ANNUAL RESEARCH REPORT
U.S. WATER CONSERVATION LABORATORY

2000

USDA - AGRICULTURAL RESEARCH SERVICE
Phoenix, Arizona

ANNUAL RESEARCH REPORT

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U.S. WATER CONSERVATION LABORATORY
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INTRODUCTION

During 1999 and 2000, the Agricultural Research Service's (ARS) National Program Staff worked hard at defining ARS's *National Programs*. These *National Programs* define the research agenda for the agency and relate these research activities to the nation's needs. These are further divided into components and within these components, into more well defined research thrusts. Each of our research programs can be related to these research thrusts and thus to the overall *National Program* and to the needs of the general public. Our research staff has been actively involved in the development of these *National Programs* to assure that our research program and our client's needs are well represented. In the future, our research program will be judged based on how well we fulfill the objectives of the associated *National Program*. Our research program is diverse and is included in several ARS *National Programs*, namely:

108 - Food Safety
201 - Water Quality and Management
204 - Global Change
207 - Integrated Farming Systems
301 - Plant, Microbial, and Insect Genetic Resources, Genomics, and Genetic Improvement

At the end of 1999, Susan Moran 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. During 2000, Robert LaMorte resigned from the lab to pursue other opportunities. We wish him well in his new adventure.

For 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. Microbiologist Norma Duran was hired to conduct this research. She came on board in October 2000. Welcome Norma!

Water conservation is an immense challenge. It is so broad and so critical to society both here and abroad that the opportunities for positively impacting both science and practice are almost limitless. With our present funding and staff, we are able to tackle only a few aspects of this problem. However, the laboratory should be 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 its 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.

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.

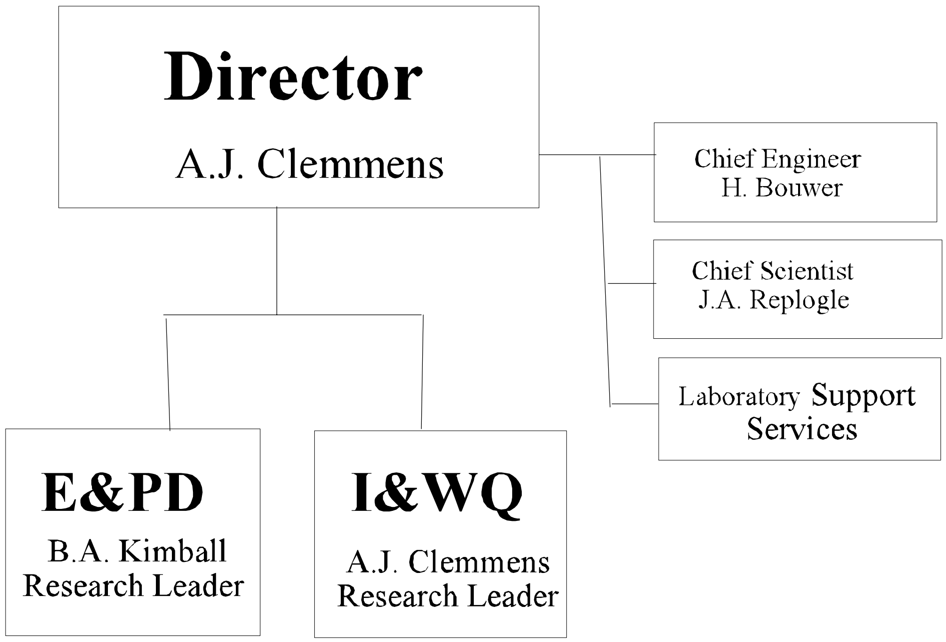
The U. S. Water Conservation Laboratory was established in central Arizona in 1959 to develop methods to conserve surface and groundwater used for agriculture. Research focuses on more efficient use of water and reduction of water losses in the soil-plant-atmosphere continuum. More recently, research 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 works directly with 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 work closely in a multi-disciplinary, cooperative manner: the Irrigation and Water Quality (I&WQ) and the Environmental and Plant Dynamics (E&PD) Research Units.

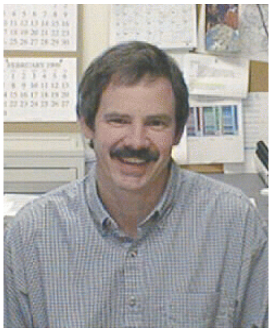
Laboratory Organization



Mission

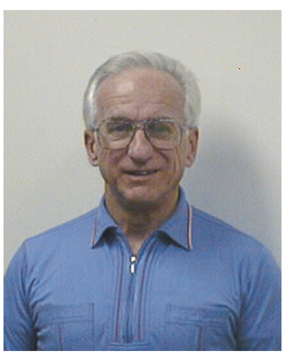
The mission of the U. S. Water Conservation Laboratory (USWCL) is to conserve water and protect water quality in systems involving soil, aquifers, plants, and the atmosphere. Research thrusts involve developing more efficient irrigation systems, improving the management of irrigation systems, developing 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.

