ANNUAL RESEARCH REPORT
U.S. WATER CONSERVATION LABORATORY

1999

USDA - AGRICULTURAL RESEARCH SERVICE
Phoenix, Arizona

ANNUAL RESEARCH REPORT

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U.S. WATER CONSERVATION LABORATORY
U.S. Department of Agriculture
Agricultural Research Service
4331 E. Broadway Road
Phoenix, Arizona 85040

Telephone: (602) 379-4356
FAX: (602) 379-4355
E-mail: bclemmens@uswcl.ars.ag.gov
Website: www.uswcl.ars.ag.gov

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INTRODUCTION

Water conservation is an immense challenge. It is so broad and so critical to society, both here and abroad, that the opportunities for positive impact on both science and practice are almost limitless. With our present funding and staff, we can undertake only a few aspects of this problem. However, the laboratory is proud of its long history of producing meaningful and useful research results. Our job is to identify those areas of research that are most critical to the long-term sustainability and enhancement of modern society. While water is a renewable natural resource, it is also a limited one, and one upon which the entire planet depends for survival.

In the last century, once abundant water resources have become over-allocated by an ever-growing population. We can only imagine the critical water problems we will face if this trend continues for another century. But whatever that scenario, science will play a key role in helping society find the appropriate balance between the environment and human needs. That is our challenge.

We will be facing that challenge by focusing our research within a new national program structure which the Agricultural Research Service (ARS) National Program Staff is working hard to define. These National Programs define the research agenda for the agency and relate these research activities to the Nation's needs. National Programs are further divided into components and within these components, into more defined research thrusts. Each of our research programs can be related to these research thrusts and thus to the overall National Program and to public needs. Our research staff has been actively involved in the development of the National Programs to assure that our clients' needs are well represented. In the future, our research will be judged on how well it meets the objectives of the associated National Program. Our research program is diverse and is included in several ARS National Programs, namely:

- Water Quality and Management
- Global Change
- Integrated Agricultural Systems
- Plant, Microbial, and Insect Genetic Resources Genomics, and Genetic Improvements
- Food Safety

The year 2000 will have some significant changes in personnel and programs at the lab. Susan Moran has left the laboratory to become Research Leader for the Southwest Watershed Research Laboratory, Tucson, Arizona. We will miss Susan's contribution to the laboratory, but expect to continue cooperation with her in the future. Susan, we wish you well in your new position. In FY2000, we received additional funds for research on food safety. These new funds will be used to study the use of municipal and animal waste for irrigation and the associated potential degradation in groundwater quality. Detailed plans for the project are being prepared, and we will be hiring a new scientist during 2000 to conduct this research.

We marked the millenium by looking both backward and forward: planning for an observance of the laboratory's 40th anniversary, "40 Years of Progress"; and seeing plans move ahead for a new laboratory facility at the University of Arizona Maricopa Agricultural Center where much of our research is done on site. We are thus gratified by the laboratory's past and excited about its future.

Bert Clemmens, Director

Laboratory Program

HISTORY

The U.S. Water Conservation Laboratory is part of the Agricultural Research Service (ARS), the major research arm of the U. S. Department of Agriculture. The primary mission of ARS is to help meet the nation's food and fiber needs. ARS works closely with the State Experiment Stations, State Departments of Agriculture, other government agencies, public organizations, farmers, ranchers, and industry. The organizational structure of ARS is designed to insure active research programs and to provide maximum responsiveness to the needs and problems of the public.

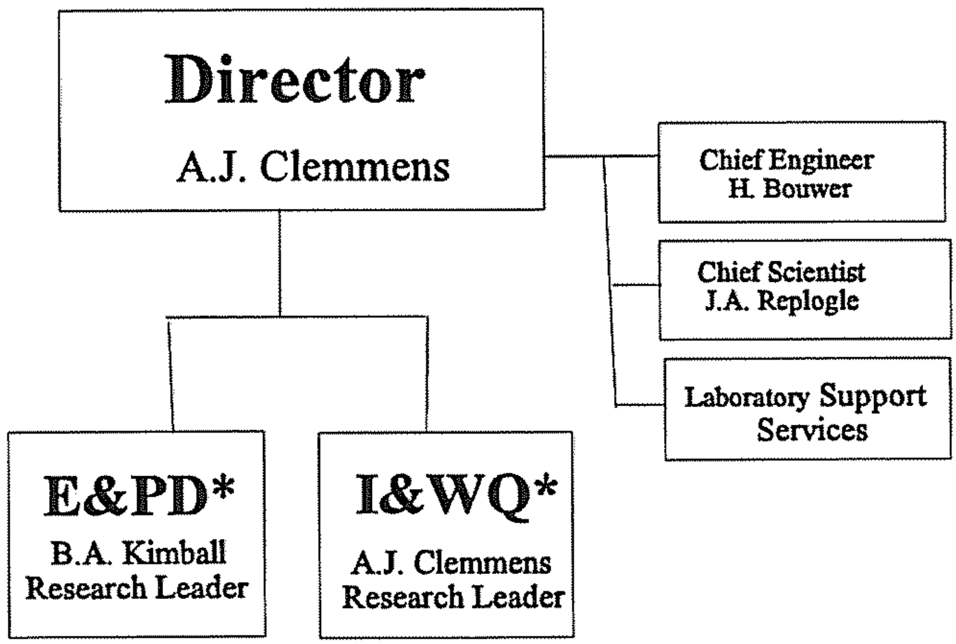
The U. S. Water Conservation Laboratory was established in central Arizona in 1959 to develop methods to conserve surface and groundwater used for agriculture. Research focuses on more efficient use of water and reduction of water losses in the soil-plant-atmosphere continuum. More recently, research has expanded to include studies in water quality, new crops with low water requirements, and effects of increased carbon dioxide on crop production, water use, and climate. The research is national in scope with international impact and deals with both present and potential problems. Although research results are documented primarily in technical literature, the staff also works directly with other State and Federal agencies.

In addition, the staff works closely with industry and individuals to facilitate technology transfer. New concepts and prototype equipment are tested cooperatively under actual conditions. The Laboratory does both theoretical and applied research at field sites and in laboratories. Facilities are well equipped for these purposes. Specialized electronic and mechanical prototype equipment is made in-house. Basic equipment to support the research programs includes electronic instrument calibration apparatus, data acquisition and processing computers, controlled environmental rooms, sophisticated water flow calibration, control and measuring devices, and a spectral imaging analyzer system. Specialized laboratory analytical instruments consist of a mass spectrometer, gas and high performance liquid chromatographs, automated titrator, solution analyzer, infrared gas analyzer, electropheretic equipment, and cytological microscope.

The research teams are composed of engineers and scientists trained in various disciplines. The disciplines represented are civil, agricultural, and hydraulic engineering; soil and biological sciences; physics; chemistry; and plant physiology and genetics. Support staff consists of agricultural, biological, and physical science technicians, an electronics engineer, a computer systems manager, a program analyst and a machinist. Administrative support includes secretaries, clerks, and maintenance personnel.

The total Laboratory research effort operates under two research groups that interact in a multi-disciplinary, cooperative manner: the Irrigation and Water Quality (I&WQ) and the Environmental and Plant Dynamics (E&PD) Management Units.

Laboratory Organization

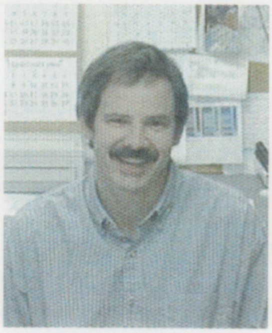


Mission

The mission of the U. S. Water Conservation Laboratory (USWCL) is to conserve water and protect water quality in systems involving soil, aquifers, plants, and the atmosphere. Research thrusts involve developing more efficient irrigation systems, improving the management of irrigation systems, developing better methods for scheduling irrigations, developing the use of remote sensing techniques and technology, protecting groundwater from agricultural chemicals, commercializing new industrial crops, and predicting the effect of future increases of atmospheric CO_2 on climate and on yields and water requirements of agricultural crops.

*Management Units
EP&D - Environmental and Plant Dynamics
I&WQ - Irrigation and Water Quality

LABORATORY MANAGEMENT



ALBERT J. CLEMMENS, B.S., M.S., Ph.D., P.E., Laboratory Director, Research Leader for Irrigation and Water Quality, and Supervisory Research Hydraulic Engineer
Surface irrigation system modeling, design, evaluation, and operations; flow measurement in irrigation canals; irrigation water delivery system structures, operations management, and automation.

HERMAN BOUWER, B.S., M.S., Ph.D., P.E., Chief Engineer and Research Hydraulic Engineer
Water reuse; artificial recharge of groundwater; soil-aquifer treatment of sewage effluent for underground storage and water reuse; effect of groundwater pumping on stream-flow; surface water-groundwater relations.

JOHN A. REPLOGLE, B.S., M.S., Ph.D., P.E., Chief Scientist and Research Hydraulic Engineer
Flow measurement in open channels and pipelines for irrigation; irrigation water delivery system structures, operations, and management.

BRUCE A. KIMBALL, B.S., M.S., Ph.D., Research Leader for Environmental and Plant Dynamics and Supervisory Soil Scientist
Effects of increasing atmospheric CO_2 and changing climate variables on crop growth and water use; free-air CO_2 enrichment (FACE) and CO_2 open-top chambers and greenhouses; micrometeorology and energy balance; plant growth modeling.

LABORATORY SUPPORT SERVICES

COMPUTER FACILITY

T.A. Mills, Computer Specialist

The computer facility oversees all Laboratory and Location Administration Office computer equipment and applications. The facility is responsible for recommending, purchasing, installing, configuring, upgrading, and maintaining the Laboratory's Local and Wide Area Networks (LAN, WAN), computers, and peripherals. The LAN consist of multiple segments of 10 Base-T, 100 Base-T hubs and one 100VG hub. The LAN is segmented using a high speed switching hub. Segments are made up of CAT 3, CAT 5 and standard Ethernet. This configuration currently provides over 200 ports to six Laboratory buildings. Internet service is provided by Arizona State University (ASU) via a Point-to-Point T-1 line. Our Laboratory also provides Internet access to the Western Cotton Research Center by an additional T-1 line through our router. The Laboratory maintains a Class C block of Internet addresses operating under the domain uswcl.ars.ag.gov. The Laboratory LAN is comprised of several servers operating under Windows NT 4.0. End users operate mainly under Windows 95 and Windows NT 4.0 with a few OS/2 workstations. Services such as E-Mail, print, file, remote access, and backup are provided by the LAN. The Laboratory maintains its own Web Server, which can be accessed at www.uswcl.ars.ag.gov.

The Laboratory is currently in the process of adding three fiber optic gigabyte backbone segments.

LIBRARY AND PUBLICATIONS

Stefani Morgan, Publications Clerk

Library and publications functions include maintenance of records and files for publications authored by the Laboratory Research Staff, including publications co-authored with outside researchers, as well as for holdings of professional journals and other incoming media. Support includes searches for requested publications and materials for the Staff. Library holdings include approximately 2200 volumes in various scientific fields related to agriculture. Holdings of some professional journals extend back to 1959.

The U.S. Water Conservation Laboratory List of Publications, containing over 2000 entries, is maintained on PROCITE, an automated bibliographic program. The automated system provides for sorting and printing selected lists of Laboratory publications and is now accessible on LAN by the Research Staff and on the USWCL home page (www.uswcl.ars.ag.gov) by the public. Publications lists and most of the publications listed therein are available on request.

ELECTRONICS ENGINEERING LABORATORY

D.E. Pettit, Electronics Engineer

The electronics engineering laboratory provides design, development, evaluation, and calibration functions of electronic prototypes in support of U.S. Water Conservation Laboratory research projects. Other responsibilities include repairing and modifying electronic equipment and advising staff scientists and engineers in the selection, purchase, and upgrade of electronic equipment. Following are examples of work orders performed in 1999:

- Continued to design hardware and software for the GEN II probes.
- Designed and constructed a five-channel narrow band infra-red amplifier board with temperature monitor and power regulators.
- Continued GEN II probe software modifications.
- Installed LPKF circuit board mill machine and the following software packages: (1) ORCAD Schematic Capture, (2) ORCAD Printed Circuit Board, (3) Circuit CAM, and (4) Board Master. These four software packages interconnect and were backed-up to a CD ROM disk. The CD ROM writer hardware was installed for archiving shop project designs which include schematics, printed circuit board files, computer aided design (CAD) computer aided machine (CAM) mill machine files and writeups on operations.
- Designed schematic capture parts and printed circuit board footprints for the appropriate ORCAD libraries being used in the five-channel infra-red amplifier.
- On-site training by LPKF representatives plus self-packing training of both Circuit CAM, Board Master, and ORCAD programs.

MACHINE SHOP

C.L. Lewis, Machinist

The machine shop provides facilities to fabricate, assemble, modify and repair experimental equipment in support of U.S. Water Conservation Laboratory research projects. The following are examples of work completed in 1999.

Stainless steel cylinders 10 - 12" in diameter were modified for sewage effluent irrigation and recharge studies. Modification included removal of 2½" tubes, plugging ¼" pipe holes and 2½" tube holes. A ¾" stainless steel coupling was welded into place 1" from bottom of each cylinder. A 13" x 13" x 3/16" stainless steel plate was welded to the bottom of each cylinder.

A static head probe for measuring irrigation well discharges was fabricated. The probe was fabricated from schedule 40 pvc pipe 6" diameter 12" in length. The pvc pipe was cut in half with a horizontal saw mill cutter @ ± .002, 3⅛" holes were drilled and reamed for press fit pins, 3⅛" holes were drilled and reamed for body fit pins.

Modification to Z chipping machines used to produce guayule homogenate were made. Modifications included design and fabrication of adjustable stabilizing legs. The legs were fabricated from ¾" round cold rolled steel tubing, ⅛" wall and ¾" cold rolled steel channel ⅛" wall. Shredded panels were modified by welding ¼" x ¼" square cold rolled @ ⅛" spacing.

Using Microsoft Access, an inventory data base was developed to track and control use of 1248 items kept in supply by the shop for use in the support of research programs. The inventory consists of a wide variety of items from adhesives and bolts to vises and zerks.

USWCL OUTREACH ACTIVITIES

During 1999, the USWCL staff participated in numerous activities to inform the public about ARS and USWCL research, to solicit input to help guide the USWCL research program, to foster cooperative research, and to promote careers in science. A summary of activities follows:

"Experiments for the Classroom." The USWCL web site contains experiments suitable for high school science classes.

Arizona State University Center for Agribusiness Policy Studies, February 4. Terry Coffelt, John Replogle, Ed Barnes, and Brian Wahlin provided an exhibit at the annual "Stratum '99 Conference," which is attended by area government and agribusiness representatives.

Arizona High School Science Bowl, Glendale Community College, Arizona, February 20. Terry Coffelt, Brian Wahlin, and Mike Wiggett served as rule judges of science bowl. Gail Dahlquist, Dave Dierig, and Skip Eshelman were moderators. The science bowl is an annual science knowledge competition among Arizona high school students.

Arizona Science Center, March 6-7. Brian Wahlin, Ed Barnes, Terry Coffelt, and John Replogle staffed an"On-the-Farm" exhibit featuring agricultural irrigation. The Arizona Science Center in Phoenix is a heavily attended hands-on science attraction for young (and not-so-young) people.

Arizona Ag Day Exhibit, March 10. Ed Barnes, Brian Wahlin, and Shirley Rish provided a USWCL exhibit at the annual Arizona Ag Day celebration in downtown Phoenix. Attendance at the event was estimated at 6,000, and many USWCL and ARS materials were distributed.

Earth Day at McKemy Middle School, March 23; and Evans Elementary School, April 8. Ed Barnes visited McKemy Middle School and Brian Wahlin visited Evans Elementary School. They provided hands-on exhibits and distributed USWCL and ARS materials.

Soil, Water, and Groundwater Management Symposium, Tohono O'odham Farming Authority, Eloy and Casa Grande, Arizona, March 24-25. Doug Hunsaker and Fedja Strelkoff presented information on USWCL software for surface irrigation simulation, design, and management.

Governor's Committee for Best Management Practices for Particulate Matter 10. Bert Clemmens presented an overview of the USWCL research program to the ad hoc technical advisory committee that reports to the Governor's Committee.

Scottsdale, Arizona, Public Meeting, May 26. Herman Bouwer spoke on sewage, salt, and nonpoint pollution of groundwater in the Salt River Valley and long-range water issues at the Scottsdale Civic Center, Scottsdale, Arizona.

Summer Agricultural Institute, June 18. USWCL hosted 30 elementary and junior high teachers for one day as part of the week-long Summer Agricultural Institute. The program encourages teachers to incorporate agricultural information into school curricula.

Minority Hiring, Sept.-Dec. Five minority work-study students were hired from Arizona State University and the University of Arizona.

Maricopa Agricultural Center Field Trip, Sept. 8. Ed Barnes, Tom Clarke, Stacy Richards, and Mike Baker hosted a field trip at Maricopa Agricultural Center for students in two University of Arizona classes in Agricultural and Biosystems Engineering. The event featured demonstrations of current research in applying remote sensing to farm management. Guest lectures also were presented to the classes on Sept. 13 and 15 in Tucson.

Joint Outreach-Education Programs for Students. In October, USWCL entered into an agreement with the University of Arizona Maricopa Agricultural Center and the Natural Resource Education Center to cooperate in providing science and agricultural programs for junior and senior high school students to educate and to encourage careers in science.

Central Arizona Water Conservation District (CAWCD), November 2. Bert Clemmens met with officials of CAWCD to discuss their research needs in water conservation.

ARS Irrigation and Drainage Exhibit at the International Irrigation Show, November 7-9. John Replogle and Shirley Rish coordinated an exhibit on irrigation and drainage (I&D) research at the annual Irrigation Association International Show in Orlando, Florida. The exhibit featured a hands-on display of the "Directory of ARS I&D Researchers and Research" on the ARS web site. Registered attendance was over 7000, and the ARS exhibit was well attended. The Irrigation Association provided complimentary exhibit space, and the exhibit was otherwise supported by Dale Bucks, National Program Leader for Water Quality and Water Management. The exhibit booth was staffed by members of the National Program Staff and I&D researchers from ARS locations at Phoenix, Arizona; Ft. Collins, Colorado; Florence, South Carolina; and Lincoln, Nebraska.

SAFETY

T. Steele

The Laboratory Safety Committee enjoys well-deserved respect from the employees. The committee takes its duties seriously and has worked diligently to insure compliance with all EPA and OSHA regulations and radiological safety protocols. Employees are encouraged to report all safety concerns, even those that might seem trivial.

In addition to several standing committee members, six other members serve three year terms, with two members rotating off each year. Current committee members are Terry Coffelt, Doug Hunsaker, Paulina Harner, Brian Wahlin, Stacy Richards, and Stephanie Johnson, rotating members; Bud Lewis (shop), Francis Nakayama (radiological/chemical), and John Replogle (hydraulics lab), standing members.

It is a time-consuming commitment, and requires judicious management of time and work priorities. Serving on the safety committee, however, is gratifying in terms of its record of accomplishments. Following are some of the results of the committee's efforts in1999:

- Procurement and installation of new free standing chemical storage buildings on the grounds of the Western Cotton Laboratory.
- Disposal of radiological sealed and unsealed sources that resulted in a significant reduction of radiological materials at the location.

The Lab staff thanks the committee for their good work on our behalf.

STUDENTS AT USWCL

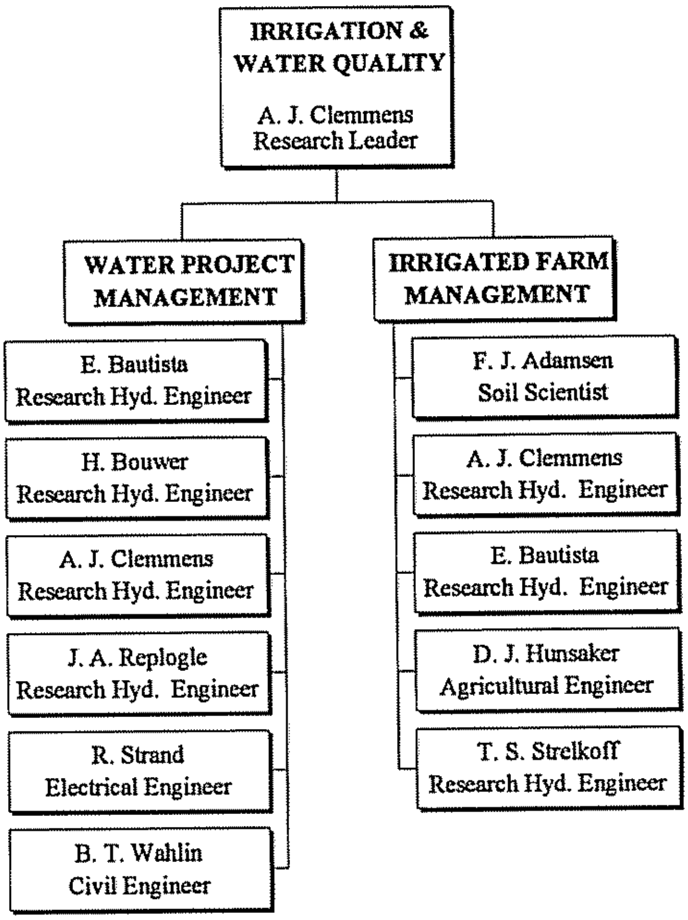
J. Askins

The USWCL has enjoyed a mutually beneficial relationship with students from nearby Arizona State University and the University of Arizona over the years. Students come under work-study agreements and student federal appointments. They perform a variety of tasks from collecting samples to solving computer problems, numbering vials to writing protocols, and weighing soil to processing and analyzing non-soil data. Students who work in the clerical/administrative area have worked in personnel and safety as well as doing general clerical work such as filing and copying. Operation of ARS automated systems, publication clerk duties, and literature searches are also performed. Graduate students A.B. Cousins from Arizona State University and T.J. Brooks, J.M. Triggs, P. Tomasi, Jamie Ludke, and Chandra Holifield from the University of Arizona have authored or co-authored contributions to this issue. Jon Tel, a master's degree student from Delft Technical University, The Netherlands, worked on a more accurate radial gate calibration for Salt River Project.

The students and visiting scientists benefit from the income and experience, and we benefit from their enthusiasm, up-to-date expertise, and energy. Some have stayed on after graduation, even earning Ph.D.s under ARS assistance programs.

I&WQ Management Unit

I&WQ Organization



Mission

The mission of the Irrigation and Water Quality Management Unit is to develop management strategies for the efficient use of water and the protection of groundwater quality in irrigated agriculture. The unit addresses high priority research needs for ARS's National Programs in the area of Natural Resources & Sustainable Agricultural Systems. The unit primarily addresses the Water Quality and Management National Program. It also addresses the application of advanced technology to irrigated agriculture.

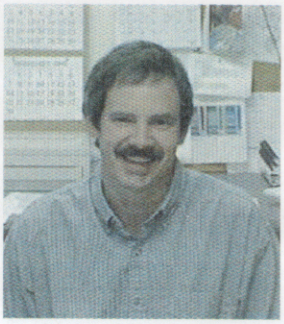
I&WQ RESEARCH STAFF

FLOYD J. ADAMSEN, B.S., M.S., Ph.D., Soil Scientist
Management practices that reduce nitrate contamination of groundwater while maintaining crop productivity; application of 100% irrigation efficiency; winter crops for the irrigated Southwest that can be double-cropped with cotton; contributions of natural and urban systems to nitrate in groundwater.

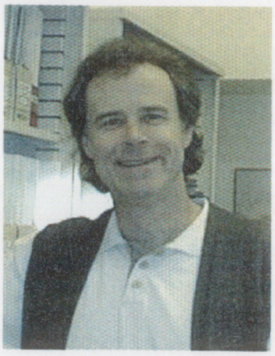
EDUARDO BAUTISTA, B.S., M.S., Ph.D., Research Hydraulic Engineer
On-farm irrigation system hydraulic modeling; hydraulic modeling of irrigation delivery and distribution systems; control systems for delivery and distribution systems; effect of the performance of water delivery and distribution systems on-farm water management practices and water use efficiency; integrated resource management and organizational development for irrigated agricultural systems.

HERMAN BOUWER, B.S., M.S., Ph.D., P.E., Chief Engineer and Research Hydraulic Engineer
Water reuse; artificial recharge of groundwater; soil-aquifer treatment of sewage effluent for underground storage and water reuse; effect of groundwater pumping on stream-flow, surface water-groundwater relations.

ALBERT J. CLEMMENS, B.S., M.S., Ph.D., P.E., Laboratory Director, Research Leader for Irrigation and Water Quality, and Supervisory Research Hydraulic Engineer
Surface irrigation system modeling, design, evaluation, and operations; flow measurement in irrigation canals; irrigation water delivery system structures, operations management, and automation.

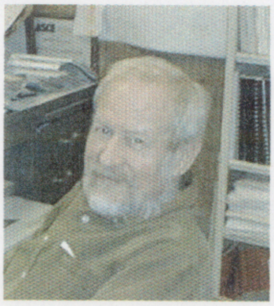


DOUGLAS J. HUNSAKER, B.S., M.S., Ph.D., Agricultural Engineer
Effects of soil and irrigation spatial variability on crop water use and yield in large irrigated fields; level basin irrigation design and management procedures for applying light, frequent water applications to cotton; CO2 effects, in particular, of evapotranspiration in the free-air CO2 enrichment (FACE) environment; evaluation of water requirements and irrigation management of new industrial crops--lesquerella and vernonia.



JOHN A. REPLOGLE, B.S., M.S., Ph.D., P.E., Chief Scientist and Research Hydraulic Engineer
Flow measurement in open channels and pipelines for irrigation; irrigation water delivery system structures, operations, and management.

ROBERT J. STRAND, B.S., Electrical Engineer
Automatic control of irrigation delivery systems; development and integration of field sensors, intelligent field hardware, USWCL feedback and feedforward control software, and commercial supervisory control software to create a plug-and-play control system.



THEODOR S. STRELKOFF, B.C.E., M.S., Ph.D., Research Hydraulic Engineer
Surface-irrigation modeling: borders, furrows, two-dimensional basins; erosion and deposition; design and management of surface-irrigation systems; canal-control hydraulics; flood-routing methodologies; dam-break floodwaves; flow in hydraulic structures.

BRIAN T. WAHLIN, B.S., M.S., Civil Engineer
Flow measurement in open channels and pipelines for irrigation; irrigation water delivery system structures, operations, and management.

IRRIGATED FARM MANAGEMENT ANALYTICAL LABORATORY

J. Askins, K. Johnson, and S. Colbert, Physical Science Technicians

High performance liquid chromatography (HPLC) is used to analyze nitrate, sulfate, chloride, and bromide ions in soil samples. Total elemental carbon and nitrogen and isotopic ratios of C^{13} and N^{15} are determined with the mass spectrometer. The autoanalyzer, a system utilizing colorimetry to determine nitrate and ammonia content of water samples and extracts of soil samples, has been expanded to include bromide capability. The atomic absorption spectrometer has been moved into this laboratory.

In addition to running and maintaining instruments, research technicians process data and address the precision of the data. Good precision testing alerts the operator to the necessity of a rerun and informs scientists of data reliability. Technicians also weigh soil samples, combine and summarize data from HPLC, autoanalyzer, and weighings, collect samples in the field, help with irrigation and other field work, update protocols, count seeds, and perform numerous other duties as needed.

IRRIGATED FARM MANAGEMENT

CONTENTS

IRRIGATED FARM MANAGEMENT

MISSION

To develop irrigation farm management systems for arid zones that integrate year-round crop rotational strategies with best management practices (BMPs) for water, fertilizer, and other agricultural chemicals. These systems will be economically viable and environmentally sustainable, including protection of groundwater quality.

STUDIES ON CONSUMPTIVE USE AND IRRIGATION EFFICIENCY

D.J. Hunsaker, Agricultural Engineer; and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Effective irrigation management provides the timely and correct amount of water consistent with the crop water demands, soil conditions, crop production goals, and environmental quality goals. Irrigation efficiency (IE) is a term often used to describe the effectiveness of irrigation, where IE is defined as the ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied. Beneficial uses include crop evapotranspiration (ET_c), salt leaching, frost protection, etc. General measures that can be taken to improve surface irrigation efficiencies include increasing the uniformity of the water applied, reducing deep percolation and surface runoff, and improving the control of application depths. However, proper irrigation management is a vital requirement for attaining the optimum irrigation efficiency of the system. Thus, the ability to predict actual daily crop water consumption, or ET_c, is of major importance.

A practical and widely used method for estimating actual ET_c is the crop coefficient approach, which involves calculating a reference crop evapotranspiration (ET) with climatic data: ET_c can then be determined by multiplying the reference ET with an appropriate crop coefficient (K_c). The Food and Agricultural Organization (FAO) Paper 24 (FAO-24), *Crop Water Requirements*, published in 1977, has been used worldwide as a primary source for crop coefficients and related ET procedures. Recently, the FAO published FAO-56, *Crop Evapotranspiration*, a revision of FAO-24, which presents updated procedures for calculating reference and crop ET from meteorological data and crop coefficients. In addition to the single K_c model developed in FAO-24, FAO-56 also includes a dual, or basal, crop coefficient model. Here, K_c is determined on a daily basis as the summation of two terms: the basal crop coefficient (K_{cb}) and the contribution of evaporation from wet soil surfaces following irrigations or rain (K_e). When the soil surface is dry, K_c is equal to K_{cb}, assuming soil moisture is adequate to sustain full crop water use. The usefulness of the dual crop coefficient model is that it provides better estimates of day-to-day variations in soil surface wetness and the resulting impacts of irrigation frequency on daily crop water use.

FAO-56 also introduced the need to standardize one method to compute reference ET from meteorological data and thus recommended the FAO Penman-Monteith as the sole method for the calculation of grass-reference evapotranspiration (ET_0). Although FAO-56 presents generalized crop coefficient values for use with FAO Penman-Monteith ET_0, derivation of localized values based on the FAO ET_0 is advisable due to the effects of local climatic conditions, cultural practices, and crop varieties on K_c or K_{cb}. In order to calculate daily crop ET by the FAO-56 dual crop coefficient approach, information on the evaporation characteristics of the soil type is also needed in additional to K_{cb}. The FAO-56 procedure requires two soil drying parameters called the readily evaporable water (REW), defined as the maximum depth of cumulative soil water evaporation (E_s) from the soil surface layer at the end of the stage 1 (energy limiting stage) drying cycle, and the total evaporable water (TEW), defined as the total maximum cumulative depth of water that can be evaporated from the soil surface layer. FAO-56 presents typical values of REW and TEW for certain soil types and recommends that the effective depth of the soil evaporation layer (Z_e) used in the procedures be about 0.10 to 0.15 m.

Recently, several different entities have approached the USWCL interested in new information on consumptive use of crops in the area. A particular concern is the realization that many farmers have been unable to meet a target irrigation efficiency of 85%. In addition to obtaining information on basal ET for crops, quantifying the contribution of wet-soil evaporation is particularly important since soil evaporation in excess of basal ET is sometimes included in ET_c as a beneficial use and sometimes it is not. The objective of this project is to determine the consumptive use and attainable irrigation efficiencies for crops presently produced, as well as for several new industrial crops that are being developed in the region.

APPROACH: Research is being conducted through a series of field experiments to determine crop evapotranspiration for current varieties of cotton, wheat, alfalfa, rape, lesquerella, and guayule grown under irrigation and soil conditions common in the region. Crop ET and soil evaporation during different growth stages in the season will be determined primarily with a soil water balance using neutron probes and time-domain-reflectometry (TDR) measurements, although other methods such as sap flow gauges and lysimeters also will be used when possible. Basal crop coefficients will be derived from the ET_c and soil evaporation data using the FAO-56 ET_0 method calculated with local meteorological data. For each crop, K_{cb} values derived from the different experiments will be combined and used to develop crop coefficient models as a function of common time-based indexes; e.g., days past planting and cumulative growing degree days. The crop coefficient curves will then be tested to determine their effectiveness in predicting ET_c for different field conditions and years.

The FAO-56 soil evaporation parameters, REW and TEW, were derived for a clay loam soil using data collected during lysimeter studies by USWCL personnel in March-April of 1971. The experimental site was a 72- by 90-m field in Phoenix, Arizona. The flat, bare field was divided into three plots, each plot surrounding one weighing lysimeter. On March 2, 1971, two of the lysimeters and surrounding plots were irrigated with 100 mm of water. After irrigation, the lysimeter weight loss, and hence soil evaporation, as well as meteorological data, were monitored at 0.5-hour intervals for 16 continuous days and also for the 23rd and 37th days after the irrigation. In the surrounding plots, soil water contents were determined from gravimetric soil samples for the 0- to 0.10-m surface layer and from neutron probe measurements for deeper soil layers at 0.5-hour intervals starting two days after irrigation through 16 days after irrigation and also for the 23rd and 37th days after irrigation. Soil water contents for the clay loam at field capacity (FC) and wilting point (WP) are 0.34 and 0.16 m^3 m^{-3}, respectively.

FINDINGS: Figure 1 shows the average daily E_s for the clay loam soil determined from two lysimeters during March 1971 for 16 continuous days after irrigation and for the 23rd day after irrigation. Also shown in the figure are estimates of daily E_s based on the average change in soil water contents ($\Delta\theta$), between the 00:00- and 24:00-hour measurements of a day, calculated over the 0-0.10-, 0-0.15-, 0-0.20-, and 0-0.30-m soil layers. The data of Figure 1 suggest that the total daily soil water evaporation that was measured in the lysimeters occurred from a soil layer deeper than 0.10 m. From the 4th through the 10th day after irrigation, the daily change in soil water contents within the 0-0.15-m layer matched the daily measured E_s particularly well, whereas the daily change within

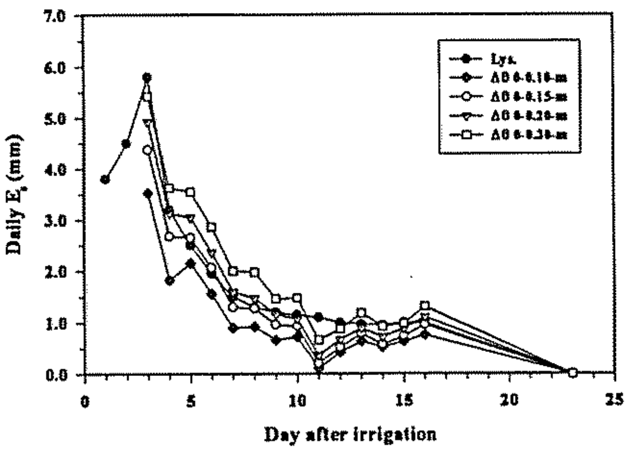


Figure 1. Average daily soil evaporation (E_s) as determined by lysimeters and the change in soil water content ($\Delta\theta$) calculated over 0-0.10-, 0-0.15-, 0-0.20-, and 0-0.30-m soil layers during March 1971.

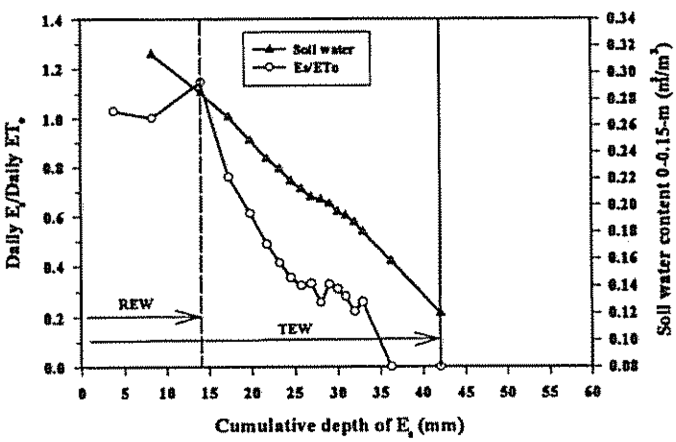


Figure 2. Ratio of daily E_s to ET_0 and the soil water content within the 0-0.15-m layer with cumulative depth of E_s during March-April 1971.

the 0-0.20-m and 0-0.30-m layers was often greater than the measured E_s. From the 11th through the 16th day after irrigation, the data suggest that the soil water change within the 0-0.30-m layer was often a better reflection of the measured E_s than were the changes calculated over shallower soil layers. However, the determinations of minute daily changes in soil water contents for days occurring 11 days after irrigation and beyond (which typically were on the order of less than 1 mm) were probably subject to error arising from diurnal water loss and recovery characteristics of the surface layer, measurement inaccuracy, spatial variability, etc. Therefore, in the following evaluation of the REW and TEW parameters, it was assumed that the effective depth of surface evaporation layer (Z_e) for the clay loam soil was best represented by the 0.15-m layer.

Figure 2 shows the ratio of the daily E_s to daily ET_0 for each of the 16 days following irrigation, plus those for the 23rd and 37th days after irrigation, plotted as a function of cumulative depth of E_s. The figure also shows the decline in soil water contents within the 0-0.15-m layer from the 2nd through the 37th day after irrigation. Note that cumulative evaporation between the 16th and 23rd day and between the 23rd and 37th day after irrigation was estimated from the change in soil water contents within the 0-0.15-m depth. Early in the drying cycle, when the surface layer was moist, water evaporation occurred at a rate close to the potential rate, as reflected by the near 1:1 ratio of E_s to ET_0. This stage of evaporation, referred to as the stage 1 drying cycle, occurred during the first three days after the irrigation. Therefore, it can be inferred that REW for this soil is about equal to the 14 mm of cumulative E_s during the first three days of drying. As the soil layer dried further, the rate of evaporation decreased relative to the evaporative demand until it reached a very low rate ($\approx$0 mm on the 23rd day after irrigation). Although there was no soil evaporation on the 23rd day after irrigation, the soil layer had dried from 0.18 $m^3\ m^{-3}$ on the 16th day to 0.16 $m^3\ m^{-3}$, the wilting point, on the 23rd day. At that point, the estimated total cumulative evaporation was 36 mm. On the 37th day, the soil water content of the surface layer had declined to 0.12 $m^3\ m^{-3}$ and the TEW, 42 mm, had essentially been reached. In most soils, evaporation can continue to dry the surface layer to a water content below wilting point. An approximate estimate of TEW is obtained by multiplying the depth of the soil layer by the difference between the field capacity soil water content and the water content halfway between the wilting point and the oven-dry point. For example, the calculation based on the FC and WP of our clay loam soil for a 0.15-m soil layer would result in an estimated TEW of 39 mm, close to the TEW derived in the analysis.

FAO-56 procedures were used to derive and partition the seasonal water consumption for a commercial cotton grown on a sandy loam in central Arizona during 1994. Using the FAO-56 approximations, the values determined for REW and TEW for this soil type were only 9 mm and 19 mm, respectively. As shown in Table 1, soil evaporation represented about 7% of the total crop ET contributed solely from irrigation water. An additional 88 mm of ET were contributed from in-season and pre-season precipitation. About one-third of the seasonal precipitation, which occurred primarily during the early portion of the season before full crop cover, evaporated from the soil surface. Of the total 1162 mm of ET consumed by the crop, 9% was evaporation from wet soil conditions.

Table 1. Water consumption for a grower's cotton field in 1994.

	Irrigation water	In-season precip.	Pre-season precip.	Total
Basal ET	996	48	13	1057
Soil E_s	78	27	n/a	105
Total crop ET	1074	75	13	1162

INTERPRETATION: Findings from our evaluations of a grower's field indicated that evaporative water losses from the soil need to be considered in determining crop water use and irrigation efficiencies. This was further illustrated by the 1971 lysimeter data presented above, which showed that over 40% of the 100 mm of water applied to a bare clay loam soil was evaporated from the surface layer. In arid or semi-arid conditions, soil water evaporation, particularly following pre-plant and early season irrigations, can therefore represent a significant amount of water loss above the basal crop water requirement. Information to quantify crop ET and soil evaporation more accurately will continue to be developed in this project.

FUTURE PLANS: Once appropriate basal crop coefficient curves and soil drying parameters have been developed, they will be incorporated into the FAO-56 dual crop coefficient model, which can then be used as an effective irrigation scheduling tool for determining ET_c and soil evaporation on a daily basis. The FAO model for ET also will provide a means to estimate on-farm irrigation efficiencies on a single irrigation basis, as well as for the entire season.

COOPERATORS: Rick Allen, Professor, Utah State University; Ed Martin, Irrigation Specialist, The University of Arizona; Huanjie Cai, Professor, Northwest Agriculture University, Yangling, Shaanxi, China.

DEVELOPING GUIDELINES FOR "FERTIGATION" IN SURFACE-IRRIGATED SYSTEMS

F. J. Adamsen, Soil Scientist; D. J. Hunsaker, Agricultural Engineer; and A. J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Applying fertilizer through irrigation water, when properly done, can be a highly effective fertilizer management practice. This method of fertilizer application, "fertigation," offers certain advantages compared to conventional field spreading or soil injection techniques, such as reduced energy, labor, and machinery costs. Moreover, it allows growers to apply nutrients in small amounts throughout the season in response to crop needs without the potential crop damage or soil compaction caused by machinery-based application methods. Although fertigation is more commonly associated with microirrigation and sprinkler irrigation systems, injecting nitrogen (N) into irrigation water has become increasingly frequent and widespread among surface irrigation growers in the western United States. However, unlike pressurized irrigation systems, which are designed to apply controlled and precise amounts of water to the field, application of water by many surface irrigation systems can be highly nonuniform and is often subject to excessive deep percolation and surface water runoff. Consequently, N-fertigation through surface irrigation systems may result in fertilizer distributed unevenly throughout the field and potential nitrate-nitrogen (NO_3-N) contamination of groundwater through deep percolation and of surface water through tail water runoff. Because the environmental fate and distribution of nitrogen applied in surface irrigation water has not been studied extensively in the field, adequate N-fertigation management guidelines have not been developed.

APPROACH: The primary objective of the research is to develop information that will lead to best management practices (BMPs) for N-fertigation through surface irrigation systems. The project will derive this information through a series of extensive farm-scale field experiments conducted on representative surface irrigation systems commonly used in the western U.S. The measurement objectives include the determination of the spatial distribution and seasonal variation of N within the field, and the relative potential of groundwater and surface water contamination as a function of the timing and duration of N injection during the irrigation event. Irrigation water application distribution also will be determined for each irrigation. Ultimately, the data derived from this project will be used to incorporate chemical fate and transport components into existing soil water and surface irrigation simulation models, which once validated, will allow more comprehensive evaluation of fertigation practices and an expansion of BMPs for conditions and irrigation systems other than those encountered in this project.

In 1999, two simulated fertigation events were conducted on cotton grown in furrowed level basins at the Maricopa Agricultural Center (MAC). The first fertigation was conducted following cultivation which provided a rapid infiltration rate and a high degree of surface roughness. The second event was carried out during the third irrigation following cultivation which provided lower infiltration rates and less surface roughness than the first fertigation. During both events, potassium bromide (KBr) was injected into the water stream. The treatments for the experiments were injection during 100%, first 50%, and last 50% of the irrigation. Water was applied to five furrows in a 185 m long field. Soil samples were taken before and after the event to a depth of 1.2 m in the turn around area at the head of the field and every 30 m along the run. In the turn around area, two samples were taken and at the sampling locations along the length of run samples were taken from two adjacent cotton beds and from the furrow bottom of a wheel and non-wheel furrow. Samples were analyzed for bromide concentration. Irrigation parameters measured were advance and recession times, flow rate, and surface water depth.

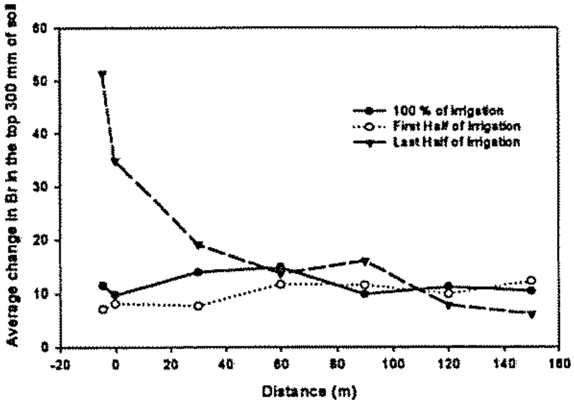


Figure 1. Distribution of the change in bromide concentration in the top 300 mm of soil with distance after application of bromide during 100%, the first 50%, and the last 50% of the irrigation of a level basin.

FINDINGS: Figure 1 shows the average field distribution of the change in bromide concentration within the 0-300 mm soil depth for each of the three fertigation treatments following the first irrigation. The bromide concentration for our 100% fertigation treatment was depressed at the head end of the basin (reflecting possible deep percolation losses), peaked at a distance of 60 m, and then decreased slightly with distance towards the end of the basin. The distribution of bromide that was applied during only the first 50% of the irrigation followed a trend quite similar to the bromide distribution for the 100% fertigation treatment. There was not an apparent increase in bromide level at the far end of our level basin. In contrast, the bromide pattern that resulted when fertilizer was injected during just the last 50% of the irrigation showed strong downward trends with distance.

In level basins, a controlled volume of water is applied from one end or one corner of a basin, completely enclosed with perimeter dikes to prevent runoff. Figure 2 shows a relatively uniform infiltrated depth distribution for a level basin irrigation, estimated by a simple advection (volume balance) model. This example illustrates a situation in which applying fertilizer during 100% of the irrigation event may be the best fertigation option. Injecting fertilizer during just the first 50% of the irrigation may result in poor fertilizer distribution uniformity throughout the basin, as suggested by the rather large differences between the infiltrated depths at the far end versus other areas of the basin after 50% of the irrigation had been applied. Also, deep percolation losses would be proportionately high with this fertigation application, since all deep percolation water is contributed just from water applied during the first 25% of the irrigation. In contrast, adding fertilizer during just the last half of the irrigation would result in too much N at the front end of the basin and too little at the far end, although there would be no N lost due to deep percolation. Applying fertilizer during 100% of the irrigation would result in a relatively even distribution of N in the root zone with a small portion of the total N leached with deep percolation (as represented by the area underneath the deep percolation curve).

INTERPRETATION: The example of Figure 2 suggests that if irrigation uniformity is relatively good, adjustment of the timing and duration of fertigation, as opposed to continuous injection during the entire irrigation, may not be warranted. However, it is important to point out that fertigation recommendations derived using modeling techniques, e.g., the simple advection model used above, are highly speculative, since dispersion, adsorption, and desorption processes are either ignored entirely in the models or models have not been validated based on actual field conditions. In practice, fertigation recommendations are expected to vary widely, subject to the myriad of combinations of irrigation specifics; e.g., the split between the deep percolation and runoff, relation between advance and opportunity time, soil texture, changing infiltration and surface roughness characteristics, cultural practices, etc. In order to develop models which adequately describe and predict solute transport processes during fertigation of surface systems, comprehensive field studies must be undertaken to develop data over a wide range of irrigation systems, practices, and field conditions.

