AGRICULTURAL PRODUCTIVITY AND WATER USE: EFFECTS OF GLOBAL CHANGE

Bruce A. Kimball, Supervisory Soil Scientist
Gerard W. Wall, Plany Physiologist
Paul J. Pinter, Jr., Research Biologist
Neal R. Adam, Plant Physiologist

PROJECT SUMMARY

We propose to conduct global change research over the next three years with the following objectives: (1) Determine the long-term effects of elevated CO_2 on the physiology, growth, wood production, fruit yield, fruit nutritional quality, and water use efficiency of sour orange trees, as well as its effects on soil structure and carbon. This is a continuation of an ongoing open-top chamber experiment started in 1987, which is the longest such continuous CO_2-enrichment experiment ever conducted. (2) Assess likely impacts of global change on the productivity of agricultural crops via synthesis and integration of existing large accumulated experimental data base plus additional crop growth modeling. (3) Determine effects of elevated CO_2 on the physiology, growth, yield, N_2-fixation, persistence, and soil carbon sequestration of alfalfa using the free-air CO_2 enrichment (FACE) approach. This experiment is the logical follow-on to prior such FACE experiments on cotton, wheat, and sorghum conducted at Maricopa, AZ. (4) Determine effects of elevated CO_2, water supply, and grazing pressure on productivity, shrub-grass competition, carbon sequestration, and water relations of the piñon-juniper rangeland ecosystem, also using the FACE approach. This new project, called Carbon Exchange and Sequestration in Arid Regions (CESAR), would utilize CO_2 from a huge geologic source within this ecosystem, and it would involve a large consortium of universities, ARS, private industry, and others. Achieving Objectives 3 and 4 is contingent upon obtaining outside funding.

OBJECTIVES

1. Determine the long-term effects of elevated CO_2 on the physiology, growth, wood production, fruit yield, fruit nutritional quality, and water use efficiency of sour orange trees, as well as its effects on soil structure and carbon sequestration beneath the trees.

2. Assess likely impacts of potential global change on productivity of agricultural crops via synthesis and integration of large accumulated experimental data bases.

   [Note: Objectives 3 and 4 are contingency plans dependent upon obtaining outside funding.]

3. Determine effects of elevated CO_2 on the physiology, growth, yield, N_2-fixation, persistence, and soil carbon sequestration of alfalfa.

4. Determine effects of elevated CO_2, water supply and grazing pressure on the productivity, shrub-grass competition, carbon sequestration, and water relations of the piñon-juniper rangeland ecosystem.

NEED FOR RESEARCH

Description of the Problem to be Solved

1. Sour orange: Whether enough carbon can be sequestered in the boles of tress and in the soil beneath them to significantly slow the rate of rise of atmospheric CO_2 concentration is an important question facing global change research, as are the implications of the ongoing CO_2 rise for human nutrition. *Sour orange* represents such long-lived woody species, which is being studied to determine (1) whether an initial CO_2-induced enhancement in wood and fruit production will be maintained over a tree's life span, (2) whether quality of wood and fruit will change, and (3) whether increases will occur in soil carbon storage beneath the trees.

2. Synthesis and Integration: Policymakers often have difficulty perceiving principles from the vast array of facts before them, so a common refrain is that the products of scientific research are "data rich and knowledge poor." Currently, about 2 papers are being published every 3 days about the effects of CO_2 and other environmental variables on agricultural crops, from which more definitive knowledge about global change effects on agriculture needs to be synthesized. Furthermore, available assessments may be suspect. The Inter-governmental Panel for Climate Change is now writing its third major assessment of likely impacts of global change on agriculture (as well as many other facets of world society), but most of the predictions are based on simple plant growth models which ignore some important plant processes (IPCC, 2001).

   Four simple models (Tubiello et al., 1999; Jamieson et al., 2001) were able to simulate the responses of wheat to elevated CO_2 interacting with soil water and soil nitrogen supplies as observed in our free-air CO_2 enrichment (FACE) wheat experiments. Nevertheless, such simple models as tabulated by the IPCC (2001) cannot address some important aspects of plant growth responses to elevated CO_2. For example, they "grow" the crops at air temperature rather than at the crop's own temperature; yet, we have shown that elevated CO_2 causes wheat canopies to warm 0.6 to 1.2°C above air temperature due to the direct effects of the elevated CO_2 on the plants' stomatal apertures (Kimball et al., 1992, 1995, 1999). Such warming would be in addition to any global warming of air temperature, and it could cause similar consequences, such as changes in yield and major shifts in optimal production regions of crops. A second effect that is not adequately addressed by simple daily-time-step models is that plants make their photosynthate during daytime, yet they continue to translocate material and grow at night. Therefore, daily temperature patterns may be very important in determining plant responses to elevated CO_2. One prediction of general circulation models is that night temperatures are likely to warm more in the future than daytime temperatures (Collatz et al., 2000; Easterling et al., 1997; Hansen et al., 1995). Therefore, another generation of assessments needs to be done -- with detailed process-oriented models capable of simulating all known effects of elevated CO_2, as well as of other interacting environmental variables, on crop physiology, growth, yield, carbon sequestration, and water relations.