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 and 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

ELECTRONICS ENGINEERING LABORATORY

D.E. Pettit, Electronics Engineer

The electronics engineering laboratory is staffed by an electronics engineer whose duties include design, development, evaluation, and calibration 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 performed in 2000:

- Continued designing software for the Generation II probes measuring water advanced recession date and times.
- Designed a low power fiber optics amplifier and source/detector board using surface mount technologies to interface to the GEN II probe. Designed, constructed and experimented with a fiber optic transducer for water detection.
- Generated new fiber optics control and Generation II probe software.
- Designed schematic capture parts and printed circuit board footprints for the appropriate ORCAD libraries being used in the fiber optics board.
- Experimented with mold making and plastics/potting compounds that are translucent and reflective to design and construct an optic transducer jell block used with fiber optic light pipes.
- Constructed 10 new fiber optic sensing Generation II probes for field evaluation.
- Repaired cream separator and Nuclear Magnetic Resonance (NMR) equipment.
- Updated LPKF circuit board mill machine and the following software packages: (1) ORCAD Printed Circuit Board, (2) Circuit CAM, and (3) Board Master. These three software packages interconnect and were backed-up to a CD ROM disk.

LIBRARY AND PUBLICATIONS

Lisa DeGraw, Publications Clerk

Library and publications functions, performed by one publications clerk, include maintenance of records and files for publications authored by the Laboratory Research Staff, including publications co-authored with outside researchers, as well as holdings of professional journals and other incoming media. Support includes searches for requested publications and materials for the Staff. Library holdings include approximately 2600 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.

COMPUTER FACILITY

T.A. Mills, Computer Specialist

The computer facility is staffed by one full-time Computer Specialist and one full-time Computer Assistant. Support is provided to all Laboratory and Location Administration Office computer equipment and applications. Network support is also provided to Western Cotton Research Center, and network access for a Phoenix ARS, APHIS location.

The facility is responsible for designing, recommending, purchasing, installing, configuring, upgrading, and maintaining the Phoenix Location's Local and Wide Area Networks (LAN, WAN), computers, and peripherals. The Laboratory LAN consist of multiple segments of 10 Base-T, 100 Base-T hubs and switches. The LAN is segmented using a high speed switches. Segments are made up of fiber optics, 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 and APHIS by an additional T-1 line through our router. The facility maintains a Class C block of Internet addresses for our Laboratory operating under the domain uswcl.ars.ag.gov, and a block of 128 addresses for the Western Cotton Research Center and APHIS operating under the domain wcrl.ars.usda.gov. The Laboratory LAN is comprised of several servers operating under Windows NT 4.0. End users operate mainly under Windows 95, 98, 2000, and Windows NT 4.0 with a few OS/2 workstations. Services such as print, file, remote access, and backup are provided by the Laboratory LAN. Other services such as DNS and E-Mail are provided to both the Laboratory and Western Cotton Research Center. 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 two additional fiber optic gigabit segments.

MACHINE SHOP

C.L. Lewis, Machinist

The machine shop, staffed by one machinist, provides facilities to fabricate, assemble, modify, and replace experimental equipment in support of U.S. Water Conservation Laboratory research projects. The following are examples of work orders completed in 2000:

- <u>Resin Impregnation Chamber</u>: This tool required machining and welding to withstand vacuum and 125 psi pressure. Some of the machining had to be within +/- .002". Chamber 10" + 32" and 18" long.
- Machined three different dimensions in Fo-St female connector. Two dimensions within ± .002. Machine Fo-St male fiber optic connector two dimensions also ± ,002. Thirty of each. All for GEN II probe.
- Cut teflon/nylon washers to .440 length (8 each) ± .0015 for Five-channel IR amplifier board.

USWCL OUTREACH ACTIVITIES

During 2000, 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.

"Water & Science Ag-Ventures," Feb. 16 & 18. USWCL, in cooperation with the University of Arizona Maricopa Agricultural Center and the Natural Resource Education Center of NRCS, provided a hands-on science and agricultural program for junior high school students. The event was held at the Maricopa Agricultural Center and included hands-on exhibits based on USWCL research programs, an actual hands-on irrigation event, a tour of the aquiculture ponds, and an informational presentation on careers in science.

Arizona Regional Science Bowl, Glendale Community College, Arizona, February 19. Gail Dahlquist, Dave Dierig, Floyd Adamsen, and Kathy Johnson served as moderators for the science bowl. Mike Wiggett and Terry Coffelt served as rule judges. The science bowl is an annual science knowledge competition among Arizona high school students.