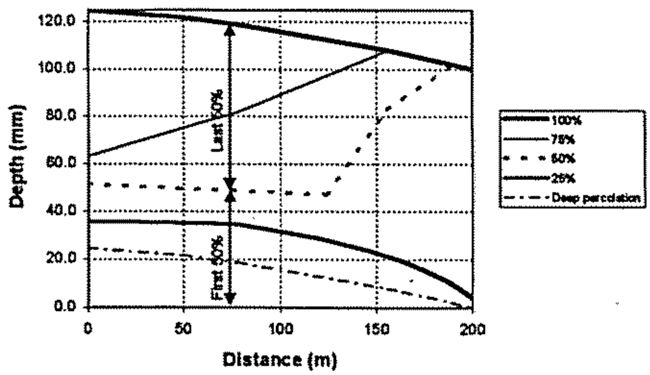


Figure 2. Cumulative infiltrated depth with distance after 25%, 50%, 75%, and 100% completion of the irrigation and deep percolation with distance for a level basin irrigation system.

The lines in Figure 2 represent the infiltrated depth of the first, second third and fourth quarters of an irrigation applied to a 200 m long level basin. It is interesting to note that some similarity exists between the pattern of bromide distribution for a particular fertigation treatment in our level basin experiment (Fig. 1) and the predicted pattern based on the infiltrated depth distribution estimated with different field conditions for the level basin of Figure 2. Our preliminary research results on the timing and duration of fertigation during the irrigation event suggest that significant progress can be made towards defining the best fertigation management strategies for surface irrigation systems. However, technology in this area is underdeveloped and progress has been greatly hindered by a lack of sufficient field data.

FUTURE PLANS: Analysis of remaining soil samples will be completed. Irrigation data will be analyzed using the software package EVALUE to estimate average field infiltration and to estimate Manning n values for surface roughness. Pending additional outside funding, similar data sets will be developed for unfurrowed level basins, furrowed and unfurrowed sloping borders with and without runoff over a variety of soil types and lengths of run in Arizona and California. When completed, the data sets will provide a sufficient range to develop fertigation guidelines for a large portion of the surface irrigated acreage in the western United States.

COOPERATORS: Donald Ackley, Program Coordinator, Coachella Valley Resource Conservation District, Indio CA; Bob Roth, Resident Director, Maricopa Agricultural Center, Maricopa, Arizona.

USE OF A LOW COST COLOR DIGITAL CAMERA TO MEASURE PLANT PARAMETERS

F. J. Adamsen, Soil Scientist; P. J. Pinter, Jr., Research Biologist; T. A. Coffelt, Research Geneticist; and E. M. Barnes, Agricultural Engineer

PROBLEM: The number and timing of flowers a plant produces is of interest because it can be an important factor in determining yield. The time required manually to count flowers in the field makes it difficult to carry out large studies involving flower numbers. It is possible to detect flowers on plants which are not obscured by leaves and stems in digital images. Documenting plant parameters such as crop senescence rates, fertility levels, insect damage, salinity problems, disease and nematode damage, etc., which result in changes in plant color, is often difficult due to the need for frequent sampling during periods of rapid change and the subjective nature of visual observations. Digitized images of crops should show temporal changes in the greenness of crop plants as well as differences related to treatments. Low cost digital cameras, which are available in the market, provide an easy and inexpensive method of obtaining digital images of plants that can be analyzed for a number of plant parameters. The objectives of this work are (1) to develop the methodology needed to use digital color images for documenting crop senescence rate, flowering, and other plant parameters, and (2) to apply the methodology to improve nitrogen and water management practices.

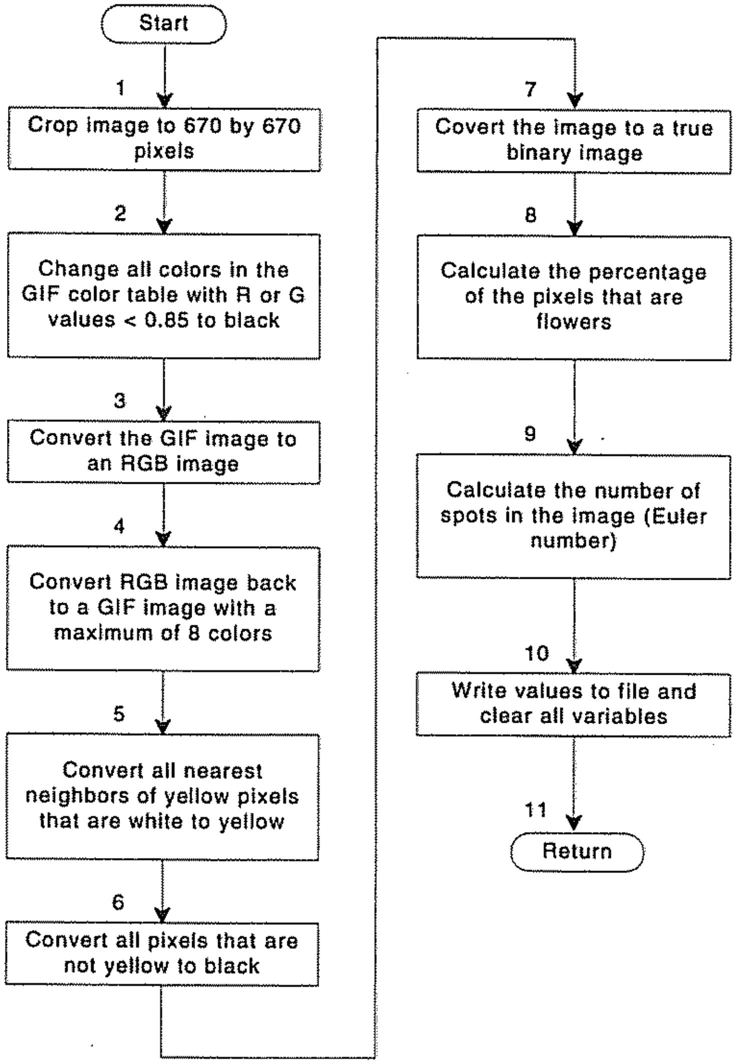


Figure 1. Flow diagram of main automated image processing loop for flower counting.

APPROACH: A digital camera which costs less than $1000 was used to obtain images of lesquerella (*Lesquerella fendleri*) in a field experiment of fertility and seeding rate at the University of Arizona's Maricopa Agricultural Center (MAC), near Phoenix, Arizona. The experimental design was a complete factorial of three fertilizer rates and four seeding rates. Fertilizer as ammonium sulfate at rates of 0, 60, and 120 kg ha^{-1} was applied at flowering. Digital images of the plots were taken periodically from mid-March to early-June using a color digital camera. Images were acquired between 1030 and 1300 h MST. The camera had a 1024 by 768 pixel resolution and twenty-four bit color resolution. The method described in Fig. 1 was used to count the number of flowers in the images. The first step in processing the images was to crop the image so that it showed an area of 1m by 1m. All pixels with yellow color were identified, and spots of yellow color were then counted (Fig. 2). Two indices were developed. The simplest was the number of pixels in the image identified as flowers and the second was a count of the number of spots. Thus far, the number of flower pixels has been the most useful.

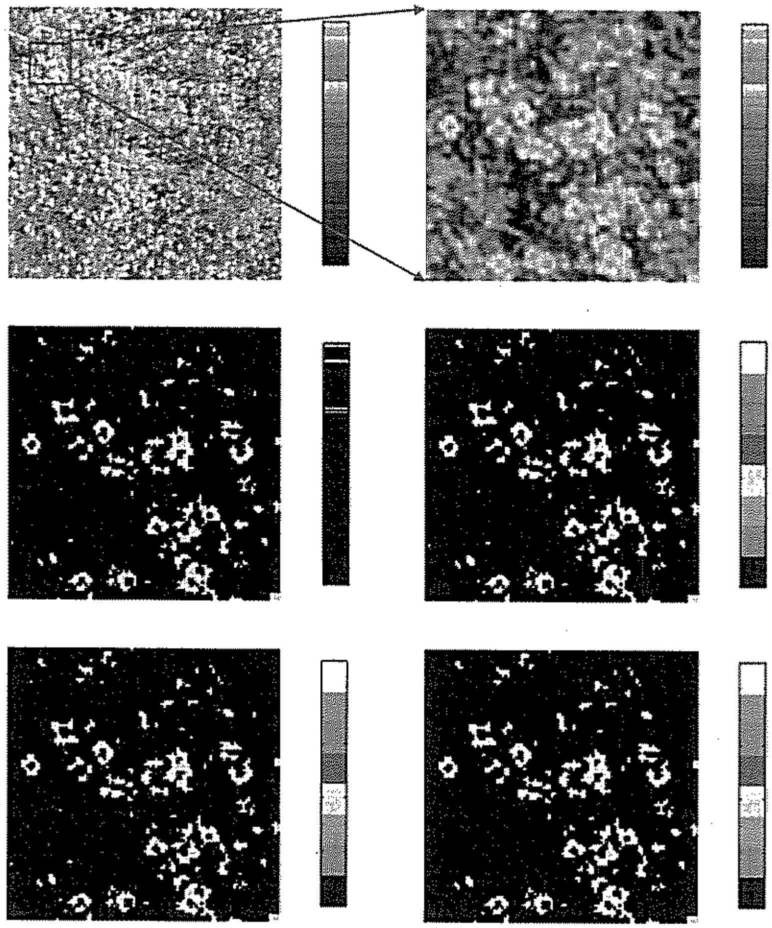


Figure 2. Results of image processing on the image from Plot A on April 15, 1997; (a) cropped image; (b) area of cropped image outlined in red; (c) after color depletion; (d) after color remapping; (e) after search for yellow spots; (f) after elimination of non-yellow pixels.

FINDINGS: Flowering responded to the amount of fertilizer applied but not to seeding rate (Fig. 3). Peaks in flowering occurred following irrigations through March and April (Fig. 3). In May as the crop approached maturity, flowering responded to irrigation only at the lowest nitrogen level (Fig. 3a). In plots where fertilizer was applied at flowering, flower production continued at a higher rate than in the unfertilized plots which received only preplant fertilizer (Fig. 3). Peak flowering occurred on March 26, 1998, for the 0 N treatment but not until April 16, 1998, for both the 60 and 120 kg N ha^{-1} treatments. Peaks in flowering were less pronounced and the decline in flowering was more abrupt in the 60 and 120 kg N treatments than in the 0 N treatment. By June 4, 1998, the last date that images were acquired, all of the treatments ha essentially stopped flowering. Treatment means of % flower pixels for each date and the sum of % flower pixels from March 19, 1998, through each date were regressed against the treatment means of yield. The coefficient of determination for the regression was then plotted against date (Fig. 4). Flowers formed in March and early April appear to have little impact on yield. The r^2 values for this period are less than 0.30 while the r^2 values from the first three weeks in May were all 0.85 or higher. The largest r^2 for a single date was 0.95 for May 14. For sums of % flower pixels, the regression with yield never provided as good a fit as the single dates from the first three weeks in May. The drop off in r^2 values for single date regressions after May 14, 1998, occurs because there is no difference between treatments in flowers after mid-May while there are differences in yields between treatments. Daily high temperatures in late May typically approach 40° C and may reduce flowering.

INTERPRETATION: The flowering data show that while flowering lasts for twelve weeks, there is a four to six week period beginning 180 d after planting that has the greatest influence on yield. The number of flowers present at the beginning of flowering reflect the emergence and survival of seedlings, but the early flowers do not reflect yield. Substantial growth occurs after fertilization at the start of flowering thus much of the seed is formed later in the growing season.

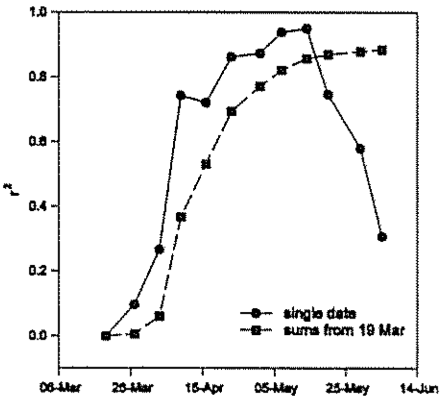


Figure 4. Change in coefficients of determination for regressions of treatment means of percent flower pixels against treatment means of yield for single dates and for the sums of percent flower pixels across dates beginning on March 19, 1998.

The data suggest that fertilizer application at flowering may not be the best nitrogen management strategy. Applying fertilizer to achieve growth prior to flowering should shorten the flowering period and take better advantage of the first flush of flowers formed by having a larger healthier plant. However, an impediment to early fertilizer application is the slow emergence and early growth of lesquerella. Because of slow emergence, it was necessary to make four irrigations for stand establishment. When the crop is grown with surface irrigation, as in this case, minimum water applications were 50 mm. In this case, that means at least 200 mm of water was applied when the crop was not able to use it. Applying 200 mm of water to a fertilized crop often results in leaching of nitrate from preplant applications below the root zone.

While not shown directly by this study, the flowering data suggest that the reason lesquerella responds to planting date is related to growth of the plant before flowering begins. Earlier planting dates allow for more vegetative growth, resulting in larger plants when flowering begins in the spring.

Results from this study validate the method proposed by Adamsen et al. (in press) for using a digital camera to monitor flowering in a crop. They also show that by monitoring flowering, critical flowering times can be identified. This can lead to altering production practices, such as earlier application of fertilizer, to maximize yield and smaller more frequent irrigations to reduce the effects of short term water stress. The cessation of flowering in conjunction with weather data should be useful in determining precise harvest dates.

FUTURE PLANS: Flowering data will be developed for rape, crambe, alfalfa, and vernonia. Rape flowers are similar to lesquerella flowers in color and crambe flowers are white. Vernonia and alfalfa flowers are purple to pink in color but appear blue in digital images. These crops should test the applicability of the general methodologies developed for lesquerella. If this effort is successful, the feasibility of counting flowers on other crops such as cotton will be evaluated. Greenness indices will be developed for sorghum and alfalfa. The use of greenness indices with forage crops can help assess the effects of various treatments on regrowth and harvest date. The relationships of greenness indices and flower number with fertility and water management will be developed. Once these relationships are developed the will be used to develop improved water and fertilizer management practices.

COOPERATORS: John M. Nelson, The University of Arizona Maricopa Agricultural Center; James M. Krall, University of Wyoming Research and Extension Center, Torrington WY.

SURFACE IRRIGATION MODELING

T.S. Strelkoff, Research Hydraulic Engineer; and
A.J. Clemmens, Supervisory Research Hydraulic Engineer and Laboratory Director

PROBLEM: Throughout the irrigated world, water is applied to fields unevenly and excessively, leading to wastage, soil loss, and pollution of surface and groundwaters. Computer modeling would allow rapid evaluation of physical layouts and operation in a search for an optimum. But most models are limited to single furrows or border strips and basins with zero cross-slope and a uniformly distributed inflow at the upstream end. Yet large basins are usually irrigated from a single inlet. The flow spreads out in all possible directions, and any one-dimensional simulation must be viewed as a very coarse approximation. A non-planar basin surface influences the flow as well. An irrigation stream concentrated in the lower-lying areas can significantly affect infiltration uniformity. Only a two-dimensional model can simulate these factors.

While a one-dimensional approach is suitable for furrows, in real fields, flows in neighboring furrows of a set are often coupled through common head and tail-water ditches. Tailwater from a fast furrow can enter a slower furrow from its tail end and modify its ultimate infiltration profile. To appreciate the effects of such coupling fully, simulation of interconnected furrows is necessary.

Irrigation management can influence the quality of both surface and ground waters as well as of the field soils. Irrigation streams can be of sufficient power that soil boundaries erode, with the material entrained into the stream and transported downfield, reducing soil fertility upstream. Farther downstream, as infiltration reduces the discharge or as the result of slope reduction, part of the load, perhaps only the coarse fractions, might deposit back onto the bed. Or else, entrained material can run off the field, introducing turbidity into drainage water or deposit in quiescent areas, to the detriment of aquatic life.

Chemigation introduces agricultural chemicals into the irrigation water. Alternately, initially clean irrigation water picks up agricultural chemicals and naturally occurring minerals, some toxic, from the surface of fields and from contact by percolation through the porous soil medium. Nitrogen, phosphorus, and heavy metals, for example, brought to farm fields in agricultural operations and naturally occurring chemicals, such as selenium, can be transported to surface or subsurface water supplies by irrigation water, to the detriment of both human consumers of the water resource and wildlife dependent on the receiving water bodies. Nutrients or pesticides adsorbed to eroded soil in irrigation tailwater is an important example.

APPROACH: The objective of current work is validated computer simulation models for providing quick responses to a wide variety of "what-if" situations. For example, the trade-offs between irrigation efficiency and uniformity, on the one hand, and soil loss, on the other, could be explored. Recommendations could then be made on the basis of environmental considerations as well as water conservation and crop yield. Funding for this effort is provided in part by the Natural Resources Conservation Service.

For one-dimensional single-furrow, border, or basin simulation, user-friendly, menu-driven data input and output graphs and text are linked to a simulation engine based on the universal laws of hydraulics

MEASUREMENT AND CONTROL OF WATER FLOW UNDER DIFFICULT CONDITIONS

J.A. Replogle, Research Hydraulic Engineer; and B.T. Wahlin, Civil Engineer

PROBLEM: There are many flow conditions that are not amenable to the use of simple flumes and weirs. Many other measurement devices and methods are more expensive, more difficult to use, or less accurate than flumes and weirs. Improvements in these other methods are needed to complement the advances with flumes and weirs. Problems of continuing interest related to pipe flows include flow profile conditioning in pipes, field applications of several flow meters to irrigation wells, and automatic regulation of flow through large irrigation outlet pipes from main canals to lateral canals.

Most delivery canal systems use pipes through the canal banks to deliver flows to farm canals. Propeller meters, end-cap orifices, Pitot systems, and ultrasonic meters placed in these pipes frequently are subjected to poorly conditioned flow profiles that compromise the meters' operation. All of these are affected by upstream pipe bends and valves. Propeller meters readily clog in debris-laden flows and usually can be inserted into trashy flows for only a few minutes. End-cap orifice meters do not work well on rusted pipe ends. Pitot systems are considered difficult to apply to discharges from wells without special wall taps and insertion ports. Inserting a standard combination Pitot-static tube, such as the Prandtl tube, into the outflow end of a pipe has been used. However, these tubes are expensive, requiring specialized manufacturing techniques not available in most machine shops. Methods to condition flows and improve the flow profiles are needed, particularly when short lengths of straight pipe precede the meter.

Fluctuating flow-rate deliveries from a main canal to a secondary canal increase the difficulty of effective irrigation and may require expensive means to monitor total delivered water volume. The same type of pipe outlets described above are being considered for retrofitting with mechanical-hydraulic mechanisms that would stabilize the discharge rate through them regardless of changes in the level of the source canal. Steady flows can use simple time clocks for total volume.

Several ongoing objectives associated with pipe system flows are: (a) to complete papers and technical notes regarding the design and calibration of the modified Pitot system for irrigation wells that can be constructed in ordinary shop settings, the back pressure effects of flap gates at pipe outlets, and the suggestions for simplifying the use of portable end-cap orifices (see previous Annual Reports); (b) to develop practical methods to achieve effective flow conditioning for flow meters installed in difficult short-pipe situations, and (c) to evaluate prototypes of clog-resistant propeller meters that have been manufactured to our suggestions.

APPROACH: Standard calibration procedures were previously completed on the end-cap orifice system. An alternate pressure tapping system was studied. This involved using a small static pressure tube (with holes drilled through its walls), similar to that used for the Pitot system described last year, to detect the pressure in the approach pipe upstream from the orifice. The tube was inserted through a grommet-sealed hole in the face of the orifice plate near the pipe wall so that the pressure sensed was that for one pipe diameter upstream from the face of the orifice. No further lab data were gathered.

applied implicitly in fully nonlinear form. Constants in commonly accepted empirical equations for infiltration, roughness, and soil erosion are entered as input. The computer model, SRFR, is based on this approach.

Two-dimensional simulation is also based on hydraulic principles. Under the assumption of flow velocities small enough to neglect accelerations, force components in each of two mutually perpendicular directions on the field are in equilibrium. The resulting parabolic partial differential equations, solved implicitly by locally linearized finite differences in the two directions and time, yield a wave-like solution encompassing both wet and dry areas of the field. A similar but one-dimensional approach, treating wet and dry cells uniformly, is applied to multiple coupled furrows.

Erosion, transport, and deposition of irrigated soil is too complex to simulate on the basis of general physical principles alone. Currently, it is *fundamentally* an empirical science, in which the trend in recent years has been towards ever more general relationships, containing as much general physics as possible. Many conceptual models of parts of the total process have been proposed in order to avoid pure empiricism, but these are only partially convincing, with researchers intuitively leaning toward one or another. The measures of a good predictive relationship or procedure are its generality with respect to different soils and different irrigation conditions, and ability to predict soil transport at different locations in a furrow, especially in the tailwater runoff, at all times during the irrigation.

FINDINGS: The SRFR 4.00-series surface-irrigation simulation model has been released for downloading through the U.S . Water Conservation Laboratory (USWCL) web site (also newly available at this site are the earlier programs, BASIN and BORDER, design and management aids for level-basin and border-strip irrigation). In addition to the wide variety of surface-irrigation techniques and scenarios that can be simulated with this menu-driven graphics-oriented program, a preliminary erosion component is available to cooperating researchers. Figure 1, drawn from the animation displayed by SRFR during a simulation, illustrates typical behavior of the transport-capacity function and resultant sediment loads at one instant of time (61 minutes into the irrigation). Note the lengthy region behind the stream front in which the transport capacity and detachment are zero. Because of upstream infiltration, the flow rate is so small there that the boundary shear is below the threshold for entrainment. Far upstream, the sediment load grows the fastest at the clear-water inflow, where the transport capacity is a maximum

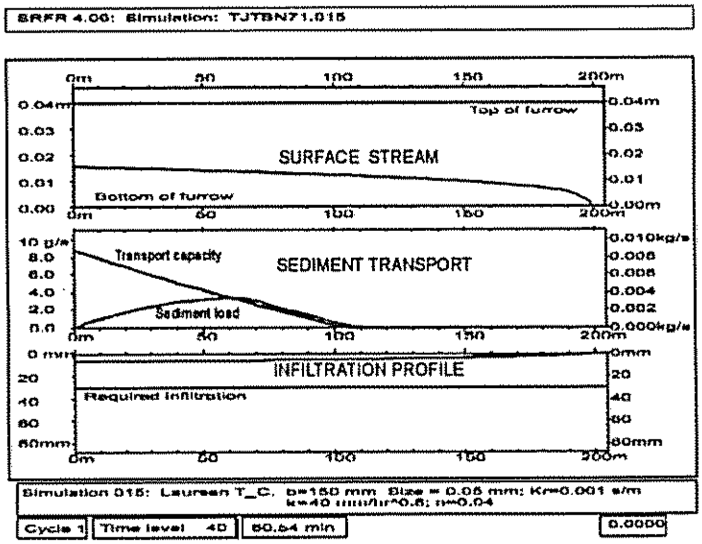


Figure 1. Frame of animated output of SRFR simulation – profiles of surface stream depth, sediment load and transport capacity, and infiltrated depths; time=61 min

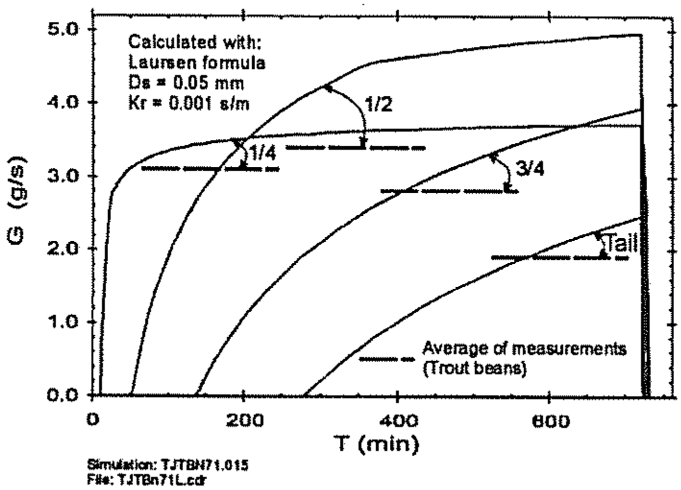


Figure 2. Comparison of simulated sediment transport hydrographs at furrow quarter points with averages from measured Trout bean data of July 1, 1994. Site-specific Kr=0.001s/m, τ_c=1.2 Pa. Laursen (1958) transport-capacity formula in effect. (Strelkoff and Bjorneberg, 1999)

and the existing sediment load zero. With distance downstream, the transport capacity decreases due to infiltration, and the sediment load increases due to upstream entrainment; both factors lead to reductions in further growth in the load. Eventually, though, transport capacity *is* exceeded, and some of the load starts to deposit back onto the bed. Finite fall velocities are seen in the "super-saturated" concentration of sediment evident in the figure.

Strelkoff and Bjorneberg (1999), utilizing in SRFR's erosion module the Laursen (1958) formula with a representative particle size midrange in the field-measured mix, got a reasonable match between results of the simulation and Idaho field data, as in Figure 2. They also found that the Yang (1973) and Yalin (1963) formulas (WEPP) greatly overestimated the capacity of furrow flow to carry sediment, with consequent under-prediction of deposition back to the lower reaches of the furrow.

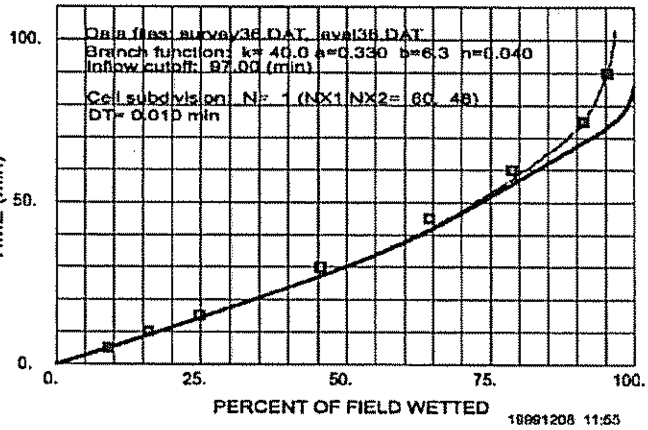


Figure 3. Advance curves –
Squares: measured;
Dotted: computed, with surveyed field elevations;
Solid line: computed, for a plane, level field.

The two-dimensional simulation model was tested against field measurements obtained in a 3 ha (7 acre) basin at the Gila River Farms, irrigated from the center of one side. Monitoring of water levels in 26 locations and a land-level survey allowed estimation of the soil infiltration characteristics, represented by a power law of time in the early stages, branching to a constant infiltration rate after 4 hours of wetting. Assumption of the reasonable Manning n=0.04 yielded the results shown in Figure 3. Predictably, the irregular field surface requires additional time to wet the high spots; in fact, it is apparent that some 4% of the field area is so high that with the given cutoff, at 97 minutes, it is never wetted. The computations appear to agree with field data to within measurement errors.

INTERPRETATION: The growing body of simulation software is finding users in the national and international irrigation community for design, management, and evaluation of surface irrigation. It is likely that studies of the interrelationship among distribution uniformity, standard deviation of surface elevations, and inflow rate will provide a useful adjunct to current design software. Predictions of soil erosion, transport, and deposition are significantly less accurate than predictions of hydraulic performance, but the influence of design and management is easy to see, so that these aspects also can be taken into account.

FUTURE PLANS: In order to get a more accurate simulation of sediment transport and, in particular, for subsequent simulation of chemical adsorption to the surface areas of that sediment, the distribution of particle sizes in the sediment mix should be accounted for. For example, the extensive field work of Fernandez (1997) shows consistent decreases in sediment concentrations with irrigation time at various locations along the furrow. This suggests a supply-limited erosion event, which is, in the absence of scour-hole formation, a concept possible only in a graded mix. This is because in a cross section essentially constant with time, a homogeneous soil provided with a constant supply of, say, clean water continues to churn out sediment at a constant rate. The reductions with time noted most likely stem from the fact that gradually all of the particles which *can* be detached *are*. What remains on the bed are particles too large or heavy to be entrained, with finer ones underneath, protected from scour by the coarse layer at the soil-water interface.

Deficiencies in SRFR noted by users will be addressed, including coalescing of successive surges. As funding becomes available, the two-dimensional pilot model will be reoriented towards routine application. Increasing the allowable time step, currently very small in basins with a fine grid of soil and water surfaces, will be explored. A multiple-furrow model will be completed, and additional field verification for both the two-dimensional and the coupled-furrows programs will be sought, pending outside financial support. Long-term plans include incorporation of relationships for cohesive soils, a relatively poorly understood area in the field of sediment transport. Incorporation of soil-chemistry components is contemplated; water and soil salinities play a great role in erosion, especially in clays. Estimates should be made of the pre-wetting effect for surge irrigation. Pre-wetting phenomena have been shown to have a significant effect on detachment; but virtually all of the WEPP erosion database is for pre-wetted (rained-on) soils, which do not exhibit the violent fine-scale commotion observed at the front of a wave of irrigation water in a dry, powdery bed. Also, soil and water temperature effects on infiltration and erosion require quantification.

As funding becomes available, chemical transport and fate will be included in SRFR.

COOPERATORS: Thomas Spofford, Natural Resources Conservation Service, National Water and Climate Center, Portland OR; Luciano Mateos, and Rafael Fernandez, Instituto de Agricultura Sostenible, CSIC, Cordoba, Spain; David Bjorneberg, Rick Lentz, Robert Sojka, ARS Northwest Irrigation and Soils Research Laboratory, Kimberly ID; Thomas Trout, Water Management Research Laboratory, Fresno CA; D.D. Fangmeier, University of Arizona, Tucson AZ; Marshall English, Oregon State University, Corvallis OR; Roger Stone, Gila River Farms, Pinal County AZ.

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WATER PROJECT MANAGEMENT

CONTENTS

WATER PROJECT MANAGEMENT

MISSION

To develop tools for the management and augmentation of water supplies in arid-region water projects, particularly those associated with irrigation. This includes methodologies for measuring and monitoring water fluxes with natural and man-made systems, methods for improving control of water within distribution networks, conjunctive management of groundwater and surface water supplies, artificial recharge of groundwater, natural water treatment systems (e.g., soil-aquifer treatment), and methods for assessing the performance of water projects in terms of water quality and quantity management.

A new float-operated valve that can be used in combination with a water inflated bag is proposed to be inserted under a gate, made to raise a weir, or fitted into the pipeline from a main canal to a secondary canal to maintain a desired flow level at locations. The objectives are to develop hydraulic flow control devices applicable where access to electricity may not be convenient and to evaluate the effectiveness of their function. This is an extension of the previously developed DACL (Dual Acting Controlled Leak) systems.

Methods to condition flow profiles in pipe outlets will include insertion of minimum contraction orifices and sidewall vanes. A special 30-inch diameter pipe facility is now ready for conducting these tests.

A meter builder in Fair Oaks, California, (Global Water) constructed and furnished two industrial propeller meter prototypes following our debris shedding design proposals. They will be tested in the 30-inch diameter pipe facility mentioned above. An ultrasonic velocity probe will be used to define this flow field.

FINDINGS: End-cap Orifice: The orifice system calibrated as expected from theory, and is more repeatable than corner tappings on a pipe of uncertain end quality. The convenience aspects of the system were demonstrated. (No new data acquisition is planned.)

Flap Gate: We expected that, as the flow in the pipe increased, the change in the pressure grade line should decrease because there would be more kinetic energy used to keep the flap gate open. However, no distinct pattern could be seen from the data. Low flows and high flows produces back pressures on the order of only 4 mm to 6 mm of water column. (No new data acquisition is planned.)

Flow Profile Conditioning: There are no new findings to report.

Propeller Meter: This has been delayed for higher priority studies. There are no new findings to report.

Pipe Flow Control System: A new DACL valving system was developed because a commercial version did not provide the needed functions. The new valve appears to be capable of all required functions but needs to be laboratory and field proven. A variety of low-cost bag products has been collected. The bag concept was tried on a small model and appeared to function well. Scaling problems have not been ruled out. Progress includes designing and building the low-cost valving system and companion pipe flow obstruction method that is ready to be tested (Fig. 1 & 2). A small model of the concept operated as hoped. The new valving equipment was not used in these tests, but had to be simulated by other means. The test facility has been modified to allow testing of the control concept.

INTERPRETATION: End-Cap Orifice: This version of the end-cap orifice can be installed on well pipe outfalls without any specially drilled holes. The corner tap locations of the original version, which also did not require pipe drilling, are somewhat sensitive to poor pipe-end conditions. While this version cannot be used if the pipe is in badly eroded condition, it is somewhat forgiving. The orifice still requires the installation to provide standard lengths of straight pipe from the last pipe bend.

Flap Gate: While the analysis is still incomplete, preliminary findings are that flap gates cause negligible back pressure on pipelines that are flowing full. No new interpretations have been developed, pending reactivation to complete the technical note. The difference between low and high speed flow was not significant.

Pipe Flow Control System: Stable flows in secondary canals permit low-cost totalization of flow deliveries to farms because time clocks will suffice instead of complex recorder systems. Known constant flows allow more precise management of irrigation systems. Preliminary indications are that the concept can be made to work. If this proves out, then we should be able to provide economical flow stabilization from main canals to lateral canals.

FUTURE PLANS: End-Cap Orifice: Prepare report.

Flap Gate: Prepare a technical note on the findings that the effects are usually negligible.

Flow Profile Conditioning: Start laboratory study phase and refine test facility, and conduct this study in conjunction with the flow profile study.

Pitot System: The Pitot System reported last year has been completed and one report has been published. A report on the complete data collection and interpretation is still in technical review, and we will continue to follow through to anticipated publication. The control system for constant flow delivery from main canals to lateral canals through pipes will be studied.

COOPERATORS: Robert Roth, Maricopa Agricultural Center, Univ. of Arizona, Maricopa AZ; Charle Slocum, Wellton Mohawk Irrigation and Drainage District; Brian Betcher, Maricopa-Stanfield Irrigation and Drainage District, Stanfield AZ; John Dickerman, Global Water, Fair Oaks CA; and John Vitas, Plasti-Fab, Inc., Tualatin OR.

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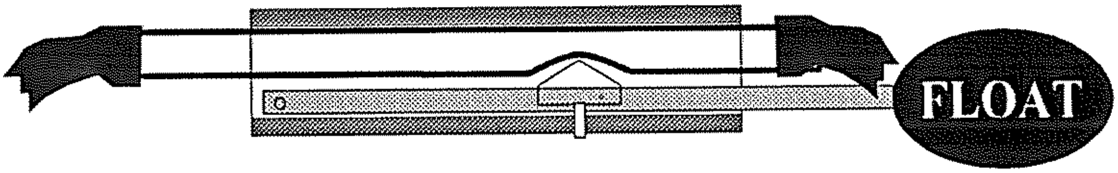

Figure 1. Low-cost valve scheme. Two valves required per system.

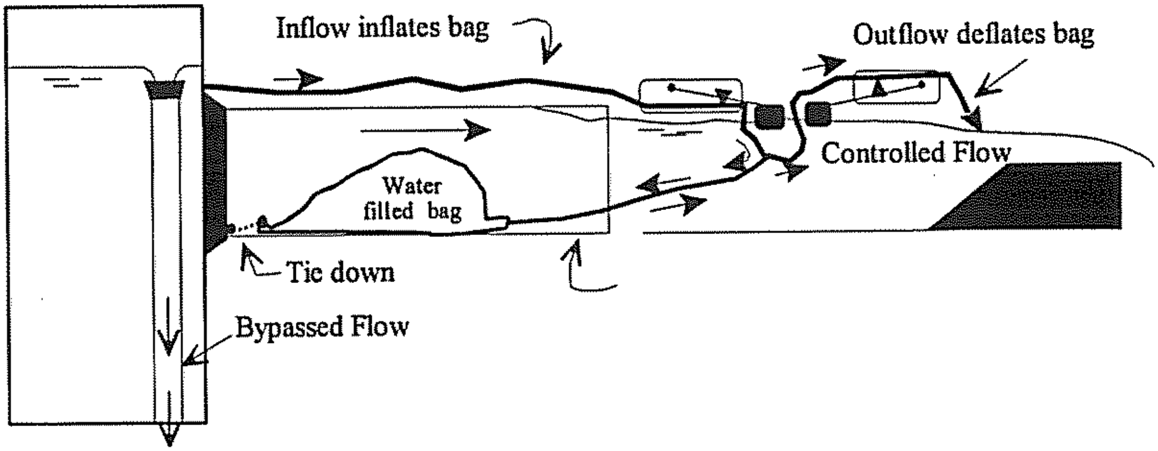

Figure 2. General laboratory set-up for evaluating valve and bag system for flow level control.

FLOW MEASUREMENT WITH FLUMES AND WEIRS

J.A. Replogle, Research Hydraulic Engineer; B.T. Wahlin, Civil Engineer; and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEMS: Continuing concerns involve needs related to open channel flow measurement and control. These include:

Sediment-laden discharges in natural streams are difficult to measure because of sediment movements and accumulations.

Parshall flumes have been popular flow measurement devices for open channels since their introduction in 1926. Traditionally, problems have arisen in Parshall flumes if they are not constructed to specifications. For example, a large Parshall flume installed in California has a field-verified calibration that differs by 10% to 20% from the historical calibrations for that size. This determined difference may or may not be structural.

One of the most important factors in installing a broad-crested weir is vertical placement of the sill. If the sill is too low, the flume may exceed its limit of submergence. If the sill is too high, upstream canal banks may be breached. While this has been partly addressed with the Adjust-A-Flume, simplifications in its construction and adaptation to economical recorders are still needed.

The FLUME3 program does not run well with Windows 95. Cooperative efforts with the USBR to re-code the program for Windows, while nearly complete, have generated some follow-through ideas.

APPROACH: The general objective is to address these problems economically and practically with user-friendly technology.

A prototype self-calibrating flume for sediment-laden flows was designed and installed in northern California (Fig. 1). The objective is to evaluate the idea of the self-calibrating flume system and to determine its operational limitations. The design was based on estimated hydraulic behavior of a chute outlet attached to a "computable" trapezoidal long-throated flume. Two stilling wells, one on the main flume and one on the chute, are expected to provide field calibration for the chute after the main flume no longer can function because of sediment deposits. A laboratory model is part of a thesis study at the University of Arizona to check the limits of sediment handling, the best slope for the chute, and whether the calibration of the chute remains stable after the sediment fills the main flume.

The historical calibrations of a one-fourth scale model of an eight-foot Parshall flume were previously verified. The objective is to develop methods to modify wrongly constructed Parshall flumes to recover their function for accurate flow measurement and to identify construction anomalies that can cause large calibration shifts. The same model will be fitted with a modified entrance and other changes in an attempt to identify causes of calibration shifts that have been noted in a larger Parshall flume.

Compilation of field experiences by users of the commercialized version of the patented adjustable-sill, long-throated flume will be used to advise on expansion of the product line and to evaluate field durability and vulnerability to damage from frost and animals. The objective is to evaluate field installations and to assist in design and materials changes that may be needed to hasten technology transfer.

New software being written to make flume calibration and design software compatible with the computer Windows environment will be user tested, and supplemented with a user manual, either in paper copy, on-line, or CD versions.

FINDINGS: As reported last year, the California Water Quality Control Board used the flume data from last year to demonstrate the severity of the cinibar tailings (mercury ore) problem to EPA. Based on that, emergency super-fund money ($2.5 million) to stabilize the mine tailings was authorized. More data has been collected to verify the initial findings and to evaluate progress in the effectiveness of the clean-up.

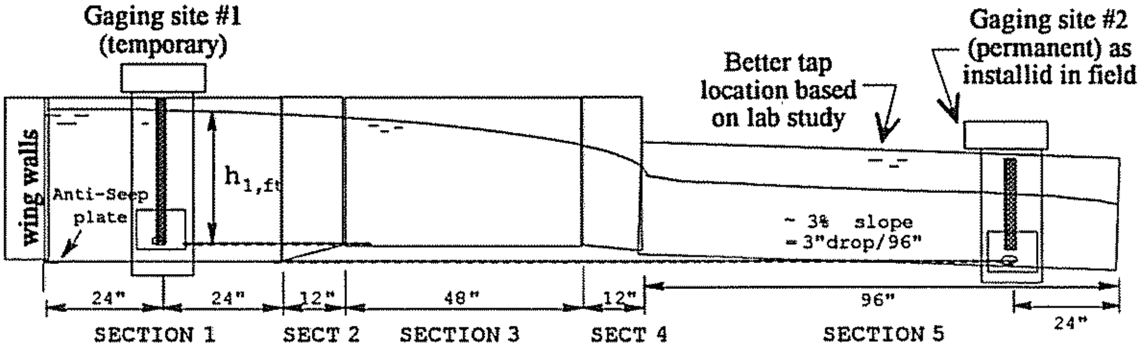

Figure 1. General layout of sediment-resistant flume as installed.

With the laboratory model study completed, the Ph.D. student study was successfully submitted to final exam on September 28, 1999. Basically, the sediment (sand) altered the upstream (subcritical) stilling well as predicted. The model indicated that the detection in the chute will provide discharge rates with errors less than 5%. The downstream stilling well in the chute (supercritical) has about the same response with and without sand, as postulated. Findings include that the midpoint of the chute is a more reliable point of depth detection than the point shown on figure 1.

A 50-foot Parshall flume, whose calibration differs from published calibrations by 10% to 20%, has been in operation for nearly 20 years. It has a modified entrance flare that differs from the published rounded entrance. This modification was suspected of causing the calibration difference. Laboratory studies to verify this on a model of a related eight-foot Parshall flume failed to implicate this type of construction anomalies as a cause. Distorted flow entry also was ruled out. Attention now is centered on the published calibration for this size.

Field observations and reports have been compiled for flumes ranging in maximum capacity from 200 gpm (12 l/s) to 35 cfs (1 m^3/s). The users find the devices easy to install and able to meet their operating requirements. The standard versions are now commercially available under the name "Adjust-a-Flume" (Nu-Way Flume and Equipment Company). Widespread acceptance appears to be growing, as is interest to adding recording instrumentation to the product line that is complicated by the movable reference throat level. Commercial components have been identified that hold the possibility for developing a "kit" to field adjust to many sizes of flumes.

The WinFlume program has been distributed in trial versions to many users, and bugs are corrected when they are found. Current thoughts are for a CD version of a users manual. The format for this has not been firmly decided.

INTERPRETATIONS: The ability to measure flows in heavy sediment carrying flows is important to studies of erosion, runoff, and the effectiveness of best management practices on watersheds. This system expands the range and flume shapes available for such use.

Parshall flumes may not behave as originally specified if installation differs from the standard, or if the flow is distorted at the flume entry. Effects of these problems were evaluated and appear to be of too small a consequence to account for the large errors noted. Therefore, the original calibration may be in question and more definitive model studies may be needed to resolve the questions concerning calibration.

The field problems involving the vertical placement of flumes and broad-crested weirs are greatly reduced for farm-sized earthen channels by the commercialization of a series of semi-portable, long-throated flumes with adjustable throat sills and maximum capacities ranging from 200 gpm (12 l/s) to 35 cfs (1 m^3/s). Sizes above 6 cfs are not intended to be portable. The addition of an instrumentation package will extend the use of the flume systems.

The new flume program will hasten the technology transfer of good flow measuring and monitoring for irrigation management.

FUTURE PLANS: The sediment resistant flume in California will continue to collect data from storm events. The laboratory model study may be "mothballed" for possible extension studies by another student, which may include development of sediment sampling equipment attached beyond the chute. A second, clear-plastic model is being considered so that sediment movements can be observed more readily in future studies.

The new DACL valve will be laboratory and field evaluated for desired control functions. Further laboratory and field evaluations for function and durability of assembled control systems using the concepts will be reinitiated.

The findings for the field installation of the 50-foot Parshall flume will be further evaluated to see if a calibration shift can be produced, even though the 8-foot Parshall flume, which is not a scale model of the 50-ft version, showed little effects from the usual suspected sources (Fig. 2).

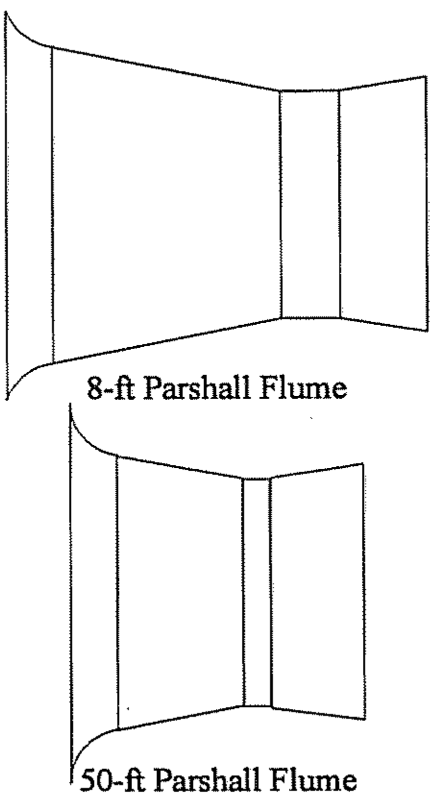

Figure 2. Relative proportions of 8-ft and 50-ft Parshall flumes.

Advice on design changes for adjustable flumes and evaluation of field performance will continue. "Kits" of a possible recording instrumentation system have been sketched that involve minor modifications to commercial equipment and should be available for under $500. This will be continued to see if it can indeed be demonstrated and evaluated.

Write a new book/users manual for the WinFlume Program.

COOPERATORS: Informal cooperation exists among: Tony Wahl and Cliff Pugh, U.S. Bureau of Reclamation, Hydraulics Laboratory, Denver CO; Harold Bloom, Natural Resources Conservation Service, Phoenix AZ; Anisa Divine, Imperial Irrigation District, Imperial CA; Joe Kissel and Kirk Kennedy, Salt River Project, Phoenix AZ; Charles Slokum, Wellton Mohawk Irrigation and Drainage District, Wellton AZ; Brian Betcher, Maricopa-Stanfield Irrigation and Drainage District, Stanfield AZ; Jackie Mack, Buckeye Irrigation District, Buckeye AZ; Randy Stewart, Plasti-Fab, Inc., Tualatin OR; Don Slack, The University of Arizona, Tucson AZ; Dyan White, California Water Quality Control Board, Sacramento CA; and Charles Overbay, Nu-way Flume and Equipment Company, Raymond WA.

WATER REUSE AND GROUNDWATER RECHARGE

H. Bouwer, Research Hydraulic Engineer

PROBLEM: Increasing populations and finite water resources necessitate more water reuse, as do increasingly stringent treatment requirements for discharge of sewage effluent into surface water. The aim of this research is to develop technology for optimum water reuse and the role that soil-aquifer treatment can play in the potable and nonpotable use of sewage effluent. Present focus in the U.S. is on sustainability of soil-aquifer treatment, particularly the long-term fate of synthetic organic compounds (including pharmaceutically active chemicals and disinfection byproducts) in the underground environment. The fate of pathogens and nitrogen also needs to be better understood. In Third World countries, simple, low-tech methods must be used, including lagooning, groundwater recharge, and sand filtration to treat the sewage.

