FINAL REPORT
Interagency Agreement No. DE-AI03-97ER62461
Elevated CO₂ and Limited Water Supply Effects on Carbon Processes and
Sequestration in a C4 Grass (Sorghum) Ecosystem

Under the funding umbrella provided by Interagency Agreement No. DE-AI03-97ER62461, free-air CO₂ enrichment (FACE) experiments were conducted at ample and limited levels of soil moisture on sorghum in 1998 and 1999 at the University of Arizona, Maricopa Agricultural Center, Maricopa, AZ. Numerous measurements were taken including biomass production, grain yield, soil carbon sequestration, N₂O production, stomatal conductance, leaf water potential, canopy temperature, net radiation, and reflectance at many wavelengths. Accomplishments included the following:

1. To determine the likely effects of the increasing atmospheric CO₂ concentration on the physiology, growth, yield, water use, and carbon sequestration of sorghum, plots of field grown sorghum at ample and limited supplies of soil water were exposed to free air CO₂ enrichment (FACE) at about 550 ppm, such as expected near the middle of this century. The FACE experiments were conducted by ARS researchers from Phoenix, AZ, together with many collaborators, especially from the University of Arizona, during the summers of 1998 and 1999 at the University of Arizona's Maricopa Agricultural Center, Maricopa, Arizona. The results showed elevated CO₂ stimulated shoot growth 16% and grain yield 25% in the water-stressed plots, but under ample water, there was no consistent effect on shoot growth, and yields decreased about 5%. These results suggest that increased atmospheric CO₂ will affect future sorghum productivity little under irrigation or in wetter climates, but in drier, semi arid regions, where much sorghum is grown today because of its drought tolerance, the future high CO₂ concentrations likely will increase productivity.

2. In order to determine the likely response of so-called C4 plants such as sorghum to future high levels of atmospheric CO₂, it is necessary to establish whether young leaves have a fully developed C4 photosynthetic apparatus and whether photosynthesis in these leaves is responsive to elevated CO₂. ARS researchers from Phoenix, AZ, in cooperation with researchers from Arizona State University, the University of Arizona, and others, grew sorghum using free-air CO₂ enrichment (FACE) at 550 ppm at ample irrigation, and measurements were made of net leaf photosynthesis and of fluorescence from young leaves. Photosynthesis in the second leaf of FACE plants increased 37% compared to controls, which was partially due to suppressed photorespiration, and the FACE treatment also increased energy-use efficiency, possibly by decreasing CO₂ leakage from bundle sheath cells and by decreasing over-cycling of the C4 pump. Therefore, young sorghum leaves clearly showed stimulation of photosynthesis to elevated CO₂, which would have the potential to stimulate sorghum productivity even under ample water, but unfortunately the effect was too short-lived to significantly improve yields in these experiments.

3. The degree to which photosynthesis of a crop will be stimulated by elevated levels of atmospheric CO₂ likely will affect its future productivity, and some so-called C4 plants

like sorghum have been predicted to be unresponsive, but prior data have not been definitive. Therefore, ARS researchers from Phoenix, AZ, in cooperation with researchers from the University of Arizona and others, grew sorghum using free-air CO₂ enrichment (FACE) at 550 ppm at ample and limited supplies of water, and measurements were made of leaf photosynthetic rates, stomatal conductance, and ratios of the ¹³C carbon isotope to that of ¹²C in the leaf tissue. From these data it was possible to calculate the leakiness of bundle sheath cells used in C₄ photosynthesis, and it was found that FACE ameliorated the effects of drought on the leakiness. Thus, it appeared that direct effects of elevated CO₂ on C₄ photosynthetic metabolism were minimal, but that an important interaction occurs with water stress, which was consistent with yield results, and which suggests that increased atmospheric CO₂ will affect future sorghum productivity little under irrigation or in wetter climates, but in drier, semi arid regions, where much sorghum is grown today because of its drought tolerance, the future high CO₂ concentrations likely will increase productivity.

4. To determine the likely effects of the increasing atmospheric CO₂ concentration on future evapotranspiration (ET, water use), ARS scientists from Phoenix, Arizona, and cooperators from the University of Arizona and elsewhere exposed plots of field grown sorghum at Maricopa, Arizona, to concentrations of 550 ppm CO₂, such as expected at mid-century, using a free air CO₂ enrichment (FACE) facility at both ample and limiting levels of water supply. Soil water content was measured before and after irrigations, and ET was calculated as a residual in the soil water balance. Elevated CO₂ reduced seasonal ET by 10% under ample water and about 4% under limited water, but it also increased water use efficiency about 16% under both water treatments. These data suggest that in a future high-CO₂ environment, water requirements for irrigated sorghum will be lower while dry-land productivity will increase.