Arizona Ag Day Exhibit, March 15. Ed Barnes, Brian Wahlin, Dave Dierig, Gail Dahlquist, 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.

Minority Hiring. A woman, Norma Duran, was hired as a permanent, full-time microbiologist.

Seminar on USDA-ARS Research Organization. On September 6, Bruce Kimball gave a seminar, "How Research is Organized in USDA-ARS," to the National Institute of Agro-Environmental Research, Tsukuba, Ibaraki, Japan.

Seminar on FACE Studies. On September 26, Paul Pinter presented a seminar, "Consequences of Rising Atmospheric CO_2 for Agriculture: A Decade of FACE Studies," at the Institute for the Study of Planet Earth, University of Arizona, Tucson.

Association for Persons with Disabilities in Agriculture (APDA) 2000 "Super Supervisor" Award. On October 25, Michael Wiggett, Phoenix Location Administrative Officer, was presented this award by the President of APDA in Washington, DC, for his sensitivity to and support of location employees with disabilities.

Disabilities Month Observance. On October 26, as part of Disabilities Month, the EEO Committee hosted an all employee potluck/program at which the special guest speaker was Kim Peek. Kim, who is autistic, is the real life character portrayed by the actor Dustin Hoffman in the movie "Rainman." Kim was born with brain damage and neuromotor dysfunctioning. He and his father spoke about respecting rather than ridiculing differences.

ARS Irrigation and Drainage Exhibit at the International Irrigation Show, November 12-14. Shirley Rish coordinated an exhibit on irrigation and drainage (I&D) research at the annual Irrigation Association International Show in Phoenix, Arizona. 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 Baton Rouge, Louisiana.

Visitors to USWCL. During 2000, USWCL had over 187 visitors, including 1 from Canada, 12 from India, 35 from Mexico, 4 from Senegal, 3 from Uzbekistan, 1 from The Netherlands, and 2 from Saint Vincent and The Grenandines.

Training and Learning Opportunities for Minority Students. USWCL continued to provide training and learning experiences for part-time minority student employees from Arizona State University.

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.

The Safety Committee membership was revised this past year to provide better reaction to issues brought before the committee. The committee has also undertaken a major project, gathering information for inclusion into a data base that the Phoenix Fire Department uses in a new emergency response program. The program provides the fire department with information about site layout, building construction and composition, hazard location, and other information that enables better effectiveness in the event of an emergency such as a fire.

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.

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

STUDENTS AT USWCL

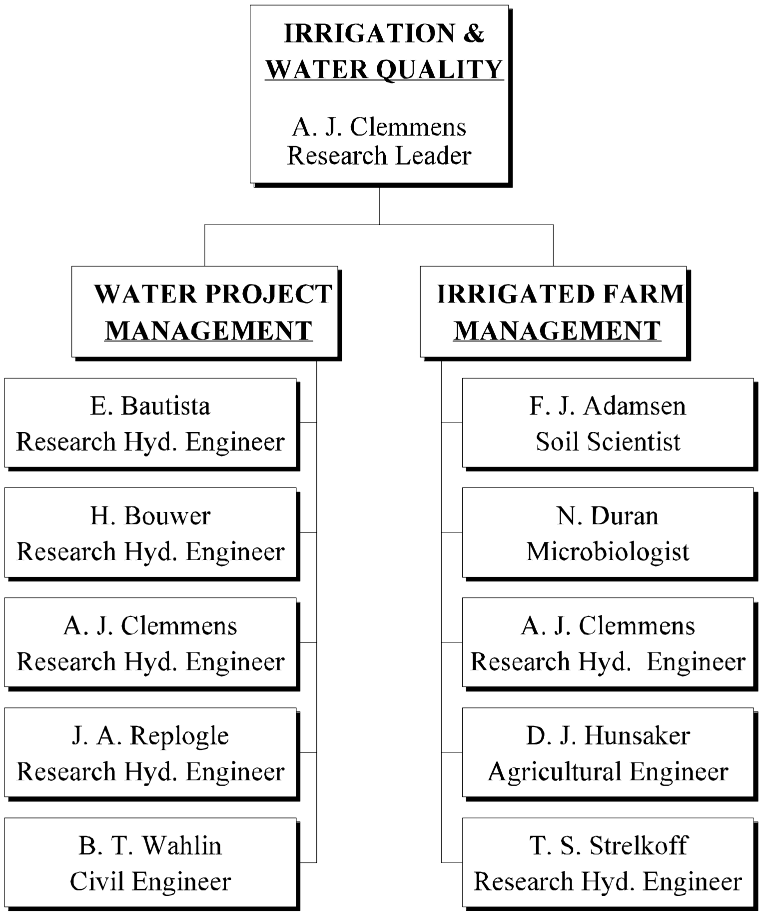
J. Askins

The USWCL has enjoyed a mutually beneficial relationship with students from nearby Arizona State University 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; from numbering vials to writing protocols; from weighing soil to processing and analyzing non-soil data. Students who work in the clerical/administrative area have worked in personnel and safety areas 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.