Artificial recharge with infiltration basins for storing fresh water underground as part of integrated water management and conjunctive use of surface water and groundwater, or for underground storage and soil-aquifer treatment (SAT) of sewage effluent for water reuse, is still rapidly increasing. The permeable soils that such systems require are not always available, so that less permeable soils like the loamy sands, sandy loams, and even light loams of agricultural and desert areas are increasingly used to obtain recharge and SAT benefits. Such soils require reliable techniques for infiltration measurements and other pre-investigations to assess the feasibility of the project, and for management of recharge basins to maintain maximum infiltration rates. Climate change is going to be an important factor in future management of water supplies. Because it is impossible to predict it with any accuracy on a local or regional scale, managers increasingly must develop flexible water management schemes so that they can handle excessive as well as inadequate water supplies. This requires more long-term (years to decades) storage of water or "water banking," which is best achieved via artificial recharge of groundwater to avoid the evaporation losses that occur with long-term surface storage behind dams. SAT principles can be extended to river bank filtration systems where wells are drilled at some distance from the river so that river water is "pulled" through the aquifer and receives SAT before it goes to the water treatment plant.

Seepage from ponds, reservoirs, lagoons, wetlands, or other water impoundments often needs to be controlled using earth or plastic linings. Where earth linings are used, the soil material can be placed on the bottom and banks and mechanically compacted when the impoundment is dry, or it can be applied dry or as a slurry to the water itself. The question then is: what gives more seepage control, a compacted soil layer on the bottom where the soil is thoroughly mixed, or a slurry applied to the water where the coarser particles sink faster than the finer particles to create a lining layer that is coarser at the bottom and finer at the top?

Long-term effects of irrigation with sewage effluent on soil and underlying groundwater must be better understood so that future problems of soil and groundwater contamination can be avoided. Potential problems include accumulation of phosphate and metals in the soil and of salts, nitrate, toxic refractory organic compounds, and pathogenic microorganisms in the groundwater. Water reuse is a good practice, but it should not ruin the groundwater. Long-term salt build-up in groundwater will occur in groundwater below any irrigated area (agricultural or urban), regardless of the source water, if there is no drainage, groundwater pumping, or other removal and export of water and salt from the underground environment. Groundwater levels then also will rise, which eventually requires drainage or groundwater pumping to avoid waterlogging of surface soils and formation of salt flats. In urban areas, such groundwater rises will damage buildings, pipelines, landfills, cemeteries, parks, landscaping, etc. The salty water removed from the underground environment must be properly managed to avoid problems.

APPROACH: Technology based on previous research at the U. S. Water Conservation Laboratory (USWCL) and more recent research are applied to new and existing groundwater recharge and water reuse projects here and abroad. Main purposes of the reuse projects range from protecting water quality and aquatic life in surface water to reuse of sewage effluent for nonpotable (mostly urban and agricultural irrigation) and potable purposes. Soil columns in 8 ft x 1 ft stainless steel pipes have been set up in a laboratory greenhouse to study movement of pathogens and chemicals (including exotic organics) in systems involving irrigation with sewage effluent, artificial recharge with sewage effluent, and Colorado River water. Various scenarios of rising groundwater levels and salt buildups due to irrigation were considered and compared with field data to get an idea of rates of rise in groundwater levels and salt content of the upper groundwater, and how to handle this water (i.e., disposal in salt lakes, sequential irrigation of increasingly salt tolerant crops ending with halophytes to concentrate the salts in smaller volumes of water, membrane filtration to remove the salts and allow municipal or agricultural use of the water, and disposal of the reject brines).

The effect of placement of an earth lining in an impoundment for seepage control was evaluated in a laboratory column study using 4-inch diameter clear plastic tubing. At the bottom of each column was an 11 cm layer of silica sand. In column 1, the silica sand was covered with a 16 cm layer of Avondale silt loam at optimum water content to give maximum compaction when packed with a rod. The column was then filled with water and a constant water level was maintained to give a water depth of about 160 cm. The other three columns also were filled with water with the same constant level at the top. Column 2 received the same amount (dry weight) of soil as column 1 but it was poured in as a thick slurry at the top of the column. Column 3 also received the same amount of soil as a thick slurry, but it was poured in 5 split applications at least 24 hours apart so that the water in the column had become completely clear when the next slurry was applied. Column 4 received the same amount of soil in the same way but in 15 split applications. Seepage rates were then monitored for about 40 days to reach well-defined final values.

FINDINGS: Field and laboratory tests continued to show the usefulness of recharge and soil-aquifer treatment in water reuse. Main issues still are sustainability of soil-aquifer treatment and fate of recalcitrant organic compounds, including disinfection byproducts, pharmaceutically active chemicals, and humic and fulvic acids and other organic compounds that react with chlorine to create new disinfection byproducts. Calculation of the water and chemical balance (including salts) indicates that the drainage or deep-percolation water from sewage irrigated fields will be seriously polluted, especially in dry climates.

The slurry applied earth liners had a fine, slowly permeable layer at the top of each layer. Thus, the integranular pressure below the fine top layers was relatively high since the fine layers "carried" the weight of the water. This produced considerable compaction of the liner for about 2 weeks as evidenced by reduced thickness of the layer and reduced infiltration rates until both became constant at the following values.

	Compacted soil	1 slurry application	5 slurry applications	15 slurry applications
Final thickness in cm	16	21	21	19
Final infiltration rate in cm/day	2.7	1.2	1.0	0.85

The seepage rate for the silica sand alone was 9.6 to 11.1 m/day. Thus, the earth lining was very effective in reducing the seepage rate, especially when applied as a slurry. The biggest percentage of reduction from compacted earth to slurry applied soil was achieved when the total amount of soil was given in one slurry application (56%). Five split slurry applications gave further seepage reduction and so did the fifteen split applications. However, the additional seepage reductions (i.e., 17% and 15%) were not as high as the 56% reduction obtained from a compacted lining to a one-application slurry-applied lining. Thus, segregation of soil particles in the earth lining due to slurry application gave better seepage control than a uniform compacted liner. In practice, slurry applications can be repeated until an acceptable seepage level is reached.

INTERPRETATION: The developments of better technologies or concepts for predicting infiltration rates with cylinder infiltrometers, estimating volumes of water that can be stored underground for water banking, and managing relatively fine textured soils to achieve maximum infiltration for recharge will extend the use of artificial recharge of groundwater to "challenging" soil and aquifer conditions. This will enable water resources planners and managers to benefit from the advantages that artificial recharge offers in conjunctive use of surface water and groundwater, in water reuse, and in integrated water management.

FUTURE PLANS: These plans consist primarily of continuing existing research and of developing new field and laboratory research projects, mostly with universities and water districts, on long-term effects of irrigation with sewage effluent on soil and groundwater. Also, infiltration test plots will be installed to verify concepts of recharge basin management developed for finer textured soils where clogging, crusting, fine particle movement or wash-out wash-in, hard setting, and erosion and deposition can seriously reduce infiltration rates.

COOPERATORS: P. Fox, Dr. P. Westerhoff, J. Drewes, Arizona State University, Tempe AZ; R. Arnold, M. Conklin, University of Arizona, Tucson AZ; David Sedlack, University of California, Berkeley CA; J. Swanson, The City of Surprise; and Fort Huachuca, Arizona, United States Army Garrison through ASU, and M. Milczarec of GeoSystems Inc., Tucson AZ.

IRRIGATION CANAL AUTOMATION

A.J. Clemmens, Supervisory Research Hydraulic Engineer; R.J. Strand, Electrical Engineer; B.T. Wahlin, Civil Engineer; B. Schmidt, Computer Programmer; and E. Bautista, Research Hydraulic Engineer

PROBLEM: Modern, high-efficiency irrigation systems require a flexible and stable water supply. Typically, open-channel water delivery distribution networks are controlled manually and are not capable of providing this high level of service. Stable flows can be achieved when little flexibility is allowed since canal operators can force canals flows to be relatively steady. Allowing more flexibility increases the amount of unsteady flow and leads to more flow fluctuations to users.

Most canal systems operate with manual upstream control. With this approach, all flow errors end up at the tail end of the system and result in water shortages or spills. In some canals, supervisory control systems are used to try to match inflows with the expected outflows. Because this adjustment is done by trial-and-error, pool volumes and water levels can oscillate until a balance is achieved. In canals with large storage volumes, these fluctuations may have little impact on deliveries. Smaller canals with insufficient storage need more precise downstream control methods than are currently available. Development of improved canal control methods requires convenient simulation of unsteady flow by computer. Many computer models of unsteady canal flow have been built in the last twenty years, some very complex and expensive, designed to model very complicated systems. Only recently have these programs allowed simulation of control algorithms for canal automation.

The objective of this research is to develop technology for the automatic control of canals as a means of improving canal operations. This includes development and testing of canal control algorithms, development of necessary sensors and hardware, development of centralized and local control protocols, refinement of simulation models needed for testing these methods, and field testing of algorithms, hardware, and control protocol.

APPROACH: A Cooperative Research and Development Agreement between ARS and Automata, Inc., was established for the purpose of developing off-the-shelf hardware and software for canal automation; i.e., plug-and-play. We will work closely with Automata in the application and testing of this new hardware and software. The core of this system is the U.S. Water Conservation Laboratory (USWCL) canal automation system that consists of

- feedforward routing of scheduled flow changes (similar to gate stroking),
- feedback control of downstream water levels (to balance canal inflow and outflow), and
- flow control at check structures.

The system is controlled from a personal computer at the irrigation district office. A Supervisory Control and Data Acquisition system (SCADA) is used by operators to monitor the irrigation system and to control gates remotely through radio communications. We plan to use a commercial SCADA package, FIX Dynamics from Intellution, Inc. Standard MODBUS communication protocol will be used to communicate between FIX Dynamics and Automata's Base Station. Eventually all communications in the system will use MODBUS. The USWCL canal control scheme logic (USCWL controller) will be interfaced with FIX Dynamics. The research approach will be to use simulation models to test and further develop various control schemes that can be used within the proposed automation system. The hardware and software components will be assembled and made compatible in the field. Finally, the combined hardware and software automation system will be tested in the field on the WM lateral canal of the Maricopa Stanfield Irrigation and Drainage District.

Simulation of unsteady flow in canals is needed to understand canal pool properties. We routinely use the unsteady-flow simulation package CanalCAD to study canal properties and to test controller performance. The canal properties taken from CanalCAD tests are used within a mathematical analysis software package, MATLAB, to design various controllers. We have been using a centralized proportional-integral (PI) controller that accounts for system delays. This format allows selection from a series of controllers, including a series of simple local PI controllers. Selection of controllers for testing on the WM canal are based on simulation tests of controller performance on the American Socity of Civil Engineers (ASCE) test cases and simulation of the WM canal itself.

FINDINGS: Poor canal control performance is caused by a mismatch between pool inflows and outflows and/or incorrect pool volumes. Thus, canal controller methods must address control of both flow rates and pool volumes. An understanding of (1) wave travel times and (2) pool volume as a function of flow rate are necessary and sufficient for the development of feedforward control logic, while for feedback control (1) wave travel times and (2) pool backwater surface area can be used.

Simulation studies of downstream-water-level feedback controllers: A comprehensive set of simulation tests was made for ASCE test canal 1. First, for a series of local PI controllers of pool downstream water level, there was little difference between control of gate position or control of flow rate at each check structure. However, use of flow rate control separates control of pools from control of structures. Second, better control was obtained when control actions from one pool were passed upstream to other check structures, invoking the so-called decoupler I. In general, the completely centralized PI controller provided the best performance. Accounting for the system delays led to mixed results. If our estimate of the delays was poor, then including the delays in the controller hurt the overall performance. If our estimate of the delays was accurate, then including the delays in the controller improved performance. A reasonable compromise between controller performance and complexity is to pass a portion of the PI control actions one pool upstream and one downstream. Finally, the integrator-delay model of Schuurmans for defining canal pool properties appears to work very well for controller design.

Development of accurate gate position controller: The canal automation system was installed on the WM canal at MSIDD using Automata hardware, including Remote Terminal Units (RTUs), gateposition sensors, and a base station. The RTUs were programmed to move the gate according to the number of pulses requested by the controller and the number of pulses sent from the gate position sensor. This system is functioning very well. Run-on, or gate movement after the motor is turned off, is usually zero and occasionally one pulse. Each pulse represents roughly 0.95 mm, thus we are able to position these gates to within 1 mm. Automata programmed their base station to translate from the MODBUS protocol of the SCADA system to Automata's protocol which is communicated with the RTUs by radio. This communication is functioning, but needs some improvement.

SCADA implementation: The WM canal was set up within the FIX Dynamics SCADA system. Digital photographs of the canal and the check structures were used as background screens for the

SCADA control functions (See Figures 1 and 2). The system was set up to monitor continuously the headgate, all check structures, water levels above two flumes, and water levels at the downstream end of all canal pools. Within FIX, digital signals are sent to the RTU indicating how many pulses to move a gate, and in what direction.

The USWCL canal automation system control program was interfaced to the FIX Dynamics SCADA package. The USWCL control program is a separate program running in parallel with FIX in a Windows NT environment. Information on the state of the system are read from the FIX database by the control program through an ActiveX interface. Control actions determined by the control program are passed to FIX, also through ActiveX. Additional ActiveX elements are used to allow the operator to enter manual changes from FIX screens (for example to move the gate a certain distance rather than a number of pulses (Fig. 2), or to adjust manually water level and check flow setpoints). A first level of error checking was added to the control program so that the controller would not overreact if sensors or communications failed. These were essential during early testing.

Field testing: The control system was made operational and run several times during October 1999. These tests were all run with only the first 5 pools since there were no deliveries downstream. The system functioned as intended. An example of one test run is shown in figure 3. For this test, a series of local PI controllers were used. The test consisted of starting with the initial water level as the setpoint and gradually raising the setpoint to the desired level. The controller and control program were functioning properly, but had not yet stabilized by the end of the test. Numerous communications and other small problems will require additional RTU, base-station, and control programming to clean up.

INTERPRETATION: The feasibility of a plug-and-play type canal automation system looks promising. Ensuring proper functioning of the system for a given canal will still require some engineering analysis to determine hydraulic properties and controller constants so that the automation performs adequately.

FUTURE PLANS: Communication has been the biggest problem. Assuring that the controller will perform appropriately requires that the control program have some control over the obtaining of information from the RTUs. MODBUS allows this, but it is not programmed into the base-station translator. A better solution appears to be programming MODBUS into the RTU software. This will allow the base-station to control the collection of information rather than relying on FIX's periodic querying. The current RTU programming has unneccessary code that is left over from other Automata applications. We plan to eliminate as much of this unnecessary code as possible and to remove the automatic periodic reporting. Additional features need to be added to the RTU and control programs. Work will continue on the development of feedback and disturbance controllers that perform better under unusual circumstances. Finally, a number of controllers will be tested on the WM canal in real time, which also will serve to test the control and RTU programs.

COOPERATORS: Lenny Feuer, Automata, Inc., Nevada City CA; Gary Sloan, MSIDD, Stanfield AZ; Jan Schuurmans, University of Twente, The Netherlands; Dave Rogers, USBR, Denver; Charles Burt, Cal Poly, San Luis Obispo CA; Bob Gooch, Salt River Project, Phoenix AZ; Victor Ruiz, IMTA, Cuernavaca, Mexico; Pierre-Olivier Malaterre, CEMAGREF, Montpellier, France.

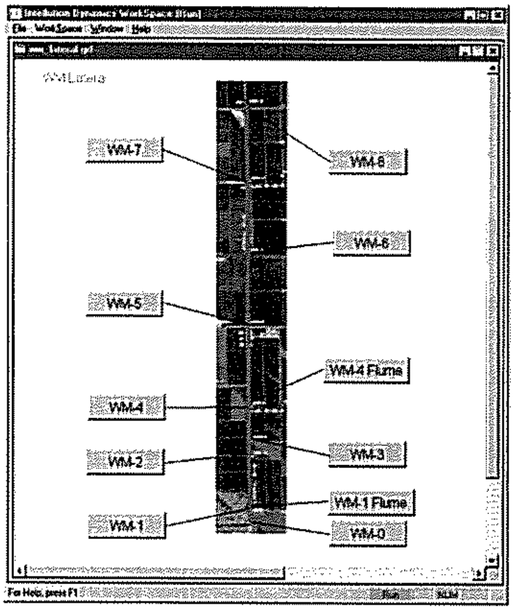

Figure 1. FIX SCADA screen showing WM canal layout.

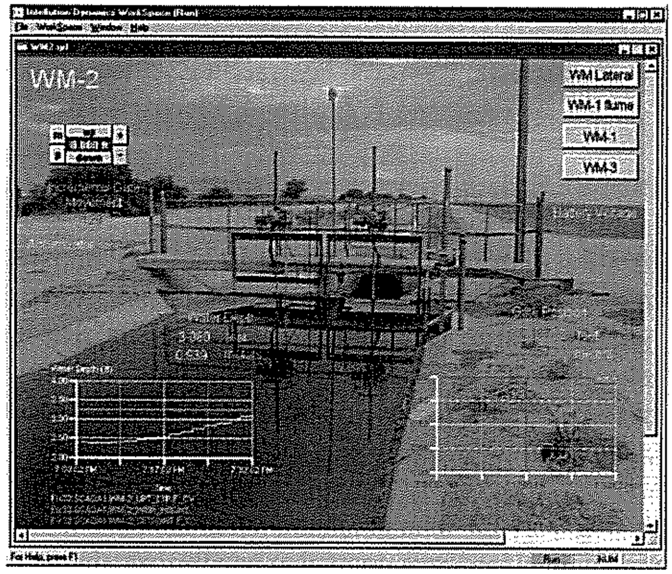

Figure 2. FIX SCADA screen of WM-2 check structure, including graphs of water level and gate position and activeX element for changing gate position.

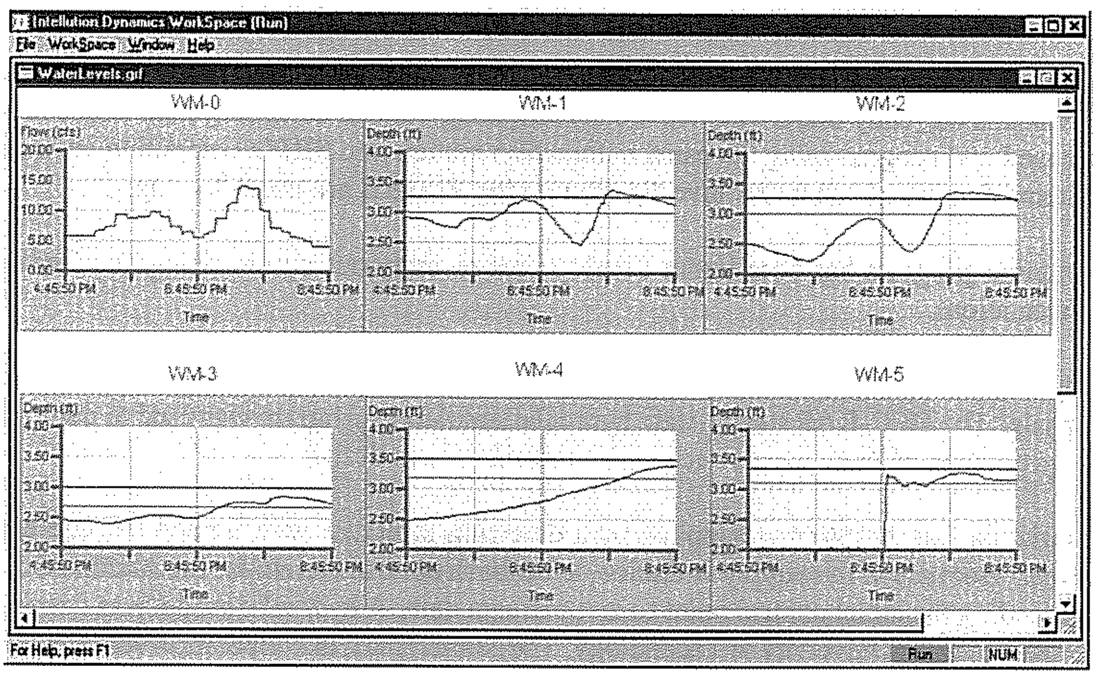

Figure 3. FIX SCADA screen showing results of test on Oct. 19, 1999. Red lines are water level setpoints and green lines are overflow weirs.

CANAL AUTOMATION PILOT PROJECT FOR THE SALT RIVER PROJECT ARIZONA CANAL

E. Bautista, Research Hydraulic Engineer; A.J. Clemmens, Supervisory Research Hydraulic Engineer; R.J. Strand, Electrical Engineer; and B.T. Wahlin, Civil Engineer

PROBLEM: The Salt River Project (SRP) is the largest municipal and agricultural water supplier in the Phoenix valley. The district also has a long history of being progressive in the management of its water distribution system. In 1995, SRP initiated an in-house research and development project, in cooperation with the U.S. Water Conservation Laboratory (USWCL), to determine the feasibility of implementing canal automation within its distribution network. Canal automation is expected to improve service, reduce operating costs, and improve SRP's stewardship of resources. The objective of this project is to develop an automated canal control system that is compatible with SRP's current canal operational strategies and systems.

APPROACH: The proposed canal control scheme has three main components: (1) downstream water-level feedback control to handle disturbances or errors in flow rate, (2) open-loop feedforward routing of scheduled or measured offtake flow changes, and (3) check structure flow-rate control. Phase I of this pilot project consisted of the development of an automatic control system and simulation studies to test its ability to control water levels on an SRP canal system reach. The upper portion of the Arizona Canal was chosen as the study site. This section includes 5 pools, separated by check structures, and a major branch point at the heading of the Grand Canal. Findings of this initial phase were reported in Clemmens et al (1997).

In view of the promising results, SRP decided to continue with the next phase. In Phase II of the pilot project, which is currently underway, we are investigating various control system issues identified during Phase I and programming the canal automation system into SRP's computing environment. Specific items that have been under investigation during Phase II are the following:

(1) A computer program has been under development to carry out automatically the feedforward control calculations.

(2) Analysis of the feedforward control problem was expanded to include the entire Arizona and Grand Canals. The HEC-RAS steady-state hydraulic simulation program was used to determine the hydraulic properties of these canals needed for control system design.

(3) The Arizona Canal system is supplied by a diversion structure with limited storage capacity, Granite Reef. Because of this supply limitation, a feedback control system for the Arizona Canal may require extending the initial control point to an upstream dam. A hydraulic model was developed by Rogier Visser, of Delft University of Technology, The Netherlands, in cooperation with the USWCL, of the river system that supplies water to Granite Reef. The model includes a river reach between Stewart Mountain and Granite Reef on the Salt River and a reach between Bartlett Dam and Granite Reef on the Verde River. Data for the study were provided by SRP, U.S. Geological Survey, and the Maricopa County Flood Control District. Additional field data also were collected by Rogier Visser.

(4) Since the proposed canal control system uses flow rate as a control variable, check gate discharges need to be measured. In practice, these measurements can be inaccurate. This is true for SRP's gates, particularly under submerged flow conditions. While the control system can stabilize water levels even with inaccurate gate discharges, control improves substantially with better flow predictions. Therefore, a laboratory study was initiated to obtain a more accurate head-discharge relationship for radial gates. The study was conducted by Jan Tel of Delft University of Technology, the USWCL, and SRP.

(5) Automated control simulations have been conducted by assuming initial steady-state flow conditions. Steady-state is difficult to achieve in real canal systems. A start-up strategy has been developed that assumes initial unsteady flow and has been tested with simulation.

(6) Currently, the water-masters serve as the interface between the water orders and the main canal check structures. Daily water orders are transmitted by field operators and consolidated in a UNIX-based database. Daily operational schedules are developed manually based on these demands and on the available supplies. Through a VAX-based supervisory control and data acquisition (SCADA) system, watermasters keep track of water levels and gate positions and make necessary adjustments. Work was begun to integrate the proposed control system with SRP's current operations and computer environments.

FINDINGS: (1) A canal scheduling program is being developed in the Windows environment (Bautista and Clemmens, 1999). The program has standard graphical user interface features and is able to communicate with a local database for data input and output. The program will be modified during implementation to be able to interact with SRP's database systems. A beta version of the program has been provided to SRP to test the scheduling procedures under different flow conditions, to debug the software, and to identify needed graphical interface improvements.

(2) Figure 1 is an example of the discharge schedule computed at the head of the Arizona-Grand Canal system, based on actual demand data. The canal system consists of 30 pools and 44 offtakes. The scheduling program allows the user to impose constraints on the frequency and the magnitude of the computed flow rate changes. For example, the schedule of figure 1 was computed by constraining the frequency of changes to a 5-minute interval and the magnitude to multiples of 1 cfs. Programming work is still pending to enable the unsteady simulation software being used in this project, Mike11, to perform automatic control simulations for the entire Arizona-Grand Canal system. Simulation tests will be conducted with the computed schedules when the Mike 11 programming work is completed.

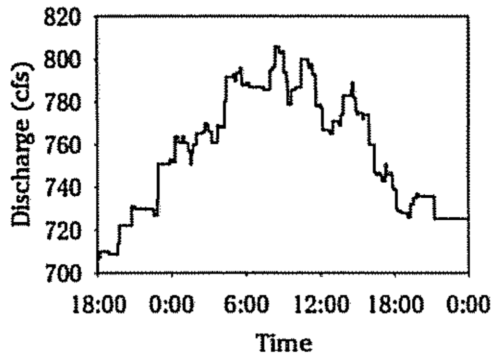

Figure 1. Computed feed forward schedule at the head of the Arizona Canal.

(3) The hydraulic model was developed by extrapolating currently available data cross-sectional and elevation data for the Salt and Verde River. While the model oversimplifies the river's topographical features, simulation results were promising in that predicted water levels at the downstream boundary of the system, Granite Reef Dam, compared relatively well with observed water levels (Fig. 2). Simulation tests have shown that modeling results are most sensitive to water losses in the river bed, which are relatively large on the Verde River, and less sensitive to potential errors in cross-sections and hydraulic roughness. Supercritical flow conditions occur at various locations along the Salt River reach and the unsteady flow model used in this study, SOBEK, can simulate those conditions. However, results computed with and without these supercritical flow reaches were not very different from each other. Detailed results are reported in Visser (1998).

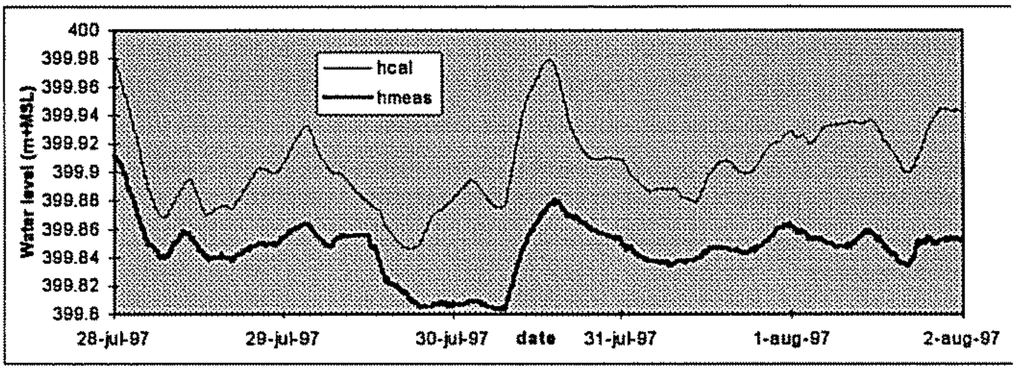

Figure 2. Measured surface water surface elevation at Granite Reef Dam for July 28-August 1, 1997, and values simulated with the Salt-Verde River system model.

(4) A scaled model of an SRP radial gate was installed on a laboratory canal along with pertinent instrumentation. Water depths, pressure distribution, and flow jet contraction were measured as a function of gate opening and flow rate. These measurements are being used to determine the adequacy of the head-discharge equations currently used by SRP and to test alternative head-discharge relationships. SRP uses a relationship that has been documented in the literature (Bos, 1989), but that was modified to reflect a gradual transition from free flow to submerged flow conditions. Data from this study are still being analyzed.

(5) Simulation tests have shown that attempting to start the automation system when the actual water levels are far from the setpoints can result in unstable behavior. To overcome this problem, when the control system is turned on, the water level setpoints are initialized to the actual water levels. Water levels are then gradually adjusted to the desired target by varying the setpoint linearly in time and by using a combination of feedforward and feedback control to make the necessary flow changes. The strategy was programmed into the unsteady flow model, CanalCAD, and tested with the ASCE Task Committee's Test Case 1 (Clemmens et al., 1998). The results of figure 3 show the change in water levels in an eight-pool canal system in which water levels in all pools are required to change simultaneously at 2:00. In combination, the feedforward and feedback control systems are able to maintain a stable control during the transient. Programming of this strategy into the unsteady flow simulation software being used in this project, Mike 11, is still pending.

(6) During most of 1999, SRP has been installing and testing a new SCADA system for Y2K

compliance. This work prevented us from making any significant progress in that area. Late in 1999, SRP decided to replace its VAX operating system, which currently hosts the SCADA system. Therefore, programming of the control system will be postponed until the new operating system and a SCADA package that works under that environment are installed.

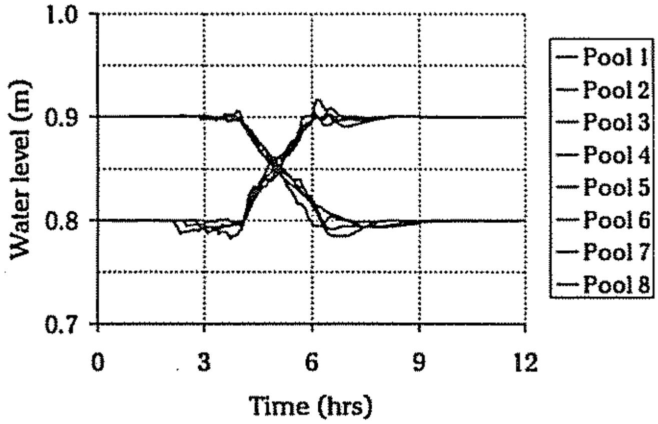

Figure 3. Simulated water levels in ASCE Test Canal 1.

INTERPRETATION: Based on the analysis to date, it appears that canal automation (remote computer control) has some real potential for improving canal operations over supervisory (manual remote) control. The magnitude of unscheduled flow changes that can be allowed is still limited by the canal's hydraulic properties. Automation itself cannot fully overcome these limitations.

FUTURE PLANS: Work will continue to complete the various tasks that were included in the Phase II workplan and a report will be prepared by early next year. During Phase III, if funded, the system will be tested in real time. Although the pilot project's objective testing the feasibility of the control system and not full implementation, to test its potential fully some level of implementation is required.

COOPERATORS: Robert Brouwer, Rogier Visser,and Jan Tel, Delft U. of Technology, The Netherlands; Jan Schuurmans, University of Twente, The Netherlands; Robert Gooch, Joe Rauch and Grant Kavlie, Salt River Project, Phoenix AZ.

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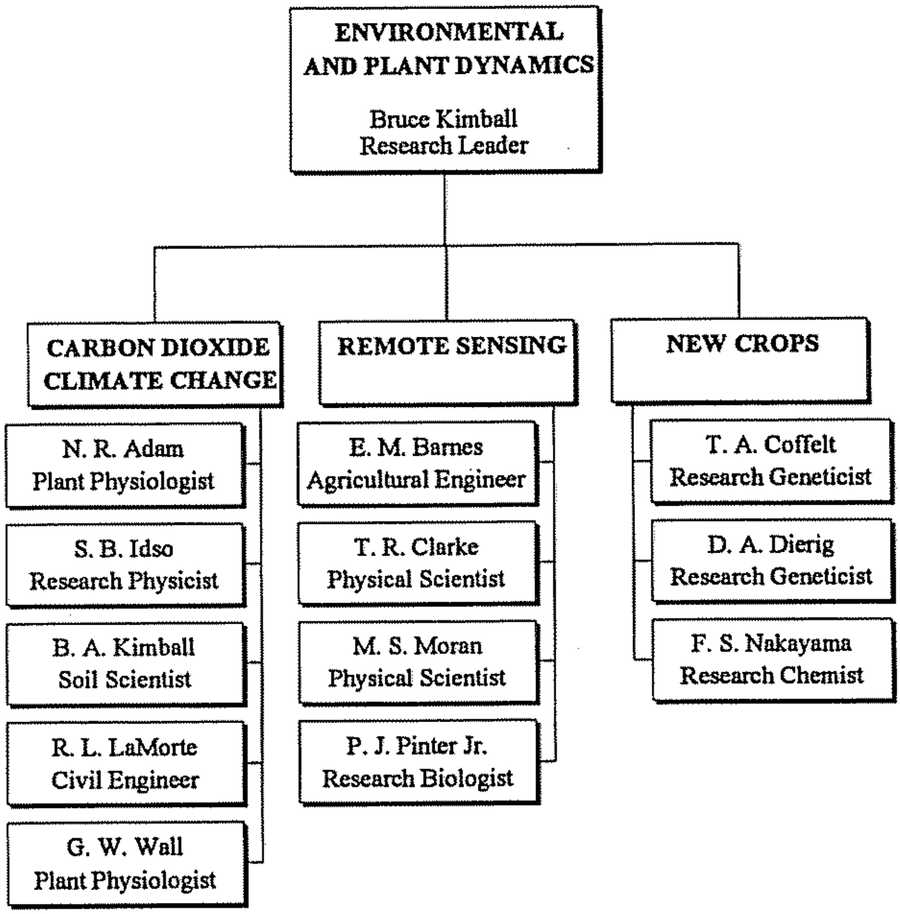
E&PD Management Unit

E&PD Organization



Mission

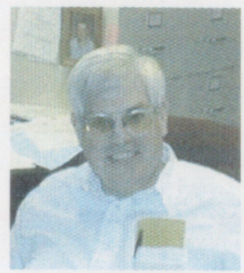
The Environmental and Plant Dynamics Management Unit seeks to develop optimum resource management strategies for meeting national agricultural product requirements within the context of possible changes in the global environment. There are three main research thrusts. The first is predicting the effects of the increasing atmospheric CO_2 concentration and climate change on the yield and water use of crops in the future. The second thrust seeks to develop remote sensing approaches for observing plant conditions and biophysical processes that are amenable to large-scale resource monitoring using aircraft- and satellite-based sensor systems. The third research thrust is to develop new industrial crops with unique high value products and lower water requirements for commercial production within the context of changing environments.

E&PD RESEARCH STAFF

NEAL R. ADAM, B.S., M.S., Ph.D., Plant Physiologist
Research regarding physiological, biochemical and molecular responses of wheat to CO2 enrichment in FACE crop canopy experiment. Establish protocol for enzyme activity assays, SDS-PAGE and other biochemical procedures on leaf samples. Design and implement data collection and processing tools.

EDWARD M. BARNES, B.S., M.S., Ph.D., Agricultural Engineer
Remote sensing applications for farm management; consideration of approaches that integrate remotely-sensed measurements with crop growth models and decision support systems.

THOMAS R. CLARKE, B.A., Physical Scientist
Remote sensing for farm management, thermal and optical radiometry, and instrument calibration.



TERRY A. COFFELT, B.S., M.S., Ph.D., Research Geneticist-Plants
Breeding, genetics, and germplasm evaluation of new crops--guayule, lesquerella, and vernonia; development of acceptable production practices.

DAVID A. DIERIG, B.S., M.S., Ph.D., Research Geneticist-Plants
Breeding, genetics, germplasm collection and evaluation of new industrial crops with unique, high-value products, including lesquerella, vernonia, and guayule.

SHERWOOD B. IDSO, B.S., M.S., Ph.D., Research Physicist
Effects of atmospheric CO_2 enrichment on biospheric and climatic processes.

BRUCE A. KIMBALL, B.S., M.S., Ph.D., Research Leader for E&PD and Supervisory Soil Scientist
Effects of increasing atmospheric CO_2 and changing climate variables on crop growth and water use; free-air CO_2 enrichment (FACE), and CO_2 open-top chambers and greenhouses; micrometeorology and energy balance; plant growth modeling.

ROBERT L. LaMORTE, B.S.E., Civil Engineer
Instrumentation, operation and data collection for the control of atmospheric CO2 in global change experiments on agricultural crops.

M. SUSAN MORAN, B.S., M.S., Ph.D., Physical Scientist
Estimation of soil moisture and evapotranspiration; detection of physical and biological stress in plants; and evaluation of energy and water balances at local and regional scales utilizing models and remote sensing techniques.

FRANCIS S. NAKAYAMA, B.S., M.S., Ph.D., Research Chemist
New crops such as guayule (for latex rubber and resin), lesquerella (hydroxy fatty acid) and vernonia (epoxy fatty acid); including extraction and analytical techniques for the various components; Editor-in-Chief of Industrial Crops and Products, an International Journal.

PAUL J. PINTER, JR., B.S., M.S., Ph.D., Research Biologist
Remote sensing applications for agricultural resource management and research; effects of global change, elevated CO_2, and environmental stresses on biophysical properties of plants.

GERARD W. WALL, B.S., M.S., Ph.D., Plant Physiologist
Derivation of experimental databases to quantify growth, development, and physiological response of agronomic crops to full-season CO_2 enrichment; development of deterministic and stochastic digital simulation models of the soil-plant-atmosphere continuum in response to a CO_2 enriched environment.

PLANT GROWTH AND WATER USE AS AFFECTED BY ELEVATED CO_2 AND OTHER ENVIRONMENTAL VARIABLES

CONTENTS

PLANT GROWTH AND WATER USE AS AFFECTED BY ELEVATED CO_2 AND OTHER ENVIRONMENTAL VARIABLES

MISSION

To predict the effects of elevated CO_2 and climate change on the photosynthesis, growth, yield, and water use of crops under optimal and limiting levels of water and fertility.

THE FREE-AIR CO_2 ENRICHMENT (FACE) PROJECT: PROGRESS AND PLANS

B.A. Kimball, Soil Scientist; P.J. Pinter, Jr., Research Biologist; G.W. Wall, Plant Physiologist; R.L. LaMorte, Civil Engineer; N.R. Adam, Plant Physiologist; M.M. Conley, Physical Science Technician; and T.J. Brooks, Research Technician

PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. This project seeks to determine the effects of such an increase in CO_2 and any concomitant climate change on the future productivity, physiology, and water use of crops.

APPROACH: Numerous CO_2 enrichment studies in greenhouses and growth chambers have suggested that growth of most plants should increase about 30% on the average with a projected doubling of the atmospheric CO_2 concentration. However, the applicability of such work to the growth of plants outdoors under less ideal conditions has been seriously questioned. The only approach that can produce an environment today as representative as possible of future fields is the free-air CO_2 enrichment (FACE) approach. Therefore, the FACE Project was initiated, and experiments were conducted on cotton from 1989-1991 (Hendrey, 1993; Dugas and Pinter, 1994). Then, from December 1993 through May 1994 two FACE experiments were conducted on wheat at ample and limiting levels of water supply, with about 50 scientists from 25 different research organizations in eight countries participating. About 42 papers have been published (e.g., Kimball et al., 1995, 1999; Pinter et al., 1996) or are in press from these experiments, and more are being prepared.

However, one of the greatest uncertainties in determining the impact of global change on agricultural productivity, as well as on natural ecosystems, is the response of plants to elevated CO_2 when levels of soil nitrogen are low. Therefore, we conducted two additional FACE wheat experiments at ample and limiting supplies of soil nitrogen from December 1995 - May 1996 and December 1996 - May 1997. Funded by the Department of Energy through a grant to the University of Arizona, U.S. Water Conservation Laboratory (USWCL) personnel were major collaborators on the project and provided management support. In addition, soil cores and leaf samples were obtained and were stored frozen for later analyses of root biomass and soil nitrogen, photosynthetic proteins, and carbohydrates. Thanks to a grant from a NSF/DOE/NASA/USDA program (TECO II) plus ARS Temporary Global Change Funds, personnel to do these analyses were hired, and many analyses were conducted during this past year. Much data from many kinds of measurements made during these latter experiments have been analyzed during the past year, manuscripts are being prepared, and papers are starting to appear in print (e.g., Kimball et al., 1999).

Much of the CO_2 enrichment research that has been conducted in the past has been with C3 plants and relatively little with C4 crops such as corn, sugarcane, or sorghum. The neglect of C4s was because their photosynthetic process was known to respond relatively less to elevated CO_2. However, their stomata do partially close in elevated CO_2, thereby suggesting the possibility of some water conservation. Therefore, with grants (one to the USWCL and one to the University of Arizona) from the NASA/NSF/DOE/USDA/EPA (TECO III) Program, we conducted an initial

FACE experiment on sorghum from mid-July through mid-December 1998. Then we conducted a second replicate experiment from mid-June through October 1999. Our hypothesis was that there will be only a small enhancement of growth due to the FACE treatment when the plants have ample water; but, under water-stressed conditions, there will be a substantial growth enhancement resulting from the water conservation due to the partial stomatal closure.

Similar to the previous experiments, measurements included leaf area, plant height, aboveground biomass plus roots that remained when the plants were pulled, morphological development, canopy temperature, reflectance, chlorophyll, light use efficiency, energy balance, evapotranspiration, soil and plant elemental analyses, soil water content, photosynthesis, stomatal conductance, grain quality, video observations of roots from minirhizotron tubes, soil CO_2 and N_2O fluxes, and changes in soil C storage from soil and plant C isotopes. Some soil cores for roots also have been obtained. As before, all of the data will be assembled in a standard format for validation of plant growth models.

FINDINGS: Analyses of the data from the FACE wheat experiments are nearing completion. Briefly, the results indicate that under the high nitrogen treatment, wheat grain yields were increased about 15% by FACE at 200 μmol/mol above ambient. At low nitrogen, elevated CO_2 increased yields by about 12% in 1996 and only 5% in 1997. The low nitrogen treatment reduced yields about 20% at both levels of CO_2.

Despite some problems, the 1998 and 1999 FACE sorghum experiments were successfully conducted. A problem encountered both years is that relatively large irrigations were required to get good distribution uniformity because the Trix clay loam soil in the field cracks severely when it dries. Therefore, besides the initial irrigation at planting time, only one additional irrigation was applied to the Dry plots. Bird and insect damage were minimal both years. In 1998, there was some frost damage before the final harvest, and on September 19, 1999, there was a hail storm that tattered the upper leaves, but the heads appeared to survive all right.

Preliminary results from 1998 showed that the effects of elevated CO_2 were minimal on the biomass and grain yield in the plots with ample water. However, under water-stress conditions there were significant stimulations of growth (+13%) and yield (+17%), consistent with the CO_2-induced partial stomatal closure and resultant water conservation.

INTERPRETATION: The data from the FACE wheat experiments suggest that with ample water, wheat production is likely to increase 10-15% by an increase in atmospheric CO_2 levels to 200 μmol/mol above current levels (about 370 μmol/mol). Moreover, in contrast to many chamber studies, our results suggest that the yield increases will occur even at low levels of soil nitrogen characteristic of the agriculture in developing countries and most natural ecosystems. Irrigation requirements may be unchanged or slightly reduced for future wheat production, provided climate changes are minimal.

The preliminary FACE sorghum data suggest that there will be little effect of higher atmospheric CO_2 concentrations on future sorghum productivity when there is ample water. Under water-stress conditions, which are typical of much of the rain-fed areas where sorghum is grown in the U.S. and in Africa and other developing countries, the future higher levels of CO_2 are likely to increase productivity by 15% or so.

FUTURE PLANS: Analyses and reporting of the results from the FACE wheat and especially from the sorghum experiments will continue. This is the last partial year of funding from the TECO III program, so the FACE project will have to terminate unless additional funding can be obtained. If an appropriate request for proposals is made by a funding agency, a proposal will be prepared. Neither the choice of crop nor the experiment design has been decided.

COOPERATORS: A. Webber, A. Cousins, D. Clark, G. Wechsung, Arizona State University, Tempe AZ; G. Hendrey, K. Lewin, J. Nagy, Brookhaven National Laboratory, Upton NY; M. Rillig, Carnegie Institution of Washington, Stanford CA; M. Howden, CSIRO Wildlife and Ecology, Lyneham, ACT, Australia; H. Johnson, H.A. Torbert, Grassland Protection Research, USDA-ARS, Temple TX; R. Vanderlip, Kansas State University, Manhattan KS; F. Tubiello, C. Rosenzweig, NASA-Goddard Institute for Space Studies, New York NY; Y. Harazono, K. Kobayashi, National Institute of Agro-Environmental Sciences, Tsukuba, Japan; S. Prior, H. Rogers, National Soil Dynamics Laboratory, USDA-ARS, Auburn AL; P. Jamieson, New Zealand Inst. for Crop & Food Res. Ltd., Christchurch, New Zealand; G. Koch, Northern Arizona University, Flagstaff AZ; J. Amthor, Oak Ridge National Laboratory, Oak Ridge TN; F. Wechsung, T. Kartschall, S. Grossmann, M. Bauer, J. Grafe, K. Waloszcyk, Potsdam Inst. for Climate Impact Research, Potsdam, Germany; M. Badiani, A.R. Paolacci, Università della Tuscia, Viterbo, Italy; M. Estiarte, J. Peñuelas, Universitat Autònoma, Barcelona, Spain; R. Grant, University of Alberta, Edmonton, Alberta, Canada; S. Leavitt, M. Ottman, T. Thompson, A. Matthias, D. Williams, M. O'Dea, T. Brooks, J. Triggs, L. Cheng, J. Welzmiller, R. Roth, D. Langston, University of Arizona, Tucson and Maricopa AZ; E. Pendall, University of Colorado, Boulder CO; A. Ball, S. Long, F. Porteous, University of Essex, Colchester, UK; A. Hunt, University of Guelph, Guelph, Ontario, Canada; H. BassiriRad, J. Constable, University of Illinois, Chicago IL; L. Aiguo, University of Idaho, Moscow ID; T. Sinclair, University of Florida, USDA-ARS, Gainesville FL; J. Schleucher, University of Wisconsin-Madison, Madison WI; B. Kimball, P. Pinter, Jr., G. Wall, R. LaMorte, D. Hunsaker, F. Nakayama, F. Adamsen, E. Barnes, N. Adam, M. Conley, U.S. Water Conservation Laboratory, USDA-ARS, Phoenix AZ; A. Frumau, H. Vugts, Vrie Universiteit of Amsterdam, Amsterdam, Netherlands; C. Morris, Western Wheat Quality Laboratory, USDA-ARS, Pullman WA.