5. While determination of likely effects of increasing CO₂ and climate change on vegetation has received much attention, the additional effects on soil biota and soil properties have been little studied. Therefore, ARS scientists from Phoenix, AZ, and Beltsville, MD, together with cooperators from the University of Montana, the University of Arizona, and others, determined the hyphae lengths of mycorrhizal fungi and of the stability of soil aggregates in soil samples taken following one season of growing sorghum using a free air CO₂ enrichment (FACE) facility at both ample and limiting levels of water supply. The hyphae lengths were increased 109 and 267% due to elevated CO₂ at ample and low water supply, respectively, and water-stable aggregates were increased 30% while easily extractable glomalin, a "glue" that helps stabilize aggregates, was also increased. Such a change in soil structure would be expected to increase infiltration, decrease erosion, and alter other soil hydrological properties in the future.

6. The continuing rise in atmospheric CO₂ concentration is predicted to cause warmer mean air temperatures and altered precipitation patterns, which could increase the likelihood of high temperature extremes and the occurrences of severe drought conditions. To determine the interactive effects of atmospheric CO₂ concentration and soil water content on plants with the C₄ photosynthetic pathway, ARS researchers from Phoenix, AZ, in cooperation with scientists from Arizona State University, the University

of Arizona, and others, grew grain sorghum under well watered (Wet) and water stressed (Dry) soil moisture regimes, and at ambient and 200 ppm above ambient CO₂ concentrations using free air CO₂ enrichment (FACE) technology. Compared with control, FACE caused less negative (i.e., improved) total leaf water potentials by 9% and 3% under Dry and Wet, respectively, and it also reduced stomatal conductances by 32% and 37%, while increasing net assimilation rates by 23% and 9%. Therefore, by ameliorating the adverse effects of drought, elevated atmospheric CO₂ improved the plant water status for a C4 warm season annual grass, which indirectly resulted in a net increase in daily and seasonal carbon gain (i.e., growth).

7. In order to determine the likely overall response of so-called C4 plants such as sorghum to future high levels of atmospheric CO₂ and possible climate change, it is necessary to establish the interactive effects of elevated CO₂ and drought on photosynthesis. ARS researchers from Phoenix, AZ, in cooperation with researchers from Arizona State University, the University of Arizona, and others, grew sorghum using free-air CO₂ enrichment (FACE) at 550 ppm at ample and limited irrigation, and measurements were made of net leaf photosynthesis and fluorescence. Under drought-stress, FACE increased the quantum yield throughout the day, whereas at ample water, the enhancement occurred only at midday. Therefore, as was also confirmed by other grain yield measurements, future high levels of CO₂ are likely to stimulate sorghum growth under dry conditions but have little effect under well-watered conditions.

8. In order to determine the likely responses of rangeland and other ecosystems with assemblages of plants to future high levels of atmospheric CO₂ and changing climate, it is necessary to establish the likely competitive advantages among species to these changing factors in their environments. Therefore, ARS researchers from Temple, TX and Phoenix, AZ, in cooperation with others from the University of Arizona and elsewhere, grew sorghum (a so-called C4 plant not expected to respond to CO₂) along with cotton (a so-called C3 plant expected to respond to CO₂) in mixtures and in pure stands under free-air CO₂ enrichment (FACE) at 200 ppm above ambient. In the pure stands, elevated CO₂ increased the growth of cotton but not sorghum, whereas in the mixtures, cotton performance was reduced, indicating sorghum was the superior competitor, yet FACE increased total (sorghum + cotton) biomass production at high plant density. Thus, elevated CO₂ likely will affect future species composition and overall productivity of multi-species ecosystems.

9. The CO₂ concentration in the atmosphere is increasing, which likely will affect plant photosynthesis in the future, as well as causing a partial closure of the stomata in plant leaves through which the plants exchange CO₂ and water vapor with the atmosphere. A plant growth model called *ecosys*, which was developed to predict what effects the elevated CO₂ on plant growth and plant water requirements by a scientist from the University of Alberta, Edmonton, Alberta, Canada, was tested against the results of an experiment where open-field-grown sorghum was exposed to elevated levels of CO₂ using free-air CO₂-enrichment (FACE) technology at ample and limited levels of soil water by scientists from the ARS U.S. Water Conservation Laboratory, Phoenix, AZ, the University of Arizona, and others. Most model results were acceptably close to observed

values, predicting for example, that CO₂ concentrations of about 550 ppm, such as expected near the middle of the this century, should cause sorghum grain yields to change little at ample irrigation, but the amount of water required will decrease about 17%, provided climate does not change much. On the other hand, when water supply is limited, sorghum yields should increase about 13%.

