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Data from the Arizona FACE (Free-Air CO_2 Enrichment) Experiments on Wheat at Ample and Limiting Levels of Water and Nitrogen

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Abstract: Four free-air CO_2 enrichment (FACE) experiments were conducted on wheat (*Triticum aestivum* L. cv. Yecora Rojo) at Maricopa, Arizona, U.S.A. from December, 1992 through May, 1997. The first two were conducted at ample and limited (50% of ample) supplies of water, and second two at ample (350 kg N ha^{-1}) and limited (70 and 15 kg N ha^{-1}) supplies of fertilizer nitrogen. More than 50 scientists participated, and they collected a large and varied set of data on plant, soil, and microclimatic responses to the elevated CO_2 and its interactions with the water and N treatments. The dataset has been popular with wheat growth modelers who have utilized the growth, yield, and other data to validate their models, which get used to predict likely future wheat productivity with projected global change. The dataset assembled herein contains many of these data, including management, soils, weather, physiology, phenology, biomass growth, leaf area, yield, quality, canopy temperatures, energy balance, soil moisture, nitrogen assimilation, and other data.

Keywords: CO_2, carbon dioxide, wheat, drought, nitrogen, free-air CO_2 enrichment, FACE, climate change, global change

1 BACKGROUND: During the 1980s, after more than two decades of CO_2 concentration measurements at Mauna Loa (http://www.esrl.noaa.gov/gmd/ccgg/trends/full.html) documenting the increasing atmospheric CO_2 concentration, there was concern about what higher CO_2 concentrations would portend for agricultural crops, as well as for natural ecosystems. From prior growth chamber and greenhouse studies, it was known that elevated levels of CO_2 could stimulate plant photosynthesis, growth, and yields (e.g., Kimball, 1983). However, because chambers, even open-top chambers, drastically affect wind flow, shading, and many other microclimatic factors (e.g., Kimball et al., 1997), there was concern whether results from such chamber studies would pertain to an open field. This concern led the Department of Energy to fund Brookhaven National Laboratory to develop free-air CO_2 enrichment technology (FACE), which was successfully demonstrated on cotton at Maricopa, Arizona from 1989-1991 (Hendrey, 1993; Hendrey and Kimball, 1994).

Following the successful FACE experiments on cotton, the research shifted to wheat, the world's foremost food and feed crop. Two free-air CO_2 enrichment (FACE) experiments at ample and limiting levels of water supply were conducted from December through May 1992-93 and 1993-94. Two CO_2 levels were used [ambient (about 370 µmol/mol) and FACE (550 µmol/mol)] along with two levels of water supply (100% and 50% replacement of potential evapotranspiration since previous irrigation, adjusted for rainfall). Next, FACE experiments at ample and limiting levels of nitrogen supply were conducted from December through May 1996-97. Two CO2 treatments were used [Blower which had air flow but no added CO2 above normal levels (365 µmol/mol average daytime over season) and FACE (186 µmol/mol above ambient)] along with two levels of soil nitrogen supply (350 and 15 kg/ha of nitrogen, NH_4NO_3, applied in the irrigation water).

More than 50 scientists from about 30 research organizations in 8 countries have participated, measuring leaf area, plant height, above-ground biomass plus roots that remained when the plants were pulled, root biomass from soil cores, apical and morphological development, canopy temperature, reflectance, chlorophyll, light use efficiency, energy balance, evapotranspiration, sap flow, soil and plant elemental analyses, tissue nitrogen biochemistry, soil water content, photosynthesis, respiration, stomatal conductance, leaf water potential, carbohydrates, photosynthetic proteins, antioxidants, phenolics, stomatal density and anatomy, digestibility, decomposition, grain quality, bread baking quality, soil CO_2 fluxes, and changes in soil C storage from soil and plant C isotopes. Details about many of these measurements can be found in papers listed in the *REFERENCES.*

Besides the direct determination of the responses of wheat to elevated CO_2 and its interactions with water supply and nitrogen, the data collected in the FACE Wheat experiments have also proved useful for validating wheat growth models. To date, at least 13 papers have resulted from such model tests, as listed in the *REFERENCES.* Initially, the management, weather, growth, and yield data were formatted in the IBSNAT format, which is now obsolete, and then they were re-formatted to ICASA Version 1.0. More recently, they have been converted to ICASA Version 2.0 (White et al., 2013), which in turn is undergoing some modifications under the umbrella of the AgMIP (Agricultural Model Inter-comparison and Improvement Project; http://www.agmip.org/). These data are included in this dataset in file *Biomass Area Phenology Management Weather Soil Moisture.ods*. They currently are being used in another AgMIP model inter-comparison study involving wheat models which utilize canopy temperature information (as opposed to just growing the crop at air temperature).