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WATER RELATIONS OF GRAIN SORGHUM GROWN IN FREE-AIR CO_2 ENRICHMENT (FACE) WITH VARIABLE SOIL MOISTURE REGIMES

G.W. Wall and N.R. Adam, Plant Physiologists; B.A. Kimball, Supervisory Soil Scientist; P.J. Pinter, Jr., Research Biologist; L. Olivieri and M. Conley, Biological Technicians; and T.J. Brooks and J. Triggs, Research Technicians

PROBLEM: Based on reports by the IPCC (Intergovernmental Panel on Climate Change, 1996) atmospheric CO_2 is rising. Because elevated CO_2 is known to reduce stomatal conductance (g_s) in plants, it may decrease the transpiration rate and the increase net assimilation rate (Garcia et al. 1998; Wall et al.,2000a). An increase in the pool of total non-structural carbon supply may result in an increase in the translocation of carbon below ground for the development of a more robust root system. As observed in wheat, a more robust root system for absorbing water and a greater resistance to water loss by stomata might enable a sorghum plant grown under elevated CO_2 and limited water supply to avoid drought by conserving water (Wall et al.,2000b) and increasing drought tolerance by an enhancement in its osmoregulatory mechanism (Wall et al.,2000c). Consequently, a sorghum plant grown under elevated CO_2 and limited water supply is likely to have less negative leaf water potential (Ψ_T). Based on these observations, a need exists to determine how the interactive effect of elevated CO_2 and water stress will effect Ψ_T for sorghum grown in an open field. Hence, a reasonable hypothesis to test is that any enhancement in water relations through a combination of a reduction in g_s, improvement in osmoregulation, and an increase in water uptake capacity of roots due to elevated CO_2 will result in less negative Ψ_T for sorghum leaves throughout the ontogeny of the crop.

APPROACH: In this study we characterized and qualified values of g_s and Ψ_T for field-grown sorghum grown in air enriched with CO_2 and in ambient air under water-stressed and well-watered soil moisture regimes. During the 1998 and 1999 growing seasons, two experiments were conducted to investigate the interactive effects of elevated CO_2 and limited soil moisture on a sorghum (*Sorghum bicolor* L. *Moench* cv. Dekalb Hybrid DK54) crop grown in an open field at The University of Arizona's Maricopa Agricultural Center, located 50 km south of Phoenix, Arizona (33.1 N, 112.0 °W). Seeds were sown into flat beds in north-south rows ~ 0.76 m apart on July 15-16 ,1998 and June 14-15 ,1999; seeding rates were 10.9 kg ha^{-1} (~40 mm apart for 33 seeds m^{-2};plant density of 22 plants m^{-2}) during 1998 and 10.0 kg ha^{-1} (~41 mm apart for 32 seeds m^{-2}; plant density of 21 plants m^{-2}) during 1999. Regardless of year, a final plant population of about 90,000 plants ha^{-1} was obtained. Fertilizer amounts were applied so that nutrients were non-limiting. Plants were exposed to an elevated CO_2 treatment of ~200 µmol mol^{-1} above ambient (ca. 370 µmol mol^{-1}) for 24 hrs using the FACE approach (Hendrey, 1993). The main CO_2 plots were split. Flood irrigation created a water (H_2O) treatment with each half of the circular plots receiving either ample irrigation regime (Wet, well-watered) or a water-stress treatment with only two irrigation events. The CO_2 and H_2O levels gave four treatment combinations of Control-Dry (CD), Control-Wet (CW), FACE-Dry (FD), and FACE-Wet (FW) replicated four times. Several portable closed-exchange (transient) systems with a 250 cm^3 transparent assimilation chamber were used to make in-situ measurements of g_s at mid-morning (MM; 2.5 h prior to solar noon), midday (MD; solar noon), and mid-afternoon (MA; 2.5 h after solar noon). During similar time periods, values of Ψ_T were obtained from excised uppermost fully-expanded sunlit leaves using a pressure chamber.

FINDINGS: At the stem-elongation growth stage on day of year (DOY) 252, g_s was independent of time of day (Fig. 1). A significant CO_2xH_2O interaction occurred because g_s was lower due to CO_2 under Wet, but there was no effect of CO_2 on this particular day under Dry. As evidenced in the Wet treatment, CO_2 reduced g_s, but the water conserving effect of the CO_2-based reduction in g_s in the Dry plots may have delayed reductions in g_s due to water-stress. Consequently, g_s was actually slightly higher under elevated CO_2 for the Dry plots for a few days (data not shown). Nevertheless, in agreement with other FACE trials on wheat (Wall et al., 2000a,b), FACE consistently reduced g_s in sorghum.

The CO_2-based reductions in g_s for both Wet and Dry treatments caused less negative Ψ_T throughout the ontogeny of the crop (Fig. 2). But, on a relative basis, the water-conserving effect of elevated CO_2 was more pronounced in Dry compared with Wet, and in dehydration cycle II compared with I (significant CO_2xH_2O interaction effects for Ψ_T during dehydration cycle II). Apparently, plants had become preconditioned to drought during dehydration cycle I, and CO_2 affected this effect in a positive manner because in dehydration cycle II the water conserving effect of elevated CO_2 was more significant. A reduction in the internal water deficits in sorghum leaves grown under elevated CO_2 is best explained by the direct effect of CO_2 in reducing g_s (Fig. 1), which conserved water throughout the ontogeny of the crop.

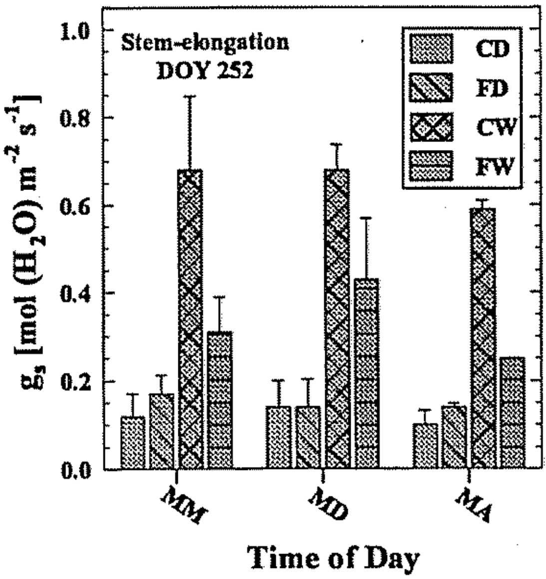

Figure. 1. Leaf stomatal conductance (g_s) of uppermost sunlit sorghum leaves at the stem-elongation growth stage during 1998. The CO_2 treatments were Control [ambient 370 µmol (CO_2) mol^{-1}] and FACE [ambient +200 µmol (CO_2) mol^{-1} for 24 hs. d^{-1}], and the H_2O treatments were either ample or only two irrigation events for well-watered (Wet) and water stress (Dry) treatments, respectively. The combination of CO_2 and H_2O treatments resulted in Control-Dry (CD), FACE-Dry (FD), Control-Wet (CW), and FACE-Wet (FW) treatments. Measurements were taken at mid-morning (MM, 2.5 h prior to solar noon), midday (MD, solar noon), and mid-afternoon (MA, 2.5 h after solar noon). Vertical bars around each datum represent one standard error of the replication means.

INTERPRETATION: In a future high CO_2 world, the pore size of stomata for a sorghum leaf will decrease which will decrease g_s and increase the resistance of water vapor flux from the sub-stomatal cavity to the atmosphere (Fig. 1). For comparable atmospheric and soil moisture conditions, the transpiration rate per unit leaf area of a sorghum leaf grown under elevated CO_2, will be lower than that for a leaf growing at present-day ambient CO_2 (~370 µmol mol^{-1}) levels. Consequently, a leaf growing under elevated CO_2 should have the capacity to maintain higher internal water content throughout the day than a leaf growing at present-day ambient CO_2 levels. A higher internal water content will result in less negative values of Ψ_T at MM, MD, and MA (MD given in Fig. 2) throughout the ontogeny of the crop. The water conserving effect of elevated CO_2 will delay the onset of drought symptoms, thereby enabling stomata to remain open for longer into the day-lit period, even as the drought condition becomes more severe. In the absence of any adverse effects of a concomitant rise in global temperature resulting from the rise in atmospheric CO_2, improved water relations for a herbaceous, warm-season, perennial, C4 grain crop, i.e, sorghum, are anticipated in the future as the CO_2 concentration of the atmosphere continues to rise.

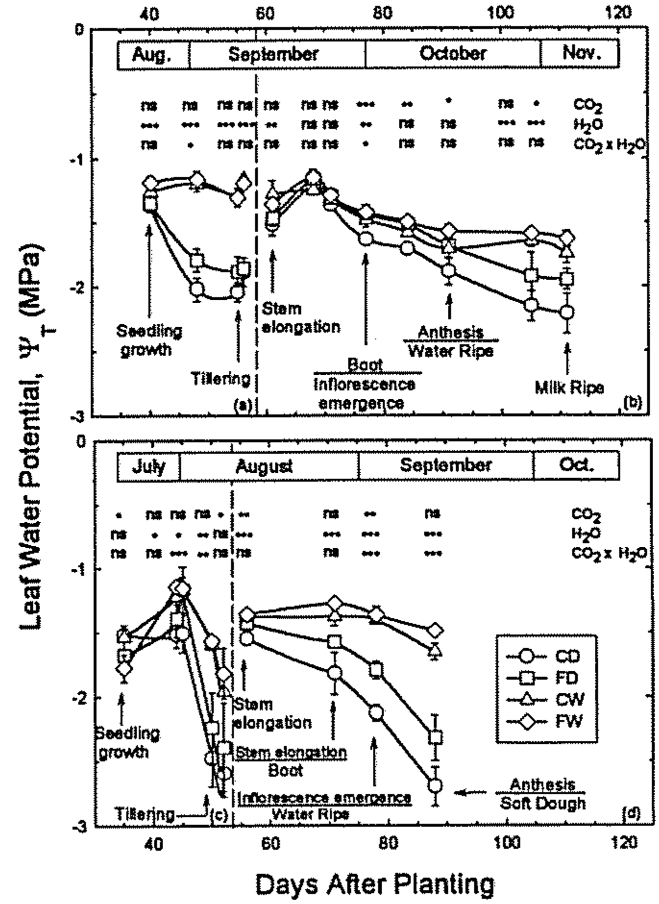

Figure 2.. Midday total leaf water potential (Ψ_T) during 2 soil dehydration/rehydration cycles [cycle I given in panels a and c, and cycle II given in panels b and d, during 1998 and 1999, respectively]. The CO_2 treatments were Control [ambient 370 µmol (CO_2) mol^{-1}] and FACE [ambient +200 µmol (CO_2) mol^{-1} for 24 hrs d^{-1}], and the H_2O treatments were either ample or only two irrigation events for well-watered (Wet) and water stress (Dry) treatments, respectively. Legend same as Fig. 1. Vertical bars around each datum represent one standard error of the replication means. Results of ANOVA for CO_2, H_2O and CO_2xH_2O interaction effects given for each growth stage above each datum as ***, **, *, and NS for $p \leq 0.01$, $p \leq 0.05$, $p \leq 0.10$, and not significant, respectively.

FUTURE PLANS: Our intention is to focus on data summary, analysis, interpretation, and documentation of results from previous FACE experiments on wheat and sorghum. We also will actively plan our next FACE experiment and attempt to obtain the necessary funding.

COOPERATORS: The research was supported by Interagency Agreement No. DE-AI03-97ER62461 between the Department of Energy, Office of Biological and Environmental Research, Environmental Sciences Division, and

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FACE 1998-99: SOIL MOISTURE AND EVAPOTRANSPIRATION IN SORGHUM UNDER ELEVATED CO_2 AND WATER STRESS CONDITIONS

M.M. Conley, Physical Science Technician; B.A. Kimball, Soil Scientist;
G.W. Wall and N.R. Adam, Plant Physiologists; P.J. Pinter Jr., Research Biologist;
D.J. Hunsaker, Agricultural Engineer; and R. LaMorte, Civil Engineer

PROBLEM: Deforestation and increased combustion of fossil fuels due to global industrialization are causing increases in atmospheric CO_2 concentrations. Increases in CO_2 concentration affect plant growth. Previous FACE experiments investigated the impact of a 200 μmol mol^{-1} CO_2 increase on cotton and wheat, which utilize the C3 photosynthetic pathway. The 1998-99 FACE experiment investigated this futuristic atmospheric environment on sorghum, which is a C4 plant.

APPROACH: A Free-Air CO_2 Enrichment (FACE) system consisting of four 25-m diameter rings was used to increase the background CO_2 over field-grown sorghum by 200 μmol mol^{-1}. Four additional rings with identical air flow but at ambient CO_2 served as experimental controls. Vertical 2.5-m-tall CO_2 vent pipes were spaced 2 m apart along the perimeter of each ring. Wind direction, wind speed, and CO_2 concentrations were measured for each FACE ring. These data were used in a computer controlled system that delivered CO_2-enriched air to the upwind side of each FACE ring. The system maintained CO_2 concentrations at 200 μmol mol^{-1} above ambient, 24 hours a day, throughout the growing season.

Half of each ring received ample flood irrigation (Wet) while the other half was water stressed (Dry) in a split-strip plot design. Thus, there were two levels of CO_2 and two levels of soil water supply, each replicated four times creating sixteen semicircular plots.

Soil moisture in terms of percent water by volume, or volumetric theta (m^3 H_2O / m^3 soil), were determined through use of a Cambell Pacific nuclear Hydroprobe. A two-inch-diameter neutron access tube was inserted vertically into the ground in each of the sixteen plots. Measurements were taken at each foot to the six-foot depth during the 1998 season and to the ten-foot depth during the 1999 season. Additional measurements were taken during the 1999 season, including a profile measurement where 120 measurements were taken over a ten-foot profile.

FINDINGS: Significant differences in soil water were detected between Wet and Dry plots during dry-down periods (Fig. 1). There were also substantial differences in soil water between the CO_2 treatments. In addition, a high degree of variability was detected among plots, and by depth. The majority of this variability could be attributed to variable soil texture. Although there was a high degree of relative variability in total water by soil volume, the portion of water available to plants, between field capacity and permanent wilting point, spanned from 1-8% of soil volume with an average of 4%, over a ten-foot profile.

Data for Wet plots in 1998, over six feet of depth (Fig. 1, panel 1), indicate a soil texture difference between the average FACE-Wet plot (more sand) and the average Control-Wet plot (more clay). This resulted in a consistent 1% volumetric water content difference between the two treatments. The soil texture difference between FACE-Dry and Control-Dry plots was smaller. Additionally, two distinct dry-down periods for the Dry plots were apparent, first DOY 228-254 and second, DOY 275-330. A small amount of rainfall (5 mm) occurred on DOY 331.

Soil water content data for the 1999 season, across ten feet of depth (Fig. 1 panel 2), show a consistent 1% difference in soil water similar to 1998 (Fig. 1, panel 1), again suggesting that FACE-Wet contained slightly more sand on average. There was no significant difference in soil water content between the CO_2 treatments under the Dry irrigation treatment. Also shown were three dry-down periods involving the Dry treatments, DOY 200-218, DOY 228-258, and DOY 268-290. Rainfall totaling 56 mm occurred between DOY 263-267.

Evapotranspiration (ET) was calculated using the volumetric dry-down of stored soil water between irrigations. ET was extrapolated during days exhibiting increased volumetric water (due to irrigation or rain water application) by averaging the estimated ET before and after the volumetric increase.

Figure 2, panel 1, depicts mean cumulative evapotranspiration (ET) for the 1998 season calculated over six feet of depth. A difference in cumulative ET occurred between Wet and Dry treatments in early September DOY 240. FACE-Wet and Control-Wet plots show different cumulative ET by mid September. This trend continued until the end of the season where FACE-Wet evapotranspirated 161 mm less water than Control-Wet. FACE-Dry and Control-Dry plots did not show significant differences in cumulative ET. This is consistent with previous FACE experiments (Hunsaker et al., 1996).

Figure 2, panel 2, shows ET data for the 1999 season calculated over six feet of depth. Trends are similar to the 1998 season results except that FACE-Dry and Control-Dry treatments do show a difference in cumulative ET by mid August, and by the end of the season FACE-Dry evapotranspirated 102 mm of water less than Control-Dry. One reason why the FACE effect is visible in Dry treatments during the 1999 season and not in the 1998 season is that Dry treatments in 1999 were more water stressed than in 1998 due to an earlier planting date and decreased amount of applied irrigation. FACE-Wet evapotranspirated 159 mm less water than Control-Wet.

Figure 3, panel 1, shows the soil water profile of plot FACE-Wet Replication-1 on two different days. DOY 236 occurred after an irrigation, while DOY 295 took place near the end of the season in a dry period. Fluctuations in volumetric soil moisture through the ten-foot profile are indicative of a varying soil texture. A "surface effect" created by the scattering of neutrons to the atmosphere is evident in the first nine inches of depth. Estimations of available water and bulk density were derived from physical sampling before the season. Soil horizon labels and relative soil texture designations are provided. There was significant drying of the whole ten-foot profile between the two days.

Figure 3, panel 2, depicts the soil water profile of plot FACE-Dry Replication-1 on the same two days as in Figure 3, panel 1. As with Figure 3, panel 1, the neutron scattering "surface effect" is evident and soil horizon and general relative texture designations are given. Of special interest is that most of the soil dry-down occurred between 0 - 5.5 feet of depth, which suggests that there was a reduced rooting zone in the Dry plots (0 - 5.5 feet).

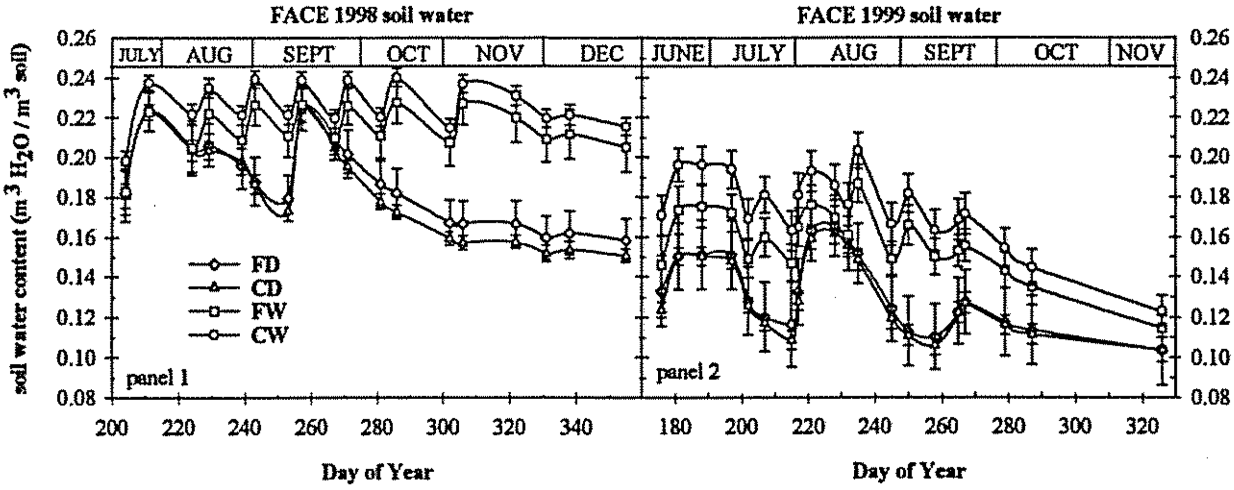

Figure 1. Soil water content means averaged over four replicates and six feet of depth for 1998 (left panel) and over ten feet of depth for 1999 (right panel) verses day of year; where FD = FACE-Dry, FW = FACE-Wet, CD = Control-Dry and CW = Control-Wet. Error bars show standard error calculated for each day between replications.

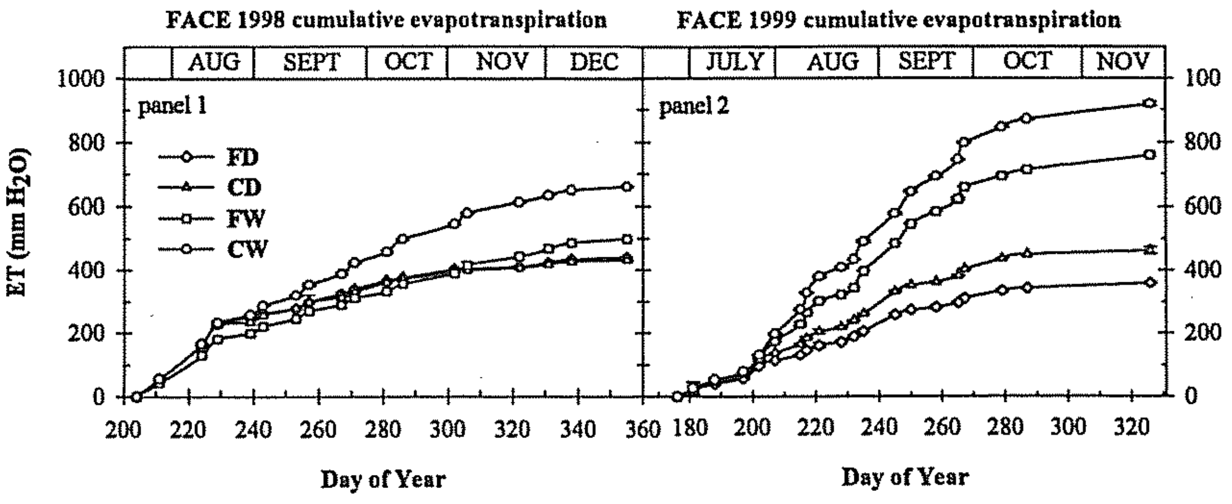

Figure 2. Cumulative evapotranspiration (ET) verses day of year, calculated across six feet of depth for the 1998 and 1999 seasons, where the treatment designations and errors are the same as Figure 1.

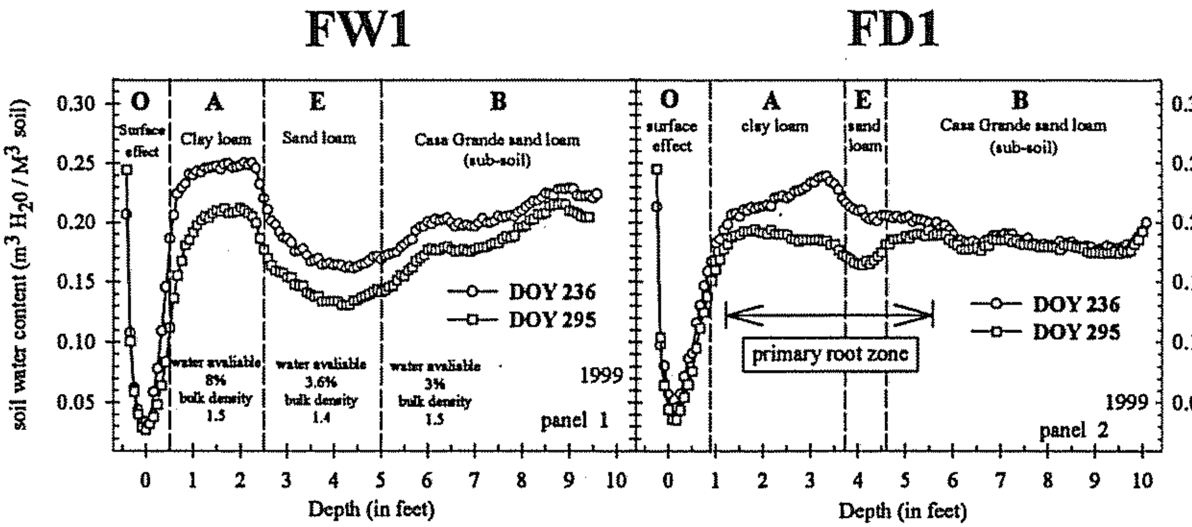

Figure 3. Soil water content in the FACE-Wet Replication-1 plot (FW1) left panel and in the FACE-Dry Replication-1 plot (FD1) right panel, verses depth, taken on contrasting (wet / dry) days with soil horizon, texture, available water and bulk density information.

INTERPRETATION: Measurements with neutron scattering equipment confirmed that a wide separation in the soil water content was achieved between the ample (Wet) and water-stress (Dry) irrigation treatments, as planned. However, within an irrigation treatment, consistent differences in water content were observed that appeared to be due as much to field variability in soil texture, i.e., water holding capacity, as to the CO_2 treatments. Nevertheless, when cumulative evapotranspiration (ET) was computed from the changes in water content during drying within each plot, a consistent, statistically significant pattern emerged. The average cumulative ET for 1998 and 1999 showed sorghum plants in the FACE-Dry plots used 10% less water than those in Control-Dry plots. Likewise, in the amply irrigated (Wet) plots, elevated CO_2 from the FACE treatment reduced seasonal ET by about 20.9%, which suggests that irrigation requirements for sorghum will be smaller in the future high-CO_2 world, provided that global climate changes are minimal.

FUTURE PLANS: Measurements of the soil moisture release characteristic, saturated K^+, bulk density, porosity, and soil texture are to be determined from the plot locations.

COOPERATORS: See list given by Kimball et al. (this volume).

ENERGY BALANCE AND EVAPOTRANSPIRATION OF SORGHUM: EFFECTS OF FREE-AIR CO_2 ENRICHMENT (FACE) AND SOIL WATER SUPPLY

B.A. Kimball, Soil Scientist; J.M. Triggs and T.J. Brooks, Research Technicians; M.M Conley, Physical Science Technician; R.L. LaMorte, Civil Engineer; C. O'Brien, Research Assistant; P.J. Pinter, Jr., Research Biologist; G.W. Wall and N.R. Adam, Plant Physiologists; T.R. Clarke, Physical Scientist; and R. Rokey, Biological Technician (Plants)

PROBLEM: The CO_2 concentration of the atmosphere is increasing and is expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. Such increases in CO_2 and possible climate change could affect the hydrologic cycle and future water resources. One component of the hydrologic cycle that could be affected is evapotranspiration (*ET*), which could be altered because of the direct effects of CO_2 on stomatal conductance and on plant growth. Therefore, one important objective of the Free-Air CO_2 Enrichment (FACE) Project (Kimball et al., this volume) is to evaluate the effects of elevated CO_2 on the *ET* of sorghum and other crops.

APPROACH: We conducted two FACE experiments on sorghum from mid-July to mid-December 1998 and again from mid-June to the end of October 1999 (Kimball et al., this volume).

Briefly, the FACE apparatus consists of the following: Four toroidal plenum rings of 25 m diameter constructed from 12" irrigation pipe were placed in a sorghum field at Maricopa, Arizona, shortly after planting. The rings had 2.5-m-high vertical pipes with individual valves spaced every 2 m around the periphery. Air enriched with CO_2 was blown into the rings, and it exited through holes at various elevations 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 wind direction information to turn on only those vertical pipes upwind of the plots so that the CO_2-enriched air flowed across the plots no matter which way the wind blew. The system used the wind speed and CO_2 concentration information to adjust the CO_2 flow rates to maintain desired CO_2 concentrations at the centers of the rings. The FACE CO_2 concentration was elevated by 200 ppm CO_2 above ambient (about 360 ppm in daytime) 24 hr/day all season long. Four matching Control rings with blowers to provide air flow but no added CO_2 were also installed in the field. Some additional measurements were made in "mid-field" areas between the FACE and Control plots where neither CO_2 nor air flow were altered.

In addition to the CO_2 treatments, varying soil water supply was also a factor. Using a split-plot design, the main circular CO_2 plots were divided into semi-circular halves, with each half receiving an ample irrigation regime (Wet) or else receiving a water-stress treatment (Dry). Using flood irrigation, the Wet plots were irrigated on roughly a two-week schedule, whereas the Dry plots were irrigated only twice (shortly after planting and at mid-season).

The determination of the effects of elevated CO_2 on *ET* by traditional chambers is fraught with uncertainty because the chamber walls that constrain the CO_2 also affect the wind flow and the exchange of water vapor. Therefore, as done previously in the FACE cotton and wheat experiments (Kimball et al., 1994, 1995, 1999), a residual energy balance approach was adopted whereby *ET* was calculated as the difference between net radiation, R_n, soil surface heat flux, G_0, and sensible heat flux, H:

$$\lambda ET = R_n - G_0 - H$$

R_n was measured with net radiometers and G_0 with soil heat flux plates. H was determined by measuring the temperature difference between the crop surface and the air and dividing the temperature difference by an aerodynamic resistance calculated from a measurement of wind speed. Air temperatures were measured with aspirated psychrometers, and crop surface temperatures were measured with infrared thermometers (IRTs) mounted above each plot. Fifteen-minute averages were recorded on a datalogging system. The net radiometers and IRTs were switched weekly between the FACE and Control plots. Moreover, the instruments were carefully calibrated before and after each experiment.

FINDINGS: The micrometeorological data have not yet been analyzed, so no report of the effects of the FACE treatment on the *ET* of sorghum can be made. In the prior FACE cotton experiment, the cotton had a large growth response (40% increase) to the elevated CO_2, but no effect on *ET* was detectable (Kimball et al., 1994). In contrast, with wheat which had a modest growth response (about 20%), the FACE treatment decreased, *ET*, by an average 6.7% (± 1.2%) for the four seasons under Wet, high-nitrogen conditions. Under low nitrogen, the reduction in *ET* was 19.5% (Kimball et al., 1999).

The sorghum growth response to elevated CO_2 was insignificant under the Wet conditions (Kimball et al., this volume), so we hypothesize that there was a reduction in *ET*. Then under the Dry conditions, the lower rate of *ET* following an irrigation enabled the FACE plants to photosynthesize and grow longer into a drought cycle, which resulted in greater total growth and yield under the FACE treatment compared to the Control plots.

INTERPRETATION: It appears from the prior FACE cotton experiments that cotton irrigation requirements will not change, whereas for wheat they may become somewhat lower in the future high-CO_2 world (provided that any global warming is small). We can make no definitive statement about sorghum yet.

FUTURE PLANS: Complete the analysis of the micrometeorological data from the two FACE sorghum experiments and write the corresponding manuscript.

COOPERATORS: See Kimball et al., "The Free-Air CO_2 Enrichment (FACE) Project: Progress and Plans" (this volume).

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FACE 1999: CHANGES IN PHOTOSYNTHETIC APPARATUS OF SORGHUM IN RESPONSE TO CO_2-ENRICHMENT AND WATER STRESS

N. R. Adam and G.W. Wall, Plant Physiologist; B.A. Kimball, Research Leader; P.J. Pinter, Jr., Research Biologist; and R.L. LaMorte, Civil Engineer

BACKGROUND: With the expected doubling of atmospheric levels of CO_2 sometime in the 21st century, it is important to understand how this change will affect our way of life and, more specifically, how it will affect plant life. The Free Atmospheric CO_2 Enrichment (FACE) facility at the University of Arizona Maricopa Agricultural Research Center is helping to determine how plants respond and acclimate to long-term exposure to elevated levels of CO_2 in the field. A compilation of the Maricopa FACE data from 1995 and 1996 showed that elevated CO_2 caused final grain yields of spring wheat, a cool-season crop, to rise by an average of 16% under non-limiting water and nutrient conditions (Pinter et al., 1997). However, under lower levels of nitrogen, CO_2 enrichment increased yields by 8%. In order to predict the responses of wheat to further increases in atmospheric CO_2, we investigated the responses of photosynthetic parameters and proteins of spring wheat to elevated CO_2.

Plants acclimate to changes in CO_2 concentration through changes in the amounts and activities of enzymes required to reestablish a balance within the photosynthetic apparatus. An earlier report (Adam et al., 1997) presented data from a gas-exchange technique in which photosynthesis (A) is measured at a range of intracellular CO_2 concentrations (Ci), providing information on changes within the photosynthetic apparatus. Since Rubisco (the enzyme catalyzing the initial reaction of photosynthesis in spring wheat) capacity is limiting at low values of Ci, the slope of the A-Ci relationship at those low values of Ci can be used to assess changes in the ability of Rubisco to fix CO_2. This slope, called the "carboxylation efficiency", can be used as an indicator of down-regulation in which the amount of Rubisco is decreased in response to the greater concentration of atmospheric CO_2. Because Rubisco can fix either CO_2 or O_2, increases in the relative proportion of CO_2 in the atmosphere could be expected to help the plant fix more CO_2 or to reduce (or down-regulate) the amount of Rubisco in order to fix the same amount of CO_2. If down-regulation does occur, we could expect an upper limit to the yield increases commonly seen under CO_2 enrichment. The carboxylation efficiency of spring wheat was affected by growth in elevated CO_2. Follow-up work to support the carboxylation efficiency data was presented by Adam et al. (1998). By assaying the Rubisco activity and content of the leaves which were used for the A-Ci gas-exchange analysis, we provided further support for down-regulation. The Rubisco activity and content data supported the interpretations of the carboxylation efficiency data, indicating that down-regulation of the photosynthetic apparatus in response to elevated CO_2 did occur. However, the responses of Rubisco activity of wheat to CO_2 enrichment and N fertilization were dependent on growth stage and the position of the leaf within the canopy.

The work with spring wheat, a so-called C_3 plant, indicated that, in order fully to assess the response of crop plants to elevated CO_2, various growth stages and a canopy profile must be measured. Similar experiments were conducted in 1998 and 1999 on sorghum, a warm-season crop with a different, so-called C_4, carbon-trapping mechanism. The carbon-trapping enzyme of sorghum is PEPCase which, unlike Rubisco, fixes only CO_2 and not O_2. The product of the reaction catalyzed by PEPCase is then shuttled to Rubisco and into the Calvin cycle. Because PEPCase has the effect of concentrating CO_2 in the leaf, then plants with this pathway have not been expected to respond greatly to increases in atmospheric CO_2 concentrations. The objective of these experiments was to determine the effect of growth in elevated CO_2 on the gas exchange parameters and photosynthetic proteins of sorghum.

APPROACH: *Sorghum bicolor* (L.) Moench (cv. Dekalb 54) was planted in an open field at The University of Arizona Maricopa Agricultural Research Center, located 50 km south of Phoenix, Arizona (33.1 °N, 112.0 °W). Sorghum was planted on July 13 and 14, 1998, and again on June 14 and 15, 1999, (Kimball et al., 1999, this volume). Fifty percent emergence occurred July 30, 1998, and July 1, 1999. Following sowing, a FACE apparatus was erected on site to enrich the CO_2 concentration of the ambient air (ca. 370 $\mu mol\ mol^{-1}$) to ca. 570 $\mu mol\ mol^{-1}$. Water was applied as a split plot factor using flood irrigation such that "Wet" plots received ample water while "Dry" plots received only two irrigations and were severely stressed. All plots received 278.7 kg ha^{-1} N.

For the first sampling date (the 4^{th} and 5^{th} leaf stage), gas exchange analyses were conducted on the uppermost fully-expanded leaf (referred to as flag leaf) and on the flag minus one leaf. Thereafter, measurements were made on the flag leaf and the flag minus two leaf. Photosynthesis rates were measured over a range of intracellular CO_2 levels, generating an A-Ci curve. At the end of each curve, the leaf was frozen as quickly as possible with a liquid nitrogen-cooled clamp and stored in liquid nitrogen. Activity of Rubisco, PEPCase, and PpdK will be assayed from leaves collected from both years.

FINDINGS: The A-Ci gas exchange measurements made on sorghum during the 1998 season showed a strong reduction in the initial slope of the A-Ci curve due to CO_2 enrichment in the early part of the season (Fig 1). The effect of the CO_2 on the flag leaf was not influenced by irrigation level. However, the effect of the CO_2 on the flag minus two leaf was more consistent in the dry treatment.

INTERPRETATION: The reductions in the carboxylation efficiency of sorghum due to CO_2 enrichment were surprising and seemed to depend on leaf age or growth stage. However, biochemical assays on the frozen leaf pieces must be conducted before conclusions may be drawn as to whether down-regulation did occur.

FUTURE PLANS: Biochemical assays will be conducted on both the 1998 and 1999 samples to determine activities and relative quantities of key enzymes of the sorghum photosynthetic pathway. The assay results will be compared to the gas exchange data in order to determine whether down-regulation is occurring or if there is some other mechanism involved.

COOPERATORS: We wish to acknowledge the collaborative efforts of Andrew Webber of Arizona State University, Tempe AZ, for helpful advice and the use of his laboratory; Steve Leavitt, Alan Matthias, and Tom Thompson of the University of Arizona, Tucson AZ; Bob Roth and Dave Langston from the Maricopa Agricultural Center, Maricopa AZ; Keith Lewin, John Nagy, and George Hendrey of Brookhaven National Laboratory, Uptown NY; and George Koch of Northern Arizona University, Flagstaff AZ. We also thank Jonathan Triggs and Jose Olivieri for technical assistance.

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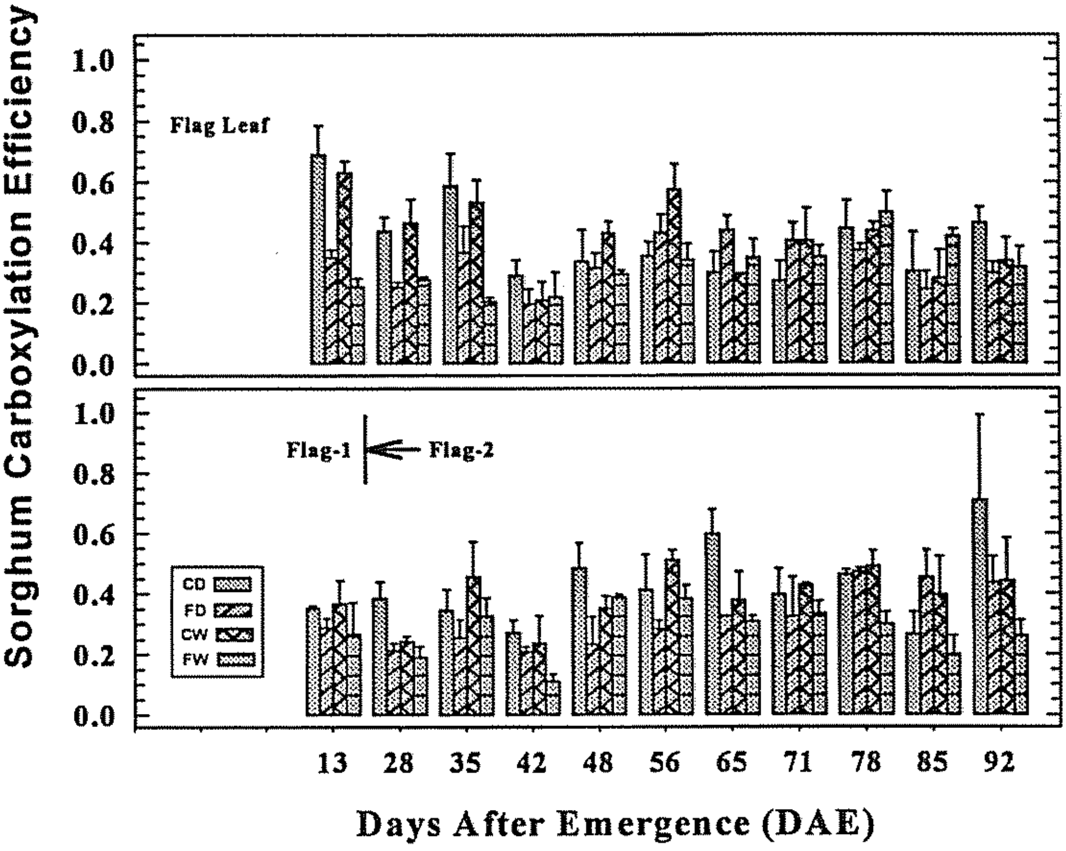

Figure 1. Carboxylation efficiency of the uppermost, fully-expanded (flag) leaf and a lower (flag-1 or flag-2) leaf of sorghum throughout the 1998 season. Treatments include: CD or Control-Dry (normal CO_2 and water stress); FD or FACE-Dry (enriched CO_2 and water stress); CW or Control-Wet (normal CO_2 and ample water); and FW or FACE-Wet (enriched CO_2 and ample water).

THE ENHANCEMENT OF PHOTOSYNTHESIS DURING THE 1999 FACE SORGHUM EXPERIMENT.

A.B. Cousins, Graduate Student; N.R.Adam and G.W. Wall, Plant Physiologists; and A.N. Webber, Professor

PROBLEM: Natural processes of the earth, coupled with the onset of the industrial revolution and the exponential growth of the human population, are causing rapid changes to our environment at unprecedented rates. By the end of the next century, anthropogentic activities are predicted to cause the earth's atmospheric carbon dioxide (Ca) concentration to double to ca. 700 µmol mol^{-1} (McElroy, 1994). Researchers have studied effects of elevated Ca on many aspects of plant development, metabolic regulation and net photosynthetic productivity (see recent reviews Stitt, 1991; Bowes, 1991). Increasing Ca is predicted to cause a significant response in photosynthesis of terrestrial plants, in particular the assimilation of carbon by Ribulose bisphosphate carboxylate/oxygenate (Rubisco) and Phosphoenol Pyruvate carboxylate (PEPC) (Edwards and Walker, 1983).

C4 plants, such as sorghum, have the ability to concentrate CO_2 at the site of Rubisco to concentrations 10-20 times that of atmospheric levels. Coordination and compartmentalization of specific biochemical and anatomical features are required to maintain and utilize this CO_2 pump. In mesophyll cells (MSC) CO_2, in the form of HCO_3^-, is fixed by PEPC into Oxalacetic Acid (OAA), which is converted to malate (MA) and passively transported into bundle sheath cells (BSC). Within BSC, MA is decarboxylated releasing CO_2 which enters the photosynthetic carbon reduction (PCR) cycle. Two adenosine-triphosophate (ATP) molecules are required to regenerate Phosphoenol Pyruvate (PEP) from pyruvate produced from the NADP-malic enzyme catalyzed MA decarboxylation reaction. The basal energy requirement of the NADPH-type C4 mechanism is 5 ATP and 2 NADPH per CO_2 fixed. However, the quantum requirement of C4 plants varies depending on the extent of CO_2 leakage from the BSC, overcycling of the C4 pump, and the contribution of the Q-cycle to the production of the proton motive force. Calculations of the resistance to CO_2 diffusion from BSC to intercellular space r_c (m^2 s mol^{-1}) and the total resistance to diffusion of CO_2 from air to chloroplast of BSC r_t (m^2 s mol^{-1}) have been made from measurements of photosynthesis, photorespiration, and O_2 isotope exchange measurements (He and Edwards, 1996). Data analyzed from Dai *et al.* (1995) shows the lowest r_c values in *Z.mays* came from young and senescing tissues. This implies that as the value of r_c decreases, the ability of CO_2 to diffuse between the BSC and the intercellular spaces of the mesophyll cells increases.

Due to the ability of C4 plants to concentrate CO_2, they are not expected to show an increased growth response to elevated Ca levels. However, several studies have shown that growth of C4 plants under elevated atmospheric CO_2 concentrations, even under well watered conditions, stimulates an increase in biomass production. One possible explanation for the growth stimulation of C4 plants at high CO_2 is that the immature C4 pathway in young leaves has C3-like characteristics, and consequently photosynthesis is responsive to increasing CO_2 supply above the current ambient concentrations. Under current atmospheric CO_2 concentrations, the carboxylation reaction in C3 plants is inhibited by the oxygenation reaction, which reduces the net uptake of carbon. A reduction in O_2 partial pressure increases the efficiency of the carboxylation reaction and stimulates the net rate of carbon assimilation. In *Zea mays*, the development of the C4 photosynthetic apparatus occurs early in leaf development. As young leaves emerge into full sunlight from the surrounding whorls formed by older leaves, the expression and compartmentalization of the C4 photosynthetic apparatus is nearly complete. A similar pattern of development of the C4 photosynthetic pathway is observed in sorghum (Cousins, unpublished observations).

In this study we monitored the effects of Free Air Carbon-Dioxide Enrichment (FACE) conditions on the photosynthetic performance of *Sorghum bicolor* DK54. Following the ontological plant development throughout the growth season of the FACE sorghum project, the uppermost fully-expanded leaves were sampled at various days after planting (DAP). We used the measurements of chlorophyll-A fluorescence and carbon assimilation to address energy utilization, quantum requirement, oxygen sensitivity and net photosynthesis (A*) enhancement of FACE-grown plants.

APPROACH: Field grown *Sorghum bicolor* (DK54) was exposed to ambient (~370 µmol mol^{-1}) and FACE (ambient +200 µmol mol^{-1}) CO_2 levels as described by Kimball *et al.* "Progress and Plans for the FACE Project" and Pinter *et al.* "Daytime CO_2 and Nighttime Blower Effects on Canopy Temperatures and Frost Damage during the 1998 FACE Sorghum Experiment" in the 1998 USWCL Annual Research Report.

Plant material was sampled prior to 7:30 am and stored at 10°C in darkness until measurements were made as described by Adam *et al.* (submitted). Leaf samples to be measured were placed into a 6400-06 PAM2000 Adapter cuvette (LiCor, Inc., Lincoln NE), which fits the fiber-optic probe of the pulse modulated fluorometer (PAM 2000, Walz, Effeltrich, Germany) above the leaf at a 60 degree angle. Plants were dark-adapted for a minimum of one hour and simultaneous measurements of chlorophyll A fluorescence and gas exchange were made to determine dark respiration rates (R_D), F_O and F_M values. Subsequently, the cuvette was illuminated with ~800 µmol photon $m^{-2}s^{-1}$ by a 400 W halogen lamp, and leaf temperature was maintained at 30±1°C. Leaf samples were acclimated for approximately one hour until steady state photosynthesis and chlorophyll-A fluorescence were attained. The quantum yield of PSII (ϕPSII), determined by $\phi PSII = (F_M - F_S)/F_M$, and carbon assimilation (A, µmol $CO_2 m^{-2} s^{-1}$) were simultaneously determined at [Ca] values of 75, 200, 370, 570 and 700 µmol mol^{-1} in air containing 21% or 2% oxygen.

FINDINGS: The photosynthetic (µmol CO_2 $m^{-2}s^{-1}$) response (A) and dark respiration rates of *S. bicolor* measured at growth CO_2 concentrations for ambient and FACE conditions were measured throughout the season, Table 1. The percent stimulation of A for FACE grown plants is shown in Table 1. At 6 days after planting (DAP), the second leaf was the uppermost fully expanded and showed the largest percent increase, 37% (p=0.027207). Less pronounced increases in assimilation occured later in the growth season at 28 (p=0.017191), 36 (p=0.017521) & 60 (p=0.02224) DAP. Carbon assimilation of fully expanded leaves of C4 plants have been reported to be saturated at current atmospheric CO_2 concentrations. To investigate further the enhancement of carbon assimilation by FACE, condition A was measured at growth CO_2 concentrations in air containing oxygen concentrations of both 21% and 2%, Figure 1a &b. A 16 % (p=0.094363) increase in stimulation of A by 2% O_2 for abmient grown plants occurred in the second leaves at 6 DAP.

The stimulation of A at 2% O_2 observed at growth [CO_2] was not observed at lower CO_2 concentrations. This may be due to the requirement of C3 cycle activity on the supply of NADPH from C4 cycle activity. The quantum efficiency of CO_2 fixation for leaves 3 and 5 are approximately 12 and 13 at higher [Ca] but increased slightly as the [Ca] decreased (data not shown). In the second leaves, the fPSII/ϕCO_2 greatly exceeded the theoretical minimum energy requirement at low [Ca] but the ratio dropped close to the minimum value of 8 as [Ca] increases. At low [Ca] the large energy requirement per CO_2 fixed may be due to the overcycling of the C4 pump and leakage of CO_2 from within the BSC. Increasing the [Ca] reduces overcycling and leakage of CO_2 from the BSC and inhibits photorespiration, causing a reduction in the ϕPSII/ϕCO_2 ratio.