3. Alfalfa: Alfalfa is a perennial deep-rooted legume crop that has the potential to respond to elevated CO_2 with deep sequestration of soil carbon, even at low soil nitrogen and thereby slow the rate of rise of the atmospheric CO_2 concentration. It is an important forage crop in the U.S.

(24 million acres; 4th in acreage behind corn, wheat, and soybeans; USDA, 2000) that grows well in Arizona. Specific scientific reasons to focus on alfalfa are: (1) being deep-rooted, alfalfa can sequester carbon at deeper depths below the plow layer where it may be able to be stored for much longer periods, (2) being perennial, alfalfa grows the year around, so the interaction between elevated CO_2 and temperature can be studied, and (3) being a legume, the effects of elevated CO_2 on nitrogen fixation can be examined, as can the importance of nitrogen for C sequestration.

4. Piñon-juniper: Piñon-juniper is an expansive ecosystem whose character may be changed by global change. This vast mid-elevation ecosystem serves as rangeland for substantial cattle production and watershed catchment for much of the Western U.S. It contains more than a dozen National Parks and Monuments, is home to numerous Native American groups, has a history of varied natural resource management (fire suppression, logging, grazing), and is under great development pressure from surrounding regions (Wilkinson 1998). Little research has addressed biosphere-atmosphere interactions of this region, yet paleoecological studies and climate change models indicate this region may be highly sensitive to global change (Cole,1985; Nielson, 1995; Grissino-Mayer et al., 1997). Land use (fire suppression, grazing) has had widespread impacts on this region (Fleischner, 1994; Brown and McDonald, 1995; Moore et al., 1999), yet we do not understand the implications of these activities for C exchange and sequestration, nor the nature of their interaction with atmospheric and climatic change. Insect outbreaks associated with climate change appear to be increasing (Walker et al., 1998). Their impacts on ecosystem C fluxes and sequestration can be significant but are little understood in arid regions. Of the region's major vegetation types, the piñon–juniper woodland is the third most extensive in the continental U.S. Therefore, there are several reasons to determine the effects of elevated CO_2 and other interacting environmental variables on this important ecosystem.

Relevance to ARS National Program Action Plan

The project is relevant to all components. While the primary emphasis is on determining and assessing the impact of global change on *agricultural ecosystems* and to develop strategies for adaptation, this research inherently involves studying all aspects of *carbon cycling* from photosynthetic carbon assimilation to soil carbon sequestration, the latter of which can mitigate the rate of global change. Production of *trace gases*, such as N_2O, will also be addressed. In addition, the influences on surface energy balance and evapotranspiration will be assessed, thereby contributing to the *water cycle* component.

Potential Benefits

The main benefit will be an enhanced ability to prepare for potential global change. Knowing the probable impacts of global change on crop production and water use in each region will give researchers and growers the incentive to develop strategies for coping with problems and maximizing benefits, as well as for sequestering carbon to mitigate the rate of global change. The growth models developed as part of this research should prove to be useful tools for developing such strategies.

Anticipated Products

Scientific publications will be produced that describe, as well as synthesize and integrate, the effects of elevated CO_2 and interacting environmental variables on plant physiology, growth, yield, light use efficiency, carbon sequestration, and water use of crops and rangeland for various regions and global change scenarios. Process-based plant growth models that have been more perfected and validated than currently exist will also be products of this research.

Customers

Other agencies, such as the Department of Energy and Environmental Protection Agency, need the information to set policy regarding carbon storage credits, energy sources (i.e., coal versus nuclear), CO_2 emissions (whether to tax or not), and land use (reforestation). Agricultural policymakers will also use the information to formulate resource conservation plans for the next Farm Bill, especially if there is a "green payments" program that encourages carbon sequestration. And, of course, farmers eventually will use the information.