2 METHODS: Two experiments were conducted during the 1992-3 and 1993-4 growing seasons to determine the interactive effects of elevated CO_2 and limited soil water on spring wheat (*Triticum aestivum* L. cv. Yecora Rojo) at the University of Arizona Maricopa Agricultural Center (MAC), Maricopa, Arizona, USA (33.06° N latitude, -111.98 W longitude, 361 m elevation). Two additional experiments were similarly conducted to determine the interactive effects of elevated CO_2 and limited soil nitrogen during the 1995-6 and 1996-7 growing seasons. A field plot plan for the 1992-3 and 1993-4 experiments is presented by Wall and Kimball (1993), while that for the 1995-6 and 1996-7 experiments is Figure 1 of Kimball et al. (1999). 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. (1992).

2.1 CO_2 TREATMENTS: The free-air CO_2 enrichment (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, 1999). Briefly, four replicate 25-m-dia. toroidal plenum rings constructed from 0.305-m-dia. pipe were placed in the field shortly after planting. 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 CO_2 was blown into the rings, and it exited near the canopy top through tri-directional jets in the vertical pipes. Wind direction, wind speed, and CO_2 concentration were measured at the center of each ring. A computer-control system used the wind speed and CO_2 concentration information to adjust the CO_2 flow rates to maintain the desired CO_2 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 CO_2-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 CO_2-enriched air was released from every other vertical pipe around the rings.

Starting with the 1995-6 season, air blowers were installed in the non-CO_2-enriched ambient control plots, hereafter called Blower plots, to provide air movement similar to that of the FACE plots (Pinter et al., 2000). 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 CO_2-enriched air from every other vertical pipe.

Also starting in 1995-6, unlike the prior experiments which had a constant set-point of 550 µmol/mol CO_2 concentration, the FACE plots were enriched by 200 µmol/mol above ambient (~ 360 µmol/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 Rep 1. Twenty seconds were required to measure the concentration in each plot, and 3 min for all of them. The minimum value from among the most recent observations of the four Blower plots and the two ambient points was selected to provide *THE* ambient value for the next 20 sec against which to reference the 200 µmol/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 CO_2 from the FACE plots.

The FACE treatment was applied continuously from emergence to harvest. For 1995-6, the average daytime CO_2 concentrations in the FACE and Blower plots were 548 and 363 µmol/mol, respectively, while the nighttime values were 598 and 412 µmol/mol. Thus, the daytime elevation of CO_2 concentration in the FACE plots above the Blower plots was 185 µmol/mol, and these data also indicate the average contamination of the Blower plots with CO_2 from the FACE plots was 15 µmol/mol above the upwind ambient concentration.

2.2 IRRIGATION TREATMENTS: 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 1992-3 and 1993-4 seasons by Hunsaker et al. (1996). Irrigation water requirements for the ample (Wet) treatment were based on a computer-based irrigation scheduling program (AZSCHED; Fox et al., 1992). After about 30% of the available water in the rooted zone was depleted, they were irrigated by an amount calculated to replace 100% of the potential evapotranspiration since the last irrigation (adjusted for rainfall). The low-water (Dry) treatment plots received 50% of the amounts of the Wet treatment for each irrigation in 1993, whereas in 1994, they were irrigated only every other time the Wet plots were irrigated. The Wet and Dry sides of both the FACE and Control plots shared the same tubes, which extended across whole replicates. Therefore, the experimental design was strip-split-plot (Hunsaker et al., 1996). Cumulative irrigation totals between crop emergence and harvest were 600 mm and 620 mm for the Wet treatments in 1993 and 1994, respectively, and 275 and 257 mm for the Dry plots. Corresponding rainfall amounts were 76 mm and 61 mm, respectively.

In 1995-6 and 1996-7 all plots were irrigated like the Wet plots in 1992-3 and 1993-4. In 1995-6 cumulative irrigation amounts were 692 and 631 mm for the high- and low-N treatments, respectively, and in 1996-7 they were 621 and 548 mm. (The amounts for the high- and low-N treatments would have been nearly identical except the last irrigations were curtailed due to earlier maturity of the low-N plants. Seasonal rainfall amounted to 39 and 29 mm, respectively for the two seasons.

2.3 SOIL NITROGEN TREATMENTS: During 1992-3 and 1993-4, the plots received ample amounts of nitrogen fertilizer via the irrigation system. A total of 271 kg N ha^{-1} was applied in 1992-3 and 261 kg N ha^{-1} in 1993-4.

During 1995-6 and 1996-7, half of each of the main FACE and Blower plots received either an ample (High-N) or a limiting (Low-N) level of nitrogen fertilizer. The High-N plots received a total of 350 kg N/ha from ammonium nitrate in 4 applications during both seasons. The Low-N plots received 70 and 15 kg N/ha during 1995-6 and 1996-7, respectively. 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 1996-7 season resulted in the nitrogen applications being switched between the High- and Low-N sides of the Blower-Replicate 3 plots on 5 March 1997 (DOY 64). The mistake was discovered about a week later, and the High-N plot was salvaged by applying additional nitrogen to it. Thus, any analysis of these data needs to account of this complication.