INTERRETATIONS: Carbon assimilation, when measured at growth [Ca], in young *S. bicolor* leaves was enhanced by FACE conditions. Partial stimulation of A in young plants was due to oxygen sensitivity as shown by the increase in A at 2% O_2. Additionally, elevated [Ca] enhanced energy use efficiency possibly by decreasing overcycling of the C4 pump and reducing the amount of CO_2 leaking from the BSC. These results suggest that the stimulation of C4 photosynthesis under elevated CO_2 is due to the enhancement of A and energy use efficiency early in the development of the plant. Further investigations are needed to understand leakiness and overcycling of leaves in young sorghum plants.

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Table 1. Gross assimilation, A, and respiration rates, R_D (μmol CO_2 m^{-2} s^{-1}), of the uppermost fully expanded leaves from ambient and FACE treatments at various days after planting. Measurements were made at ambient and FACE growth CO_2 concentrations, 370 μmol mol^{-1} and 570 μmol mol^{-1} respectively. n = 3 (SE).

	Gross Photosynthesis (A) μmol CO_2 m^{-2} s^{-1}		**% difference**	**R_D** μmol CO_2 m^{-2} s^{-1}	
DAP	Ambient	FACE		Ambient	FACE
6	23.33(±2.05)	31.90(±2.61)	36.7	-0.80(±0.28)	-1.86(±1.01)
9	27.86(±2.73)	28.00(±1.66)	0.5	-2.30(±0.13)	-2.49(±0.61)
19	29.40(±2.15)	26.33(±1.29)	-10.4	-1.19(±0.29)	-0.61(±0.21)
23	22.23(±1.51)	25.80(±1.35)	16.1	-2.39(±0.39)	-2.28(±0.17)
38	26.46(± 1.31)	29.91(±1.54)	13.0	-0.93(±0.27)	-1.10(±0.28)
60	25.91(± 0.29)	29.85(±0.93)	15.2	-1.00(±0.26)	-0.76(±0.23)

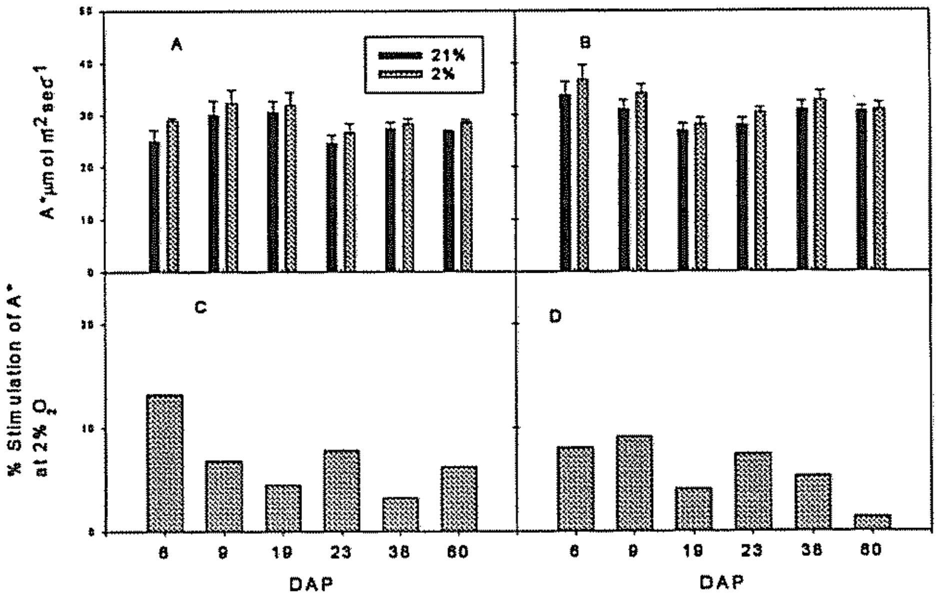

Figure 1. The response of A* to changes in ambient O_2 concentrations. Measurements were carried out at ambient growth [Ca] values of 370ppb (A) and FACE-grown conditions of 570ppb (B). The percent enhancement of A* by 2% oxygen for ambient and FACE conditions, (C) and (D).

EFFECTS OF WATER STRESS AND CO_2 ON SORGHUM CANOPY ARCHITECTURE AND GAS EXCHANGE: A RATIONALE FOR STUDY AND PROGRESS REPORT

T.J. Brooks and J.M. Triggs, Research Technicians; M.M. Conley, Physical Science Technician;
G.W. Wall, Plant Physiologist; P.J. Pinter, Jr., Research Biologist;
B.A. Kimball, Research Leader; and R.L. LaMorte, Civil Engineer

PROBLEM: The Intergovernmental Panel on Climate Change (IPCC) reports that global CO_2 levels will rise from the current ambient level of 370 μmol mol^{-1} to over 500 μmol mol^{-1} by the end of the 21st century (IPCC, 1995). Of primary concern to the human population is the impact that rising global CO_2 concentrations will have on agriculture. The U.S. Water Conservation Laboratory (USWCL) Environmental and Plant Dynamics (EPD) Group has been investigating the impact of increased CO_2 and water stress on various C3 agricultural crops for the past 8 years through the use of a Free-Air CO_2 Enrichment apparatus (FACE) (Hendrey, 1993; Hendrey and Kimball, 1994). These FACE experiments used small (1m^2) pop-on chambers to measure the rates of net photosynthesis and canopy conductance, thereby providing "snapshots" of crop physiology (Kimball et al., 1995) Results from these investigations have enabled members of the EPD Group to conclude that canopy photosynthesis and water use efficiency are improved in C_3 plants, such as wheat and cotton, when subjected to CO_2-enriched environments (Kimball et al., 1995).

The primary carboxylating enzyme for carbon assimilation in C3 plants is ribulose-1,5-bisphosphate oxygenase/carboxylase (Rubisco), though phosphoenolpyruvate carboxykinase (PEPC) is present (approximately 20:1 ratio of Rubisco to PEPC). Rubisco may account for as much as 50% of all soluble leaf protein. Rubisco is not saturated at normal atmospheric CO_2 concentration. Thus, as CO_2 is increased, the relative saturation of Rubisco increases and the overall photosynthesis rate increases.

A second type of carbon assimilation, the C4 pathway, is used by plants such as sorghum, maize, and sugarcane. This pathway relies on PEPC as the primary carboxylating enzyme. Unlike a C3 plant, special Krantz anatomy compartmentalizes the carbon assimilation pathway into the bundle sheath cells and the mesophyll. In essence, compartmentalization and PEPC act to serve as a CO_2 concentrating mechanism.

The FACE 1998-2000 investigation sought to understand if improved plant growth and yield observed for C3 crops would be similar for C4 sorghum when grown in a CO_2-enrichment x water stress experiment. For well-watered conditions, it is unlikely that sorghum will respond to CO_2 enrichment, because the CO_2 concentrating mechanism keeps PEPC near saturation regardless of ambient CO_2 concentration. However, it is suspected that drought stress may cause minute changes in the cellular structure of Kranz anatomy allowing CO_2 to "leak" in and out of the bundle sheath cells. Bundle sheath cell leakiness would allow for a greater response to CO_2 for sorghum grown under water-stressed conditions than ample-watered conditions. In addition, previous FACE experiments on C3 species have demonstrated that elevated CO_2 causes partial stomatal closure thereby improving plant water use efficiency and reducing soil water depletion. It is possible that sorghum may react in a similar manner during early growth as the C4 mechanism develops and later due to bundle sheath cell leakiness.

APPROACH: Four 25-m-diameter rings were placed in the field and used continually to enrich the CO_2 concentration of the air to 200 μmol mol^{-1} above ambient. Four identical rings served as controls. Ample water was applied to one half of each ring, while the other half was subjected to water stress (strip-split plot design). "Flow-through" chambers were placed in each treatment of replicates 3 and 4 and were used to collect canopy carbon exchange data for a period of 10 days. At the end of this time period the chambers were moved to a new location within the treatment. Measurements of canopy greenness, plant area index (PAI), mean leaf tip angle distribution (LTA), and solar radiation (PAR) were made on a weekly basis. Resulting data are in the process of being analyzed.

FINDINGS: As of the writing of this report, data collection and analysis were still under way; however, a sample of each data type collected has been provided in the following figures.

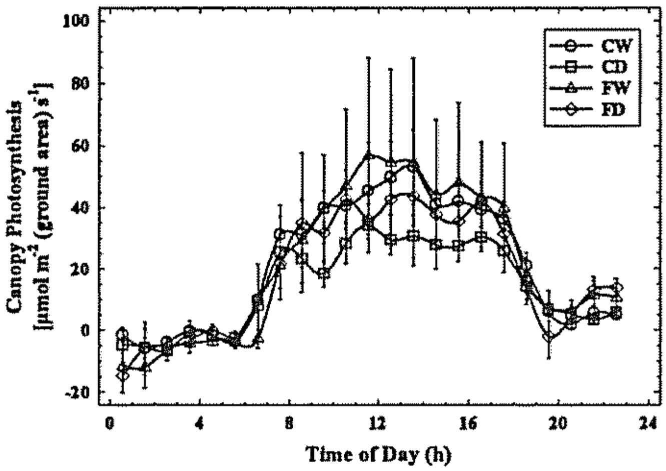

Figure 1. Sorghum canopy photosynthesis rate for July 24, 1999 (DOY 203). Data are plotted as hourly averages across 2 replicates. Error bars represent 1 standard error of the mean.

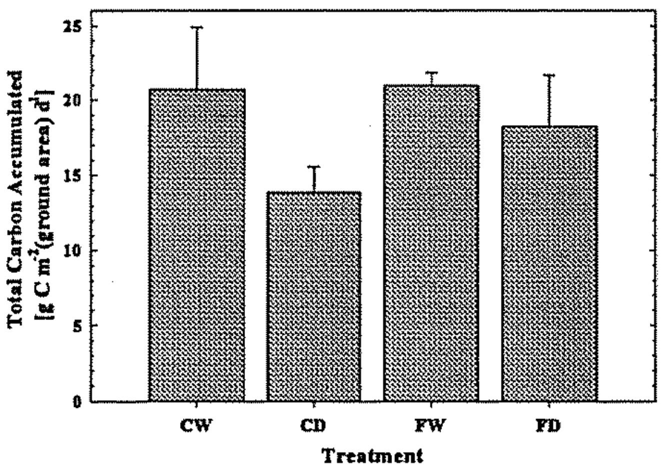

Figure 2. Daily total carbon accumulation. The areas under each curve presented in Figure 1 were integrated to provide the total amount of carbon accumulated by the plant during that day (DOY 203). Error bars represent 1 standard error of the mean.

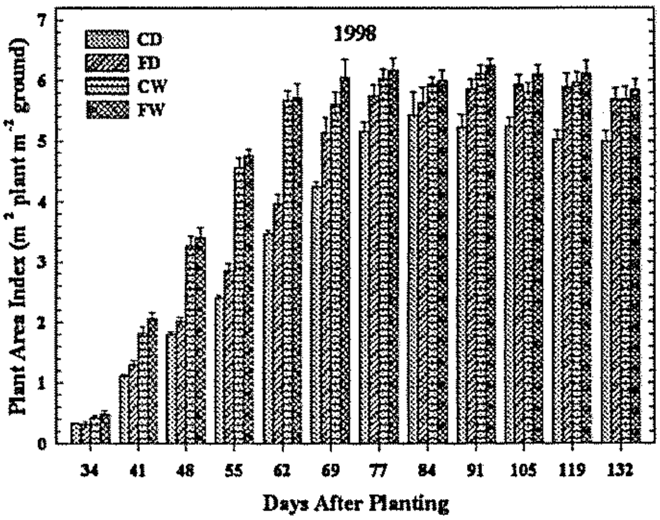

Figure 3. Plant area index for 1998. Plant area index is a derived factor relating the surface area of standing plant occupying a given ground area.

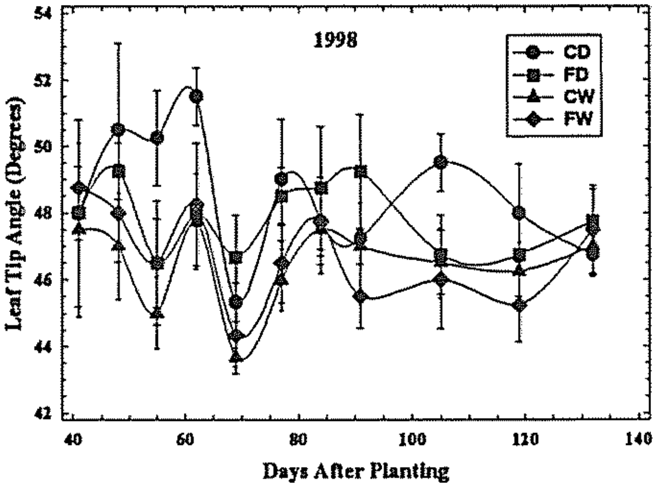

Figure 4. Mean leaf tip angle distribution during 1998. 90 degrees represents a horizontal leaf surface.

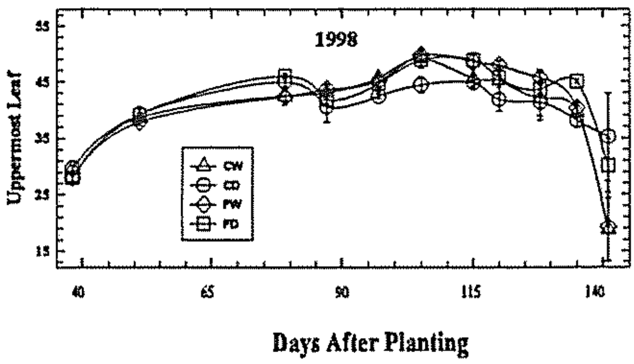

Figure 5. Uppermost fully expanded leaf greenness during 1998, as measured using a portable leaf chlorophyll meter. Similar measurements were made on leaves lower in the canopy as well.

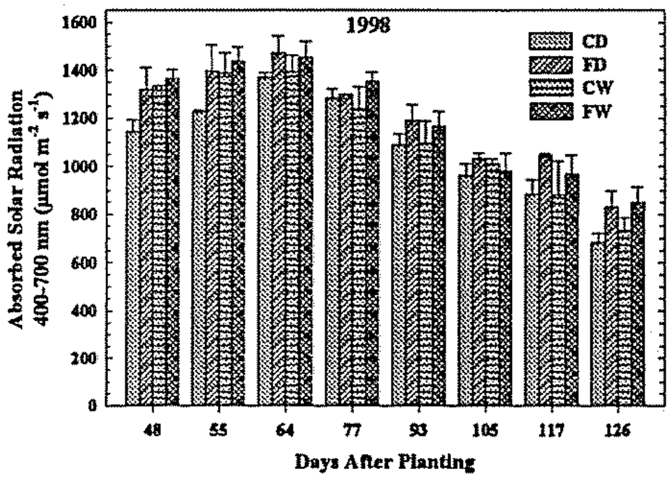

Figure 6. Total absorbed solar radiation during 1998. This data was collected in such a manner that it can be broken down into 0.20 - m increments throughout the growing season to allow for the calculation of radiation use efficiency at different canopy heights

INTERPRETATION: Initial analysis suggests that CO_2 affected whole canopy photosynthesis rates, architecture, and light capture for plants grown under water-stressed conditions more than those given ample water. The degree to which each parameter was affected is indeterminate at this stage of the analysis.

FUTURE PLANS: We will continue with data analysis; the results will be used in a manuscript for publication in a peer-reviewed journal and as a chapter in my doctoral dissertation. Data collected during this experiment also will be used as a validation data set for computer modeling applications pertaining to plant growth and global climate change. An extended stay at the University of Alberta to work with Dr. Robert Grant on the latter topic is currently planned for January-April 2000.

COOPERATORS: see Kimball et al., this report.

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NDVI, fAPAR, AND PLANT AREA INDEX IN THE 1999 FACE SORGHUM EXPERIMENT

P.J. Pinter, Jr., Research Biologist; B.A. Kimball, Supervisory Soil Scientist; R.R. Rokey and S.M. Gerszewski, Biological Technicians; T.J. Brooks, Research Technician; R.L. LaMorte, Civil Engineer; and G.W. Wall and N.R. Adam, Plant Physiologists

PROBLEM: Anticipated increases in atmospheric carbon dioxide (CO_2) and changes in global climate will have important consequences for production agriculture and the world's food supply. Evidence from Arizona Free Air Carbon dioxide Enrichment (FACE) experiments and similar studies at other FACE sites around the world have revealed positive effects of elevated CO_2 on the productivity of C_3 plants under natural field conditions. During 1998 and 1999 we used FACE to study the interactive effects of supra-ambient concentrations of CO_2 and reduced water supply on the agronomy and final yields of grain sorghum, a globally important C_4 crop species. This report discusses preliminary results from that experiment using several non-destructive methods to infer canopy development and light absorption.

APPROACH: Sorghum (*Sorghum bicolor* L. Dekalb Hybrid DK54) was sown (10.0 kg ha^{-1}; ~318,000 seeds ha^{-1}) in north-south rows spaced ~0.76 m apart at The University of Arizona Maricopa Agricultural Center (MAC) on June 14 and 15, 1999. Emergence of seedlings occurred on or about July 2, 1999; density was estimated at 26.0 plants m^{-2}. Treatments were similar to those imposed in 1998. Plants were exposed to ambient (Control, ~370 μmol mol^{-1}) and enriched (FACE, +200 μmol mol^{-1} above ambient) CO_2 levels; treatments were replicated four times. CO_2 treatment plots were split in half to test the effect of different flood irrigation regimes on sorghum response to CO_2. The final harvest of plots in the FACE arrays took place on October 26, 1999. Additional experimental details can be found in Kimball et al., "The Free-air CO_2 Enrichment (FACE) Project: Progress and Plains" pages 58-60 in this volume.

NDVI. Canopy reflectance factors were obtained 45 times between June 24 and October 22, 1999, using a handheld radiometer (Exotech, Inc., Gaithersburg, MD) equipped with 15° fov optics. Twenty-four measurements were taken along a 7 m transect on the north edge of the no-traffic, final harvest area in each treatment combination and replicate. Data were obtained at a time corresponding to a nominal solar zenith angle of 45°. Red (0.63 to 0.69 μm) and near-infrared (NIR, 0.78 to 0.89 μm) reflectance factors were used to compute the Normalized Difference Vegetation Index [NDVI = (NIR-red)/(NIR+red)].

fAPAR. Incident (I), transmitted (T), and reflected (R) light in photosynthetically active wavelengths (PAR, 0.4 to 0.7 μm) were measured just prior to midday (1100-1215h MST) on 7 dates during the season using an Accupar sensor (Decagon Instruments, Inc., Pullman, WA). Measurements were taken above and below the plant canopy in six adjacent rows along the north edge of the final harvest area. The 80 cm-long sensor was oriented perpendicular to plant rows. Data were recorded separately for each 5 cm segment of the sensor. Reflected PAR also was obtained over a bare soil plot ($RPAR_s$). The fractional amount of PAR ($fAPAR_c$) was computed using a light balance equation:

$$fAPARc = 1 - \left(\frac{TPARc}{IPAR}\right) - \left(\frac{RPARc}{IPAR}\right) + \left(\frac{TPARc}{IPAR}\right) * \left(\frac{RPARs}{IPAR}\right)$$

where the subscripts c and s refer to the sorghum canopy and a bare soil plot, respectively.

PAI. A Plant Canopy Analyzer (LAI-2000, LICOR Inc., Lincoln, Nebraska) was used to obtain data on plant area index (PAI). Data were collected shortly after dawn at 1-3 week intervals during the season (7 dates). The sensor was deployed between six adjacent rows on the north edge of the final harvest area. The sensor and canopy were shaded from direct beam solar radiation with a manually positioned, opaque panel measuring 1 by 1 m and held at a distance of 5 to10 meters from the optics. The PAI parameter was determined from a total of 3 measurements above the canopy and 18 below the canopy in each plot. A radiative transfer algorithm computes PAI from canopy light interception at 5 different angles of incidence on the fish-eye like sensor (148° field-of-view).

FINDINGS: NDVI. The seasonal NDVI data are shown in figure 1. The upper panel shows the mean ± 1 standard error of each treatment combination (abbreviations refer to: CD, Control Dry; CW, Control Wet; FD, FACE Dry; FW, FACE Wet). The bottom panel shows the mean of each treatment relative to the value observed in the Control Wet treatment. The NDVI trajectory revealed an early season phase where the signal was dominated by reflectance of bare soil and modulated by seedlings that were slowly increasing in size. This was followed by a rapid increase in NDVI as the plants entered an exponential growth phase and rapidly attained full canopy cover. Water stress between day of year 190 and 225 resulted in lower NDVI values for the dry treatments. The NDVI for the wet treatments attained a plateau for about 3 weeks before panicle emergence (~DOY 235), then declined gradually due to spectral properties of developing heads and senescing leaves. The NDVI decline was slightly faster in FACE Wet compared with Control Wet, and more pronounced in the Dry compared with the Wet treatments.

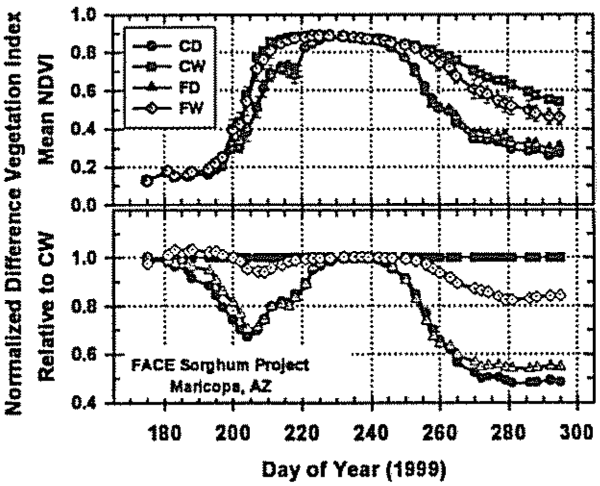

Figure 1. NDVI measured in sorghum in 1999.

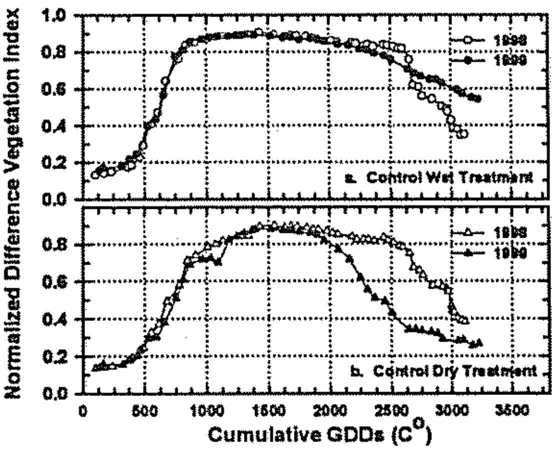

Figure 2. NDVI vs cumulative growing degree days for the Control CO_2 treatments in 1998 and 1999.

Seasonal NDVI trajectories can be superimposed to examine year-to-year differences in canopy response to treatments or variation in climate. In Figure 2, we graph NDVI against cumulative growing degree days (GDDs) calcClated from the AZMET weather station at MAC. Figure 2a reveals early season similarities in the Control Wet treatments for both 1998 and 1999 despite a one-month difference in planting date. Additionally, the NDVI data from 1999 shows what we believe is a typical end-of-season senescence pattern, while that from 1998 displays a non-typical, protracted green canopy duration caused by suboptimal late-season temperatures followed by a two-step decline in green canopy after frost events (Pinter et al, 1998 USWCL Annual Research Report). The early- and late-season water stress in the dry treatment was much more severe in 1999 than in 1998 as shown by lower NDVI from ~900 to 1100 GDDs and after 1900 GDDs.

fAPAR$_c$. Data on canopy PAR absorption were first obtained with the Accupar sensor beginning in mid-August (DOY 201), about 3 weeks after plant emergence (Fig. 3). From that point in the season until the plants completely covered the soil in mid-August, we observed rapid increases in midday fAPAR$_c$. Considering the differences in planting dates and thermal time between 1998 and 1999, the fAPAR$_c$ data were qualitatively similar in both years. Significant fAPAR differences were noted between irrigation treatments both early and late in the season while there was little effect that could be attributed to the CO_2 treatments. The fAPAR$_c$ for the wet irrigation treatments remained >90% from before heading until the end of September (early- to mid-grain fill). Towards the end of the season, the dry treatments absorbed about 10-15% less PAR than their wet counterparts.
PAI. The LAI-2000 measurements of PAI also were similar to those seen in 1998. Significant

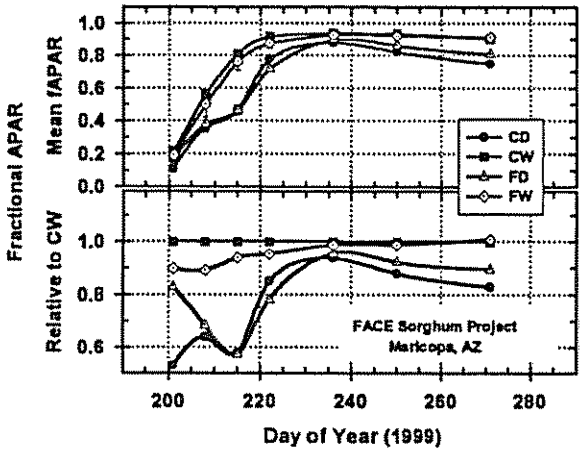

Figure 3. Fraction of absorbed photosynthietcally active radiation (fractional APAR) during 1999.

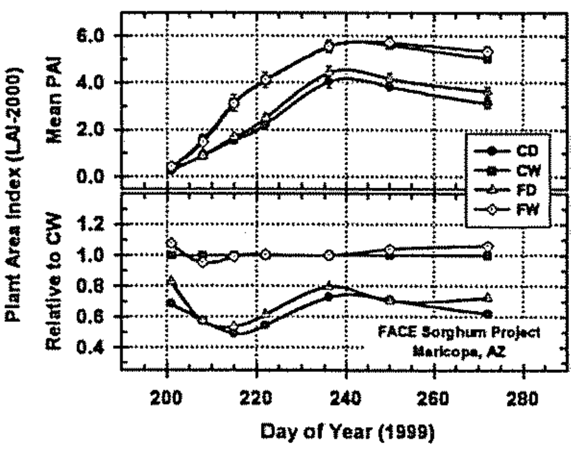

Figure 4. Plant area index measured with the LAI 2000 during 1999.

differences were observed between irrigation treatments in the rate and extent of plant canopy development (Fig. 4). There was a steady increase in PAI in the wet treatments up until early-September, and then it leveled off at about 5.5 to 6.0 units both in elevated and ambient CO_2 treatments. PAI in the dry treatments also increased in a regular fashion, albeit at a noticeably slower rate. At anthesis (early- to mid- September), PAI in the dry treatments was 70 to 80% of that observed in the wet treatments. Elevated CO_2 had little effect on PAI in either the wet or dry irrigation treatments. Unlike the NDVI, which saturated for several weeks around anthesis, PAI retained the capability clearly to distinguish between the water stressed treatments throughout the season.

INTERPRETATION: The NDVI, PAI, and fAPAR$_c$ measurements were useful for contrasting sorghum response to experimental treatments and for comparing overall canopy behavior in the 1998 and 1999 FACE experiments. The early- and mid-season canopy responses under well-watered conditions were qualitatively similar both years despite the one-month difference in planting dates. On an absolute basis, however, the maximum PAI attained under the wet treatment in 1999 was about 8% lower than the maximum measured in 1998 (5.7 versus 6.2 units, respectively), an observation that may help explain the difference in grain yields between the two years. Each of the approaches discussed in this report also showed that the dry irrigation treatment reduced canopy development and persistence significantly compared with the wet treatment. The data further confirmed that the water stress imposed on the dry treatments in 1999 was more severe than in the previous year and caused a significantly shorter green canopy duration.

The NDVI data revealed some interesting differences between 1998 and 1999 in the way the crop responded to elevated CO_2. For example, in 1998 we observed that extra CO_2 stimulated early season plant growth and increased the amount of PAR that was captured by the sorghum canopy for potential use in photosynthesis. In 1999, however, the wet treatments showed almost no effect of elevated CO_2 early in the season, and a slightly increased rate of senescence towards the end of the season. In both years however, sorghum exposed to elevated CO_2 and water stress displayed higher NDVI values than their Control counterparts. The NDVI data obtained during the final portion of the growing season revealed substantial differences between the two experimental years during the grain filling period. In 1998, the canopy stayed green later into the season. In fact, leaf senescence was not noticeable until frost actually killed the tissue. The 1999 NDVI trajectory showed a gradual decline in green canopy during grain fill, a response which may be more typical for this cultivar when end-of-season temperatures are more favorable.

In general, we found each of these non-invasive approaches very useful for monitoring the sorghum canopy. Depending on the size of the plants and stage of growth, each varied in its suitability for detecting treatment differences. Besides being much more convenient to measure, the NDVI proved superior to direct $fAPAR_c$ or PAI measurements for several reasons. First, NDVI could be measured early in the season when plants were small and the physical size of the Accupar or LAI 2000 sensors precluded their use. NDVI also showed large differences between treatments late in the season, when canopies were senescing and the two other approaches were not able to distinguish between green and senescent plant tissues. On the other hand, during the middle of the season when canopy had reached full development and NDVI saturated, the PAI measurements with the LAI 2000 sensor remained sensitive to differences between the treatments. Finally, the Accupar sensor provided fundamental information on spatial variation of $fAPAR_c$, a biophysical parameter required to calibrate the NDVI and was useful as an input for plant growth models.

FUTURE PLANS: Analysis of these data are continuing. Comparisons will be made between data from these non-invasive techniques and conventional agronomic measures of plant growth. Methods will be sought to extend the Accupar-derived $fAPAR_c$ versus NDVI relationship beyond anthesis so that NDVI can be transformed into a biophysical parameter having biological significance for the entire growing season. NDVI also will be used to confirm whether the experimental treatments or the blower apparatus itself has an influence on end-of-season rates of canopy senescence.

COOPERATORS: Collaborators include M. Ottman, A. Matthias, S. Leavitt, D. Williams and T. Thompson from The University of Arizona, Tucson AZ; B. Roth and J. Chernicky from MAC, Maricopa AZ; and K. Lewin, J. Nagy, and G. Hendrey from Brookhaven National Laboratory, Uptown NY. We also wish to thank J. Triggs and P. Bierly for technical assistance in the field. See Kimball et al. "Progress and Plans for the FACE Project" in this volume for a more complete listing of cooperators.

CO_2 ENRICHMENT OF TREES

S.B. Idso, Research Physicist; and B.A. Kimball, Supervisory Soil Scientist

PROBLEM: The continuing rise in the CO_2 content of Earth's atmosphere is believed by many people to be the most significant ecological problem ever faced by humanity, primarily because of the widespread assumption that it will lead to catastrophic global warming via intensification of the planet's natural greenhouse effect. There are also, however, many *beneficial* effects of elevated atmospheric CO_2 concentrations that are experienced by Earth's plant life; and some of them, such as the ability of elevated CO_2 to enhance plant growth rates, actually impact the global warming problem. Earth's trees, for example, account for two-thirds of the planet's photosynthesis and are the primary players in the global cycling of carbon, removing CO_2 from the air, and sequestering its carbon in their tissues and, ultimately, the soil. Consequently, we seek to determine the direct effects of atmospheric CO_2 enrichment on the growth and development of trees, concentrating specifically on the long-term aspects of this phenomenon; for until someone conducts an experiment that is measured in *decades*, we will never know what the long-term impact of the ongoing rise in the air's CO_2 content will be on the planet's most powerful contemporary carbon sink.

APPROACH: In July 1987, eight 30-cm-tall sour orange tree (*Citrus aurantium* L.) seedlings were planted directly into the ground at Phoenix, Arizona. Four identically-vented, open-top, clear-plastic-wall chambers were then constructed around the young trees, which were grouped in pairs. CO_2 enrichment—to 300 ppmv (parts per million by volume) above ambient—was begun in November 1987 in two of these chambers and, other than for brief maintenance and construction periods, has continued unabated since that time. Except for this differential CO_2 enrichment of the chamber air, all of the trees have been treated identically, being irrigated and fertilized as deemed appropriate for normal growth (Idso and Kimball, 1997).

As in all prior years, we continue to measure the circumferences of the trunks of the trees at the midpoint of each month; and from these data we calculate – on the basis of relationships developed specifically for our trees (Idso and Kimball, 1992) – monthly values of total trunk plus branch volume. Then, from wood density (dry mass per fresh volume) measurements we have made over the past several years, we calculate monthly values of the total dry weight of the trunk and branch tissue of each tree. Results for December, January, February, and March – the winter period of virtually no trunk expansion – are then averaged to give a mean value for the year, from which the preceding year's mean value is subtracted to yield the current year's production of trunk and branch biomass.

We likewise continue our yearly fruit measurements, counting the number of fruit to reach maturity on each tree, weighing each such fruit individually, and determining the percent dry weight of one hundred ripe fruit from each tree, which allows us to calculate the total dry weight of fruit produced in each of the CO_2 treatments.

The last major component of aboveground biomass that we regularly assess is leaf tissue. From previously derived relationships (Idso and Kimball, 1992), we evaluate the number of new leaves produced each year from our trunk circumference measurements. And from bi-monthly assessments of leaf dry weight similar to those of Idso et al. (1993), we calculate the total dry weight of leaves produced on the trees each year. These results, added to the trunk and branch dry weights and fruit dry weights, then give us the total aboveground dry weight production per year for all of the trees in the two CO_2 treatments.

When viewed in their entirety, the results continue to be encouraging. They indicate that the trees of both CO_2 treatments may be close to achieving a stage of maturity characterized by a near-steady-state of yearly aboveground biomass production (Fig. 1). For the last four years of the experiment, for example, the value of total aboveground productivity in the CO_2-enriched trees was 107, 90, 95, and 116 kg/tree; while for the ambient-treatment trees it was 62, 51, 57 and 61 kg/tree, producing a four-year-mean CO_2-enriched/ambient-treatment ratio of 1.77.

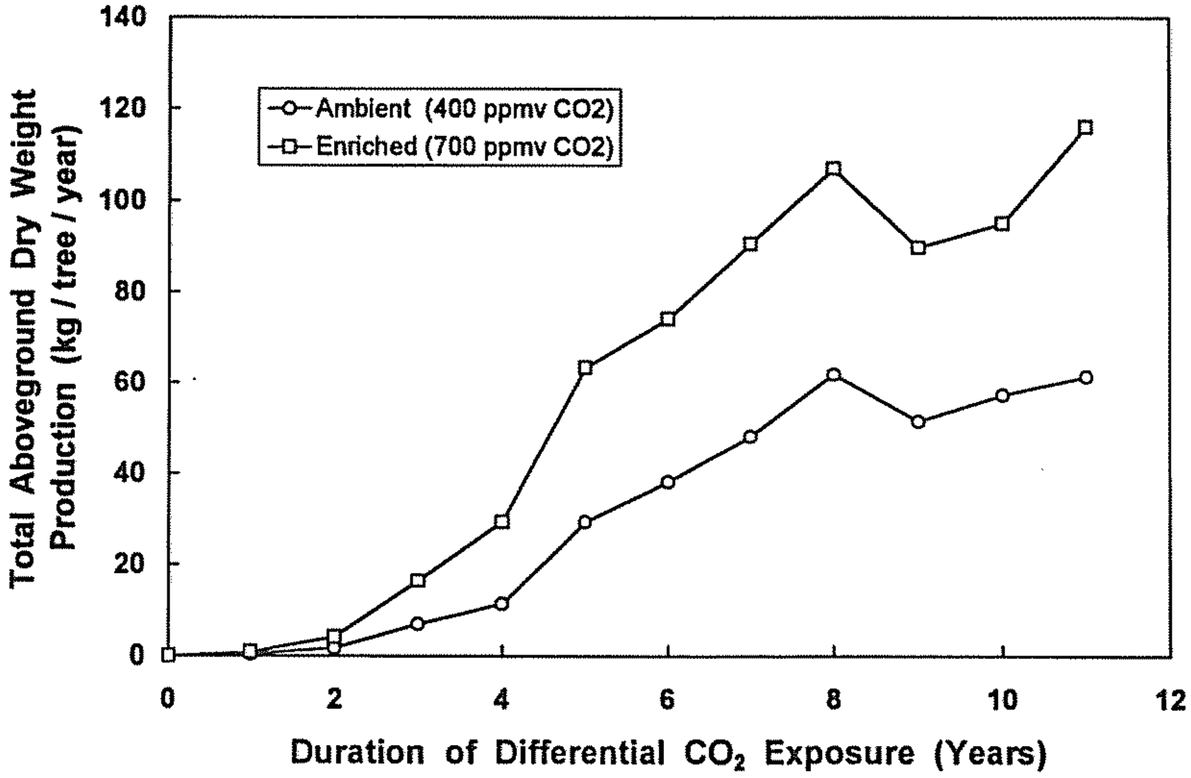

Figure 1. Yearly total aboveground biomass production in the ambient and CO_2-enriched sour orange trees as a function of time since the start of the experiment.

Fruit production has been a little more erratic; nevertheless, it too appears to be approaching an asymptotic upper limit (Fig. 2). For the last four years, for example, harvested fruit biomass has been 47, 38, 38, and 58 kg/tree in the CO_2-enriched trees; while in the ambient-treatment trees it has been 25, 13, 23, and 31 kg/tree, producing a four-year-mean CO_2-enriched/ambient-treatment fruit production ratio of 1.97. What happens from this point on could thus be of greater significance than all that has preceded it, for we are clearly close to determining the true long-term *equilibrium* response of the trees to atmospheric CO_2 enrichment.

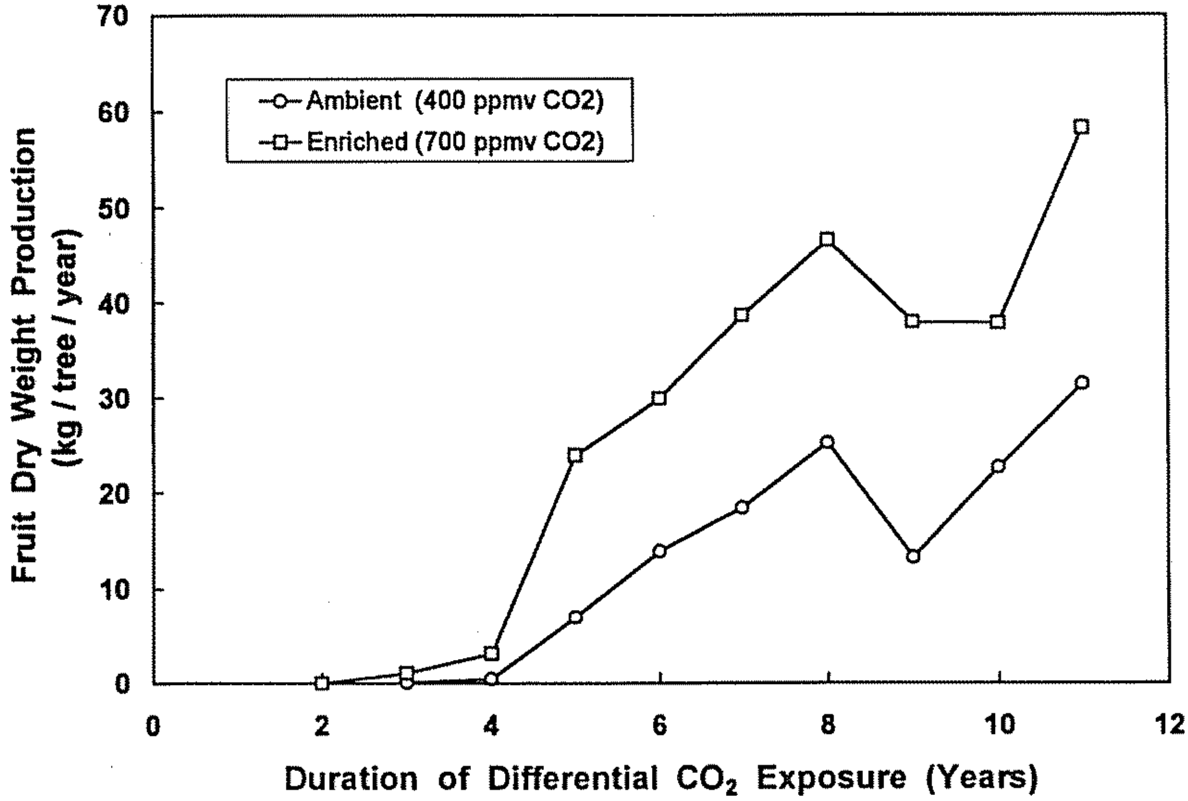

Figure 2. Yearly fruit dry weight production in the ambient and CO_2-enriched sour orange trees as a function of time since the start of the experiment.

In another intriguing development, we have discovered that in the spring of each year the CO_2-enriched trees experience an enormous growth enhancement. This initial stimulation begins immediately upon bud-burst, and three-and-a-half weeks later the new branches of the CO_2-enriched trees are typically more than four times more massive than those of the ambient-treatment trees. Furthermore, because there are more branches on the CO_2-enriched trees, their *total* new-branch biomass is generally over six times larger than that of the trees growing in ambient air.

Once achieved, peak CO_2-induced new-branch growth stimulation persists for about two weeks, whereupon the large initial biomass enhancement begins to subside. Then a decline sets in, and the CO_2-enriched/ambient-treatment new-branch biomass ratio of the trees ultimately levels out at a value commensurate with the long-term total aboveground productivity ratio of the CO_2-enriched and ambient-treatment trees; i.e., at a value of approximately 1.77.

It is possible that this phenomenon may be partially responsible for the ever-earlier spring "greening" of the Northern Hemisphere over the past few decades, which has been observed in long-term satellite studies of surface albedo, as well as in the increasingly earlier occurrence of the spring drawdown of the air's CO_2 content, which is evident in long–term studies of the atmosphere's seasonal CO_2 cycle (Idso *et al.*, in press).

INTERPRETATION: The stakes in this study are high, as no one has ever maintained an experiment such as ours for a long enough time to determine the long-term consequences of atmospheric CO_2 enrichment for long-lived woody plants. Indeed, the answer to this question is one of the critical elements that is needed to reveal the ultimate fate of the CO_2 that the people of the world yearly emit to the atmosphere. Will the trees of the planet be sufficiently stimulated by the ongoing rise in the air's CO_2 content to remove enough of it from the atmosphere to prevent a significant CO_2-induced warming of the globe? Our study provides important insight into this question and may help our government and others craft appropriate policies to meet this global environmental challenge. In the meantime, our findings continue to demonstrate that carbon dioxide is an effective aerial fertilizer, significantly increasing the size, growth rate, and fruit production of sour orange trees exposed to 75% more CO_2 than is normally in the air.

FUTURE PLANS: We hope to continue the sour orange tree experiment for as long as it takes to determine whether or not the trees will truly achieve steady-state yearly growth rates that produce a CO_2-induced productivity enhancement that can reasonably be expected to remain essentially constant over the remaining years of the trees' life span. We also are deeply involved in further studies of the ultra-enhanced spring branch growth we have observed in the CO_2-enriched trees.

COOPERATORS: J.H. Hoober and H.-S. Park, Arizona State University, Department of Plant Biology, Tempe, Arizona; R.C. Balling, Jr., Arizona State University, Department of Geography, Tempe, Arizona; C.E. Idso and K.E. Idso, Center for the Study of Carbon Dioxide and Global Change; U.S. Department of Energy, Atmospheric and Climate Research Division, Office of Health and Environmental Research.

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SIMPLE TECHNIQUES FOR CONDUCTING CO_2 ENRICHMENT AND DEPLETION EXPERIMENTS ON AQUATIC AND TERRESTRIAL PLANTS: THE "POOR MAN'S BIOSPHERE"

S.B. Idso, Research Physicist

PROBLEM: In order to act in the best interests of the biosphere in the face of the rising CO_2 content of earth's atmosphere, we need to determine the effects of atmospheric CO_2 enrichment on the growth habits of as many different plants as possible, both singly and in combination with competing plants and animals. Also needed is a knowledge of how the ongoing rise in the air's CO_2 content may interact with environmental changes such as global warming, more frequent and intense drought, and intensified soil, water, and air pollution, so we can determine if the deleterious effects of these latter phenomena will be ameliorated or exacerbated by the concurrent rise in atmospheric CO_2. Consequently, in an attempt to expand our research capabilities in this important area of science and to interest more young people in pursuing careers therein, this project has as its goal the development of a number of simple and inexpensive experimental techniques that will enable almost anyone to conduct significant research on a variety of questions related to the role of atmospheric CO_2 variability in ongoing and predicted global environmental change.

APPROACH: Over the first three years of the project, a set of guidelines was developed for using inexpensive and readily available materials to construct experimental growth chambers or "Poor Man's Biospheres," wherein CO_2 enrichment and depletion studies of both aquatic and terrestrial plants could be conducted (Idso, 1997). In their most basic form, these enclosures consist of no more than simple aquariums covered by thin sheets of clear polyethylene that are taped to their upper edges to isolate their internal air spaces from the room or outside air. Several low-cost, low-technology ways of creating a wide range of atmospheric CO_2 concentrations within these enclosures also were developed. Some of the CO_2 enrichment techniques utilize the CO_2 that is continuously evolved by the oxidation of organic matter found in common commercial potting soils, while others rely on the CO_2 that is exhaled by the experimenter. When CO_2 depletion is desired, the growth of the experimental plants themselves can be relied upon to lower the CO_2 contents of the biospheres' internal atmospheres, as can the photosynthetic activity of ancillary algal populations that often occur in watery habitats and that can be induced to grow in terrestrial environments as well. For all of these different situations, a set of simple procedures for measuring biospheric airspace CO_2 concentration has been developed. This technique utilizes any of a number of simple colorimetric CO_2 test kits that are sold in tropical fish stores throughout the world and that can be readily obtained by ordering over the internet (Idso, 1997).

To obtain hands-on experience in the technology transfer aspect of the Poor Man's Biosphere Program, outreach activities were initiated three years ago with five eighth-grade biology classes at McKemy Middle School in Tempe, Arizona, and with a fifth-grade class at the Salt River Elementary School of the Salt River Pima-Maricopa Indian Community. Students at both schools investigated the effects of atmospheric CO_2 enrichment and depletion on a common terrestrial plant, Devil's Ivy or Golden Pothos (*Scindapsus aureus*), and a common emergent aquatic plant, Yellow Water Weed (*Ludwigia peltoides*), under two different light intensities. New sets of students at McKemy Middle School repeated the Pothos experiment two years ago with some slight variations. Also, two honors biology classes at Tempe High School conducted a massive twice-replicated study of the growth response of a submerged aquatic macrophyte, Corkscrew Vallisneria (*Vallisneria tortifolia*), to three levels of atmospheric CO_2 (ambient, half-ambient, and twice-ambient) at three different water temperatures and two different light intensities, winning two $10,000 first-place awards in a state environmental science curriculum contest.