SCIENTIFIC BACKGROUND: Refer to 2001 Annual Report

APPROACH AND RESEARCH PROCEDURES: Refer to 2001 Annual Report

PHYSICAL AND HUMAN RESOURCES: Refer to 2001 Annual Report

MILESTONES AND EXPECTED OUTCOMES

	Research Objective or Area of Study			
Date	**1. Sour Orange Trees (Idso, Kimball)**	**2. Synthesis & Integration (Kimball, Idso, Wall, Pinter)**	**3. FACE Alfalfa Expt. (Kimball, Wall, Pinter)**	**4. FACE Piñon-Juniper Rangeland Expt. (Kimball, Wall, Pinter)**
Jan. 2001	Harvest fruit & tabulate monthly growth increments for 2000.	Review of free-air CO_2 enrichment (FACE) effects on agricultural crops completed.	Proposal submitted to NASA for funding.	Rough plan and pre-proposal completed.
Jan. 2002	Ditto for 2001 + folic acid production + soil fungal growth & glomalin & soil structure.	Above FACE review published, and review of carbon sequestration completed. Paper on elevated CO_2 effects on canopy temperature and crop production areas written.	If selected for NASA funding, will install FACE apparatus and plant alfalfa in fall 2001. If not, then timetable will pushed forward accordingly until funding finally achieved.	Second stage planning completed, and proposal prepared and submitted to funding agency.
Jan. 2003	Ditto for 2002 + wood density & strength + water use efficiency.	First regional study with *ecosys* on wheat completed. Paper written on relationship between radiatio use efficiency and CO_2 concentration.	Tabulation and review of first year's growth, remote sensing, energy and water balance, photosynthesis and water relations, and other data.	If selected for funding, initiate experiment in spring of 2002. If not, timetable will be delayed accordingly until funding finally achieved.
Jan. 2004	Ditto for 2003 + differing sunlit & shaded growth & fruit & antioxidant + history of leaf starch & sugar production + leaf senescence & fall history.	First regional study with *ecosys* on sorghum completed. Cotton model selected and regional study intiated.	Tabulation and review of second year's growth, remote sensing, energy and water balance, photosynthesis and water relations, and other data.	Tabulate and review of initial season's baseline measurements at ambient CO_2.
Mar. 2004	End of time for this proposed project plan.			
Jan. 2005	Ditto for 2004. This marks the minimum length of time to be sure that the CO_2-enriched trees have achieved a constant relative growth advantage over the ambient-treatment trees (Figure 1) that can reasonably be expected to continue throughout the remaining life of the trees.		Tabulation and review of third year's growth, remote sensing, energy and water balance, photosynthesis and water relations, and other data. Papers written on these topics.	FACE treatment starts spring of 2004. Tabulation and review of first season's growth, remote sensing, energy and water balance, photosynthesis and water relations, and other data.

PROGRESS

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).

Increasing atmospheric CO_2 concentration and predicted global climate change are likely to affect future water resources in several ways. Therefore, an ARS researcher from Phoenix, AZ, calculated the direct effects of elevated CO_2 on plants, as well as changes due to global warming using a "reference" evapotranspiration (ET) equation, and he reviewed literature stimates of water supply. Slight (2-6%) increases in crop ET were predicted for plausible scenarios of future CO_2 and temperature levels, whereas the predictions for water supply were much more uncertain. Therefore, it behooves future water resource planners and future growers to try to be as flexible as possible.

Rising levels of atmospheric CO2 affect transpiration and water absorption processes that influence total leaf water potential (a measure of a plant's internal water status) of agricultural crops, including wheat – the worlds foremost grain source. To determine the effect of a rise in atmospheric CO2 concentration on total leaf water potential as the soil water content ranged from field capacity to the permanent wilting point, ARS researchers from Phoenix, AZ, grew spring wheat under well-watered (Wet) and water-stressed (Dry) soil moisture regimes, and at 200 ppm above current ambient (about 370 ppm) CO2 concentrations using free-air CO2 enrichment (FACE) technology. Throughout the daylit period, more negative (i.e., improved) total leaf water potential for a given soil water content occurred in FACE-grown plants, which could be traced to both drought-avoidance and drought-tolerance mechanisms. Therefore, as the CO2 concentration of the atmosphere rises, both drought avoidance and tolerance should improve in cool-season annual grasses such as wheat, resulting in an improvement in water relations.

In order to determine the likely overall response of so-called C_4 plants such as sorghum to future high levels of atmospheric CO_2 and possible climate change, it is necessary to establish the interactive effects of elevated CO_2 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 CO_2 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 CO_2 are likely to stimulate sorghum growth under dry conditions but have little effect under well-watered conditions.