2.4 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 x water stress and FACE x 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. During the 1994-5 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 pre-plant irrigation (about 150 mm) was applied with sprinklers between 30 Nov and 2 Dec 95 in order to leach as much initial soil nitrogen as possible and germinate remaining oat seeds which were suppressed with Roundup [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] on 12 December 1995. 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 in east-west rows that were spaced 0.25 m apart (parallel to the drip irrigation tubing). In 1992-3 a large initial irrigation was applied with the drip irrigation system for germination, while in the subsequent seasons, germination was accomplished with smaller irrigation amounts applied using sprinklers. Fifty percent emergence of seedlings was observed about 1 January in all seasons, 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 42EC. 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. Final harvests of grain occurred at the end of May for each season.

Approximately 24 wheat plants were sampled from all replicates of each treatment combination at 7-10 day intervals during each season (about 18 samplings). Plant phenology of the main stem was determined using both Zadoks and Haun development scales. Green leaf and stem areas were determined on a subsample of 3 median-sized plants using an optical planimeter. Numbers of stems and heads were counted. Crown, stem, green and non-green leaf, and head components of subsample and remaining plants were separated. Component biomass was measured after oven-drying at 65-70°C. Leaf area index was computed from subsample specific leaf weight and green leaf biomass of all plants. About one week after anthesis developing grains were separated from chaff by a combination of hand and machine threshing of heads that were pooled by subplot. Grain was oven-dried for a total of 14 days at 65-70°C. In addition to the interval sampling of individual plants, final grain yield was determined by machine harvesting and threshing an approximately 20 m^2 area of each plot, which had been reserved for only non-destructive, non-contact, remote-sensing measurements during the season.

5 DATA FORMAT AND STRUCTURE

Table 1.

File Name	**Content**
Tabular reference list and measured variables.docx	Table with short reference citations, list of variables measured, and time and space scales.
Biomass Yield Area Phenology Management Weather Soil Moisture.ods	Main spreadsheet with biomass growth, yield, leaf area, growth stage, daily weather, management, soil moisture, and other data generally used for plant growth model validation.
Canopy Leaf Soil Temperatures from Hand-held Infrared Thermometers 1993.ods	Canopy, soil surface, and leaf temperatures determined near mid-day on many days per season at various view angles with portable hand-held infrared thermometers for 1992-3.
Canopy Leaf Soil Temperatures from Hand-held Infrared Thermometers 1994.ods	Ditto for 1993-4.
Canopy Leaf Soil Temperatures from Hand-held Infrared Thermometers 1996.ods	Ditto for 1995-6.
Canopy Leaf Soil Temperatures from Hand-held Infrared Thermometers 1997.ods	Ditto for 1996-7.
fAPAR fraction Absorbed Photosynthetically Active Radiation.ods	Fraction of absorbed photosynthetically active radiation.
Height of canopy 1993.ods	Height of canopy 1993
Height of canopy 1994.ods	Height of canopy 1994
Nitrate Assimilation.ods	Rates of assimilation of nitrate into plant tissue
Nitrogen balance 1997.ods	Stem, green and brown leaf, chaff, and grain nitrogen concentrations and mass for 1997.
Nitrogen Leaves 1993-1997.ods	Leaf nitrate concentrations from all four experiments.
Physiology Gas Exchange Water Relations.ods	Net photosynthesis, stomatal conductance, leaf water potential and other leaf physiological measurements.
Reflectance and NDVI.ods	Reflectance of crop canopy and derived normal difference vegetation index (NDVI, greenness).

Table 1. Continued

File Name	**Content**
Root biomass by depth 1993-1994.ods	Root biomass distribution in time and space in 1993 and 1994.
Root biomass total 1993-1994.ods	Root biomass totals for all depths 1993-1994.
Weather 1996 hourly.txt	Hourly weather data for 1995-6.
Weather 1997 hourly.txt	Hourly weather data for 1996-7.
Weather Canopy & Soil Temperatures Energy Balance 1993 hourly.ods	Hourly weather, canopy temperatures, soil temperatures, net radiation, soil heat flux, sensible heat flux, latent heat flux (evapotranspiration) for 1992-3.
Weather Canopy & Soil Temperatures Energy Balance 1994 hourly.ods	Ditto for 1993-4.
Weather Canopy & Soil Temperatures Energy Balance CO2 1996 15-min.ods	15-minute average weather, CO_2 concentrations, canopy temperatures, soil temperatures, net radiation, soil heat flux, sensible heat flux, latent heat flux (evapotranspiration) for 1995-6.
Weather Canopy & Soil Temperatures Energy Balance CO2 O3 1997 15-min.ods	Ditto plus O_3 concentrations for 1996-7.

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