This past year, as part of its environmental science education activities, the Center for the Study of Carbon Dioxide and Global Change conducted an ambitious program of employing the poor man's biosphere technique in a set of experiments that it described on its website (www.co2science.org) and updated on a weekly basis. Complete descriptions of these studies are now archived there for science teachers throughout the world to access and utilize in their classrooms.

In a further extension of the poor man's biosphere approach to conducting CO_2 enrichment and depletion experiments, the technique was successfully used over the past two years in a basic science study designed to explore the effects of atmospheric CO_2 enrichment and depletion on the production and distribution of biomass in sour orange trees grown from seed in nutrient-poor sand. This experiment, which lasted for 19 months, also included the study of tissue nitrogen concentrations and leaf chlorophyll concentrations. It revealed that even under conditions of extreme nutrient deficiency, there was still a sizable growth response to CO_2. Relative to biomass at 336 ppmv, for example, biomass at 1257 ppmv was over twice as great in leaves, four times greater in trunks and lateral roots, and nearly six times greater in tap roots. Nevertheless, these responses were only about half as great as those observed in sour orange trees of the same age growing under non-limiting conditions of nutrient availability.

FINDINGS: The simple experimental techniques developed in the initial years of the program have been found to work satisfactorily in actual classroom environments at elementary, middle, and high school levels. They now have been demonstrated to have a place in basic research programs as well. In addition, they have found a home on the internet, where anyone with a computer and internet access can go to learn of them.

INTERPRETATION: As the technology transfer aspects of the program are still ongoing, final conclusions have not yet been reached. However, all indications are that the poor man's biosphere approach to atmospheric CO_2 enrichment and depletion experiments has the potential to become a key element of environmental science education curricula in the years ahead. It is also beginning to show promise as a basic research tool.

FUTURE PLANS: A major article describing the use of the poor man's biosphere technique in a basic research program has been prepared (Idso and Adamsen, 2000). A second major journal article describing the use of the Poor Man's Biosphere Program in elementary, middle, and high schools will be prepared in the near future. Efforts to bring the program to state and national audiences of science teachers will continue via the internet in cooperation with educational organizations that have the capacity to provide such services.

COOPERATORS: Center for the Study of Carbon Dioxide and Global Change (C.D. Idso, K.E. Idso); McKemy Middle School, Tempe Elementary School District (M. Davis); Salt River Elementary School, Salt River Pima-Maricopa Indian Community (K.E. Idso); Tempe High School, Tempe Union High School District (S. Greenhaulgh).

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QUANTITATIVE REMOTE SENSING APPROACHES FOR MONITORING AND MANAGING AGRICULTURAL RESOURCES

CONTENTS

QUANTITATIVE REMOTE SENSING APPROACHES FOR MONITORING AND MANAGING AGRICULTURAL RESOURCES

MISSION

The ultimate goal of this research is to use remote sensing technology to increase our understanding of processes associated with environmental variability and to provide resource managers with information that will assist them in making tactical and strategic management decisions on farms, rangelands, and natural plant communities. Emphasis will be given to approaches that have potential for operational application, and that also have a strong physical foundation based on quantitative measurements.

IMAGE-BASED REMOTE SENSING FOR AGRICULTURAL MANAGEMENT - PERSPECTIVES OF IMAGE PROVIDERS, RESEARCH SCIENTISTS, AND USERS

M.S. Moran, Physical Scientist

PROBLEM: Precision crop management (PCM) is an emerging agricultural management system using information and technology to identify, analyze, and manage site-soil spatial and temporal variability within fields for optimum profitability, sustainability, and protection of the environment. Many experts agree that there is a good match between the information needs of PCM and the offerings of spatially-distributed information about crop and soil conditions provided by image-based remote sensing (RS). The question remains: *"Can current RS technology meet the very stringent information requirements of PCM?"*

APPROACH: To answer better the posed question about remote sensing (RS) technology, I conducted a limited survey of three groups (with number of contacts in parentheses): image providers (5), research scientists (5), and users (13). By my definitions, *image providers* are companies trying to make a profit from selling remote sensing image products for farm management; *research scientists* are people at universities or government research laboratories studying remote sensing science with the goal of providing algorithms and models for farm management; and *users* are people or corporations who have already purchased remote sensing image products for PCM. Representatives from each of the three groups were contacted by telephone and asked a series of questions related to remote sensing for PCM. The results of this limited survey provided an insight into their experiences, attitudes, and expectations and provided the foundation to answer the posed question.

FINDINGS: Measurement Accuracy: Users agreed that an accuracy of 70-75% in the measurement of most crop or soil conditions was sufficient to implement PCM and improve farm profitability. This is in contrast with the goal of many research scientists to provide algorithms and models with 90-95% accuracy. Furthermore, users were in agreement that the accuracy of the image product must be quantified through a series of documented experiments and further testing on their own farm. In all cases, users were willing to provide their own test plots and pay for the image data in return for interpretation and analysis by a scientist working with the image provider. All users in the survey were already testing other new technologies at their own expense.

Product Delivery: The highest priority for all users and image providers was quick turnaround. Unlike measurement accuracy for which users were willing to accept 70% accuracy, the users expected 100% reliability in image delivery. The consensus of all users and image providers was that images must be delivered within 24 hours, preferably within 12 hours.

Location Accuracy: The second highest priority for all users and image providers was highly accurate geo-registration. For PCM, it is necessary to pinpoint the location of the anomalous crop or soil condition for proper precision management and inclusion in a geographic information system (GIS). This was one issue for which users and image providers had largely different expectations. The user accuracy requirements of approximately 2 m contrast with the positional accuracies (20-500 m) offered by some image providers.

Revisit Period: Unlike the very restrictive requirements for turnaround time (12-24 hours with 100% reliability), users had more relaxed expectations for repeat coverage. The requirements ranged from twice per week for irrigation scheduling to biweekly for general damage detection. All users agreed that when the image products are more quantitative (that is, offering an accurate assessment of the cause of the anomaly and suggesting a management activity) then the users would request more frequent repeat coverage. Image providers working with aircraft-based sensors reported that they were stretching their personnel and equipment limits to provide repeat passes on a weekly basis. Image providers working with satellite-based sensors are confined by the orbital constraints and numbers of satellites, and are often limited to repeat passes every two weeks.

Management Unit: Like positional accuracy, the spatial resolution required for PCM depends upon the management operation. There was a user consensus that it was economical to manage crop and soil units with a nominal size of 10 m.

The user requirements for remotely sensed information in PCM based on this limited survey of users, image providers, research scientists, and the literature are summarized in Table 1. The first three user requirements translate directly to sensor and algorithm specifications, where the value-added product accuracy should be on the order of 75%, the turnaround time should be within 24 hours of acquisition, and the geo-registration should be as accurate as possible (within 1 pixel). To translate the latter two user requirements (revisit period and management unit) into sensor specifications, Moran (2000) accounted for basic sensor limitations and site-specific atmospheric conditions.

Table 1. PCM user information requirements translated to RS system specifications.

User Information Requirements		System Specifications	
Measurement Accuracy	70-75%	Algorithm Accuracy	70-75%
Product Delivery	< 24 hours	Turnaround Time	< 24 hours
Location Accuracy	2 m	Geo-registration Accuracy	1 pixel
Revisit Period	1 week	Repeat Cycle	3 days
Management Unit	10-20 m	Pixel Size	2-5 m

Remotely-Sensed Product for PCM: The users contacted in this survey were confident and unanimous in their description of the preferred image product:

(1) Users expected a color map product (hardcopy, or preferably digital) with "quantitative" information that could be used to make decisions, not simply identify anomalies. They wanted to know where the anomaly was located, how large it was, and *what had caused it.*

(2) Users wanted personal help with image interpretation in the form of person-to-person contact, a reliable help line, or user-friendly software. Person-to-person contact was the preferred information delivery method.

(3) Users expected the image provider (or research scientists) to do the product validation first,

before presenting it to the user for purchase. Users were all willing to conduct additional yield tests on their own farm, but they were not interested in high-risk ventures.

(4) Users wanted honest, reasonable marketing of the image product. All users felt that RS products had been oversold, and that users had been promised much more than had ever been delivered. As a result, users described themselves as skeptical, reluctant, and distrustful.

The image providers interviewed were aware of the users' expectations. Four of five image providers were offering "high end" products including maps of weeds, insect infestations, nutrient deficiency, water deficiency and/or yield. The fifth image provider was providing only maps of anomalies; he hoped that buyers, such as crop consultants or chemical dealers, would process the high quality image to sell value-added products to farm managers. All image providers were conducting product validation studies to some extent.

All image providers were struggling to provide help in image interpretation to the users. Some companies were providing face-to-face on-farm interpretation at a great deal of expense, but with good success. Other companies were putting similar expense into providing a useful and simple software interface that could improve users' image interpretation. Finally, one company had a 24-hour help line to allow users to get personal information at any time.

When users were asked what caused them to continue purchasing RS images for a second (or third, fourth, etc.) season, they all responded that it was profitability; that is, the imagery either improved yields or reduced costs. Secondarily, it was because they had a personal interest in the technology, and thought they might benefit economically in the future. The factors cited by users who did not continue to purchase images were lack of profitability, lack of time and labor, and inability to use variable rate technology (VRT) in response to image information. The image providers described the same story from a different perspective. They stated that they lost customers primarily due to weather and the economy, and secondarily due to instrument failures that prevented them from offering further overflights.

<u>Role of Research Scientists:</u> Both users and image providers appreciated the studies of research scientists working at universities and government laboratories. On the other hand, users would like to see more research scientists working hand-in-hand with image providers because they felt it provided more credence to the company's agricultural products. Image providers suggested that research scientists should put more effort into technology transfer to prove that their algorithms and models were robust and operational. The research scientists interviewed for this review were already working with commercial companies. In their view, the role of research scientists in promoting remote sensing for PCM was to "be practical," understand the accuracy requirements in algorithm and model development, and keep in mind that the users and image providers are interested primarily in profitability.

With these issues in mind, the role of research scientists in promoting RS for PCM could be improved through greater interaction with the client (either the user or the image provider), including

- definition of the research program based on client needs (identified by the client) and participation of clients in the program operation;
- ownership of the system by the client (clients need to help assembling information and applying it);

• education of clients on the capabilities of remote sensing, and gradual implementation of the new program (to allow the client to maintain an understanding of the new technology); and
• economic analysis to show clients the economic benefit of using RS over traditional approaches.

Furthermore, research scientists reported that universities and government laboratories were changing to reward research scientists for technology transfer and to encourage them to use a team approach and involve clients in program development.

INTERPRETATION: Nearly 9% of the one-half million farmers growing corn in the U.S. used some aspect of PCM for corn production in 1996 (representing nearly one-fifth of 1996 harvested corn acreage); and, of these PCM users, 54% used tractor-mounted yield monitors to map field variability. These numbers illustrate the large potential market for remotely sensed agricultural information and the capacity of farm managers to adopt new technology. Whether image-based RS technology is included in emerging PCM systems will depend on the ability of commercial image providers, engineers, and research scientists to meet the stringent PCM requirements for quantitative, validated information products. This will mean improvements in product turnaround and image registration, as well as successful launches of upcoming commercial satellite-based sensors with spatial resolutions of 2-5 m and/or further advances in aircraft-based mounts and sensors. A strategy will have to be developed for independent validation of algorithms produced by research scientists and proprietary products produced by for-profit commercial companies to satisfy the requirements of risk-adverse farm managers. The economics of RS for PCM will have to be determined through well-designed experiments comparing profits obtained through conventional and high-technology management systems. Finally, an effort will have to be made to encourage a systematic, triangular education of image providers, research scientists, and users through inclusion of all clients in program development and implementation.

FUTURE PLANS: Work will focus on addressing the research, development and policy issues identified in the previous section.

COOPERATORS: This work would not have been possible without the honest insights provided by the anonymous image providers, research scientists, and users contacted in this limited survey.

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A NEW CANOPY CHLOROPHYLL CONTENT INDEX FOR COTTON

T.R. Clarke, Physical Scientist, and E. M. Barnes, Agricultural Engineer

PROBLEM: According to a recent meeting between commodity group representatives and members of the remote sensing research community, one of the most important decisions a grower must make is how to manage crop fertilizer inputs in order to assure a good yield while preventing ground water contamination. Variable rate application technology has recently been developed, but the technology for directing applications effectively is less mature. A means of rapidly assessing a crop's fertilizer needs with sufficient frequency and spatial resolution is needed for this aspect of precision agriculture to succeed.

APPROACH: A Canopy Chlorophyll Content Index (CCCI) using reflectances from three wavelengths of light was developed and field tested. Reflectance measurements of a cotton field were made in the summer of 1999 using a linear move irrigation system that had been fitted with a sensor platform and precision water and fertilizer application capabilities developed by The University of Arizona Department of Agricultural and Bioengineering. The sensor platform carried a multi-spectral sensor developed at the U.S. Water Conservation Laboratory (USWCL) (1998 Annual Report) in such a manner that a 1-meter resolution image of the 16 plot, 1-hectare field could be acquired in about 2 ½ hours. Images were acquired several times per week. The initial coarse reflectances were produced using a painted reference panel attached to the central tower of the linear irrigation system, and sampled by the sensor every minute. Half of the plots received 50% of the recommended nitrogen application, which was applied before planting and at three times during the season. The remaining plots received the full 200 lbs./acre recommended nitrogen. Half of the plots also were subjected to periodic water stress, so that four replicates each of four different treatments (full-water, full-nitrogen; full-water, half-nitrogen; low-water, full-nitrogen; and low-water, half-nitrogen) were present.

FINDINGS: Preliminary findings show that the CCCI was able to clearly reveal the low nitrogen plots even when a vegetation index showed no difference, as seen in Figure 1. What is more, the CCCI differences disappeared within a couple days of a fertilizer application.

INTERPRETATION: These data are still in the early stages of analysis, but the coarse results seen so far are very promising. If a good correlation is found between the CCCI and chlorophyll meter and leaf petiole analyses, which were collected but are not yet available, the index could be converted to a fertilizer recommendation. Hand-held sensors, sensors mounted on tractors, or airborne cameras could then be used to provide spatial nutrient deficit information to variable rate applicators.

FUTURE PLANS: The methodology used in the CCCI is currently under review for patentability, and therefore details cannot yet be released. Analysis of the 1999 data must be completed. Specifically, the coarse reflectances will be refined using data from an up-looking sensor which were collected during each measurement run. An image processing program currently under development by The University of Arizona Department of Agricultural and Biosystems Engineering will then be able to produce the 70 partial- and full-field images collected. Petiole analyses and SPAD chlorophyll meter data will be used to test the CCCI sensitivity. We plan to test the index on other crops, specifically vegetables and wheat, as the opportunity arises.

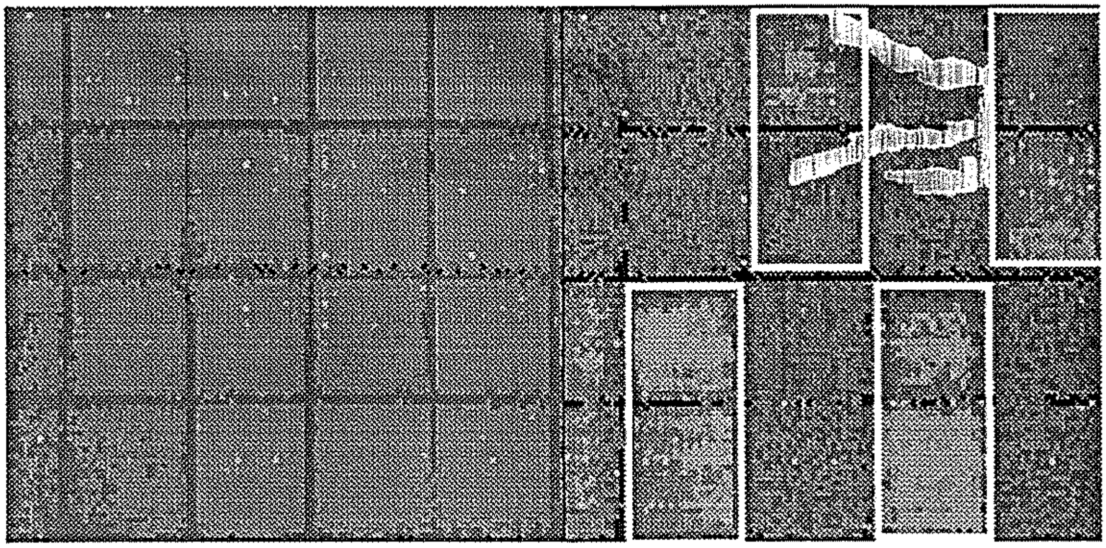


Figure 1. Image of the experimental field acquired August 19th, 1999. The left half is an enhanced Normalized Difference Vegetation Index, showing little variation among treatments. The right half of the figure is the recently developed Canopy Chlorophyll Content Index (CCCI) of the same field, the same day. Low nitrogen plots are outlined in white.

COOPERATORS: Images were collected in cooperation with The University of Arizona Department of Agricultural and Biosystems Engineering, funded through a grant from the Department of Energy's Idaho National Engineering and Environmental Laboratory. Peter Waller and Christopher Choi were assisted by graduate students Paul Colaizzi, Julio Haberland, and Michael Kostrzewski in the design and assembly of the precision application and sensor platform systems. The linear move irrigation system was provided by Valmont. Tom Thompson of The University of Arizona Department of Soil, Water, and Environmental Sciences designed the nitrogen treatment experiment and his graduate student Emily Riley supplied ground truth data on nutrient status. The experimental site, field operations, and management were provided by The University of Arizona Maricopa Agricultural Center, Robert Roth, Director.

MULTISPECTRAL DATA FOR SOIL MAPPING: OPPORTUNITIES AND LIMITATIONS

E.M. Barnes, Agricultural Engineer; M.G. Baker, Research Specialist; M.S. Moran and T.R. Clarke, Physical Scientists; and P.J. Pinter, Jr., Research Biologist

PROBLEM: Soil maps derived from random or grid-based sampling schemes are often an important part of precision crop management. Sampling and soil analysis to derive such maps require a large investment of both time and money. Aerial photos have been used as a soil mapping aid for years (e.g., Bushnell, 1932). Studies have shown such an approach can be useful for defining management units in precision farming (e.g., Thompson and Robert,1995), but these studies are often limited to a single field, not an entire farming operation. The objective of this study was to determine if multispectral airborne (green, red, near infrared, and thermal) and satellite (SPOT and Landsat TM) data could be used to derive soil maps for a 770 ha research and demonstration farm in Maricopa, Arizona [Maricopa Agricultural Center (MAC)].

APPROACH: Soil data used in this study were collected by Post et al. (1988) from May 1984 until January 1987. There were 303 sample locations in the fields considered in this analysis. For each of these samples, textural fractions of sand, silt and clay were determined and the location recorded in a UTM coordinate system. Kriging techniques were used spatially to interpolate the data to a 2-m grid. Individual grids were generated for the sand, silt, and clay percentages. These three grids were then used to derive a textural classification map of the farm (i.e., class of sandy loam, sandy clay loam, or clay loam).

Three image data sources were considered in this study:
(1) multi-temporal, aerial-borne digitized video images acquired during the summer of 1994,
(2) a SPOT High Resolution Visible (HRV) image from April 9, 1989, and
(3) a Landsat Thematic Mapper (TM) image taken April 13, 1989.

The images were geometrically registered to the same coordinate system used to identify to the soil sampling locations (UTM projection, NAD 27 datum). The airborne image was composed from portions of 56 individual video frames, forming a single mosaic of the study area. Details on the airborne data set are given by Moran et al. (1996). Both satellite images easily encompassed the entire study area in a single image frame. Image data corresponding to the location of the soil samples were extracted in a tabular format so that correlation coefficents could be calculated between the soil textural percentages (sand, silt, clay) and the spectral bands.

Unsupervised classification was conducted on the images using the Iterative Self-Organizing Data Analysis Technique (ISODATA) (Tou and Gonzalez, 1974). This technique uses iteration to define "clusters" of data in multi-dimensional spectral space. A convolution filter was then applied to the classified images to remove small, spatially discontinuous classes. The classification process was conducted across two different spatial scales: classification using data for the entire farm (farm-level) and classification on a field-by-field basis (field-level). For the farm-level classification, the resulting classes were then assigned to a soil class of sandy loam (SL), sandy clay loam (SCL), or clay loam (CL) based on the spectral classes present in two fields that contained a wide range of soil conditions.

For the field-level classification, soil data within each field were used to assign a spectral class to a soil textural class.

FINDINGS: Correlation coefficients (r) between the Landsat spectral bands and textural percentages are shown in Table 1, using data for the entire study area. Results from the other sensor platforms were very similar. With the exception of the thermal bands, all of the coefficients are significantly different from zero (p = 0.05). Also note that r values tend to increase in magnitude with increasing wavelength (excluding thermal data) for all sensor systems. Additionally, sand is positively correlated with reflectance, while sand and clay show a negative correlation.

Table 1. Correlation coefficients between the percent sand, silt, or clay and the Landsat TM bands for the entire area considered in the analysis.

	Spectral Region						
	Blue	Green	Red	NIR	SWIR1	Thermal	SWIR2
r(%Sand,Band)	0.296	0.380	0.462	0.493	0.526	-0.053	0.572
r(%Silt,Band)	-0.268	-0.346	-0.426	-0.466	-0.502	0.001	-0.547
r(%Clay,Band)	-0.309	-0.394	-0.473	-0.494	-0.524	0.094	-0.568

While statistically significant, the correlation coefficients indicate that typically less than 30 percent of the variation in any given band can be attributed to differences in soil texture.

Explanation for the remaining variation can be partially found by viewing the gray scale images in the near infrared (NIR) portion of the spectrum from the airborne sensor in figure 1. The numbers shown on the figure are field identifiers. In this figure there are several differences in reflectance levels that are not related to soil texture. The two dark rectangles in field 35 are due to irrigation in progress. There is also a distinct "corner" in the upper center portion of the field that is an artifact of the individual frames used to create the image (also visible in field 20). Field 37 appears consistantly brighter than field 36 which is an artifact of using different image dates in the mosaic and different tillage conditions in both fields. Similar confounding factors also were found in the SPOT and LandSat scenes; however, there were no moasicing problems in the satellite images as the farm is contained in a single frame. Other interfering factors found during the course of the analysis include row direction (north to south versus east to west), tillage condition (e.g., freshly tilled or rain compacted surface), and seed bed preparation (flat versus raised beds).

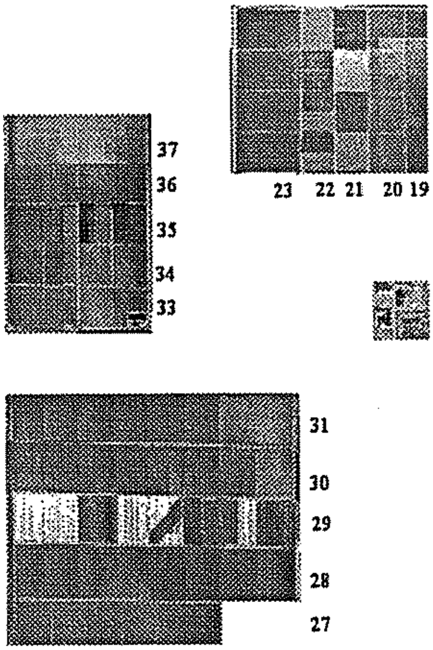


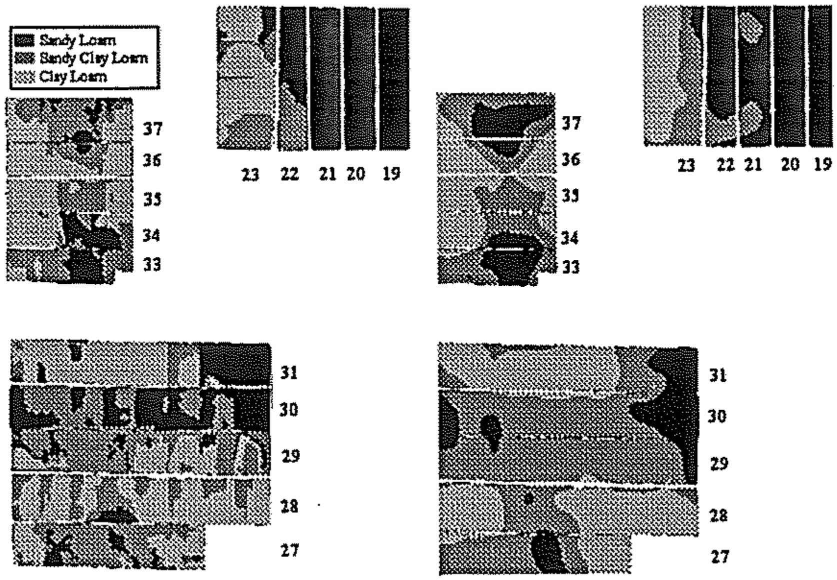
Figure 1. Near infrared image from the airborne sensor of the study area. Note numbers are field identification numbers.

All of these factors also impacted the results of the unsupervised classification procedures as evidenced in Table 2, where none of the images were classified with accuracies much higher than 50 percent when the procedures were executed for the entire farm. However, there was a signficant improvement when the classificaiton was conducted on a field-by-field basis (Table 2). The increase

Table 2. Accuracy assement results from the unsupervised spectral classification procedures.

	Sensor System		
	Airborne	SPOT	Landsat
Classification Level	Percent of points correctly classified.		
Farm	51	50	48
Field	81	88	92

in accuracy can be attributed to the fact that surface conditions are much more consistant within a field as they typically receive the same tillage practices at the same time. The results of the field-by-field classification from the airborne data is shown in figure 2 (similar results were obtained with Landsat and SPOT). For comparison purposes, the soil map based on the kriging procedures is also presented in the figure. Overall there is good agreement in the majority of the spatial patterns between the two methods. Some of the sandy loam areas that appear in field 30 on the map derived from the airborne data that are not in the kriged map and can be attributed to small grain residue in this field. The residue gives the soil a "brighter" appearence, which is also characteristic of soils with higher sand content at this site. It was determined that the area percent classified differently from the kriged map were 30, 23, and 27 for the airborne, SPOT, and Landsat derived maps, respectively. More soil samples are needed to determine if the differences between the image-derived maps and the kriged map are due to errors in the kriged map or in the classified images for cases where there were no known confounding factors. However, it is speculated that patterns derived from the images in fields with uniform soil surfaces are more



a) Airborne data b)Interpolated soil samples

Figure 2. Soil map derived from the airborne data using unsupervised classification on a field-by-field basis (a) and the map derived from the kriging procedures (b).

accurate than those from the interpolated data. Additionally, only 60 soil sample locations were used in generating the image-based maps, while 303 locations were used for the kriged map. The number of points needed for the image-based method could have been substantially reduced if the soil surface had been uniform across the farm.

INTERPRETATION: Many factors can impact a soil's apparent reflectance that are not related to the soil's physical properties (e.g., tillage patterns, residue, row direction). Therefore, the use of multispectral imagery is best suited for large fields that have a uniform soil surface at the time of image acquisition. It is also necessary that the soil property of interest exhibit a spectral response. If such conditions are present, the number of soil samples needed to map soil properties can be significantly decreased when compared to spatial interpolation techniques. In this study, a general trend was that high sand content was associated with higher reflectance levels; however, this result was specific to the study site and it is not implied that such a spectral response will be true of soil at other locations.

FUTURE PLANS: A similar study is planned for 2000 where fallow fields at MAC will be cultivated just prior to image acquistion so the fields will have similar surface conditions. It is hoped that imagery will be available from one of the satellites' recently launched cables of providing 4-m spatial resolution data in the NIR, red, and green spectral regions.

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DEVELOPMENT OF A MODELING AND SENSOR SYSTEM TO PROVIDE INFORMATION FOR PRECISION CROP MANAGEMENT

E.M. Barnes and D.J. Hunsaker, Agricultural Engineers;
T.R. Clarke and M.S. Moran, Physical Scientists;
Stacy Richards, Research Lab Assistant; and P.J. Pinter, Jr., Research Biologist;

PROBLEM: Precision farm management requires timely, georeferenced information on crop and soil conditions. In this management system, the crop is given what it needs based on the current soil and environmental conditions so that economic return (not necessarily yield) is optimized. Cost efficient methods to provide this information are lacking at the present time. The objective of this project is to provide the tools needed economically to manage crop inputs at a very fine scale (potentially as small as 1 m).

APPROACH: To provide real-time management information, a combined sensor- and modeling-based approach has been under development. This project is part of a cooperative study, primarily funded by the Idaho National Environmental and Engineering Laboratory (INEEL). The U.S. Water Conservation Laboratory is providing the expertise on the remote sensing components of the study and assisting in the execution of field experiments to collect the data needed to validate and develop the system. The University of Arizona is working on the hardware design of a carriage for the sensor and developing techniques to provide an interface between the remotely-sensed data and an energy and water balance model called ENWATBAL (Lascano and van Bavel, 1987). Texas A&M University is providing the expertise on ENWATBAL and conducting a concurrent experiment in Texas. The project also is enhanced by the participation of two private companies, Valmont, which is providing a linear move irrigation system for the project, and CDS Ag. Industries, which is providing an injection pump.

The project began in 1998 with cotton and barley field experiments during which agronomic and hand-held radiometer data were collected. These data were used to begin formulation of quantitative relationships between spectral response and crop condition (see Barnes et al., 1998). Concurrent with these experiments, construction proceeded on a system to allow the linear move irrigation system to serve as a remote sensing platform named Agricultural Irrigation Imaging System (AgIIS, i.e., "Ag Eyes"). AgIIS was completed in time for the 1999 cotton season and was able to provide images in the red, green, red-edge, near infrared (NIR), and thermal portions of the spectrum. Various components of the hardware aspects of the system are under consideration for patents by The University of Arizona and so a detailed description is not possible at present. During the growing season, the AgIIS was used to obtain images at a minimum of weekly intervals, with as many as three images per week during the period of rapid crop development.

A Latin square experimental design was used during the 1999 cotton season with four treatments: (1) control (WN, optimal conditions); (2) low nitrogen (Wn, 50% optimal plant requirements); (3) low water (wN, decreased irrigation frequency, allowing the plants to become water stressed three times during the season); and (4) low water and low nitrogen (wn). A diagram of the treatment layout is provided in Figure 1.

Soil moisture levels were monitored in every plot using a neutron probe at a minimum of weekly intervals (2 access tubes per plot). Additionally, two plots were heavily instrumented with TDR probes in 4 locations at 4 depths (5, 10, 15 and 20 cm). The probes were used to determine the soil surface moisture content at hourly intervals using an automated data acquisition system. Stem flow gages also were added to these plots to measure the cotton's daily transpiration rate. The plants were sampled weekly for nitrate status, leaf area index (LAI), leaf, stem, and boll dry weights, plant height, and percent canopy cover.

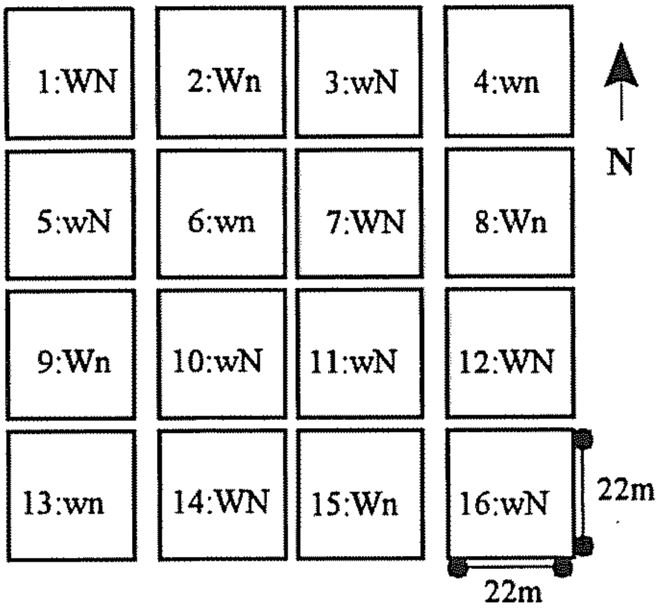

Figure 1. Plot numbers and treatment codes for the 1999 cotton experiment (see text for an explanation of the treatment codes).

FINDINGS: Analysis of all of the data collected during the experiments is still in process; however, initial results are encouraging. Figure 2 (color appendix) provides a comparison of a true color photograph of the field taken from a helicopter on October 1, 1999, and images from AGIIS acquired four days prior to the flight. The photograph was scanned at an approximate spatial resolution of 10 cm and AgIIS provides 1 m resolution. By this time in the season, most of the low nitrogen and water plots showed some signs of decreased leaf area. In the images, a higher canopy density is evident by intenser shades of green in the photograph (Fig. 2a) and intenser shades of red in the false color composite (Fig. 2b). Note that the spatial patterns in these two images are similar. The other images in Figure 2 provide a sample of the different spectral regions available from AgIIS. The visibile and NIR gray scale images (Fig. 2 c - f) were contrast stretched so that the minimum reflectance corresponded to black and maximum reflectance to white. The thermal band (Fig. 2g) represents the coolest condition as black and warmest as white. The ratio vegetation index (RVI = NIR/Red) has a color map applied so that low values are red and high values are green.

The ability to obtain images of a field is useful only if the images can be related to management information. To demonstrate the potential information from the system, Figure 3 (color appendix) provides two false color composite images from AgIIS on August 19. This day was selected because the low nitrogen treatments were established and the high water plots were irrigated three days earlier, but the low water plots were not. In the standard color infrared image of Figure 2a, most of the color patterns in the image are related to variations in canopy density (brighter red corresponds to a denser canopy); and there are no distinct signs of the experimental treatments. However, many of the color pattens in Figure 2b can be related to the treatments. In this figure, the canopy chlorophyll content index (CCCI) is displayed red (Clarke and Barnes, "A new canopy chlorophyl content index for cotton," this report), which can be related to crop nitrogen status in this experiment. The ratio vegetation index (RVI = NIR/red) is displayed as green, and the crop water stress index

(CWSI) (Idso et al., 1981) displayed as the blue band. Therefore, the control plots (WN) appear green as CCCI and CWSI are low under non-stressed conditions and RVI is higher for high canopy densities. A majority of the low nitrogen plots have a orange tint (higher CCCI values), while the low water plots have a blue tint (higher CWSI values). Plot 13 (lower left corner, wn) has a strong pink tint, as this plot had a low canopy density. The ability to distinguish between canopy density and two crop stresses demonstrates the progress being made in this study to extract more exact information about crop status than has been possible in the past.

INTERPRETATION: The system under development will provide farmers and agricultural consultants with a simple, cost effective data source to map spatial variations in crop water and nitrogen levels. These data will have the potential to serve as an integral part of a decision support system for precision crop management.

FUTURE PLANS: Work will continue to integrate the sensor information with simulation models to provide decision support in water and nitrogen management. Related studies will begin during the 1999-2000 growing season using AgIIS to determine the feasibility of remote sensing and modeling technologies to provide information relevant to quality management in broccoli.

COOPERATORS: Peter Waller, Chris Choi, Mark Riley, Tom Thompson, Paul Colaizzi, Julio Haberland, Mike Kostrzewski, and Emily Riley, University of Arizona, Tucson AZ; Robert Lascano and Hong Li, Texas A&M University, Lubbock TX; Jack Slater, INEEL, Idaho Falls ID; Jim Phene, Valmont Industries, Valley NE; Jim Stubbs, CDS Ag Industries, Chino CA.

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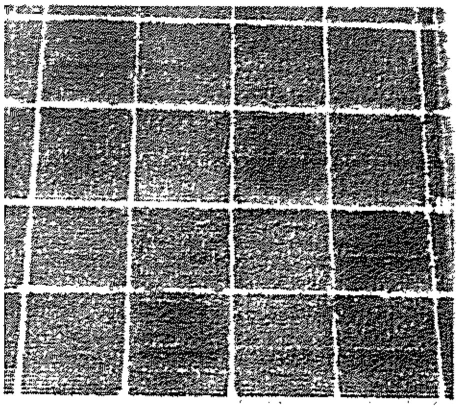
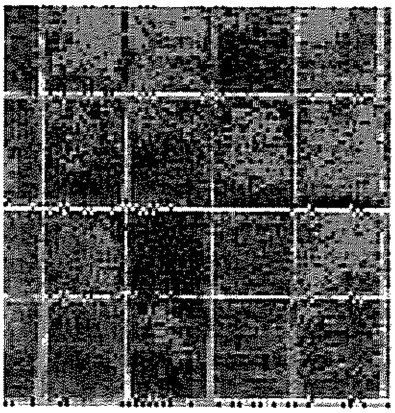
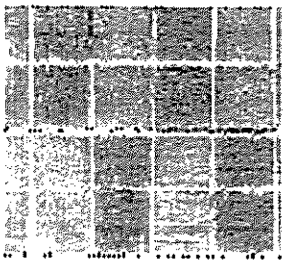


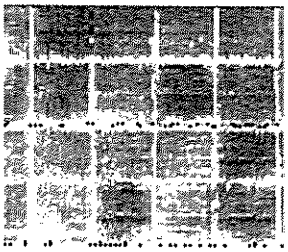
(a) True color photograph



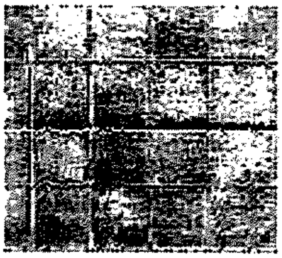
(b) False color composite



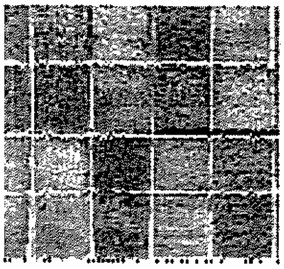
(c) Green band image



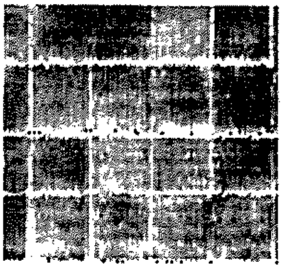
(d) Red band image



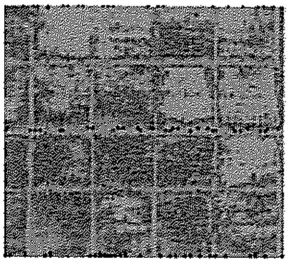
(e) NIR band image



(f) Red-edge image

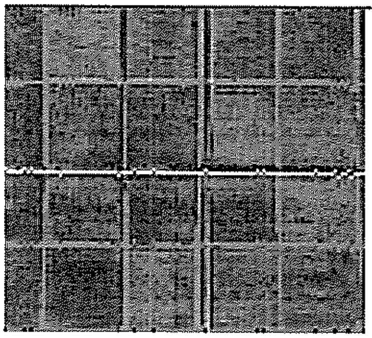


(g) Thermal image

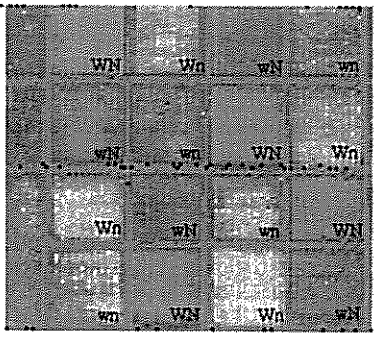


(h) RVI

Figure 2. Comparison of a true color photograph (a) acquired October 1 to images from AgIIS acquired September 27. The false color composite is a display of the NIR image (near infrared, d) as red, the red image (c) as green, and the green image (d) as red. RVI is the ratio of NIR to red.



(a) NIR, Red, Green false color composite



(b) CCCI, RVI, CWSI false color composite

Figure 3. A standard color infrared image (a) similar to fig. 2b and an "indices" false color composite image (b) from AgIIS on August 19. Treatment codes have been overlaid on the indices image. In b, CCCI is displayed as red, RVI as green and CWSI as blue.

DETERMINING CROP WATER STRESS FROM CROP TEMPERATURE VARIABILITY

R.B. Bryant, Physical Science Technician; M.S. Moran and T.R. Clarke, Physical Scientists; and P.J. Pinter Jr., Research Biologist

PROBLEM: Detection of plant water status is of primary importance for efficient and economic irrigation scheduling. Thermal infrared data in the wavelength band 8-13 µm have been found to be particularly well suited for crop water stress detection. Two of the most commonly used thermal indices for irrigation scheduling are the crop water stress index (CWSI) (Jackson et al, 1981) and the thermal kinetic window (TKW) (Burke et al., 1988). These physical indices are based on a comparison of the canopy temperature with the air temperature (in the case of CWSI) or the optimal temperature of a given crop (in the case of TKW). For both indices, it is necessary to convert the digital number (*dn*) recorded by the optical sensor to "true" or kinetic crop temperature (T_K), which is defined as the temperature measured with an accurate *in situ* thermometer in good contact with the crop. This conversion requires that the airborne optical sensor be calibrated (to convert *dn* to at-sensor radiometric temperature T_R'), the atmospheric attenuation of the sensor signal be known (to convert T_R' to surface radiometric temperature T_R), and the surface emissivity be known (to convert T_R to T_K). More often than not, airborne sensors are not calibrated; there is no information on atmospheric scattering and absorption; and there is only a rough estimate of surface emissivity.

APPROACH: The approach proposed here is based on the assumption that a crop with full cover and adequate water should display a normal distribution of thermal *dn*'s. Since the thermal image data of a well-watered crop tends toward a fixed value (the mid-range of its thermal kinetic window), it can be assumed that the data will be normally distributed if there are no other factors affecting the variability of the data (e.g., a bare spot in the field). Presumably, the further a data set of crop temperatures deviates from a normal distribution, the greater will be the plant water stress in the field. This is because, as water conditions for photosynthesis become sub-optimal, soil properties and genetic properties of individual plants will begin to influence the ability of the plant to stay within its thermal kinetic window.

We used this theory to derive an index based on the deviation of the *shape* of a histogram of the image data from the *shape* of a normally distributed histogram generated from the variance and mean of the thermal image data. In order to make the shape of each histogram comparable across different images regardless of standard deviation, the y axis of each histogram (i.e., the frequency for image data histogram and distribution for the generated histogram) was converted to a normalized frequency (f_n) and a distribution ($dist_n$) ranging from 0 to 1, where f_n = (frequency - minimum frequency) / (maximum frequency - minimum frequency), and $dist_n$ = (distribution - minimum distribution) / (maximum distribution - minimum distribution), thus allowing comparison of curve shape rather than *dn* distribution. To compute the Histogram-derived Crop Water Stress Index (HCWSI), we summed

$$HCWSI = \sum_{i=dn_{min}}^{dn_{max}} abs(f_n - dist_n)_i \qquad (1)$$

the absolute difference between f_n and $dist_n$ for each *dn*, where dn_{min} and dn_{max} are the minimum and maximum values of *dn* in the image. Graphically, HCWSI is the area represented by the shaded zones in Figure 1.

According to our theory, a recently irrigated field would have a relatively uniform thermal profile which would result in a histogram that was close to normal. A purely normal curve would have an index of 0.0 so a recently irrigated field would have a low HCWSI number. If the same field were to experience water stress, then the thermal profile would exhibit more heterogeneity and its histogram would deviate more from a mathematically normal curve. Its HCWSI should be higher than the HCWSI calculated from a recently irrigated field.

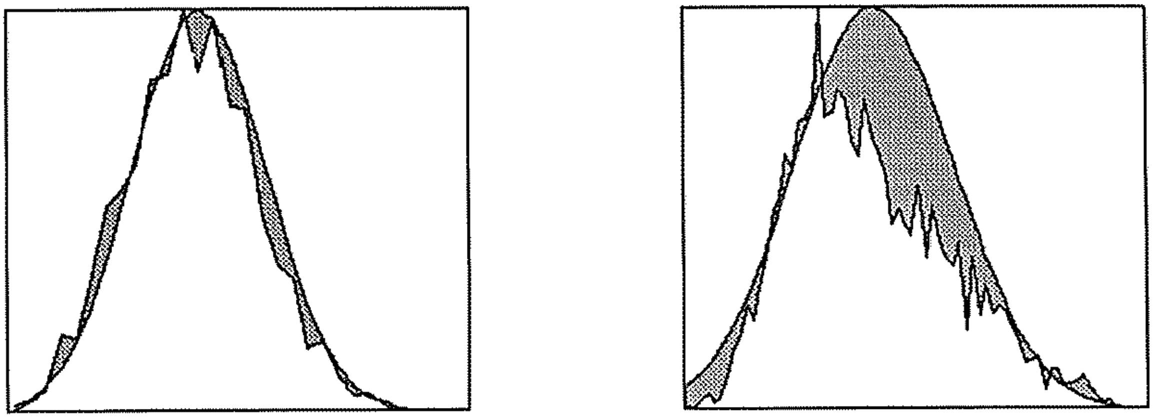


Figure 1. Example of a histogram from a thermal image of a well-watered crop (left) and a water-stressed crop (right), where the x-axis is image *dn* and the y-axis is normalized frequency and distribution. The jagged line is actual data and the smooth line is a mathematically normal histogram generated from the variance and mean of actual data. The integration of the gray area is the HCWSI.

FINDINGS: The images used in this analysis were from overflights of The University of Arizona's Maricopa Agriculture Research Center during the summer of 1994 as part of the Multi Spectral Airborne Demonstration at Maricopa Agricultural Center (MADMAC) (Moran et al., 1996). We chose three production cotton fields with 100% vegetation cover for demonstration of HCWSI. Field 31 was Upland Cotton (Gossypium hirsutum L.) and Fields 33 and 34 were planted with Pima Cotton (Gossypium barbadense). The soil at the east end of Field 33 (Border 2) was substantially more sandy than that of all other field borders. We extracted data for three irrigation borders in three fields from the thermal images with a size of 75x75 pixels which corresponded to ground dimensions of 150 x 150 meters. A histogram of each border was generated on each date using the *dn* range number (dn_{max}-dn_{min}) for the number of bins and f_n values 0-1 along the y-axis. Next, the variance and mean of each extracted data set were used to generate a histogram with a mathematically normal distribution. Using eq. (1), the HCWSI was generated for each temporally different image of each border resulting in a seasonal time series of HCWSI for each field border (Fig. 2).

Since the fields we analyzed were production crops which were regularly irrigated, the plants should not have been subjected to severe or prolonged water stress during the season. Field notes taken during the time of overflight indicated wilted plants in Fields 33 (Borders 3 ,4) and 34 (Border 2) only on one of the six dates analyzed, DOY 193. The HCWSI on that day for Fields 33 and 34 tended to be higher than the other dates for analyzed.

Irrigation occurred on DOY 199; and, according to the HCWSI, all borders in Field 34 recovered by the time of the next overflight on DOY 202. Plants in Field 33 apparently recovered more slowly. In fact, Border 2 retained a higher HCWSI for the rest of the season. This border was considerably more sandy than Borders 3 and 4, so there was a possibility that even when it was well irrigated the plants were still stressed and the thermal profile was still not normally shaped. This hypothesis was supported by the fact that Border 2 on DOY 235 still had a relatively high HCWSI (4.1) only two days after irrigation. It also had the highest HCWSI of all the borders on DOY 193 (10.6) so there is a possibility that permanent damage to the crop had occurred.

