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

Bruce A. Kimball[1*], Paul J. Pinter Jr.[2], Robert L. LaMorte[1], Steven W. Leavitt[3], Douglas J. Hunsaker[1], Gerard W. Wall[1], Frank Wechsung[4], Gabriele Wechsung[5], Arnold J. Bloom[6] and Jeffrey W. White[1]

[1]*U.S. Arid-Land Agricultural Research Center, United States Department of Agriculture, Agricultural Research Service, 21881 North Cardon Lane, Maricopa, Arizona 85138, USA.*
[2]*Retired. Phoenix, Arizona, USA.*
[3]*Laboratory of Tree Ring Research, University of Arizona, Tucson, Arizona 85721, USA.*
[4]*Potsdam Institute for Climate Impact Research, P.O. Box, 601203, D-14412 Potsdam, Germany*
[5]*Air Quality and Terrestrial Ecosystems, German Federal Environment Agency, Wörlitzer Platz 1, 06844 Dessau-Roßlau, Germany*
[6]*Department of Plant Sciences, University of California at Davis, Davis, California 95616, USA*
*e-mail: Bruce.Kimball@ars.usda.gov

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.

5 ACKNOWLEDGMENTS: This research was supported by grant DE-FG03-95ER-620072 from the Office of Biological and Environmental Research (OBER), Environmental Sciences Division, Department of Energy Terrestrial Carbon Processes Research Program to the University of Arizona, Tucson and Maricopa, Arizona (S. Leavitt, PI) and by Grant IBN-9652614 from the NSF-DOE-NASA-USDA Joint Program on Terrestrial Ecology and Global Change (TECO II) to the Agricultural Research Service, USDA, U.S. Water Conservation Laboratory, Phoenix, AZ (Gerard W. Wall, PI) and by the USDA-ARS U.S. Water Conservation Laboratory, Phoenix, Arizona (replaced by U.S. Arid-Land Agricultural Research Center, Maricopa, Arizona) and by the Potsdam Institute for Climate Impact Research, Potsdam, Germany. We acknowledge the helpful cooperation of Roy Rauschkolb (deceased) and his staff at the Maricopa Agricultural Center. The FACE apparatus was furnished by Brookhaven National Laboratory, and we are grateful to Keith Lewin, John Nagy, and George Hendry for assisting in its installation and consulting about its use. We also acknowledge the advice and participation of Floyd J. Adamsen in the soil nitrogen treatments and measurements, as well as Thomas R. Sinclair for his wheat tissue N determinations.

6 REFERENCES

Adam, N.R., G.W. Wall, B.A. Kimball, P.J. Pinter Jr., R.L. LaMorte, D.J. Hunsaker, F.J. Adamsen, T. Thompson, A. Matthias, S. Leavitt, and A.N. Webber. 2000. “Acclimation response of spring wheat in a free-air CO_2 enrichment (FACE) with variable soil nitrogen regimes. 1. Leaf position and phenology determine acclimation response.” *Photosynthesis Research* 66:65-77.

Adamsen, F.J., P.J. Pinter, Jr., E.M. Barnes, R.L. LaMorte, G.W. Wall, S.W. Leavitt, and B.A. Kimball. 1999. “Measuring wheat senescence with a digital camera.” *Crop Science* 39:719-724.

Adamsen, F.J., G. Wechsung, F. Wechsung, G.W. Wall, B.A. Kimball, P.J. Pinter Jr., R.L. LaMorte, R.L. Garcia. 2005. “Temporal changes in soil and biomass nitrogen for irrigated wheat grown under free air carbon dioxide enrichment (FACE).” *Agronomy J.* 97:160-168.

Akin, D.E., B.A. Kimball, W.R. Windham, P.J. Pinter Jr., G.W. Wall, R.L. *Garcia, R.L.* LaMorte, and W.H. Morrison III. 1995a. “Effect of free-air CO_2 enrichment (FACE) on forage quality of wheat.” *Animal Feed Science and Technology* 53:29-43.

Akin, D.E., L.L. Rigsby, G.R. Gamble, W.H. Morrison III, B.A. Kimball, P.J. Pinter Jr., G.W. Wall, *R.L. Garcia*, and R.L. LaMorte. 1995b. “Biodegradation of plant cell walls, wall carbohydrates, and wall aromatics in wheat grown in ambient or enriched CO_2 concentrations.” *Journal of Scientific Food Agriculture* 67:399-406.

