showed a 15% increase associated with a nominal +200 μmol mol⁻¹ CO₂ elevation. This translates into a CO₂ enhancement (β) factor of ~28% for a doubling of atmospheric CO₂ concentrations,³ an increase which compares favorably with the 33% average for agricultural crops reported by Kimball (1983).

4.3. Why use blowers?

Given the microclimatic disturbances associated with the use of blowers in FACE experiments, the question arises as to why blowers are used in the design. In early studies using the free-air gas enrichment concept, large fluctuations in the experimental gas concentration were frequently observed (Shinn and Allen, 1985). There was some concern that plants would respond to rapid fluctuations in atmospheric CO₂ concentrations differently from the slower changes typically observed in nature. Hendrey et al. (1997) found this to be true for CO₂ concentration fluctuations lasting more than 1 min. It was determined that dilution of CO₂ prior to its release into the plant canopy could reduce the magnitude of CO₂ fluctuations within the arrays (Hendrey et al., 1992). The momentum provided by the blower also improved the spatial distribution of CO₂ under low wind conditions. Other FACE approaches that eliminate blowers and emit pure CO₂ at the perimeter of the plots are now in use. However, these designs are reported to have more inherent variation in CO₂ con-

centrations and more difficulty maintaining a target concentration than designs using blowers, especially under calm wind conditions.

4.4. Analogies to orchard wind machines

In retrospect, blower effects on nighttime microclimate of FACE plots under stable air conditions might have been anticipated. Air movement warmed the Blower plots at night, just like wind machines that citrus growers have used for frost protection since the 1950s (e.g. Baker, 1955; Brooks et al., 1961). In a typical citrus installation, large fans are mounted above the orchard on 10-m-tall masts. They rotate completely every 4–5 min, so that a plume of disturbed air sweeps over the trees in a large circle, disrupting the layer of cold air that has settled near the ground and mixing in warmer air from above. Such wind machines only provide frost protection when the ambient air is still enough for cool temperature layers to form near the orchard canopy. They do not work under windy conditions. Typically, fans with 100 Hp (75 kW) motors protect 4 ha (Blank and Verner, 1995), which amounts to 1.8 W m⁻² of external energy supplied to the system. Although the geometry and jet configuration of a FACE ring are very different from an orchard wind machine, 2 Hp (1.5 kW) blowers supply energy to 25 m-diameter rings, which amounts to 3.0 W m⁻², i.e. more energy than the citrus growers use to disturb the microclimate of their orchards deliberately on frosty nights.

4.5. Nighttime CO₂ enrichment?

These observations of blower effects on FACE ring microclimate raise the issue of whether or not to enrich the apparatus with CO₂ at night. Indeed, some of the FACE sites around the world presently restrict their operation to daylight hours only.⁴ As already mentioned, reports exist in the literature and continue to be published (see Drake et al., 1999) about the possible effects of elevated CO₂ on respiration (although none of several investigators were able to detect any effect of elevated CO₂ on the dark respiration of wheat

³ For this extrapolation we are assuming a linear increase in the CO₂ effect on yield and 720 μmol mol⁻¹ for a doubling of CO₂ $\{[(720-360)/360]/[(550-360)/360]\} * 15\% = 28\%$ increase.

⁴ The Carbon Dioxide Information Analysis Center (CDIAC) in Oak Ridge, TN maintains a contact list of worldwide FACE sites at <http://cdiac.esd.ornl.gov/programs/FACE/whereisface.html>.

in any of the 4 years of experiments described in the present paper). Despite these reports, there are several reasons why enrichment at night might be questionable. (1) Blower-induced temperature artifacts can have a far larger effect on plant biology than the effect caused by CO₂ alone. (2) Blower-equipped plots might not be truly representative of outside field CO₂ conditions during nights when the air is extremely stable. (3) The CO₂ concentrations of the air are relatively high at night anyway, so the increment added by the FACE experiment is relatively smaller and may fall in the domain of diminishing returns on affecting plant processes. (4) Plant growth models have routines that attempt to simulate the turbulent transfer of mass and energy by the wind, and if the blowers are affecting this transport more than natural wind at night, then the data can not easily be used for such validation. (5) The effects of elevated CO₂ at night on dark respiration probably are small compared the daily carbon budget. (6) Lastly, the expense of enriching at night is high, adding 25–30% to the CO₂ costs for the experiments.

This dilemma about whether or not to enrich at night is not unique to FACE experiments. Researchers using open-top chambers also need to consider, for example, whether increased evaporation due to air movement in their chambers is sufficiently objectionable that they should stop operation at night. However, with such systems researchers usually recognize that the walls are already changing the microclimate considerably whether the blowers are on or off, so they often elect to operate them at night anyway (e.g. Kimball et al., 1997b).

5. Conclusions

The FACE technique approaches natural conditions more closely than open-top chambers or other means of exposing plants to elevated CO₂. Important advantages include an unmodified light environment, unrestricted rooting volume, and large experimental areas. Nevertheless, the blowers used to inject CO₂ in an agricultural field in the Arizona desert warmed the canopy by ca. 1°C during the night, and they also decreased the duration of time that the leaves were wet from dew. These differences in microclimate, although small, can be cumulative and were demonstrated to affect plant development. Therefore, it is

recommended that control plots for FACE experiments should be configured and operated similarly to the FACE enrichment plots, especially if they are to be run on a 24-h per day basis.

Considering the potential for errors discussed above, investigators using FACE may reasonably choose one of two operating strategies. The first is to run the system only during daytime in order to avoid microclimate effects potentially associated with nighttime operation and to reduce operating costs significantly. With this strategy, one accepts a potential for error due to the lack of inhibition of respiration at night. The second is to operate 24 h per day, but accept the higher operating costs and a potential for microclimate disturbance at night that in some circumstances can be biologically significant. Since the major photosynthetic and stomatal effects of CO₂ occur during daytime, it seems that possibility for microclimate disruption at night may introduce the larger error. Even accepting this potential error, the FACE approach remains the best way to create conditions that are representative of agricultural fields in a future high-CO₂ world.

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