The HCWSI of Border 3 in Field 33 was highest on DOY 193 when leaf wilting was recorded in the field notes. According to subsequent HCWSI values, it took several weeks for the plants to recover completely from the severe wilting on DOY 193. That is, HCWSI values were still somewhat high (3.7 and 3.9 on DOYs 202 and 214), and finally reached a low HCWSI value of 1.2 on DOY 235.

Plants in Field 31 exhibited very little stress according to the HCWSI. Borders 3 and 4 on DOY 193 showed elevated numbers of HCWSI=3.2. We inspected the images and found that these borders had a north/south line of elevated *dn* probably due to irrigation problems. The only other border with a noticeably increased index was Border 2 on DOY 214. This also may have been due to irrigation problems.

INTERPRETATION: The HCWSI is a crop stress index based on within-field thermal variability that circumvents the need for ancillary meteorological data, complex atmospheric measurements, and knowledge of surface emissivity. Preliminary results from this study indicate that the HCWSI was sensitive to both early and chronic crop stress, and to irrigation non uniformity (e.g., skipped or partially irrigated fields).

FUTURE PLANS: This study was constrained by the fact that we had only qualitative field notes and no direct information on the water needs of the crop at the time of the overflights. Irrigation schedules and weather conditions were known, but this was not enough information to estimate the water needs of each border. Also, this study considered only fields with full-cover cotton canopy. It is not known if other crops and other field conditions, such as partial canopy closure, high winds, and nitrogen stress, affect the HWCSI to make it less effective as a general index for crop water stress. Another study should be conducted in which quantitative information on crop water stress is obtained at the same time as the acquisition of the thermal images.

COOPERATORS: Jiaguo Qi, Michigan State University, East Lansing MI.

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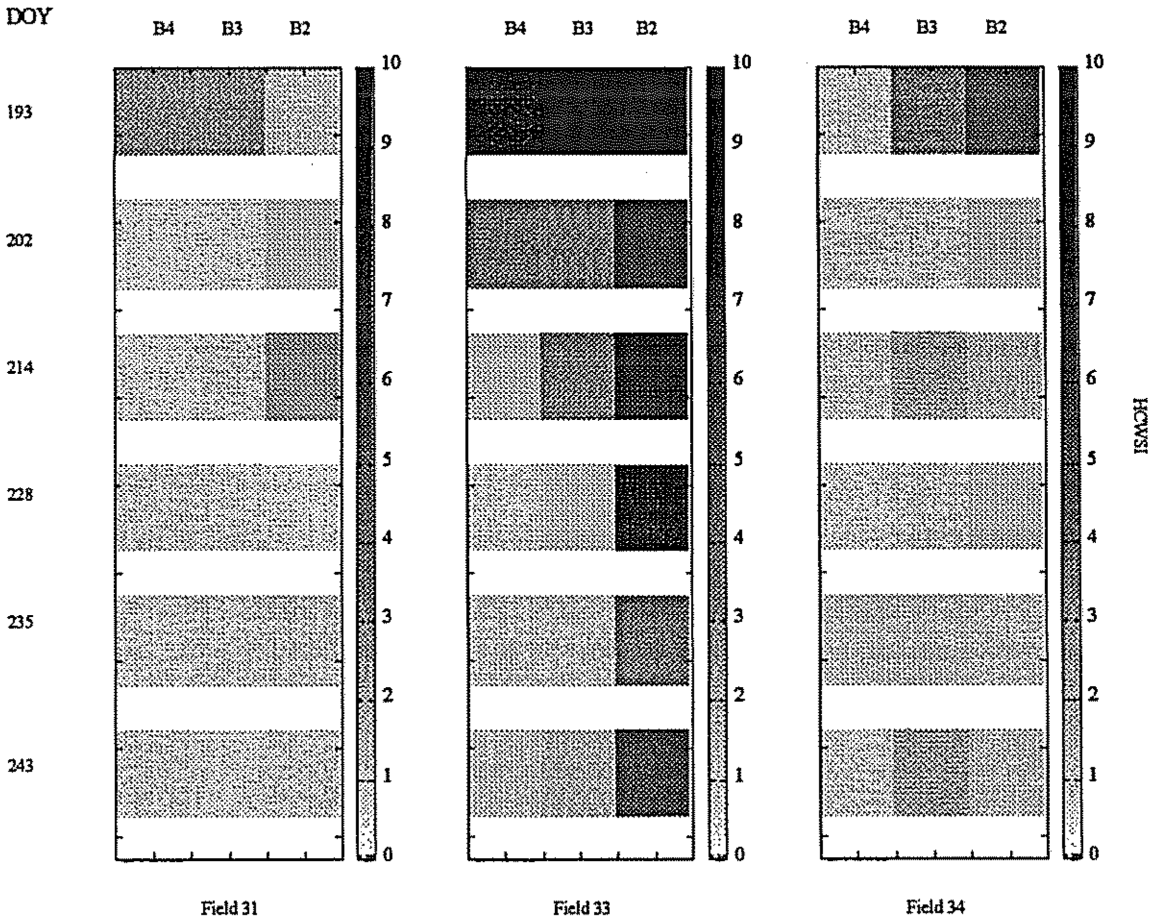

Figure 2. HCWSI values for each border of each field. B4, B3, and B2 refer to Borders 4, 3, and 2, respectively.

COMBINING SATELLITE IMAGERY WITH PLANT GROWTH AND SOIL WATER MODELLING FOR MULTI-YEAR SIMULATION OF GRASSLAND CARBON AND WATER BUDGET

Y.P. Nouvellon, Research Associate; M.S. Moran, Physical Scientist;
and R.B. Bryant and W. Ni, Biological Science Technicians

PROBLEM: Vegetation and soil functioning models have the ability to describe meaningful management processes and variables such as plant growth, crop yield, and soil water budget. Operational applications, however, have been hampered by our inability to provide a spatial distribution of the complete set of required model input parameters. This explains the growing interest in developing methodologies to incorporate remote sensing information in vegetation functioning models. In this work, we refined a Soil-Vegetation-Atmosphere-Transfer (SVAT) model to work on a spatially-distributed basis, continuously over multi-year periods, over a semi-arid grassland watershed, the Walnut-Gulch Experimental Watershed (WGEW) in Southeast Arizona.

APPROACH: The SVAT model used in this study (Nouvellon et al., 1999a, and Fig. 1) is driven by standard daily meteorological data and simulates the biomass dynamics of green shoots, dead shoots, and living roots on a daily basis (plant growth submodel). Plant transpiration, soil evaporation and soil water fluxes also are simulated in a water budget submodel.

The main processes simulated in the plant growth submodel are photosynthesis, photosynthate partitioning between aerial and below-ground compartments, translocation of carbohydrates from roots to shoots at the regrowth period, respiration, and senescence. The water balance submodel uses a simplified two-layer canopy evapotranspiration model where the soil profile is divided into three layers. The main processes simulated are the water infiltration and percolation in the soil profile, the evaporation from the soil and from the sparse grass canopy (using the Penman-Monteith equation), the canopy stomatal control, and the root water uptake in each soil layer.

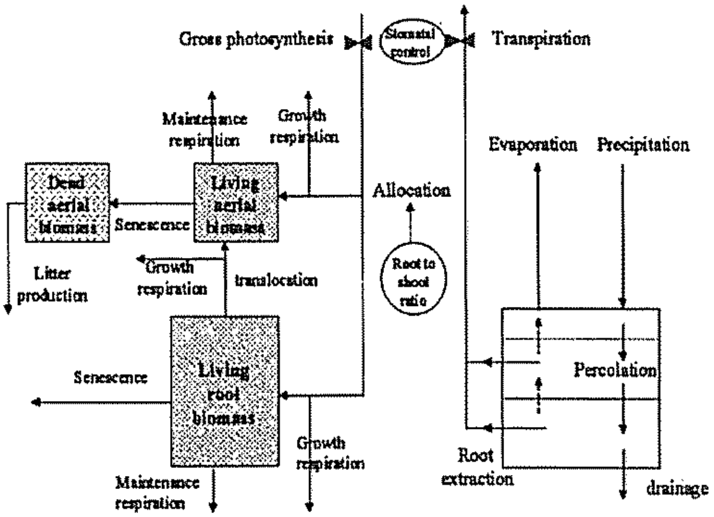

Figure 1: Schematic representation of the plant growth and water budget models.

The SVAT model was combined with a physically-based Radiative Transfer Model RTM [the Markov Chain of Canopy Reflectance (MCCR) model (Kuusk, 1995)] through the green Plant Area Index (PAI) simulated by the plant growth model. The MCCR model accounts for the non-random pattern of leaf distribution through the incorporation of a Markov model for gap fractions computation. The parameters of the Markov model and those used to describe the Leaf and Stem angle distribution (LSAD) were derived from extensive measurements of canopy structure and gap fraction on various sites in Northern Mexico and Southeast Arizona (Nouvellon et al., 1999b).

Landsat Thematic Mapper (TM) images obtained during the summer growing seasons of ten consecutive years (1990-1999) were used to calibrate the SVAT model. The SVAT model was applied over the grassland areas of the WGEW (selected using a digital vegetation map), using soil texture parameters provided by a digital soil map and daily meteorological data measured at the Kendall site from June 1990 through August 1999 (Fig. 2). At each satellite overpass, NDVI were simulated by the combined SVAT-RTM (in the same sun/view zenith angles configuration as the corresponding measurements) and compared to NDVI calculated from reflectances measured by TM sensor and corrected for atmospheric effects. Spatially unknown initial conditions and parameters were estimated using an iterative procedure based on the simplex method that minimizes the difference between simulated and measured NDVI. Parameters and initial conditions chosen to be re-parameterized / re-initialized were such that (1) the model is highly sensitive to them, (2) they are spatially variable, and (3) they are difficult to obtain by direct measurement at the regional scale. Following a sensitivity analysis and taking into account the above criteria, initial living root biomass (BR_{ini}) and maximum light use efficiency (ε_{gmax}) were selected to be initialized and parameterized respectively.

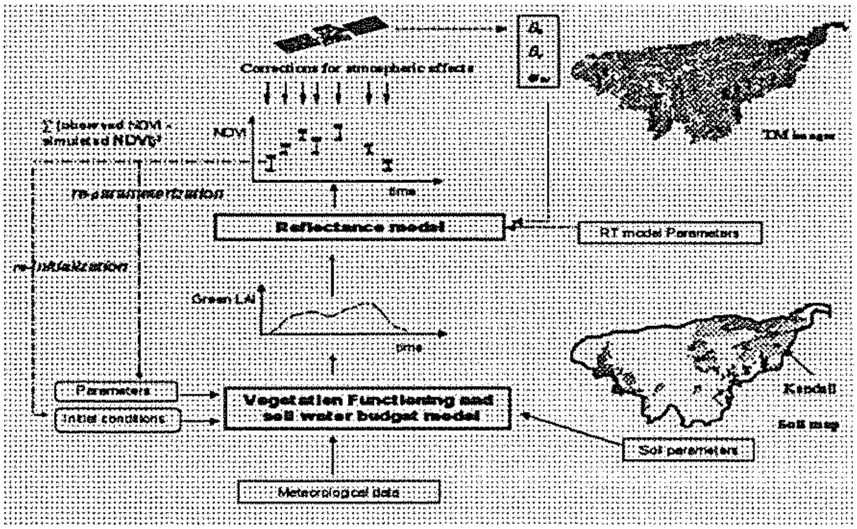

Figure 2: Synoptic view of the approach used to refine the plant growth/ soil water budget model to work on a spatially distributed basis using time series of Landsat TM images.

FINDINGS: Biomass measurements obtained at the Kendall site from 1990 to 1992 were used to evaluate model results obtained without calibration and with calibration using TM images. Daily simulations of biomass obtained for the Kendall site for the ten-year period using two a-priori sets of possible values of ε_{gmax} and BR_{ini} were compared to aboveground biomass measured from 1990 to 1992 (Fig 3). Reflectances and NDVI simulated by the combined SVAT-RTM for these two a-priori parameter sets also were compared to TM-derived red and NIR reflectances and NDVI (mean values of reflectance and NDVI of the pixels that includes the Kendall site). The first set of a-priori values of ε_{gmax} and BR_{ini} resulted in overestimation of measured aboveground biomass (RMSE of 20.0 g m^{-2}) and NDVI (RMSE of 0.065). Underestimation of biomass and NDVI resulted from the second set (RMSE of 18.8 g m^{-2} and 0.068, respectively). These results show that SVAT errors due to uncertain values of ε_{gmax} and BR_{ini} strongly propagate in the RTM resulting in a high sensitivity of NDVI to model errors.

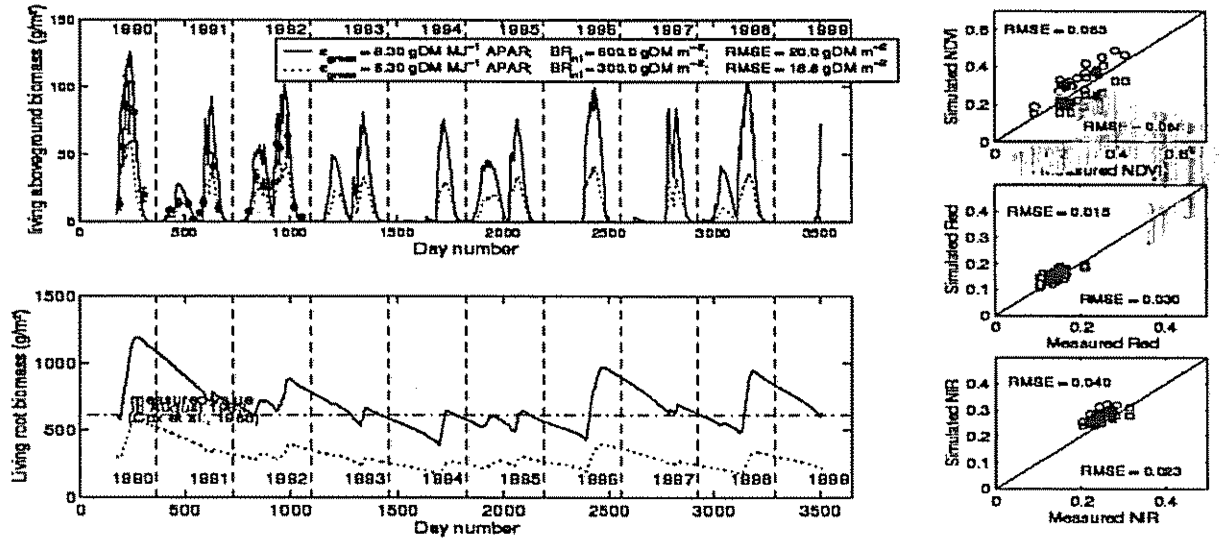

Figure 3: Simulation results obtained using two a-priori sets of reasonable values of ε_{gmax} and BR_{ini}. In the top-left graph, solid circles with error bars show aboveground biomass measurements. In the bottom-left graph, the horizontal broken line show the value of root biomass measured by Cox et al. (1986) in August 1983. The RMSE associated to each set of parameters are indicated on the graphs.

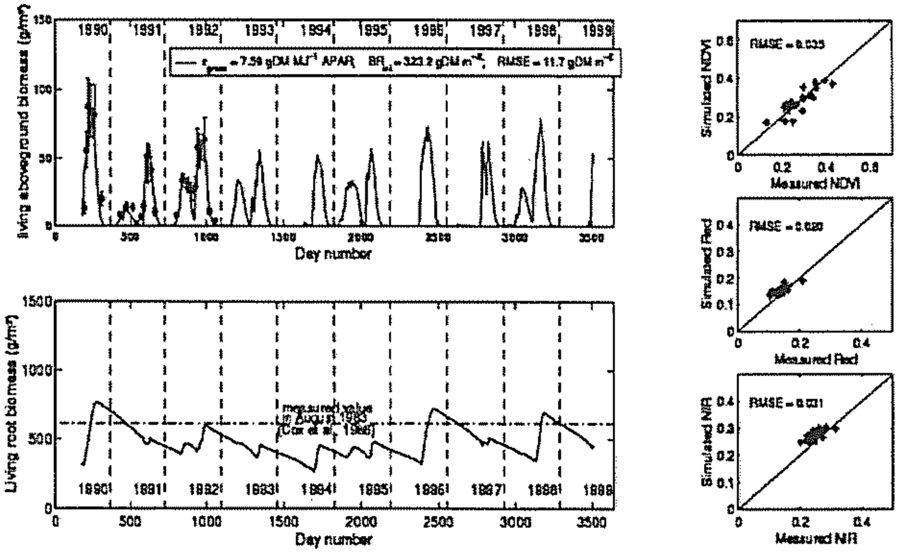

Figure 4: Simulation results obtained on the Kendall site after model calibration using TM images. The retrieved values of ε_{gmax} and BR_{ini} are indicated on the figure. In the top-left graph, solid circles with error bars show aboveground biomass measurements. In the bottom-left graph, the horizontal broken line shows the value of root biomass measured by Cox et al. (1986).

Figure 4 presents the simulation results obtained after model calibration. The results show that, after calibration, simulated aboveground biomass was in good agreement with measurements and with an RMSE of only 11.7 gm^{-2}.

INTERPRETATION: In this study, a coupled SVAT-RTM was run on a spatially distributed basis with assimilation of a ten-year time series of Landsat TM data. It was shown that satellite derived NDVI could be used to control the simulation of the coupled model through a calibration procedure which gives the estimation of two spatially variable initial conditions and model parameters. The results obtained suggest that the approach using both modeling and remote sensing may prove more useful in grassland management than either of them used alone. It also can provide spatially-distributed information about vegetation [e.g., maps of biomass obtained at a daily time step (Fig. 5)] and soil conditions for day-to-day grassland management.

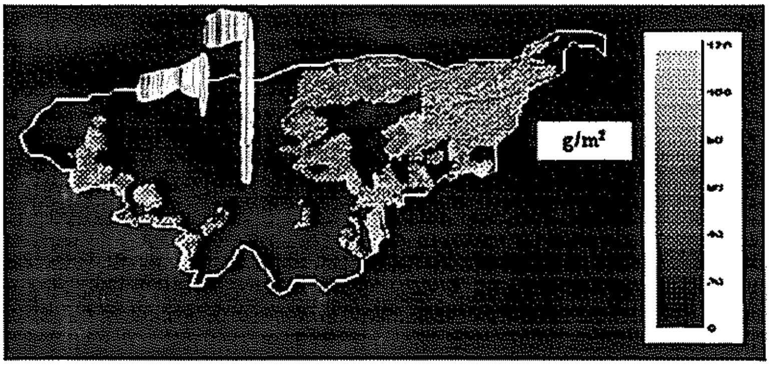

Figure 5: Map of simulated above-ground biomass (DOY 249, year 1992) on grassland areas of the WGEW.

FUTURE PLANS: We are currently initiating several works in order (1) to incorporate a runoff model in the grassland model; (2) to test more robust and faster calibration procedures; (3) to use both optical thermal and microwave remote sensing data; and (4) to address the problem of how meteorological data obtained at discrete locations can be used on a spatially distributed basis.

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SPECTRAL REFLECTANCE PROPERTIES OF INSECT TRAPS

P.J. Pinter, Jr., Research Biologist; S.M. Gerszewski, Biological Technician;
C.C. Chu, Research Entomologist; and T.J. Henneberry, Research Biologist

PROBLEM: A passive insect trap was recently developed for monitoring populations of silverleaf whiteflies (*Bemesia argentifolii* Bellows and Perring) and other insects in cotton and other field crops (Chu et al. 1998). Called the CC Trap after the initials of its inventor, C. C. Chu, the design of this new trap was based on insect behavior, primarily the attraction of insects to certain colors. No sticky materials, pheromones, or baits are used in its operation. From 1996 through 1999, scientists tested the trap efficiency in catching insects in the United States, India, and the People's Republic of China. The purpose of the U.S. Water Conservation Laboratory's involvement was to characterize the spectral properties of variously colored trap bases and relate the findings to trap performance.

APPROACH: The CC insect trap consists of a clear plastic trap top to admit light for insect orientation into the trap, a deflector plate to reduce escape of trapped insects, and a colored trap base that has an opening for insect entrance (Fig. 1). Nine different trap base colors were studied. These are described in the Monsanto Plastic (1993) color chart as white, rum, red, yellow, lime green, spring green, woodland green (dark green), true blue, and black.

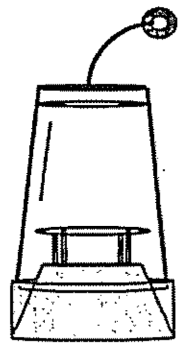

Figure 1. The CC insect trap.

A Personal Spectrometer II (PSII, Analytical Spectral Devices, Inc., Boulder, Colorado) was used to obtain spectral data from trap bases that were illuminated by midday, direct beam sunlight and diffuse sky irradiance. The spectroradiometer has a nominal 350 to 1050 nm spectral response, 1.4 nm sampling interval and approximately 3 nm spectral resolution. Fiber optics on the PSII were equipped with 10° field-of-view foreoptics. Measurements were made with the optics oriented normal (perpendicular) to the outside surface of the trap base. Reflectance factors were computed as the ratio of directional radiances of the trap base to irradiances estimated from frequent measurements over a calibrated $BaSO_4$ reference panel. Reflectance of the abaxial (under) surface of field-grown cotton leaves was used as a reference for comparison with colored trap bases.

FINDINGS: The differently colored plastic traps had spectral reflectance characteristics which varied considerably across the visible (400 to 700 nm) and near-infrared (700 to 1050 nm) portions of the spectrum. The different spectral shapes could be roughly associated with trap efficacy. We observed, for example, that the three most attractive trap colors for whiteflies and leafhoppers (lime green, spring green, and yellow in Fig. 2) had reflectances that were relatively low in the blue (400 to 460 nm) and higher in the green, yellow, and orange spectral regions (490 to 600 nm). It is relevant to note that the abaxial surfaces of green cotton leaves (also shown in Fig. 2) have a small peak at 550 nm that was spectrally similar to the prominent peaks measured on the lime green and spring green trap bases. Green cotton leaves also had low blue and red reflectances as well as high NIR reflectances. Thus the lime green and spring green trap bases seemed to mimic green leaves in an abstract sense. The lime green and spring green colored traps differed considerably from the yellow colored plastic trap and the commercially available, yellow cardboard sticky trap (not shown in figures) by having relatively low reflectances in both the red (600 to 700 nm) and red to NIR transition (700 to 740 nm) spectral regions. The yellow trap base had low blue reflectance, and, although lacking a peak in the green region (500-550 nm), displayed overall high reflectances beginning at 580 nm and continuing upwards into the NIR region. We found that the least attractive trap colors for whiteflies and leafhoppers (Fig. 3) had either very low reflectance at all wavelengths (e.g.., black and dark green) or had moderately high reflectance in the blue (400 to 480 nm; e.g., true blue trap) or red regions of the spectrum (600 to 700 nm, eg. red trap).

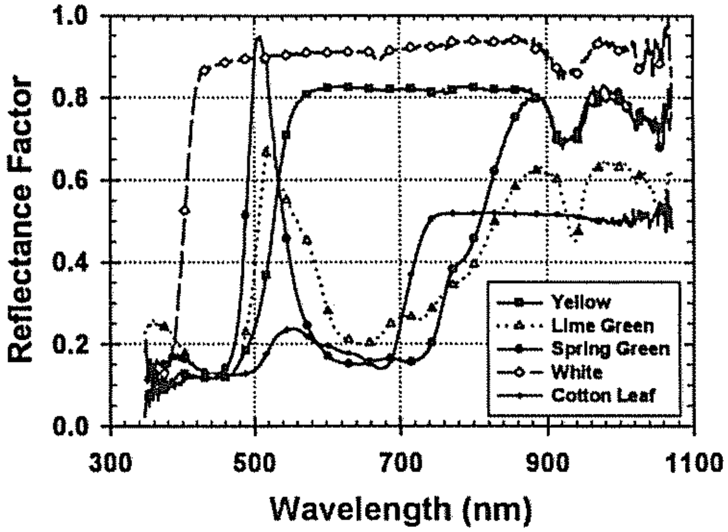

Figure 2. Spectral properties of CC trap base colors yellow, lime green, spring green, and white in reference to the abaxial surface of a cotton leaf.

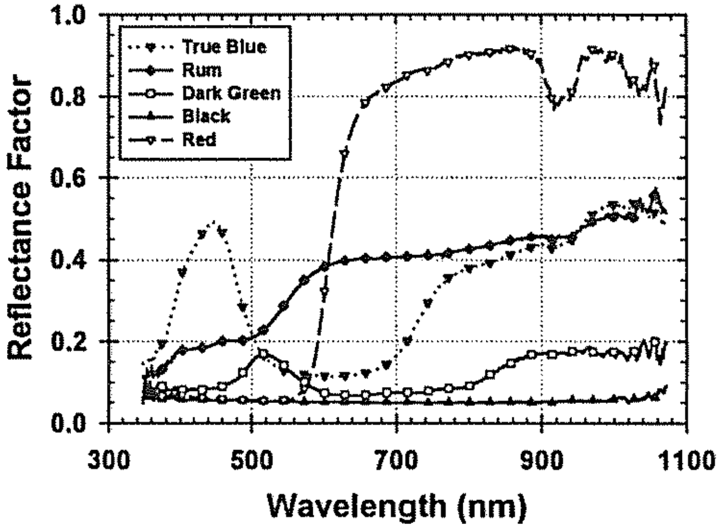

Figure 3. Spectral reflectance of CC trap base colors true blue, rum, dark green, black, and red.

INTERPRETATION: The reflectance factors that we measured from the most attractive trap base colors (lime green, spring green, and yellow) for the silverleaf whitefly and leafhoppers were somewhat similar to the spectral properties of healthy green cotton leaves (i.e., low reflectance in the blue, high NIR reflectance). Spectral properties of leaves and canopies vary with age and environmental conditions, and this may alter the time course of plant attractiveness to insects that use color clues in selecting host plants. We have observed, for example, that as cotton becomes nutrient stressed the green/yellow-green peak tends to become amplified slightly compared with the red (data not shown) although it never becomes as exaggerated as that observed in the lime and spring green traps.

In a previous, unpublished study (Pinter, 1994), we examined the high resolution spectral properties of cotton leaves coated with honeydew produced by actively feeding silverleaf whiteflies. We found that the honeydew caused higher reflectance in both the visible and NIR wavelengths. However, the increases were much greater in the blue and red regions than in either the green or NIR. The honeydew varnish also acted like a spectrally selective mirror so that this effect was accentuated when the leaves were viewed in the forward scattering direction (i.e., so that some sun glint could be seen on the leaf surface). Such changes in leaf spectral properties caused by honeydew may "signal" the presence of high larval densities to migrating adult whiteflies enabling them to avoid areas where resources are already being exploited. Further examination of links between trap performance and spectral deterrents or attractants could lead to improved traps having different construction materials or colors and could improve our basic understanding of insect migration and colonization behavior. Additional research also may provide insight on why some insects are attracted to plants experiencing water or nutrient stress and why some crop cultivars seem more attractive to certain insects.

FUTURE PLANS: A manuscript on the spectral properties and efficacy of the CC Trap has been prepared and submitted (Chu et al.).

COOPERATORS: Kai Umeda, University of Arizona, Maricopa County Extension Service, Phoenix AZ.

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GERMPLASM IMPROVEMENT AND AGRONOMIC DEVELOPMENT OF NEW ALTERNATIVE INDUSTRIAL CROPS

CONTENTS

GERMPLASM IMPROVEMENT AND AGRONOMIC DEVELOPMENT OF NEW ALTERNATIVE INDUSTRIAL CROPS

MISSION

To acquire and characterize germplasm of guayule, lesquerella, and other promising new, alternative crops. To evaluate and enhance germplasm of new crops for industrial raw materials. To develop knowledge of floral biology and seed production and plant responses to stresses. To develop economical cultural and seed production systems for new crops under various conditions. To develop methods for efficient guayule latex extraction and seed oil analyses for characterizing latex, resin, and oil properties.

GUAYULE LATEX, RUBBER, AND RESIN

F.S. Nakayama, Research Chemist; T.A. Coffelt and D.A. Dierig, Research Geneticists; and S.H.Vinyard and A. Faber, Research Technicians

PROBLEM: Because all the harvested guayule shrubs cannot be processed for latex extraction at one time, the plants must be stored properly to avoid loss of latex. Thus, methods must be developed to assure that the quantity of the latex is maintained in these shrubs. In addition, shrub harvest is expected to occur throughout the year; therefore, information is needed on how the extractable latex changes throughout the season to optimize harvest scheduling. Less than 10% of the plant is used for latex production and ways must be found to utilize the waste plant material.

APPROACH: Because of the dramatic effect obtained in 1998, the experiment of maintaining the water content of the stored shrub was repeated. More careful water treatment was made where a timed misting system was provided to keep the plants from drying out. The ground shrub was immersed into treated antioxidant-pH-adjusted solution immediately after chipping to avoid loss of latex. Alternate-month harvests of four lines of guayule were continued and analyzed for latex content.

FINDINGS: The latex in the stored whole shrub could be maintained for at least two weeks when the shrub was kept moist (Fig. 1). The latex content of shrubs stored under a screen shade decreased with storage time. This decrease in latex extractability was closely related to the water contents of the shrub (Fig. 2). Note that the water content presented here can exceed 100% because it is based on the plant dry weight. Under the misting system, the stored shrub actually gained water.

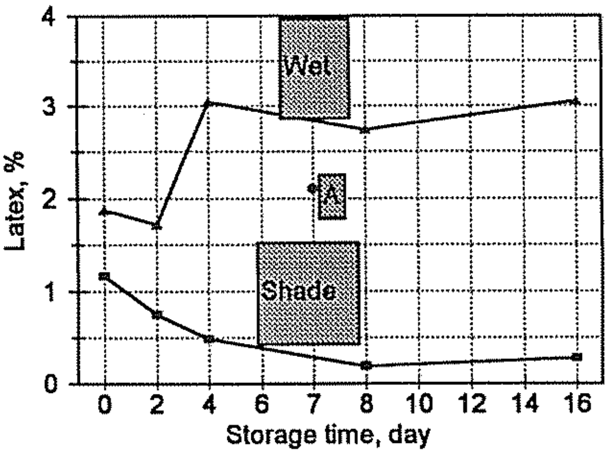

Figure 1. Effect of storage condition on latex extractability from shrub.

Shrub drying below the initial 60% water content greatly decreased the latex extracted. Drying occurred after only two days of storage in the shade. The experiment was conducted in August when dehydration is expected to be large. In contrast, by maintaining the shrub water content above 80%, latex extractability was maintained.

The importance of water in plant cells is shown by these results. Dehydration can cause the rubber particles in the cells to coagulate and no longer be in the emulsion or latex state. Thus, it is necessary to keep the plant in a moist condition before the extraction process. The point "A" in figure 1 represents a shrub that was stored in the shade for two days and then stored in the mister system for 5 days. The results show that rehydration can occur with an increase in extractable latex. For commercial purposes, adequate coordination between shrub harvest and the latex extraction process must be made to insure that the shrubs do not get dehydrated.

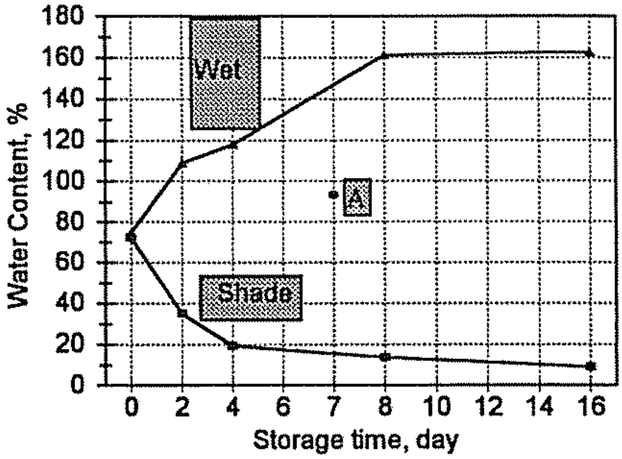

Figure 2. Effect of storage condition on water content of shrub.

The latex content of the guayule shrub appeared to follow a seasonal pattern based on the bimonthly sampling (Fig. 3). Between November (Time = 11) and March (Time = 15), the latex of the whole plant tended to increase. The line 11591 had the highest latex content per plant. The 11591 is one of the original USDA lines developed during the Emergency Rubber Project of the mid-1940s. The total latex per plant (Fig. 4) did not show the large variation as did the latex concentration. An extraordinary high latex content was present in the line G7-11, but this was caused by a very large biomass of about four times that of the other lines. Plant number for this line was limited so that the nonuniform large plants were used.

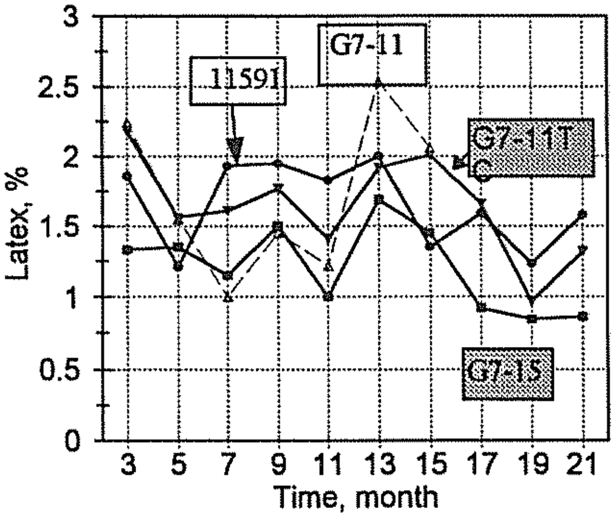

Figure 3. Relation between latex content and season.

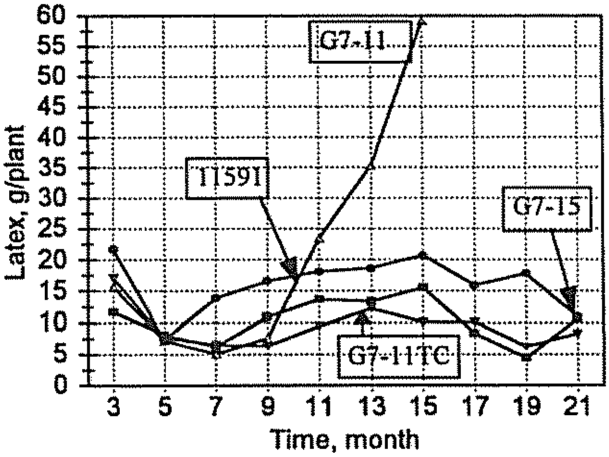

Figure 4. Relation between shrub latex content and season.

Composite wood and resin extracts were prepared from the waste bagasse material. The composite wood and resin impregnated wood were placed at field sites in May and September and will undergo testing for approximately one year.

INTERPRETATION: Shrubs must be processed almost immediately after harvest or treated with water to maintain latex extractability, if there are chances for delays in the processing of harvested plants. This is particularly important in commercial application to commercial processing where adequate coordination must be made between shrub harvest and latex extraction.

Waste bagasse materials can be utilized by fabricating particle boards. The resin contained in them also could be used in a similar manner to treat other wood types.

FUTURE PLANS: We plan to continue the latex studies with the support of a Fund for Rural America grant, which includes determining the effect of season and variety on the latex content of shrubs, storage and chemical pretreatment of shrubs, and latex characterization. Experimental work includes shrub storage in the open atmosphere and in water, and the use of other antioxidants or completely eliminating them to decrease the cost of shrub preparation. Related investigations will be done on whole shrub latex extraction to test the hypothesis that grinding the shrub directly in the extracting solution without atmospheric contact would maximize latex extraction and stability.

We plan to produce large quantities of purified latex in order for our cooperators to make latex medical products for conducting physical and chemical tests.

We will continue to find ways to utilize the waste materials for pest control. These include the fabrication of composite and resin impregnated wood products. We plan to develop cooperative testing in a more humid climate. Existing cooperative projects will continue with the possibility of establishing a Cooperative Research and Development Agreement (CRADA) to develop uses for the waste bagasse to make blends and other types of high-valued, commercially useful wood products.

COOPERATORS: K. Cornish, USDA-ARS-PWA, Albany CA; J.A. Youngquist, USDA-Forest Products Laboratory, Madison WI; Poo Chow, Natural Resources and Environmental Sciences, University of Illinois, Urbana IL; D.T. Ray and D.K. Stumpf, Plant Sciences, The University of Arizona, Tucson AZ.

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Nakayama, F.S.; Coffelt, T.A.; Dierig, D.A.; Vinyard, S.H.; and Eggemeyer, K.D. 1998. Guayule Latex, Rubber, and Resin. USWCL 1998 Annual Report.

GUAYULE BREEDING AND GERMPLASM EVALUATION

T.A. Coffelt and D.A. Dierig, Research Geneticists; F.S. Nakayama, Research Chemist; and G. S. Leake, S. H. Vinyard, A. Faber, G. H. Dahlquist, A. R. Kaiser, and P. Tomasi, Research Technicians

PROBLEM: Latex allergies caused by Heavea latex are becoming a serious health problem, and so alternative sources of hypoallergenic latex are needed. One possible source is guayule, but higher yielding, faster growing, and easier to establish germplasm is needed for it to be successful as a viable new crop. The objectives of this study have been (1) to evaluate the amount of variation within germplasm lines due to environment and genetics; (2) to establish new breeding plots for making interspecific crosses to produce higher yielding lines; and (3) to transfer technology to cooperators for wider germplasm evaluations and successful commercialization.

APPROACH: Field plots have been established at the Maricopa Agricultural Center and the U.S. Water Conservation Laboratory to provide plant material for accomplishing these objectives. Experimental designs include randomized complete block designs, completely randomized designs, and non-randomized designs depending upon the specific objectives of the experiment.

<u>Objective 1</u>: To estimate the genetic and environmental components of variation within germplasm lines, a novel approach was used. Open-pollinated (op) seed derived plants were compared with clonally propagated (cp) plants of the same line. Total genotypic plus environmental variance was assumed to be the variance observed among op plants; environmental variance was assumed to be the variance observed among cp plants; and genotypic variance was the difference between the total variance and environmental variance. Traits evaluated included plant height and width as well as rubber, resin, and latex contents. Heritabilities of these traits were estimated by dividing the genotypic variance by the total variance.

<u>Objective 2</u>: To establish new field plantings for breeding and crossing studies, plants of selected lines were transplanted at the U. S. Water Conservation Laboratory.

<u>Objective 3:</u> To transfer technology to cooperators, material transfer agreements and trust agreements were developed.

FINDINGS:

<u>Objective 1</u>: We found that a large portion of the variation is attributed to genotypic variation in years one and two of plant growth, but in the third year environmental variation is predominant. Heritability of the traits studied also decreased with increased plant age.

<u>Objective 2</u>: Plots were successfully established at the U. S. Water Conservation Laboratory for use in breeding and crossing studies next year.

<u>Objective 3:</u> Material transfer agreements were signed with cooperators in Australia and South Africa. A trust agreement was signed with Yulex Corporation.

INTERPRETATION: Currently, plant breeding strategies in guayule have been to wait until plants reach maturity at three or more years of age before making selections. Results from our studies indicate that this may not be the most efficient way to maximize selection for genetic variation. A more effect strategy appears to be to make individual plant selections during the first year or two of plant growth for the traits studied. Then breeders could mass select lines over several generations following the single plant selections. This strategy for plant improvement offers a quicker and more efficient alternative to current methods. The results also suggest one reason why progress in guayule breeding has been slow in the past. These results will benefit both public and private researchers developing guayule into a viable commercial latex crop.

FUTURE PLANS: Selection will continue both within and among lines for improved characteristics. Superior lines identified from these experiments will be considered for possible release as improved germplasm. Additional studies also will be conducted to try better to identify how much variability within lines is due to genetic vs. environmental factors. Studies to improve the chances for direct seeding of guayule also will continue. Both interspecific and intraspecific crosses will be attempted in 2000 to increase the variability for desired traits. Selections in these new populations should lead to higher yielding more uniform lines. Cooperation with industry partners and other researchers will continue to help advance the chances for commercialization of guayule.

COOPERATORS: D.T. Ray and D. Stumpf, Plant Sci. Dep., Univ. of Arizona, Tucson AZ; M.A. Foster, Texas Agric. Exp. Station, Texas A&M Univ., Pecos TX; J. Fowler, New Mexico State University, Los Cruces NM; A. Estilai, Dep. Botany and Plant Sciences, Univ. of California, Riverside CA; K. Cornish, USDA-ARS-PWA-WRRC, Albany CA; W.W. Schloman, Jr., Dep. Chemistry, Univ. of Akron, Akron OH; F.J. Adamsen and D.J. Hunsaker, USWCL, Phoenix AZ.

ENVIRONMENTAL EFFECTS ON GUAYULE SEED PRODUCTION AND QUALITY

T.A. Coffelt and D.A. Dierig, Research Geneticists; F.S. Nakayama, Research Chemist; and G.S. Leake, S.H. Vinyard, A. Faber, G.H. Dahlquist, A.R. Kaiser, and P. Tomasi, Research Technicians

PROBLEM: Data on optimal harvest time for seed production in guayule with respect to seed quantity and quality is lacking. This information is needed to maximize seed production of the highest germination. Obtaining sufficient quantities of seed is the first step in increasing the acreage of guayule for successful commercialization.

APPROACH: Seed from seven guayule lines is being harvested on a monthly schedule beginning in June 1999 and continuing until seed production is completed. So far harvests have been made through November 1999. Harvested seed is being shipped to cooperators at the University of Arizona in Tucson for weighing, cleaning, quality evaluation, and subsampling for germination testing. Subsamples will be sent to cooperators at New Mexico State University in Los Cruces for germination tests. Similar harvests are being conducted in California, New Mexico, and Texas.

FINDINGS: Evaluation of the seed samples for quality and quantity has not been completed. However, seed has been successfully harvested at each of the scheduled harvests this year. Preliminary observations indicate that the most seed was produced at the first harvest. We observed that the first harvest was approximately one month later than it should have been. We also observed significant seed loss due to shattering during summer windstorms, which affected the amount of seed harvested in July and August.

INTERPRETATION: Preliminary observations suggest that seed harvest should be started in Arizona in May or possibly earlier depending on the growing season with respect to quantity of seed produced. Results are not complete yet to know if this also applies to seed quality. Weather patterns can adversely affect the seed harvesting. Care needs to be taken when seed production is a major objective to be able to harvest seed when storms are forecast to prevent seed loss.

FUTURE PLANS: Seed will continue to be harvested for the remainder of this season and as early as possible in 2000. Seed quality and quantity will be determined for all samples from the four locations. Data will be analyzed to determine the optimum harvest date(s) for each location as well as the effects of environment and germplasm line on seed quality and quantity.

COOPERATORS: D. Ray and D. Stumpf, Plant Sci. Dep., Univ. of Arizona, Tucson AZ; M. Foster, Texas A&M Univ., Pecos TX; A. Estilai, Dep. Botany and Plant Sci., Univ. of California, Riverside CA; J. Fowler, New Mexico State University, Los Cruces NM.

BREEDING IMPROVEMENTS OF LESQUERELLA

David A. Dierig and Terry A. Coffelt, Research Geneticists;
Francis S. Nakayama, Research Chemist; and Pernell Tomasi, Gail Dahlquist,
Aaron Kaiser, and Greg Leake, Research Technicians

PROBLEM: *Lesquerella fendleri* (Gray) Wats., *Brassicaceae*, is a potential oilseed crop native to the southwestern United States. The seed oil contains hydroxy fatty acids, similar to castor. Unique properties of the oil, along with coproducts, allow additional applications that would not be in competition with castor.

Other species of *Lesquerella* produce higher quantities of hydroxy fatty acid (HFA) than *L. fendleri,* but none are as productive in seed yield. There are over 70 species from the western half of the U.S. that do not cross pollinate in the wild, or by controlled crosses, due partially to self incompatibility and incongruity between species. This also prevents plants from producing seed from their own pollen (self-pollination). Selfed plants are desired in studies requiring genetic ratios, in developing probes for molecular markers, and in breeding for plant uniformity. Bud pollination is a method used to circumvent self-incompatibility in other *Brassicaceae* by applying pollen from the same plant to the stigma before the flower opens. However, for optimum amounts of selfed seed to be produced, the correct stage of floral development must be defined. This technique could allow hybridization between *L. fendleri* and other species with more desirable oil profiles as well as allow plants to produce selfed seed.

Little information is known on variability of lesquerella for salt tolerance. Previous research indicated that high salinity caused significant plant mortality, reduced growth rates, and decreased seed yield. Selection of plants for germination, survival, and seed yield in high saline treatments could allow lesquerella to be produced in areas with saline problems.

Lesquerella could be more profitable for farmers if seed-oil traits were improved. Public releases of seed have been made in the past by this laboratory with higher oil and lesquerolic acid contents, and reduced oil pigmentation. Yield trials must be conducted to identify progress of new lines.

APPROACH: Floral buds of four different lines were self pollinated in the greenhouse between eight days and one half a day before flowers opened. The lengths of the buds also were measured at the time of pollination. Seed was obtained from the controlled pollinations, and seed yields were correlated to the number of days before anthesis and bud lengths. Plants of *L. fendleri* and five other *Lesquerella* species listed in Table 1 were reciprocally crossed by bud pollination.

Three lesquerella lines, a salt tolerant selection, the parent to this selection, and a test line for comparison, were planted in sand-filled lysimeters on October 28, 1998, at the U.S. Salinity Laboratory, Riverside CA. Irrigation solutions were salinized on January 21, 1999, and plants were harvested on June 10, 1999. Experimental design was a split plot with seven irrigation water salinities (3, 7, 11, 15, 18, 21, and 24 dSm^{-1}), 3 genotypes, and 3 replications (24 plants/rep). Plant biomass and seed yields were measured at harvest. Seed also was obtained from selected plants of the 21 and

24 dS/ m-1 treatments by controlled bud self pollination where pollen from a surviving plant in one of two treatments was transferred to the stigma of another plant within the same treatment before the flower opened.

Half sib families selected for plant height and seed yield were grown in a yield trial at Maricopa Agricultural Center (MAC) and Tucson AZ. Six additional lines, three previously released germplasm lines, and three further improved descendent lines also were planted for comparisons (Table 2). One of the three lines was selected for oil, one for lesquerolic acid content, and one for the combination of oil and lesquerolic acid content. All were compared to the three released lines (WCL-LO1, WCL-LH1, WCL-LY1) and an unselected control.

FINDINGS: The best seed yields were obtained from plants that had been bud pollinated between one and three days before flowers opened. The best bud length for this method was between five and seven mm. No differences were found among the four lines tested. Limited numbers of seeds were obtained from crosses between *L. fendleri* and *lindheimeri, gracillis,* and *pallida* species listed in Table 1. Hybrid plants are being grown for confirmation of hybridity and evaluation.