Publications Resulting from the Agreement

- Conley, M.M., B.A. Kimball, T.J. Brooks, P.J. Pinter Jr., D.J. Hunsaker, G.W. Wall, N.R. Adam, R.L. LaMorte, A.D. Matthias, T.L. Thompson, S.W. Leavitt, M.J. Ottman, A.B. Cousins, and J.M. Triggs. 2001. CO₂ enrichment increases water use efficiency in sorghum. *New Phytologist* 151(2): 407-412.
- Cousins, A.B., N.R. Adam, G.W. Wall, B.A. Kimball, P.J. Pinter Jr., S.W. Leavitt, R.L. LaMorte, A.D. Matthias, M.J. Ottman, T.J. Thompson, and A.N. Webber. 2001. Reduced photorespiration and increased energy-use efficiency in young CO₂-enriched sorghum leaves. *New Phytologist* 150(2):275-284.
- Cousins, A.B., N.R. Adam, G.W. Wall, B.A. Kimball, P.J. Pinter Jr., M.J. Ottman, S.W. Leavitt, and A.N. Webber. 2002. Photosystem II energy use, non-photochemical quenching and the xanthophyll cycle in *Sorghum bicolor* grown under drought and free-air CO₂ enrichment (FACE) conditions. *Plant Cell and Environment*. 25:1551-1559.
- Cousins, A.B., N.R. Adam, G.W. Wall, B.A. Kimball, P.J. Pinter Jr., M.J. Ottman, S.W. Leavitt, and Webber A.N. 2003. Development of C₄ photosynthesis in Sorghum leaves grown under free-air CO₂ enrichment (FACE). *Journal of Experimental Botany* 54: 1969-1975.
- Derner, J.D., H.B. Johnson, B.A. Kimball, P.J. Pinter Jr, H.W. Polley, C.R. Tischler, T.W. Bouttons, R.L. LaMorte, G.W. Wall, N.R. Adam, S.W. Leavitt, M.J. Ottman, A.D. Matthias, and T.J. Brooks. 2003. Above- and below-ground responses of C₃-C₄ species mixtures to elevated CO₂ and soil water availability. *Global Change Biology* 9:452-460.
- Grant, R.F., B.A. Kimball, G.W. Wall, J.M. Triggs, T.J. Brooks, P.J. Pinter, M.M. Conley, M.J. Ottman, R.L. Lamorte, S.W. Leavitt, T.J. Thompson, and A.D. Matthias. 2004. Modeling elevated carbon dioxide effects on water relations, water use, and growth of irrigated sorghum. *Agronomy Journal* 96:1693-1705.
- Kimball, B.A., K. Kobayashi, and M. Bindi. 2002. Responses of agricultural crops to free-air CO₂ enrichment. *Advances in Agronomy* 77:293-368.
- Ottman, M.J., B.A. Kimball, P.J. Pinter Jr., G.W. Wall, R.L. Vanderlip, S.W. Leavitt, R.L. LaMorte, A.D. Matthias, and T.J. Brooks. 2001. Elevated CO₂ increases sorghum biomass under drought conditions. *New Phytologist* 150(2):261-273.
- Triggs, J.M., B.A. Kimball, P.J. Pinter Jr., G.W. Wall, M.M. Conley, T.J. Brooks, R.L.

LaMorte, N.R. Adam, M.J. Ottman, A.D. Matthias, S.W. Leavitt, and R.S. Cervený. 2004. Free-air carbon dioxide enrichment effects on energy balance and evapotranspiration of sorghum. *Agricultural and Forest Meteorology* 124:63-79.

Wall, G.W., T.J. Brooks, N.R. Adam, A.B. Cousins, B.A. Kimball, P.J. Pinter Jr., R.L. LaMorte, J. Triggs, M.J. Ottman, S.W. Leavitt, A.D. Matthias, D.G. Williams, and A.N. Webber. 2001. Elevated atmospheric CO₂ improved sorghum plant water status by ameliorating the adverse effects of drought. *New Phytologist* 152:231-248.

Williams, D.G., B. Gempko, A. Fravolini, S.W. Leavitt, G.W. Wall, B.A. Kimball, P.J. Pinter Jr., R. LaMorte, and M. Ottman. 2001. Carbon isotope discrimination by sorghum bicolor under CO₂ enrichment and drought. *New Phytologist* 150(2):285-293.