The students 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.Ds. under ARS assistance programs.

I&WQ Management Unit

I&WQ Organization



Mission

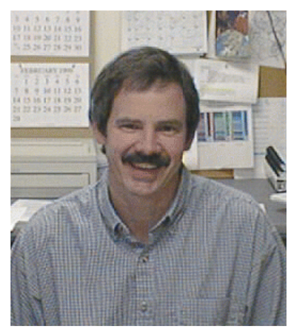
The mission of the Irrigation and Water Quality Research Unit is to develop management strategies for the efficient use of water and the protection of groundwater quality in irrigated agriculture. The unit addresses high priority research needs for ARS's National Programs in the area of Natural Resources & 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.

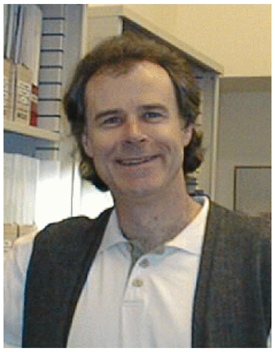
EDUARDO BAUTISTA, B.S., M.S., Ph.D., Research Hydraulic Engineer
On-farm irrigation system hydraulic modeling; hydraulic modeling of irrigation delivery and distribution systems; control systems for delivery and distribution systems; effect of the performance of water delivery and distribution systems 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 and groundwater relations.

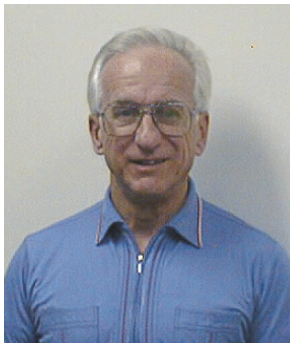


ALBERT J. CLEMMENS, B.S., M.S., Ph.D., P.E., Laboratory Director, Research Leader for Irrigation and Water Quality, and Supervisory Research Hydraulic Engineer
Surface irrigation system modeling, design, evaluation, and operations; flow measurement in irrigation canals; irrigation water delivery system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

NORMA L. DURAN, B.S., Ph.D., Microbiologist
Wastewater irrigation; molecular detection of waterborne pathogens; pathogen regrowth assessment in water distribution systems; fate and transport of pathogens in the subsurface environment.

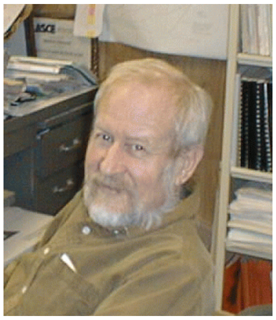


DOUGLAS J. HUNSAKER, B.S., M.S., Ph.D., Agricultural Engineer
Effects of soil and irrigation spatial variability on crop water use and yield in large irrigated fields; level basin irrigation design and management procedures for applying light, frequent water applications to cotton; CO2 effects, in particular, 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

K. Johnson, S. Colbert, and J. Askins, Physical Science Technicians; K. VanMeeteren, Biological Science Technician; and A. Jacques, Physical Science Technician

Following is a description of the functions of the Irrigated Farm Management (IFM) Analytical Laboratory. The IFM Lab is staffed by the technicians listed above, two of whom are students.

High performance liquid chromatography (HPLC) is used to test for nitrate and other anions in soil samples. The autoanalyzer utilizes colorimetry to determine nitrate, and ammonium, and bromide content of water samples and extracts of soil samples. Three stations allow collection of data from weighings directly into a spreadsheet. The extraction step has been aided by replacement of two centrifuges. C^{13} and N^{15} analyses are run on the isotope ratio mass spectrometer.

In addition to running and maintaining instruments, research technicians process data and address the precision of the data. Technicians also weigh soil samples, collect samples in the field, help with irrigation and other field work, write and update protocols for both reference and training, count seeds, and perform numerous other duties as needed. Facilities in this lab are sometimes used by other groups, and occasionally a technician from another group with extra time will lend a hand here.

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 environmentally sustainable, protect groundwater quality, and be economically viable.

STUDIES ON CONSUMPTIVE USE AND IRRIGATION EFFICIENCY

D.J. Hunsaker, Agricultural Engineer

PROBLEM: Effective irrigation management provides the timely and correct amount of water consistent with 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 ET with climatic data. ET_c can then be determined by multiplying the reference ET with an appropriate crop coefficient (K_c). Recently, the Food and Agricultural Organization (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 approach which combines basal crop ET and soil evaporation into a single value, FAO-56 also includes a dual, or basal, crop coefficient approach. In the dual approach, 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). The usefulness of the dual crop coefficient model is that it can provide 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 weather data and thus recommended the FAO Penman-Monteith (PM) as the standard equation for the calculation of grass-reference ET (ET_o). Although FAO-56 presents generalized crop coefficient values based on FAO PM ET_o, derivation of localized crop coefficients is advisable due to the effects of local climatic conditions, cultural practices, and crop varieties on the crop coefficient.