Asseng, S., P.D. Jamieson, B.A. Kimball, P.J. Pinter Jr, K. Sayre, J.W. Bowden, and S.M. Howden. 2004. “Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO_2.” *Field Crops Research* 85:85-102.

Bloom, A.J., M. Burger, B.A. Kimball, and P.J. Pinter, Jr. 2014. "Nitrate assimilation is inhibited by elevated CO_2 in field-grown wheat." *Nature Climate Change* 4:477-480.

Brooks, T.J., G.W. Wall, P.J. Pinter Jr., B.A. Kimball, R.L. LaMorte, S.W. Leavitt, A.D. Matthias, F.J. Adamsen, D.J. Hunsaker, and A.N. Webber. 2000. "Acclimation response of spring wheat in a free-air CO_2 enrichment (FACE) atmosphere with variable soil nitrogen regimes. 3. Canopy architecture and gas exchange." *Photosynthesis Research* 66:97-108.

Dugas, W.A., and P.J. Pinter Jr. 1994. "Introduction to the Free-Air Carbon Dioxide Enrichment (FACE) Project." *Agricultural and Forest Meteorology* 70:1-2.

Estiarte, M., J. Peñuelas, B.A. Kimball, D.L. Hendrix, P.J. Pinter Jr., G.W. Wall, R.L. LaMorte, and D.J. Hunsaker. 1999. "Free-air CO_2 enrichment of wheat: leaf flavonoid concentration throughout the growth cycle." *Physiologia Plantarum* 105:423-433.

Estiarte, M., J. Peñuelas, B.A. Kimball, R.L. LaMorte, P.J. Pinter Jr., G.W. Wall, and R.L. Garcia. 1994. "Elevated CO_2 effects on stomatal density of wheat and sour orange trees." *Journal of Experimental Botany* 45(280):1665-1668.

Ewert, F., D. Rodriguez, P. Jamieson, M.A. Semenov, R.A.C. Mitchell, J. Goudriaan, J.R. Porter, B.A. Kimball, P.J. Pinter Jr., R. Manderscheid, H.J. Weigel, A. Fangmeier, E. Fereres, and F. Villalobos. 2002. "Effects of elevated CO_2 and drought on wheat: testing crop simulation models for different experimental and climatic conditions." *Agriculture Ecosystems & the Environment* 93:249-266.

Fox, F.A. Jr., T. Scherer, D.C. Slack, and L.J. Clark. 1992 *AriZona irrigation SCHEDuling User's Manual*. University of Arizona, Tucson, Arizona, USA.

Garcia, R.L., S.P. Long, G.W. Wall, C.P. Osborne, B.A. Kimball, G.Y. Nie, P.J. Pinter Jr., and R.L. LaMorte. 1998. "Photosynthesis and conductance of spring wheat leaves: Field response to continuous free-air atmospheric CO_2 enrichment." *Plant Cell and Environment* 21:659-669.

Grant, R.F., B.A. Kimball, P.J. Pinter Jr., G.W. Wall, R.L. *Garcia, R.L*. LaMorte, and D.J. Hunsaker. 1995a. "CO_2 effects on crop energy balance: Testing ecosys with a free-air CO_2 enrichment (FACE) experiment." *Agronomy Journal* 87:446-457.

Grant, R.F., B.A. Kimball, *T.J. Brooks*, G.W. Wall, P.J. Pinter Jr., D.J. Hunsaker, F.J. Adamsen, R.L. LaMorte, S.W. Leavitt, T.L. Thompson, and A.D. Matthias. 2001. "Modeling interactions among carbon dioxide, nitrogen, and climate on energy exchange of wheat in a free air CO_2 enrichment (FACE) experiment." *Agronomy Journal* 93(3):638-649.

Grant, R.F., G.W. Wall, B.A. Kimball, K.F.A. Frumau, P.J. Pinter Jr., D.J. Hunsaker, and R.L. LaMorte. 1999. "Crop water relations under different CO_2 and irrigation: Testing of *ecosys* with the free air CO_2 enrichment (FACE) experiment." *Agricultural and Forest Meteorology* 95: 27-51.