Table 1. Chromosome number, oil, lesquerolic acid, and auricolic acid of *L. fendleri* and five other species used for interspecific crosses.

Lesquerella species	*n* = x	Oil content	Lesquerolic acid (C20-1OH)	Auricolic acid (C20-2OH)
fendleri	6	23.6	50.2	trace
lindheimeri	6	21.6	81.7	0.35
mcvaughiana	6	17.1	46.3	1.23
gracillis	6	28.9	68.8	trace
auriculata	8	33	8.1	17.4
pallida	6	na	81.4	3.68

The selected salt tolerant line had significantly higher rates of survival than the parental line after three weeks salination and the test line after six weeks. Vegetative growth also was reduced more by salinity in the parental and test lines than in the salt tolerant line. Seed yield (g / plant) increased in all lines up to 11 dS/m. The salt tolerant line out-yielded the parental line by about 2:1 (Fig. 1). At higher salinities, seed yield of the salt tolerant line was greater than both other lines combined. Salinity treatments of 11 dS/m and higher resulted in increased oil and lesquerolic acid content compared to the low salinity treatments.

Performance in seed yield and other yield related traits were better in Maricopa compared to the Tucson location (Table 2). Oil and lesquerolic acid content of WCL-LY2 were higher than the unselected control and released lines. Seed yield was not directly selected but was improved in WCL-

LY2 compared to the unselected control. No significant difference was found for plant height and seed yield from the half sib lines at either location.

Table 2. Comparison of six lines and a control line for oil, lesquerolic acid, and both oil and lesquerolic acid grown at Maricopa and Tucson AZ. The lines starting with 98 are new lines being tested, the WCL lines are previously released, and the control is unselected.

	Oil content (%)		Lesquerolic acid (%)		Seed yield (g/plant)	
Line (sel. basis)	Maricopa	Tucson	Maricopa	Tucson	Maricopa	Tucson
98LO (oil)	29.0 a	25.4 ab	53.9 bc	52.6 ab	na	na
98LH (lesq acid)	25.2 c	23.8 b	54.9 a	53.8 a	na	na
98LY(WCL-LY2)(both)	29.41 a	26.7 a	54.1 b	53.1 ab	35.5 a	24.1 a
WCL-LO1 (oil)	26.4 b	24.4 b	52.6 d	52.4 ab	28.6 b	23.9 a
WCL-LH1 (lesq acid)	26.8 b	24.5 b	53.9 bc	51.6 b	32.4 ab	23.9 a
WCL-LY1 (both)	27.1 b	25.1 ab	53.5 c	52.7 ab	31.8 ab	19.7 a
Control	24.85 c	24.0 b	53.5 c	52.9 ab	27.1 b	22.0 a

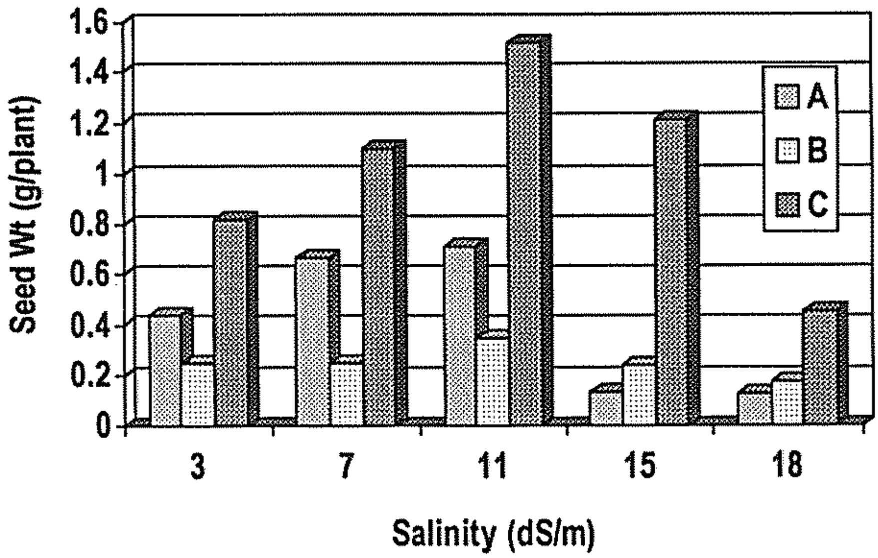

Figure 1. Comparison of three lines growing under different salinity treatments. Line A is an unselected control, B is the parent line of the selection, and C is the salt tolerant selection.

INTERPRETATION: A method for bud pollination has been defined for lesquerella. This breakthrough has allowed seeds to be produced from a plant with its own pollen and produce a segregating generation. Ratios reported in last year's U.S. Water Conservation Laboratory Annual Research Report indicated male sterility in lesquerella is controlled by two epistatic genes can be verified using this method of seed production. This also has allowed interspecific hybrids to be produced with potentially much higher levels of lesquerolic acid contents.

The salt tolerant selection outperformed the two comparison lines in vigor, growth, and seed yield. This germplasm is now in the process of a public release under the name WCL-SL1 and seed will be available to researchers by written request. This germplasm should be suitable for planting in saline problem areas of Texas, New Mexico, Arizona, and California.

The WCL-LY2 was significantly higher in oil, lesquerolic acid content, and seed yield when grown at MAC. MAC was a superior location to Tucson for this germplasm. This germplasm is also in the process of a public release and seed will be available to researchers upon written request. The Tucson location has potential as a growing site but selection would need to be done there. These results also indicate the need to test germplasm at multiple locations in order to select lines that are stable for high yield in multiple environments, in order to insure that growers will receive the highest yielding germplasm for their growing conditions.

FUTURE PLANS: Interspecific progeny from *L. fendleri* X *pallida*, *gracillis*, and *lindheimeri* are being evaluated. Backcrosses and self pollinations will be made, and oil and fatty acid contents measured. Selfed seeds of five plants will be grown and selfed for another generation. This will continue for several more generations in an attempt to produce near isogenic lines. Seed from the past male sterility study that resulted in 1:3 ratios will be planted and selfed to obtain a 1:1 generation that would confirm the 13:3 epistasis hypothesis.

Crosses from the 21 ds m^{-1} treatment will be planted again in the same treatment for further salt tolerance selection. Plants will be direct seeded into sand tanks.

The seed from the WCL-LY2 will be planted in a field at MAC for continued recurrent selection. The number of plants harvested will be increased, and selection will be based on oil content and seed yield. Lesquerolic acid content will not be a selection criteria because progress has been poor for that trait.

COOPERATORS: R.L. Roth, University of Arizona, Maricopa AZ; Catherine M. Grieve and Michael C. Shannon, ARS, US Salinity Lab., Riverside CA; D.T. Ray, University of Arizona, Tucson AZ.

LESQUERELLA GERMPLASM COLLECTION AND EVALUATION

D.A. Dierig and T.A. Coffelt, Research Geneticists; F.S.Nakayama, Research Chemist; and A. Salywon, A. Kaiser, G. H. Dahlquist, G. Leake, and P. Tomasi, Research.Technicians

PROBLEM: Lesquerella seed could provide U.S. industrial markets with a source of hydroxy fatty acids. In the past, these markets have been satisfied by imports of castor for many types of industrial applications, such as paints, coatings, lubricants and greases. Imports of castor oil and derivatives amount to more than 65,000 tons per year at a value exceeding $100 million per year. The unique chemical structure of the oil from Lesquerella, although similar to castor, offers distinct advantages for development of other applications, as well as being a partial replacement for castor oil.

There are some lesquerella species native only to Mexico that have not previously been collected or evaluated. Species such as *L. fendleri* occur both in the U.S. and Mexico; however, different biotypes are location specific. Increasing genetic diversity improves potential plant breeding progress.

Only limited amounts of seed from germplasm collections are able to be obtained from the wild. Seed increases, evaluation, and passport information are necessary to successfully utilize these accessions in our breeding program. It is also necessary to make seed available to other researchers through the National Plant Germplasm System (NPGS).

APPROACH: Plant permits for collection in Mexico were obtained through the U.S. Embassy in Mexico City, Office of Environment, Science and Technology Affairs. A database of plant localities was assembled by visiting Herbaria at Missouri Botanical Gardens in St. Louis, Arizona State University, and Universidad Autonoma Agraria Antonio Narro in Saltillo Mexico. Harvard University's Gray Herbarium sent information from their collections and Kathryn Rollins donated the field book of the late Dr. Reed Rollins from his Mexico collection to us. Our cooperator in Mexico was Dra. Diana Jasso de Rodriguez. The states visited for collection in Mexico included Coahuila, Nuevo Leon, Tamaulipas, Durango, Zacatecas, and San Luis Potisi. Sites were visited; and, if plants were found, seeds were collected, voucher specimens taken and pressed for herbarium mounting, and the location recorded from a GPS reading. In many cases, we located plants while in flower and returned when seed was ripe.

Seeds originating from past collection trips between 1993 and 1996 from the U.S. were field or greenhouse grown at the U. S. Water Conservation Laboratory (USWCL) for seed increase and evaluation. When only limited seed quantities were available, seeds were started in the greenhouse in October and transplanted into the field in November and December. When plants began to flower, screen cages were placed over individual field plots and supplied with housefly larvae which then emerged for pollination. Houseflies were effective pollinators and are very inexpensive compared to honey bees. The pollinators within cages prevented cross pollination with other accessions. Plants also were grown in greenhouses if the accession of a species was not adaptable to an Arizona climate. Plants of different species could be grown together since they will not cross-pollinate. Flies also were placed in the greenhouses on a weekly basis during the flowering period. Larvae were incubated at room temperature for one day before placing in the greenhouse. Plant growth measurements were taken throughout the season. After harvest, seeds from each accession were analyzed for oil content and composition. Following harvest, seeds of increased accessions were sent to the Agriculture Research Service (ARS) Curator in Pullman, Washington, to be entered in the NPGS.

FINDINGS: Sixty-five accessions from 26 species were increased this year at the USWCL (Table 1). Some accessions could not be successfully grown outdoors in this climate and, as a result, had to be grown in the greenhouse. Seed yields in the greenhouse were improved this year due to the addition of houseflies (*Musca domestica*) as pollinators. In past years we have had to pollinate flowers by hand to obtain seed because of self-incompatibility. We tried unsuccessfully using blue orchard bees, *Osmia lignaria*, and leaf cutter bees that we obtained from cooperator ARS Scientist Vince Tepedino. Some accessions were grown in the field and in the greenhouse. The trend was that oil and lesquerolic acid contents were higher in the field. Descriptive data on plant growth also were collected. There were adequate amounts of seed harvested from many of these accessions so they could be sent for entry into NPGS.

Table 1. Results of evaluation of Lesquerella species increased and evaluated at the USWCL,1998-99.

	Collection Number	Lesquerella Species	Oil (%)	Lesquerolic Acid (%)	Seed Weight (g)
1	A1800	*gordonii*	20.54	59.21	118.28
2	A1834	*fendleri*	22.24	48.58	8.59
3	A1835	*purpurea*	19.44	59.88	4.51
4	A1854F [1]	*fendleri*	25.44	52.14	105.95
5	A1859	*pinetorum*	21.85	56.81	76.03
6	A1869F	*cinerea*	24.98	54.57	47.57
7	A1873	*rectipes*	19.37	48.48	5.24
8	A1875	*rectipes*	23.54	50.48	48.76
9	A1879	*intermedia*	23.81	47.12	10.98
10	A1882F	*intermedia*	24.75	50.18	3.18
11	A1894F	*arizonica*	26.78	52.66	12.18
12	A1902	*kaibabensis*	16.06	48.69	4.54
13	A1903	*rectipes*	24.25	52.46	23.19
14	A1911	*ovalifolia*	na	na	3.12
15	A1922F	*ovalifolia*	26.79	50.19	3.88
16	A1923	*rectipes*	16.22	44.78	4.60
17	A1927	*intermedia*	20.24	52.27	19.36
18	A1930F	*intermedia*	23.83	53.27	11.61
19	A1931	*cinerea*	22.25	49.58	3.61
20	A2202	*densiflora*	16.29	59.56	43.35
21	A2203	*recurvata*	16.87	68.92	6.49
22	A2205	*recurvata*	17.81	67.99	8.52
23	A2208	*recurvata*	13.49	66.75	6.49
24	A2210	*argyraea*	15.92	70.77	34.90
25	A2212	*argyraea*	13.53	53.55	26.85
26	A2225	*argyraea*	17.13	60.66	85.77
27	A2239	*argyraea*	23.62	58.34	133.89
28	A2258F	*fendleri*	23.90	52.29	12.14
29	A2279F	*mcvaughiana*	21.22	55.20	80.97

	Collection Number	Lesquerella Species	Oil (%)	Lesquerolic Acid (%)	Seed Weight (g)
30	A2297	*angustifolia*	na	48.61	43.92
31	A2401	*douglasii*	15.27	42.97	1.94
32	A2402	*douglasii*	17.17	48.17	33.90
33	A2403	*douglasii*	20.48	46.71	22.12
34	A2404	*douglasii*	na	na	0.10
35	A2405F	*douglasii*	24.08	48.99	1.04
36	A2406F	*douglasii*	24.03	49.17	3.20
37	A2894	*densipila*	17.41	1.56 [27.4]*	3.55
38	A2914	*gordonii*	15.21	52.72	2.51
39	A2919F	*ovalifolia*	16.18	52.37	8.96
40	A2920F	*ovalifolia*	18.15	54.84	11.88
41	A2921	*gracilis*	17.43	63.13	0.64
42	A2922	*ovalifolia*	9.80	50.45	23.66
44	A2926	*gracilis*	17.72	63.56	129.50
45	A2933	*angustifolia*	na	na	0.30
43	A2934	*ovalifolia*	12.34	49.05	28.22
47	A2935	*ovalifolia*	15.44	55.50	78.39
48	A2939	*gordonii*	27.80	59.91	23.64
49	A2997F	*fendleri*	24.48	47.17	0.76
50	A3000	*lyrata*	18.98	19.89	2.92
51	A3010	*gordonii*	14.68	56.04	1.01
52	A3009	*auriculata*	19.33	4.35	24.77
53	A3003	*gordonii*	na	na	19 seeds
54	A3011	*auriculata*	16.37	2.63	81.51
55	A3029	*intermedia*	18.84	49.26	1.31
56	A3042	*ludoviciana*	20.10	47.63	5.12
57	A3060	*ludoviciana*	18.84	28.43	1.27
58	A3062	*ludoviciana*	na	na	168 seeds
59	A3079	*montana*	na	na	0.19
60	A3103	*parvifolia*	na	na	0.20
61	A3132	*ludoviciana*	20.81	na	3.55
62	A3178	*montana*	24.83	50.36	43.37
63	A3179	*hemiphysaria*	25.88	56.58	2.67
64	A3219	*pallida*	17.37	79.69	2.35
65	A3220	*hanford*	21.57	46.06	28.39

* bracket [ ] indicates a value for densipolic acid, C18:2OH;
**bracket [] indicates a value for auricolic acid, C20:2OH;
na indicates data not available;
[1]an F following the collection number indicates it was field rather than greenhouse grown.

Thirty accessions of four species of lesquerella were collected in Mexico. Two of these, *L. mexicana* and *L. schaffneri*, have never been in the NPGS before. Sixteen of the collections were *L. fendleri*, which was emphasized because this is the primary species identified for domestication. Some of the collection sites need to be revisited for more seed because some did not germinate. The inviable seed was likely due to seed immaturity.

INTERPRETATION: Breeding *L. fendleri* with wild relatives may yield offspring that bear bigger seeds with more oil and higher amounts of hydroxy fatty acid. It also may expand the growing region outside the southwest U.S. Considering the cost of obtaining seed from germplasm collection trips, the seed from this project is very valuable. Special care must be taken to assure that seed is increased without contamination from other accessions, evaluated to obtain usable information about the accession, and properly handled from harvest to storage. The seed deposited into NPGS benefits researchers nationally and internationally. It also has a long term benefit to our breeding program.

It is unknown at present how the seed from the Mexican collection will impact breeding of lesquerella. These plants need to be characterized and compared to US collections. This will be carried out next year.

FUTURE PLANS: A service contract is in place with the cooperator in Mexico to continue collecting from October 1, 1999, until September 30, 2000. There were some locations where plants were not flowering, and we were not able to return in time for seed or there was not enough rain for plants to reach the full flowering cycle. Seed will be obtained from these accessions and other localities not visited this year. The germplasm collected in Mexico will be evaluated and increased next season.

COOPERATORS: K. Williams and A.S. Stoner, National Germplasm Resources Laboratory, Beltsville MD; R.H. Lawson, ARS-NPS; D. Jasso de Rodriquez, Raul Rodriquez, and Jose Angel Villarea Universidad Autonoma Agraria Antonio (UAAAN), Saltillo, Mexico; Ignacio Moreno Murrieta, ITESM, Monterrey, Mexico; D.T. Ray, University of Arizona, Tucson AZ; Vicki Bradley and Steve Clement, Plant Germplasm Introduction Station, Pullman WA; Vince Tepedino, ARS, Logan UT.

1999 Publications

Technology Transfer

Weekly Reports

Support Staff

Cooperators

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TECHNOLOGY TRANSFER

Following are summaries of the laboratory's major technology transfer accomplishments for 1999.

Irrigation and Water Quality

Scientists: Fedja Strelkoff and Bert Clemmens - Release of Surface Irrigation Simulation Software

Bert Clemmens and Fedja Strelkoff, a University of Arizona cooperator, formally released a new generation of user-friendly software for the simulation of surface irrigation events. The software provides quick responses to a variety of "what-if" scenarios that can be proposed by field advisors, consultants, extension personnel, etc., to assist in the development of recommendations for water-saving, high-efficiency surface irrigation with the methods suitable for their geographical area. A wide variety of surface-irrigation techniques and scenarios can be simulated with this program, and the output also can be used in irrigation training courses. In a nontraditional application, the program is being used in design efforts to reduce the sediment load of storm runoff passing through agricultural lands into waterways. The Natural Resources Conservation Service made its web site available to the general public for downloading the software. It is being downloaded by NRCS personnel, field offices, consultants, and university researchers. The expected impact is better design and management of surface irrigation systems with increased efficiency and decreased degradation of streams and groundwaters receiving the effluent.

Scientist: Herman Bouwer - Sewage Effects on Underlying Groundwater

Through meetings of such groups as the World Federation of Scientists, who met in Erice, Italy, in August 1998; presentations, and publications, Herman Bouwer has informed a broadly based audience in the scientific community and the public sector of a less-well-known potential groundwater hazard from irrigating with sewage effluent. In addition to the normal concern about groundwater contamination from salts, nitrates, and pesticides, careful scrutiny of effluent quality parameters indicates that other contaminants such as disinfection byproducts (DBPs) and pharmaceutically active chemicals (PACHs) can also reach groundwater. In relatively dry climates, the concentrations of these chemicals in the drainage water can be a multiple of those in the effluent itself. This is a worldwide problem. Sewage effluent increasingly will become an important source of irrigation water as growing cities need more water, growing populations need more food, and streams and lakes need to be kept clean. The impact of disseminating this information is to prompt research needed to guide policy and practices to address the problem. There are currently two research thrusts: a controlled greenhouse study with vegetated soil columns below fields to be conducted at the U. S. Water Conservation Laboratory (USWCL) and field studies in developing countries to sample groundwater below fields with a long history of sewage irrigation. Within the U.S., studies in cooperation with universities and health agencies are being planned, and plans for international participation have been initiated through the World Federation of Scientists.

Scientist: Herman Bouwer - Simplified Cylinder Infiltrometer Technologies

The simplified cylinder infiltrometer technology developed at the USWCL is gaining national and international acceptance as a simple and effective method to predict infiltration rates for groundwater recharge basins or other flooded areas. The infiltrometers are relatively small with diameters of about

2 feet, and they are about 1 foot deep. Effects of lateral flow in the soil around the cylinder, which formerly led to grossly overestimated infiltration rates, are taken into account. Also considered are water depth in the cylinder and limited depth of wetting of the soil to convert measured infiltration rates inside the cylinder to infiltration rates that would be expected for large flooded areas. The method has been used as a tool to screen sites for artificial recharge of groundwater and for design of infiltration systems. Technology transfer was via personal contacts with users, manuscript handouts, presentations at conferences, and publication in a peer-reviewed engineering journal.

Scientist: Bert Clemmens - Release of Software for Flow Measurement Structures
Over the last three decades, scientists at the USWCL developed technology for measuring the flow rate of irrigation water in open channel canals. In particular, research focused on development and use of long-throated flumes, which have become standard devices worldwide because of their low cost, simplicity, and high accuracy. Software developed by USWCL for the design and calibration of these structures was recently greatly improved through cooperation with U. S. Bureau of Reclamation engineers who converted the software to a more user-friendly windows environment. This software is now available on the Bureau's web site and has been distributed widely. This should significantly improve the adoption of this flow measurement technology.

Scientist: John Replogle - Measuring Irrigation Well Discharges
Construction and field-use information has been published related to a device developed by John Replogle that can be used to measure irrigation or drainage well discharges or to evaluate the behavior of an existing installed pipe meter. This special combination pitot-static-tube system is inexpensive and convenient to use, particularly on wells that spill directly into canals or streams. It can be constructed from standard materials using ordinary machine shop procedures, and the entire kit fits into a standard briefcase. The system provides irrigation district technicians an inexpensive, convenient tool to evaluate existing meter installations and to measure discharges from previously unmeasured wells. This device is expected to provide a means to evaluate both irrigation and drainage pumps, particularly in those instances where a few evaluations are needed on an infrequent basis and investment in alternate technology, such as ultrasonic-meter equipment and training, is not economically feasible.

Environmental and Plant Dynamics

Scientist: Bruce Kimball - FACE Wheat Data Sets
Testing of several wheat growth models against Arizona Free-Air CO_2-Enrichment (FACE) wheat data sets was one of the primary activities at the Workshop of the Global Change in Terrestrial Ecosystems (GCTE) Wheat Modeling Network held in Potsdam, Germany, in November 1998. Because the growth data were obtained at frequent intervals through the growing season and because many needed ancillary measurements were made, these data were especially valuable for the validation process for both present and future CO_2 conditions. The performance of each model in terms of its ability to simulate two of the Arizona FACE wheat data sets (as well as some others) is being made a part of the GCTE Wheat Network Metafile record of each registered wheat model. These experiments were supported primarily by the U.S. Water Conservation Laboratory and a Department of Energy grant to the University of Arizona.

Scientist: Dave Dierig - Release of New *Lesquerella fendleri* Germplasm Line

Scientists at the USWCL have developed and released a new line of *Lesquerella fendleri*, a potential new industrial oilseed crop, that will significantly advance its commercialization. The new line has less pigmentation, thereby overcoming the requirement for expensive processing to remove pigmentation from the oil needed for many uses. Development of lesquerella into a viable commercial crop will provide an alternative crop for U.S. farmers and an alternative domestic source of hydroxy fatty acids, presently filled by imported castor.

WEEKLY REPORTS

Following are USWCL "ARS Weekly Activity Report" submissions for 1999. Each research scientist submits a minimum of one report per year. These reports are consolidated at ARS Area level and submitted to ARS headquarters for the information of agency and departmental management.

Floyd J. Adamsen, Soil Scientist
ARS scientists at the U. S. Water Conservation Laboratory in Phoenix, Arizona, have begun evaluation of a new generation of probes that measure soil moisture. The new probes utilize time domain reflectance (TDR), which provides accurate measurement of soil moisture over a wide range of conditions. New prototypes from a commercial manufacturer are being evaluated under a range of soil moisture and soil salinity conditions to determine the limitations of the probes. These probes can be used with standard data loggers and the data collected used to control irrigation system. The new prototypes under evaluation are projected to cost less than $100. Older TDR systems cost from $800 to $8000. The cost of the new probes is low enough to make them practical at the farm level and from a research standpoint the new probes are inexpensive enough to allow detailed studies of soil water relations that can account for field variability. A CRADA may be initiated to support further development of this technology.

Edward M. Barnes, Agricultural Engineer
ARS scientists at the U. S. Water Conservation Laboratory in Phoenix, Arizona, are involved in a cooperative project with the University of Arizona, Texas A&M University, and the Idaho Environmental and Engineering Laboratory to determine new information sources for precision crop management systems. The project is focused on the integration of data collected by sensors which are mounted on farm equipment. These sensors are equipped with a computer simulation model that determines the water and nitrogen status of a crop. The sensors, measuring the amount of reflected light in the visible and near-infrared part of the spectrum, provide an inexpensive method to describe the within-field variation in crop development to the model. As the sensor data is collected at infrequent intervals, the model is used to provide predications of daily conditions when the sensors are not in use. The first year of the project is complete and initial results from data collected in cotton and barley experiments have demonstrated the sensor's ability to detect differences in water and nitrogen levels. A second cotton experiment is in progress to refine and validate the system. Ultimately this approach could provide agricultural producers with an inexpensive and convenient method to collect the data needed to practice site-specific crop management.

Eduardo Bautista, Agricultural Engineer
ARS scientists at the U.S. Water Conservation Laboratory in Phoenix are developing a computerized approach for scheduling the operation of irrigation water delivery systems for known or predicted water demands. Most scheduling approaches currently in use are empirical and rely on operator experience. With these traditional approaches, water control is not very precise and can result in significant variations in delivery flow rates to users and operational spills. Computerized scheduling approaches, which are based on an understanding of the canals hydraulic properties, can improve water control and thus improve the management of the resource at the canal level and ultimately at the farm level. Computerized canal scheduling has not been applied extensively in the past, partly because implementation of the schedule requires control hardware that is relatively expensive, and partly because of the complexity of the approaches. Because the cost of control hardware is

decreasing rapidly and labor costs for water delivery organizations are rising, significant adoption of computerized canal control technology is likely to occur in the near future, making these approaches more attractive. The proposed scheduling approach is computationally simple and intuitive to users and therefore appealing for practical applications.

Herman Bouwer, Research Hydraulic Engineer

Herman Bouwer, Research Hydraulic Engineer at the U. S. Water Conservation Laboratory in Phoenix is currently conducting research on how sewage irrigation affects underlying groundwater. Globally, increasing populations and finite water resources will lead to serious water shortages, more transfers of water from agricultural irrigation to municipal use, and more use of sewage effluent for urban and agricultural irrigation. The normal concern for such irrigation is that it will contaminate underlying groundwater with salts, nitrates, and pesticides to the point where this major water resource can no longer be used for drinking without further treatment. However, careful scrutiny of effluent quality parameters indicates that other contaminants such as disinfection byproducts (DBPs) and pharmaceutically active chemicals (PACHs) can also reach groundwater. In relatively dry climates, the concentrations of these chemicals in the drainage water can be a multiple of those in the effluent itself. Plant nutrients in effluent can enhance plant growth , leaving more plant residue in the field to decompose which increases the formation of humic and fulvic acids. DBPs include known and suspected carcinogens, PACHs comprise a multitude of drug residues and industrial chemicals, some of which can mimic estrogen. Long-term health effects and synergisms are of concern. Humic substances are DBP precursors, so that when contaminated groundwater is pumped up and chlorinated for drinking, a whole new suite of DBPs will be formed. More research on how sewage irrigation affects underlying groundwater is urgently needed. Various studies in cooperation with universities and health agencies are being planned. They range from sewage irrigated vegetated soil columns , where chemical inputs and outputs can be monitored, to analyzing groundwater below areas with a long history of sewage irrigation. Plans for international participation have been initiated through the World Federation of Scientists (WFS). A paper on these issues has been prepared and published, as well as a position paper on water for the 21st century and emerging issues for WFS.

Thomas R. Clarke, Physical Scientist

A remote sensing experiment run during the 1999 cotton growing season is showing promising results in the development of a suite of sensors for detecting the crop's fertilizer and water needs. A very rugged multi-spectral radiometer built at the U.S. Water Conservation Laboratory in Phoenix measured surface temperature and reflected light from the crop three to five times a week throughout the season. Scientists at the laboratory believe these combined sensors will enable growers to manage water and fertilizer applications more precisely. The experiment was conducted in cooperation with The University of Arizona Department of Agricultural and Bio-Engineering

Albert J. Clemmens, Laboratory Director

ARS scientists and Bureau of Reclamation engineers collaborate on the release of software for flow measurement structures--an important contribution to water management and conservation. Over the last three decades, ARS scientists at the U.S. Water Conservation Laboratory in Phoenix, Arizona, have developed technology for measuring the flow rate of irrigation water in open channel canals, particularly using long-throated flumes, which have become standard devices worldwide because of their low cost, simplicity, and high accuracy. ARS previously developed software for design and calibration of these structures and recently worked with U.S. Bureau of Reclamation engineers who converted the software to a more user-friendly windows environment. This software is now available on the Bureau's web site and has been distributed widely.

Terry A. Coffelt, Research Geneticist
ARS scientists at the U. S. Water Conservation Laboratory in Phoenix, Arizona, and Western Regional Research Center in Albany, California, in cooperation with scientists at the University of Arizona, Texas A&M University, University of California, New Mexico State University, and University of Akron have been awarded a two-year grant from the Fund for Rural America to help solve problems in the commercialization of guayule for the U.S. Guayule is a source of hypoallergenic natural rubber latex suitable for making medical products. Latex allergies are becoming a serious health problem with over 40 % of U.S. medical workers and 60% of multiple surgery cases now allergic to Hevea latex products. Specific goals of this project are: 1) to identify weed control strategies necessary for successful production; 2) to determine optimum seed harvest times for maximum seed production and seed quality; and 3) to determine methods for optimizing the yield and quality of guayule latex as they relate to harvest methods and harvest time as well as storage conditions prior to latex extraction. Knowledge obtained from this cooperative project will facilitate the commercialization of guayule.

David A. Dierig, Research Geneticist
Scientists at the U. S. Water Conservation Laboratory in Phoenix have developed a new line of *Lesquerella fendleri*, a potential new industrial oilseed crop, that will significantly advance its commercialization. The improved line overcomes an important obstacle to the plant's commercialization. Many applications of this hydroxy seed-oil require special processing, thereby increasing costs, to remove pigmentation from the oil. Plants were selected for a mutant seed coat color, which is associated with the seed-oil pigment. The oil from this new germplasm line has less pigmentation and provides germplasm with high genetic diversity for future improvements by public and private researchers. Development of lesquerella into a viable commercial crop will provide an alternative crop for U.S. farmers and an alternative domestic source of hydroxy fatty acids, presently filled by imported castor.

Sherwood B. Idso, Research Physicist
Scientists at the U.S. Water Conservation Laboratory at Phoenix, Arizona, and Arizona State University's Cancer Research Institute, have recently completed a study of the effects of atmospheric CO_2 enrichment on the growth of a tropical spider lily plant that produces a number of substances that possess strong anti-viral and anti-tumor activity. The findings have positive implications for the production of a number of important new medicines, as well as the long-term health effects of natural products obtained from plants growing in earth's increasingly-CO_2-enriched atmosphere. In two 2-year field studies, they found that a 75% increase in the air's carbon dioxide concentration increased the production of spider lily bulbs (where the medicinal substances are found) by an average of 56%. In addition, they found that the average concentration of the therapeutic substances in the plant bulbs was increased by 18%.

Bruce A. Kimball, Supervisory Soil Scientist
Future water requirements for wheat production in the future may be reduced somewhat by the increasing atmospheric carbon dioxide (CO_2) concentration according to recent measurements by personnel at the U.S. Water Conservation Laboratory, USDA-ARS, in Phoenix, Arizona. Previous

studies, mostly using chambers, have found evidence that the increasing atmospheric CO_2 concentration may change the amount of water used by plants. Such a change in plant water use could impact regional water supplies and require farm managers to modify their management practices. To determine the magnitude of such changes under field conditions, plots of wheat were exposed to elevated CO_2 concentrations using free-air CO_2 enrichment (FACE) apparatus. Devoid of walls, the FACE approach is the most natural technique available to conduct such research. Data were collected for four growing seasons at ample water and fertilizer and for two seasons when soil nitrogen was limited The FACE treatment increased daytime foliage temperatures about 0.6 and 1.1°C (1.1 and 2.0°F) at high and low nitrogen, respectively, which suggests optimal regions for wheat production could shift in the future because of the elevated CO_2 alone, regardless of any climate change. Daily water evaporated from the soil and transpired by the plants was consistently lower in the FACE plots, by about 6.7 and 19.5% for high and low nitrogen, respectively. These results suggest that future water use requirements will decrease slightly, provided that changes in climate are not adverse.

M. Susan Moran, Physical Scientist
Information on regional soil moisture conditions is important for mapping rainfall events, monitoring different drying patterns, and assessing water availability for plant growth. Though the demand for such information is high, the means for mapping soil moisture are few. Scientists at the U.S. Water Conservation Laboratory have demonstrated that information from orbiting satellite-based sensors could provide a regional assessment of surface soil moisture content. These sensors detect the return signal from a radar beam directed at the earth's surface, and this signal is related, in part, to variations in soil moisture. The approach developed at USWCL minimizes the effects of varying topography and vegetation on the radar signal, and thus, enhances the link between the radar backscatter and surface soil moisture. With this technique, it may be possible to use the orbiting radar sensor to map soil moisture over large areas with reasonable accuracy. This will lead to a better understanding of weather conditions and improvements in management of scarce resources.

Francis S. Nakayama, Research Chemist
The fabrication of hypo-allergenic medical products from latex extracted from the guayule plant (*Parthenium argentatum*) is coming close to realization. The latex present in the harvested plant can deteriorate rapidly with more than 80% lost after only a few days of field storage. ARS scientists at the U.S. Water Conservation Lab, Phoenix, Arizona, found that the latex content could be maintained by keeping the harvested shrub moist by simply misting the plant. With this treatment, the latex level remains constant for at least a 16-day period, allowing greater flexibility in the processing of the shrub. Improved methods for optimizing latex extraction are being developed that will accelerate commercialization of guayule and its products.

John A. Replogle, Research Hydraulic Engineer
Engineers at the USDA-ARS U.S. Water Conservation Laboratory, Phoenix, Arizona, are addressing a persistent problem of flow fluctuations in farm canals caused by variations in flow conditions in the source canal. Typically, the flow to the farm ditch is through large pipes under the canal road, which are controlled by a gate on that pipe. If the main canal flow deepens in an effort to deliver more water flow further downstream, each of these side deliveries will need adjusting to prevent excess flow from diverting through them, thereby robbing the intended delivery. Because electric power is not available at many remote canal headings, this favors the use of non-electric means to control the flows. We previously built such a non-electric system that worked well enough, but required

expensive constructions at each site. This current effort is to design and evaluate a conceptual system that is expected to be in a "kit" format that will require minimal site modification and significantly reduce installation costs. The system includes newly designed, inexpensive float valves for low pressure applications. These valves will resist plugging by the trash-laden waters. If flow depth in the source canal changes slightly, the float valves will either feed or leak water from an obstructing bladder placed in the pipe to bring the water level in the farm ditch back to the desired depth.

Theodor S. Strelkoff, Research Hydraulic Engineer
The U.S. Water Conservation Laboratory's suite of software for the simulation, management and design of surface-irrigation systems was extended this summer to include a first-draft furrow-erosion component. The principle aim of the user-friendly, menu-driven software is to provide quick responses to a variety of what-if scenarios considered by field advisors, consultants, extension personnel, etc., in developing their recommendations for furrow design and operation. The simulations would show the trade-offs between irrigation uniformity and efficiency on the one hand and top-soil movement downfield or off-field on the other. With irrigation-induced furrow erosion a significant problem in the Pacific Northwest, western Nebraska, and some areas of California, for example, its control can mitigate the loss of soil fertility in the upper parts of fields -- even when the eroded soil is deposited further downfield -- and the pollution of receiving surface waters with sediment when it is not. This software suite, including earlier releases of basin and border-strip design-aid programs, is now available for downloading from the "Software..." link on the Laboratory's web-site home page: <www.uswcl.ars.ag.gov>

Preliminary comparisons between the simulations performed with Idaho soils show good agreement with some measured data on erosion, deposition, and off-field transport but an overly sensitive response to selection of a representative soil particle size. The model is slated for enhancement by inclusion of measured distributions of particle sizes in the soil mix present in the furrow beds.

Brian T. Wahlin, Civil Engineer)
The Imperial Irrigation District (IID) in Southern California has been under political pressure to reduce the amount of its diversions from the Colorado River through improved irrigation practices. Engineers at the USDA-ARS U.S. Water Conservation Laboratory in Phoenix, Arizona, have assisted IID in improving their irrigation practices by estimating the accuracy of the flow measurements into and out of the irrigation district. In this study, errors for individual flow measurements at five key sites in IID were determined and used to validate the estimates of the uncertainty of the annual volume that passes through these sites. This information can then be used to identify opportunities for improving water management practices within the district.

Gerard W. Wall, Plant Physiologist
Researchers at the U.S. Water Conservation Laboratory in Phoenix, Arizona, have shown that elevated carbon dioxide (CO_2), such as is expected in the 21st century, is advantageous for the root system of a wheat crop and consequently, for grain production. Because the atmospheric CO_2 is expected to rise throughout the next century, this work addresses the need to determine if this change in global climate would impact wheat production, the world's foremost grain supply. Scientists investigated the relationship between atmospheric CO_2 and net production by exposing a wheat crop in an open field to about double the amount of CO_2 presently in the earth's atmosphere. The root system of the crop showed an increase in branching, surface area, and thickness for all growth phases,

and the effect was more pronounced under water stress compared with a well-watered crop. This CO_2-induced enhancement in root growth was accompanied by a 10 percent increase in yield under well-watered conditions and a 20 percent increase under water-stressed conditions.

ADMINISTRATIVE OFFICE

Name	Title
Albright, Dixie D.	Safety and Occupational Health Manager
Hodge, Vanessa J.	Budget and Accounting Assistant
Johnson, Richard E.	Office Automation Assistant
Lee, Richard E.	Custodial Worker
McDonnell, Guy C.	Physical Science Aid
Martin, Kevin R.	Air Cond. Equipment Mechanic
Sexton, Judith A.	Purchasing Agent
Wiggett, Michael R.	Administrative Officer
Worthen, Michelle	Office Automation Clerk

TEMPORARY EMPLOYEES

Name	Title
Adam, Neal R.	Plant Physiologist
Bierly, Pierre-Charles	Engineering Technician
Bross, Monique T.	Physical Science Technician
Bryant, Ross	Biological Science Technician
Conley, Matthew M.	Biological Science Technician/Plants
Cowher, Lori A.	Biological Science Aid
DeGraw, Christa L.	Office Automation Clerk
Eggemeyer, Kathleen D.	Biological Science Technician
Eshelman, Trathferd G.	Science Technician
Faber, Amy	Physical Science Technician
Gardner, Scott D.	Publications Clerk
Gilbert, Kathleen	Biological Science Aid
Hartman, Travis D.	Biological Science Aid
Holifield, Chandra D.	Biological Technician
Jacob, Sally J.	Biological Science Aid
Kaiser, Aaron R.	Biological Science Aid
Luckett, William E.	Physical Science Technician
Ludke, Jamie L.	Physical Science Technician
Luna, Traci E.	Biological Science Aid
Morgan, Stefani K.	Office Automation Clerk
Ni, Wanmei	Research Specialist
Nouvellon, Yann	Post-Doc
Olivieri, Laura M.	Biological Science Technician
Terrazas, Yolanda	Biological Science Technician
Triggs, Jonathan M.	Biological Science Aid
Waichulatis, Steve R.	Biological Science Aid

U. S. WATER CONSERVATION LABORATORY PERSONNEL

PERMANENT EMPLOYEES

Name	Title
Adamsen, Floyd J.	Soil Scientist
Arterberry, Carl K.	Agricultural Science Research Technician/Soils
Askins, JoAnne	Physical Science Technician
Barnes, Edward M.	Agricultural Engineer
Bautista, Eduardo	Research Hydraulic Engineer
Bouwer, Herman	Research Hydraulic Engineer
Clarke, Thomas R.	Physical Scientist
Clemmens, Albert J.	Lab Director, Research Leader and Research Hyd. Engineer
Coffelt, Terry A.	Research Geneticist (Plants)
Colbert, Sharette M.	Physical Science Technician
Corris, Virginia D.	Office Automation Assistant
Dahlquist, Gail H.	Agricultural Science Research Technician/Plants
Dierig, David A.	Research Geneticist (Plants)
Draper, T. Lou	Secretary (Office Automation)
Gerard, Robert J.	Laboratory Support Worker
Gerszewski, Susette M.	Biological Science Technician/Plants
Harner, Paulina A.	Secretary (Office Automation)
Hunsaker, Douglas J.	Agricultural Engineer
Idso, Sherwood B.	Research Physicist
Johnson, Kathy J.	Physical Science Technician
Johnson, Stephanie M.	Biological Science Technician
Kimball, Bruce A.	Research Leader and Supervisory Soil Scientist
LaMorte, Robert L.	Civil Engineer
Leake, Greg S.	Biological Science Technician/Plants
Lewis, Clarence L.	Machinist
Mastin, Harold L.	Computer Assistant
Mills, Terry A.	Computer Specialist
Moran, M. Susan	Research Physical Scientist
Nakayama, Francis S.	Research Cheist
Pettit, Dean E.	Electronics Engineer
Pinter Jr., Paul J.	Research Biologist
Powers, Donald E.	Physical Science Technician
Replogle, John A.	Research Hydraulic Engineer
Rish, Shirley A.	Program Analyst
Rokey, Ric R.	Biological Science Technician/Plants
Strand, Robert J.	Engineering Technician
Vinyard, Stephen H.	Physical Science Technician
Wahlin, Brian T.	Civil Engineer
Wall, Gerard W.	Plant Physiologist

TEMPORARY STATE EMPLOYEES

Name	Title
Baker, Michael G.	Research Specialist-Staff
Brooks, Talbot J.	Research Technician
Lewis, Laurie A.	Senior Machinist/Staff
O'Brien, Carrie C.	Research Laboratory Assistant-Staff
Richards, Stacy	Biological Science Aid
Schmidt, Baran V.	Computer Programmer Assistant
Strelkoff, Fedja	Research Hydraulic Engineer/Research Professor (U of A)
Tomasi, Pernell M.	Research Laboratory Assistant

COOPERATORS

UNIVERSITIES

Arizona State University	Tempe, Arizona
Department of Plant Biology	
Department of Geography	
California Polytechnic State University	San Luis Obispo, California
Delft Technical University	Delft, The Netherlands
Kansas State University	Manhattan, Kansas
Loughborough University	Loughborough, England
Michigan State University	East Lansing, Michigan
New Mexico State University	Las Cruces, New Mexico
Northern Arizona University	Flagstaff, Arizona
Northwest Agriculture University	Yangling, Shaanxi, China.
Oregon State University	Corvallis/Medford, Oregon
Texas A&M University	Lubbock/Pecos, Texas
Agriculture Experiment Station	
Universidad Autonoma Agraraia Antonio Narro (UAAAN)	Saltillo, Mexico
Universita della Tuscia	Viterbo, Italy
Universitat Autonoma	Barcelona, Spain
University of Akron	Akron, Ohio
Department of Chemistry	
University of Alberta	Edmonton, Canada
University of Arizona	Tucson, Arizona
Dept of Agri & Biosystems Engineering	"
Dept of Plant Sciences	"
Dept of Soil, Water & Env Science	"
Laboratory of Tree-Ring Research	"
Maricopa Agriculture Center	Maricopa, Arizona
Maricopa County Extension Service	Phoenix, Arizona
School of Renewable Natural Resources	"
University of California	Riverside, California
University of Colorado	Boulder, Colorado
University of Essex	Colchester, United Kingdom
University of Florida	Gainesville, Florida
University of Guelph	Guelph, Ontario, Canada
University of Idaho	Moscow, Idaho
University of Illinois	Chicago, Illinois
Natural Resources and Environmental Sciences	Urbana, Illinois
University of Wisconsin	Madison, Wisconsin
University of Wyoming	Torrington, Wyoming
Research and Extension Center	
Utah State University	Logan, Utah
Vrie Universiteit of Amsterdam	Amsterdam, Netherlands

STATE, COUNTY, AND CITY AGENCIES

California Water Quality Control Board	Oakland, California
Imperial Irrigation District	Imperial, California
The City of Surprise	Surprise, Arizona

FEDERAL AGENCIES

Brookhaven National Laboratory	Upton, New York
NASA Goddard Institute for Space Studies	New York, New York
National Germplasm Resources Laboratory	Beltsville, Maryland
Natural Resources Conservation Service National Water and Climate Center	Portland, Oregon
Oak Ridge National Laboratory	Oak Ridge, Tennessee
U.S. Army Garrison	Fort Huachuca, Arizona
U.S. Department of Energy	Washington, DC
Idaho National Engineering & Environmental Lab	Idaho Falls, Idaho
U.S. Bureau of Reclamation - Water Resources Laboratory	Denver, Colorado
USDA-ARS Grassland Protection Research	Temple, Texas
USDA-ARS National Soil Dynamics Laboratory	Auburn, Alabama
USDA-ARS Northwest Irrigation and Soils Res Laboratory	Kimberly, Idaho
USDA-ARS-Pacific West Area Office	Albany, California
USDA-ARS, U.S. Salinity Laboratory	Riverside, California
USDA-ARS Water Management Research Lab	Fresno, California
USDA-ARS Western Wheat Quality Laboratory	Pullman, Washington
USDA-FS, Forest Products Laboratory	Madison, Wisconsin

OTHER

Automata, Inc.	Grass Valley, California
Buckeye Irrigation District	Buckeye, Arizona
CDS Ag Industries	Chino, California
CEMAGREF-Irrigation Division	Montpellier, France
Center for the Study of Carbon Dioxide and Global Change	Tempe, Arizona
CSIRO Wildlife and Ecology	Lyneham, ACT, Australia
GCTE (Global Change Terrestrial Ecosystems) Wheat Network	Oxon, UK
GeoSystems Inc.	Tucson, Arizona
Gila River Farms	Pinal County, Arizona
Global Water	Gold River, California
IMTA (Mexican Institute for Water Technology)	Cuernavaca, Mexico
Instituto de Agricultura Sostenible	Cordoba, Spain
ITESM	Monterrey, Mexico
Maricopa-Stanfield Irrigation & Drainage District	Stanfield, Arizona
McKemy Middle School	Tempe, Arizona
National Institute of Agro-Environmental Sciences	Tsukuba, Japan
New Zealand Institute for Crop and Food Research LTD	Christchurch, New Zealand
Nu-way Flume and Equipment Company	Raymond, Washington
Plant Germplasm Introduction Station	Pullman, Washington

Plasti-Fab	Tualatin, Oregon
Potsdam Institute for Climate Impact Research	Potsdam, Germany
Salt River Project	Phoenix, Arizona
Salt River Elementary School	Salt River Pima-Maricopa Indian Community
Tempe Elementary School District	Tempe, Arizona
Tempe Union High School District	Tempe, Arizona
Tempe High School	
Valmont Industries	Valley, Nebraska
Wellton-Mohawk Irrigation & Drainage District	Wellton, Arizona