Several different entities have approached the U.S. Water Conservation Laboratory (USWCL) with interest in current information on the ET requirements for crops grown in the Southwest. A particular concern is that many farmers have been unable to meet water duties established by the Arizona Deptartment of Water Resources. 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 experiments to determine crop evapotranspiration and localized crop coefficient curves for cotton, alfalfa, wheat, rape, lesquerella, and guayule grown under irrigation and soil conditions common in the region. Crop ET and soil evaporation will be determined locally from soil water measurements using neutron probes and time-domain-reflectometry (TDR) for crops grown in farm-scale fields and from previous lysimeter studies at the USWCL. These data also will be used to derive crop coefficients for local conditions based on the FAO-PM equation for grass-reference ET_o. The crop ET and K_c derived from the various experiments will be used to develop and test various crop K_c models, including the FAO-56 model, to provide better information on crop water requirements and irrigation management for the region.

During 1984 to 1986, an Arizona-adapted cultivar of alfalfa [*Medicago sativa* (L.) Lew] was grown in a 0.65-ha field located at the USWCL. The rectangular field site (70 by 90 m) contained three electronic weighing lysimeters each 1.0 m^2 and 1.6 m deep. Alfalfa was planted in February, 1984, on 18 plots, separated by border dikes. The three lysimeters (designated as L1, L2, and L3) were situated within three adjacent plots. After planting, all plots were kept well-watered via surface irrigation until late 1984, after which the plots were intermittently subjected to water-stress during subsequent growing cycles. After each alfalfa cutting, water-stress treatments were rotated to different plots so that plants were not exposed to severe drought stress during consecutive regrowth periods. The evapotranspiration in lysimeters (ET_m) and meteorlogical data were measured every 1.5 minutes and reported as time-averaged values at 0.5-hr intervals.

This report will focus primarily on the data of 1985. In 1985, alfalfa was harvested a total of nine times, where the first harvest occurred on Feb. 12 (DOY 043) and the ninth on Dec. 17 (DOY 351). At each harvest, the larger plot areas were mowed using a tractor-mounted cutter bar. Biomass from the lysimeters was harvested using a curved-blade knife. All of the aboveground plant material in the lysimeters was cut leaving a stubble height of about 0.02-0.03 m.

For each day in 1985, the daily grass-reference ET_o was calculated over 0.5-hr time steps. The measured wind speed at the alfalfa field was extrapolated to the FAO-56 standard grass-reference height of 0.12 m, before calculating the grass reference ET_o. Daily K_c values were calculated as the ratio of ET_m to ET_o for each lysimeter. For each harvest cycle in 1985, daily ET_m for lysimeters was compared with daily ET_c predicted for well-watered alfalfa using the single K_c procedure of FAO-56 and their recommended K_c values for alfalfa. The FAO-56 alfalfa K_c values were not adjusted for the effects of increased soil water evaporation due to irrigation and rain. The recommended mid-season and end of season K_c values, however, were adjusted during each cutting cycle based on the climatic and crop height conditions during those growth stages of the cycle.

FINDINGS: Figure 1 shows the daily measured K_c values for each lysimeter and the K_c model constructed from FAO-56 procedures for the second and third harvest cycles of 1985. Measured K_c for all lysimeters was generally higher than modeled K_c during the first half of the harvest cycles because of increased soil water evaporation from rain and irrigation during that period likely being underestimated by the single K_c model of FAO-56. During the mid- to late-season stages of the second harvest cycle, variations in K_c occurred among the three lysimeters although water was applied to all lysimeters on the same day. The FAO-56 K_c curve generally overestimated the K_c for L1 and L2, but underestimated the K_c for L3. During the third cycle, there was a reduction in the