Grant, R.F., *R.L. Garcia*, P.J. Pinter Jr., D.J. Hunsaker, G.W. Wall, B.A. Kimball, and R.L. LaMorte. 1995b. "Interaction between atmospheric CO_2 concentration and water deficit on gas exchange and crop growth: testing of *ecosys* with data from the free air CO_2 enrichment (FACE) experiment." *Global Change Biology* 1:443-454.

Grossman, S., T. Kartschall, B.A. Kimball, D.J. Hunsaker, R.L. LaMorte, *R.L. Garcia*, G.W. Wall, and P.J. Pinter Jr. 1995. "Simulated responses of energy and water fluxes to ambient atmosphere and free-air carbon dioxide enrichment in wheat." *Journal of Biogeography* 22:601-610.

Grossman-Clarke, S., B.A. Kimball, D.J. Hunsaker, P.J. Pinter Jr., R.L. Garcia, T. Kartschall, F. Wechsung, G.W. Wall, and R.L. LaMorte. 1999. "Effects of elevated atmospheric CO_2 on canopy transpiration in senescent spring wheat." *Agricultural and Forest Meteorology* 93:95-109.

Grossman-Clarke, S., P.J. Pinter Jr., T. Kartschall, B.A. Kimball, D.J. Hunsaker, G.W. Wall, *R.L. Garcia*, and R.L. LaMorte. 2001. "Modeling a spring wheat crop under elevated carbon dioxide and drought." *New Phytologist* 150(2):315-335.

Hendrey, G.R. (ed). 1993. *FACE: Free-Air CO_2 Enrichment for Plant Research in the Field*. C. K. Smoley, Boca Raton, FL.

Hendrey, G.R., and B.A. Kimball. 1994. "The FACE Program." *Agricultural and Forest Meteorology* 70:3-14.

Hunsaker, D.J., B.A. Kimball, P.J. Pinter Jr., G.W. Wall, R.L. LaMorte, F.J. Adamsen, S.W. Leavitt, T.W. Thompson, and *T.J. Brooks*. 2000. "CO_2 enrichment and soil nitrogen effects on wheat evapotranspiration and water use efficiency." *Agricultural and Forest Meteorology* (104)2:85-100.

Hunsaker, D.J., B.A. Kimball, P.J. Pinter Jr., R.L. LaMorte, and G.W. Wall. 1996. "Carbon dioxide enrichment and irrigation effects on wheat evapotranspiration and water use efficiency." *Transactions of the ASAE* 39(4):1345-1355.

Jamieson, P.D., J. Berntsen, F. Ewert, B.A. Kimball, J.E. Olesen, P.J. Pinter Jr., J.R. Porter, and M.A. Semenov. 2000. “Modelling CO_2 effects on wheat with varying nitrogen supplies.” *Agriculture Ecosystems & the Environment* 82:27-37.

Kimball, B.A. 1983. “Carbon dioxide and agricultural yield: An assemblage and analysis of 430 prior observations.” *Agronomy Journal* 75:779-788.

Kimball, B.A. 2006. “The effects of free-air [CO_2] enrichment of cotton, wheat, and sorghum.” In J. Noesberger, S.P. Long, R.J. Norby, M. Stitt, G.R. Hendrey, and H. Blum (eds.), *Managed Ecosystems and CO_2: Case Studies, Processes, and Perspectives*, Springer, Heidelberg, Germany. 47-70.

Kimball, B.A. 2011. “Lessons from FACE: CO_2 Effects and Interactions with Water, Nitrogen, and Temperature.” In D. Hillel and C. Rosenzweig, *Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation*, Imperial College Press, London UK. 87-107.

Kimball, B.A. 2013. “Comment on ‘Improving ecophysiological simulation models to predict the impact of elevated CO_2 concentration on crop productivity’ by X. Yin.” *Annals of Botany* 112:477-478.

Kimball, B.A. 2016. “Crop responses of elevated CO_2 and interactions with H_2O, N, and temperature.” *Current Opinion in Plant Biology* 31:36-43.