Whether or not the storage or sequestration of carbon in soils should be adopted as an international policy to mitigate the rise in atmospheric CO2 concentration is a hotly debated topic, partly because uncertainties exist with regard to how much the elevated CO2 may increase crop growth and stimulate the addition of carbon to the soil and how fast decomposition processes may subsequently return it to the atmosphere. Cooperating researchers from the University of Arizona and ARS researchers from Phoenix, Arizona, exposed wheat to an additional 200 ppm of CO_2 using free-air CO_2-enrichment (FACE) technology, and they found that the FACE treatment stimulated soil respiration rates by 40-70% during peak wheat growth periods. Moreover, carbon isotope analyses indicated some of the increase in respired CO_2 came from old organic matter. Thus, these experiments show that increased losses of soil carbon occur under elevated CO_2, but longer-term full carbon balance studies are needed to resolve the basic question of the net increase in sequestration due to wheat production under elevated CO_2.

In order to determine the likely responses of rangeland and other ecosystems with assemblages of plants to future high levels of atmospheric CO_2 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 CO_2) along with cotton (a so-called C3 plant expected to respond to CO_2) in mixtures and in pure stands under free-air CO_2 enrichment (FACE) at 200 ppm above ambient. In the pure stands, elevated CO_2 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 CO_2 likely will affect future species composition and overall productivity of multi-species ecosystems.

Storage of cryogenically-preserved samples at a cold predetermined temperature is critical in order to maintain the integrity of the specimens. To minimize any risk associated with thawing (sample degradation) during sorting and/or sub-sampling of cryogenically-preserved samples, ARS researchers from Phoenix, AZ, invented a Multi-purpose Cryogenic Surface (MCS) device that is portable, suitable for laboratory or field use, positionally stable, and easily refillable with cryogenic fluid (typically liquid nitrogen). Activity assays and gel separation of photosynthetic enzymes confirmed that the integrity of the sample was maintained though use of the MCS. The MCS has the potential to become the standard operating procedure for sorting and/or subsampling of all cryogenically-preserved samples across a wide range of disciplines.

Publications:

Adam, N.R., and Wall, G.W. Multi-purpose cryogenic surface device. 2002. U.S. Patent 6,418,750.

Conley, M.M., Kimball, B.A., Brooks, T.J., Pinter, P.J.Jr., Hunsaker, D.J., Wall, G.W., Adam, N.R. LaMorte, R.L., Matthias, A.D., Thompson, T.L., Leavitt, S.W., Ottman, M.J., Cousins, A.B., and Triggs, J.M. CO2 enrichment increases water use efficiency in sorghum. New Phytologist. 2001. 151(2): 407-412.

Hatfield, J.L., and Kimball, B.A. Future research to fill knowledge gaps. In Agricultural System Models in Field Research and Technology Transfer. Lewis Publishers. 2002. p. 331-344.

Idso, S.B. and Kimball, B.A. CO2 enrichment of sour orange trees: 13 years and counting. Environmental and Experimental Botany. 2001. 46(2):147-153.

Idso, S.B., Kimball, B.A., Shaw, P.E., Widmer, W., Vanderslice, J.T., Higgs, D.J., Montanari, A., and Clark. W.D. The effect of elevated atmosphric CO2 on the Vitamin C Concentration of (sour)orange juice. Agriculture, Ecosystems, & Environment. 2002. 90:1-7.

Kimball, B.A., Kobayashi, K., and Bindi, M. Responses of agricultural crops to free-air CO2 enrichment. Advances in Agronomy. 2002.77:293-368.

Kimball, B.A., Triggs, J.M., Pinter, P.J.Jr., Wall, G.W., Ottman, M.J., Leavitt, S.W., Matthias, A.D., and Brooks, T.J. Free-air CO2 enrichment of sorghum: energy balance and evapotranspiration. Annual Meetings Abstracts. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, WI. CD ROM. 2002. File a03-Kimball130125-P.

Pendall, E., Leavitt, S.W., Brooks, T., Kimball, B.A., Pinter, P.J.Jr., Wall,, G.W., LaMorte, R.L., Wechsung, G., Wechsung, F., Adamsen, F., Matthias, A.D, and Thompson, T.L. Elevated CO2 stimulates soil respiration and decomposition in a FACE wheat field. Basic Applied Ecology. 2001. 2:193-201.

Wall, G.W., Kimball, B.A., Adamsen, F.J., Pinter, P.J.Jr., Wechsung, G., Wechsung, F., Kartschall, Th., and Leavitt, S.W. Elevated atmospheric carbon dioxide affects root dimensions of spring wheat. Annual Meetings Abstracts. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, WI. CD ROM. 2002. File a03-Kimball150553-P.

Wall, G.W. Elevated atmospheric CO2 alleviates drought stress in wheat. Agriculture, Ecosystems and Environment. 2001. 261-271.

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