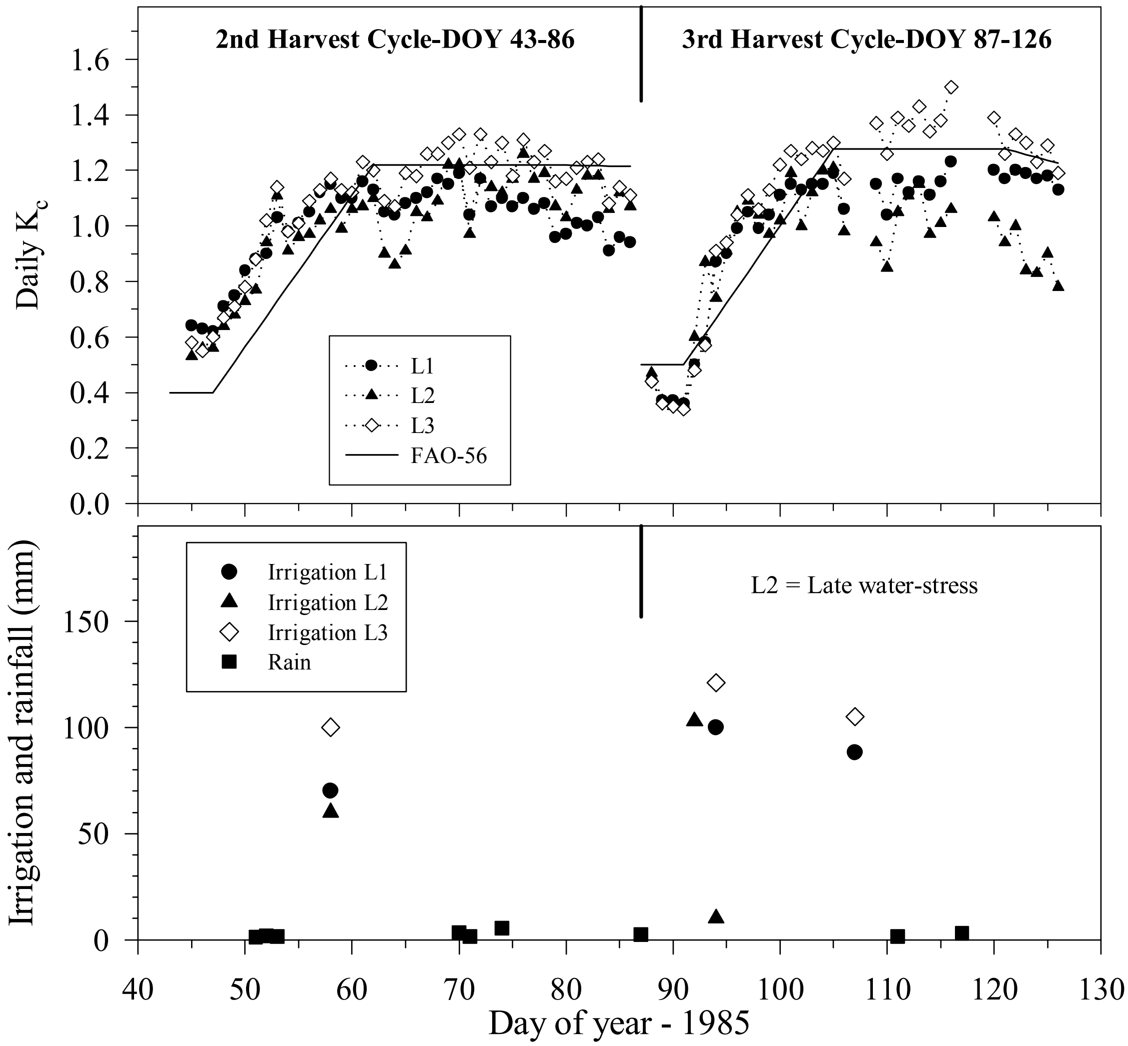


Figure 1. Daily K_c and irrigation and rain during 2nd and 3rd harvest cycles of alfalfa.

K_c values for L2 when water-stress was imposed on that lysimeter during the latter portion of the cycle.

For each lysimeter, linear regression of daily ET_m against the FAO-56 ET was applied over the data from the second to the ninth harvest cycles of 1985 (Fig. 2). Regression coefficients of determination (R^2) for L1, L2, and L3 were 0.78, 0.86, and 0.93, respectively; and for all lysimeter data combined, it was 0.85, indicating that the performance in predicting ET_m on a daily basis with the FAO-56 model was reasonably good. There was a tendency for the FAO-56 model to underestimate ET_m at small rates of measured ET. However, the greatest underestimations of ET_m were noted to occur for days following irrigation or rain, and particularly for days following water applications made during the early regrowth periods following cutting. Again, this was related to the limitations of the single K_c model to account adequately for increased soil water evaporation following water applications.