Kimball, B.A., and C.J. Bernacchi. 2006. “Evapotranspiration, canopy temperature, and plant water relations.” In J. Noesberger, S.P. Long, R.J. Norby, M. Stitt, G.R. Hendrey, and H. Blum (eds.), *Managed Ecosystems and CO_2: Case Studies, Processes, and Perspectives*, Springer, Heidelberg, Germany. 311-324

Kimball, B.A., C.F. Morris, P.J. Pinter Jr., G.W. Wall, D.J. Hunsaker, F.J. Adamsen, R.L. LaMorte, S.W. Leavitt, T.L. Thompson, A.D. Matthias, and *T.J. Brooks*. 2001. “Elevated CO_2, drought and soil nitrogen effects on wheat grain quality.” *New Phytologist* 150(2):295-303.

Kimball, B.A., K. Kobayashi, and M. Bindi. 2002. “Responses of agricultural crops to free-air CO_2 enrichment.” *Advances in Agronomy* 77:293-368.

Kimball, B.A., R.L. LaMorte, G.J. Peresta, J.R. Mauney, K.F. Lewin, and G.R. Hendrey. 1992. “Appendices: Weather, soils, cultural practices, and cotton growth data from the 1989 Face experiment.” *Critical Reviews in Plant Sciences* 11(2-3):271-308.

Kimball, B.A., P.J. Pinter Jr., G.W. Wall, *R.L. Garcia*, D.J. Hunsaker, and R.L. LaMorte. 1997a. “Effects of elevated CO_2 on cotton and wheat as determined from FACE experiments.” *Journal of Agricultural Meteorology* 52(5):787-796.

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. 1995. “Productivity and water use of wheat under free-air CO_2 enrichment.” *Global Change Biology* 1:429-442.

Kimball, B.A., R.L. LaMorte, P.J. Pinter Jr., G.W. Wall, D.J. Hunsaker, F.J. Adamsen, S.W. Leavitt, T.L. Thompson, A.D. Matthias, and T.J. Brooks. 1999. “Free-air CO_2 enrichment (FACE) and soil nitrogen effects on energy balance and evapotranspiration of wheat.” *Water Resources Research* 35(4): 1179-1190.

Kimball, B.A., P.J. Pinter Jr., G.W. Wall, R.L. Garcia, R.L. LaMorte, P. Jak, K.F.A. Frumau, and H.F. Vugts. 1997b. “Comparisons of responses of vegetation to elevated CO_2 in free-air and open-top chamber facilities.” In L.H. Allen Jr., M.B. Kirkham, D.M. Olszyk, and C.E. Whitman (eds.), *Advances in Carbon Dioxide Effects Research*. ASA Special Publication 61. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America Madison, WI. 113-130.

Ko, J., L. Ahuja, B. Kimball, S. Anapalli, L. Ma, T.R. Green, A.C. Ruane, G.W. Wall, P. Pinter, and D.A. Bader. 2010. “Simulation of free-air CO_2 enriched wheat growth and interactions with water, nitrogen, and temperature.” *Agricultural and Forest Meteorology* 150: 1331-1346.

Leavitt, S.W., E. Pendall, E.A. Paul, T.J. Brooks, B.A. Kimball, and P.J. Pinter Jr. 2001. “Stable-carbon isotopes and soil organic carbon in wheat under CO_2 enrichment.” *New Phytologist* 150(2):305-314.

Leavitt, S.W., E.A. Paul, A. Galadima, F.S. Nakayama, S.R. Danzer, H. Johnson, and B.A. Kimball. 1996. “Carbon isotopes and carbon turnover in cotton and wheat FACE experiments.” *Plant and Soil* 187:147-155.

Leavitt, S.W., E.A. Paul, E. Pendall, P.J. Pinter Jr, and B.A. Kimball. 1997. “Field variability of carbon isotopes in soil organic carbon.” *Nuclear Instruments and Methods in Physics Research* 123:451-454.

Li, A.-G., A. Trent, G.W. Wall, B.A. Kimball, Y.-S. Hou, P.J. Pinter Jr., *R.L. Garcia*, D.J. Hunsaker, and R.L. LaMorte. 1997. "Free-air CO_2 enrichment effects on rate and duration of apical development of spring wheat." *Crop Science* 37:789-796.