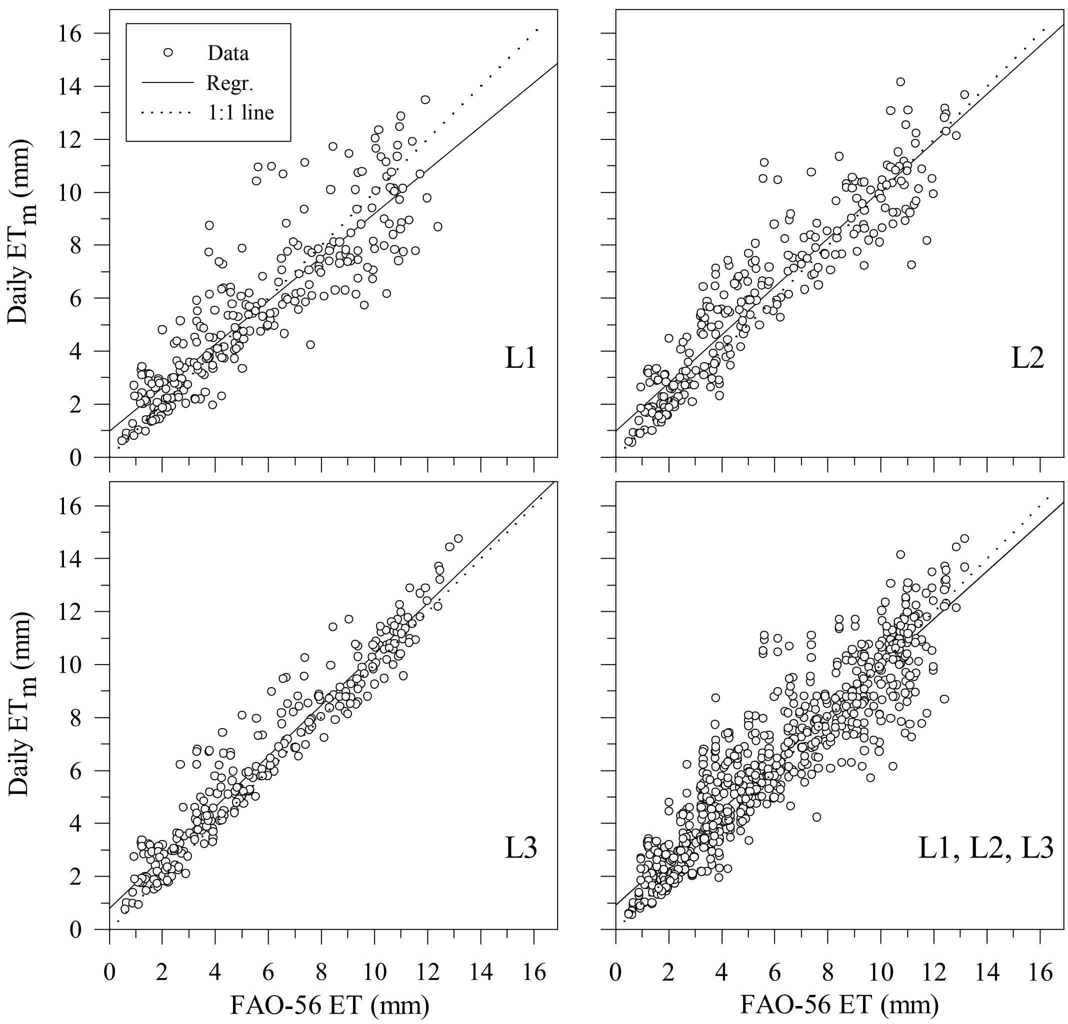


Figure 2. Linear regression of measured and predicted ET using the single K_c model of FAO-56.

INTERPRETATION: Preliminary findings from lysimeter studies indicate the single K_c model of FAO-56 adequately predicts alfalfa ET during mid- and late-season stages of the growing cycle. However, for estimating crop water use on a daily basis at the precision needed to improve irrigation management, evaporative water losses from the soil need to be accounted for more accurately.

FUTURE PLANS: The alfalfa lysimeter data will be used to develop local K_c and K_{cb} curves for alfalfa and also to determine whether the more complicated dual crop coefficient procedure of FAO-56 improves the prediction of measured ET. Additional studies are being conducted more accurately to model the limiting effects of soil water stress on crop ET and to develop information on soil evaporation parameters for soils in the area.

COOPERATORS: Wenzhao Liu, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources Engineering, Yangling, Shaanxi, P.R., 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. Compared to conventional field spreading or soil injection techniques, this method of fertilizer application, "fertigation," offers certain advantages 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 being distributed unevenly throughout the field and potential nitrate-nitrogen (NO_3-N) contamination of groundwater through deep percolation and of surface water through tailwater 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 will also 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 the mobile tracer potassium bromide (KBr) was used during two simulated N-fertigation events for cotton grown in furrowed level basins on a sandy clay loam 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 with lower infiltration rates and less surface roughness than the first fertigation. During both events, three fertigation application treatments were evaluated - KBr injection during 100%, first-half, and last-half of the irrigation application. 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 turnaround area at the head of the field and every 30 m along the run. In the turnaround 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.