Li, A.-G., Y.-S. Hou, G.W. Wall, A. Trent, B.A. Kimball, P.J. Pinter Jr., *R.L. Garcia*, D.J. Hunsaker, and R.L. LaMorte. 2000. "Free-air CO_2 enrichment and drought stress effects on grain filling rate and duration in spring wheat." *Crop Science* 40:1263-1270.

Manunta, P., R.F. Grant, Y. Feng, B.A. Kimball, Pinter Jr., P.J., R.L. LaMorte, D.J. Hunsaker, and G.W. Wall. 2002. "Changes in mass and energy transfer between the canopy and the atmosphere: model development and testing with a free-air CO_2 enrichment (FACE) experiment." *Journal of Biometeorology* 46: 9-21.

Nie, G.Y., B.A. Kimball, P.J. Pinter Jr., G.W. Wall, R.L. *Garcia, R.L*. LaMorte, A.N. Webber, and S.P. Long. 1995a. "Effects of free-air CO_2 enrichment on the development of the photosynthetic apparatus in wheat, as indicated by changes leaf proteins." *Plant Cell and Environment* 18:855-864.

Nie, G.-Y., D.L. Hendrix, A.N. Webber, B.A. Kimball, and S.P. Long. 1995b. "Increased accumulation of carbohydrates and decreased photosynthetic gene transcript levels in wheat grown at an elevated CO_2 concentration in the field." *Plant Physiology* 108:975-983.

Osborne, C.P., J. Laroche, *R.L. Garcia*, B.A. Kimball, G.W. Wall, P.J. Pinter Jr., R.L. LaMorte, G.R. Hendrey, and S.P. Long. 1998. "Does leaf position within a canopy affect acclimation of photosynthesis to elevated CO_2? Analysis of a wheat crop under free-air CO_2 enrichment." *Plant Physiology* 117:1037-1045.

Pendall, E., S.W. Leavitt, T.J. Brooks, B.A. Kimball, P.J. Pinter Jr., G.W. Wall, R.L. LaMorte, G. Wechsung, F. Wechsung, F.J. Adamsen, A.D. Matthias, and T.L. Thompson. 2001. "Elevated CO_2 stimulates soil respiration and decomposition in a FACE wheat field." *Basic Applied Ecology* 2:193-201.

Peñuelas, J., M. Estiarte, and B.A. Kimball. 1999. "Flavonoid responses in wheat grown at elevated CO2: green versus senescent leaves." *Photosynthetica* 37(4):615-619.

Pinter Jr., P.J., B.A. Kimball, R.L. LaMorte, G.W. Wall, D.J. Hunsaker, F.J. Adamsen, K.F.A. Frumau, H.F. Vugts, G.R. Hendrey, K.F. Lewin, J. Nagy, H.B. Johnson, T.L. Thompson, A.D. Matthias, and *T.J. Brooks*. 2000. "Free-air CO_2 enrichment (FACE): blower effects on wheat canopy microclimate and plant development." *Agricultural and Forest Meteorology* 103(4):319-332.

Porteaus, F., J. Hill, A.S. Ball, P.J. Pinter, B.A. Kimball, G.W. Wall, F.J. Adamsen, D.J. Hunsaker, R.L. Lamorte, S.W. Leavitt, T.L. Thompson, A.D. Matthias, T.J. Brooks, and C.F. Morris. 2009. "Effect of Free Air Carbon Dioxide Enrichment (FACE) on the chemical and composition and nutritive value of wheat grain and straw." *Animal Feed Science and Technology* 149:322-332.

Post, D.F., C. Mack, P.D. Camp, and A.S. Suliman. 1988. "Mapping and characterization of the soils on the University of Arizona Maricopa Agricultural Center." *Proceedings of Hydrology and Water Resources of the Southwest* 18:49-60.

Prior, S.A., H.A. Torbert, G.B. Runion, H.H. Rogers, C.W. Wood, B.A. Kimball, R.L. LaMorte, P.J. Pinter Jr., and G.W. Wall. 1997. "Free-air carbon dioxide enrichment of wheat: soil carbon and nitrogen dynamics." *Journal of Environmental Quality* 26:1161-1166.

Senock, R.S., J.M. Ham, T.M. Loughin, B.A. Kimball, D.J. Hunsaker, P.J. Pinter Jr., G.W. Wall, and R.L. LaMorte. 1996. "Free-air CO_2 enrichment (FACE) of wheat: Assessment with SAP flow measurements." *Plant Cell and Environment* 19:147-158.

Sinclair, T.R., P.J. Pinter Jr., B.A. Kimball, F.J. Adamsen, R.L. LaMorte, G.W. Wall, D.J. Hunsaker, N.R. Adam, T.J. Brooks, *R.L. Garcia*, T. Thompson, S. Leavitt, and A. Matthias. 2000. "Leaf nitrogen concentration of wheat subjected to elevated CO_2 and either water or N deficits." *Agriculture Ecosystems & the Environment* 79:53-60.

Tubiello, F.N., C. Rosenzweig, B.A. Kimball, P.J. Pinter Jr., G.W. Wall, D.J. Hunsaker, R.L. LaMorte, and *R.L. Garcia*. 1999. "Testing *CERES*-Wheat with Free Air Carbon-Dioxide Enrichment data: CO_2 and water interactions." *Agronomy Journal* 91(2):247-255.

Wall, G.W. 2001. "Elevated atmospheric CO_2 alleviates drought stress in wheat." *Agriculture, Ecosystems and Environment* 87:261-271.

Wall, G.W., and B.A. Kimball. 1993. "Biological databases derived from free-air carbon dioxide enrichment experiments." In E.-D. Schulze and H.A. Mooney (eds.), *Design and Execution of Experiments on CO_2 Enrichment. Ecosystems Report 6, Environmental Research Programme,* Commission of the European Communities, Brussels. 329-348

Wall, G.W., N.R. Adam, T.J. Brooks, B.A. Kimball, P.J. Pinter Jr., R.L. LaMorte, F.J. Adamsen, D.J. Hunsaker, G. Wechsung, F. Wechsung, S. Grossman-Clarke, S. Leavitt, A.D. Matthias, and

A.N. Webber. 2000. "Acclimation response of spring wheat in a free-air CO_2 enrichment (FACE) atmosphere with variable soil nitrogen regimes. 2. Net assimilation and stomatal conductance of leaves." *Photosynthesis Research* 66:79-95.

Wall, G.W., R.L. Garcia, B.A. Kimball, D.J. Hunsaker, P.J. Pinter, Jr., S.P. Long, C.P. Osborne, D.L. Hendrix, F. Wechsung, G. Wechsung, S.W. Leavitt, R.L. LaMorte, and S.B. Idso. 2006. "Interactive effects of elevated CO_2 and drought on wheat." *Agronomy J.* 98:354-381.

Wechsung, F., *R.L. Garcia*, G.W. Wall, T. Kartschall, B.A. Kimball, P. Michaelis, P.J. Pinter Jr., G. Wechsung, S. Grossman-Clarke, R.L. LaMorte, F.J. Adamsen, S.W. Leavitt, T.L. Thompson, A.D. Matthias, and *T.J. Brooks*. 2000. "Photosynthesis and conductance of spring wheat ears: field response to free-air CO_2 enrichment and limitations in water and nitrogen supply." *Plant Cell and Environment* 23:917-930.

Wechsung, G., F. Wechsung, G.W. Wall, F.J. Adamsen, B.A. Kimball, *R.L. Garcia*, P.J. Pinter Jr, and T. Kartschall. 1995. "Biomass and growth rate of a spring wheat root system grown in free-air CO_2 enrichment (FACE) and ample soil moisture." *Journal of Biogeography* 22:623-634.

Wechsung, G., F. Wechsung, G.W. Wall, F.J. Adamsen, B.A. Kimball, P.J. Pinter Jr, R.L. LaMorte, R.L. Garcia, and Th. Kartschall. 1999. "The effects of free-air CO_2 enrichment and soil water availability on spatial and seasonal patterns of wheat root growth." *Global Change Biology* 5:519-529.

White, J.W., L.A. Hunt, K.J. Boote, J.W. Jones, J. Koo, S. Kim, C.H. Porter, P.W. Wilkens, and G. Hoogenboom. 2013. "Integrated description of agricultural field experiments and production: The ICASA Version 2.0 data standards." *Computers and Electronics in Agriculture* 96:1-12.