FINDINGS: During the first fertigation event, water advanced more quickly in the wheel furrow than in the non-wheel furrow. As a result, water reached the end more quickly in wheel furrows and filled the non-wheel furrows from tail end. The infiltrated depths for 100% of the irrigation were very close for both furrows in spite of water moving from the wheel furrow to the non-wheel furrow during advance (Figs. 1 and 2). While this did not decrease the overall irrigation uniformity, filling the non-wheel furrow from the tail end changed the pattern of infiltrated depth. In the non-wheel furrow, there was a peak in the water infiltrated depth during the first-half of the irrigation between 100 m and the end of the field that would not have occurred if the furrows had been blocked on the tail end. It is interesting to note that the infiltrated depth of water from the first-half of the irrigation was relatively uniform over the first 100 m for both furrows. There was an equivalent movement of water from the non-wheel furrow that moved back into the wheel furrow during redistribution following the completion of advance.

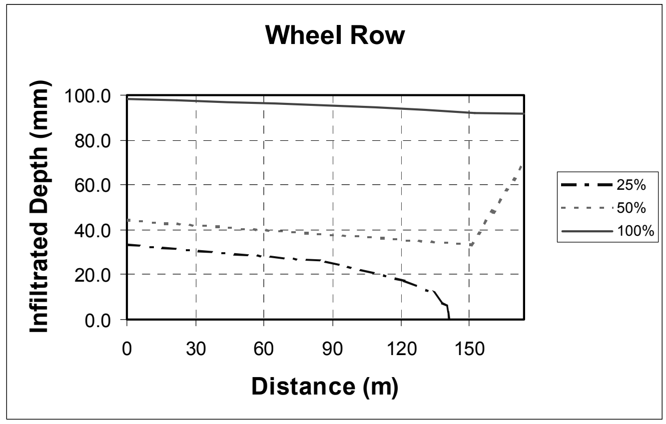


Figure 1. Cumulative one-dimensional infiltrated depth with distance after 25, 50, and 100% completion of irrigation for the wheel furrow of a fertigated furrowed level basin.

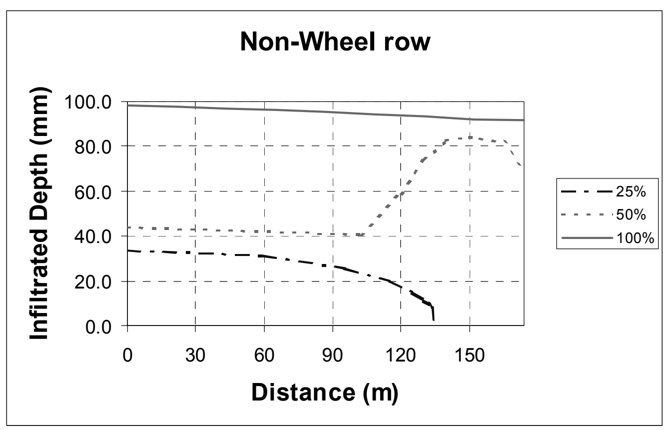


Figure 2. Cumulative one-dimensional infiltrated depth with distance after 25, 50, and 100% completion of irrigation for the non-wheel furrow of a fertigated furrowed level basin.

Presently, bromide concentration has been analyzed only for the top 300 mm of soil. In general, the bromide distributions for the top 300 mm, when averaged across all of the sampling positions within a sampling site, agreed well with the estimated infiltrated water distributions (Fig. 3). The bromide distributions in the first-half and 100% treatments were similar and uniform along the entire field length, as was the infiltrated water (Figs. 1 and 2). There was more bromide at the head end of the field than would be predicted from the infiltrated depths for the last-half treatment (Fig. 3). This may be the result of mixing, or deeper penetration into the soil than the 300 mm of soil depth accounted for here.

An examination of the bromide distribution for individual sampling locations shows some interesting trends (Fig. 3). The in-row concentrations of bromide were higher in the first-half treatment than in the 100% treatment. This is probably due to higher concentrations of the bromide in the water moving laterally into the row from the furrow in the first-half treatment than in the 100% treatment. The bed is infiltrated by the first water applied and the concentration of bromide in the first-half treatment was double the 100% treatment during the injection period. Bromide concentration increased at the tail end of the field in the first-half treatment which corresponds to changes in the infiltrated depth at the tail end of the field, but the trend in bromide concentration was weak.

The change in bromide concentration in the last-half treatment from the head to tail ends of the field is consistent with the infiltrated depth but the magnitude was much greater than would be expected (Fig.34). The peak in the bromide concentrations at 90 m in the last-half treatment for the furrows was unexpected. All of the data suggest that bromide moved below the top 300 mm of soil.

INTERPRETATION: Analysis of the remaining soil depths should provide a more complete picture of the fate of chemicals added in the irrigation stream, but a simple advection model appears to be a promising first step in estimating the application uniformity of water-applied chemicals. This type of experiment needs to be conducted over a variety of conditions to determine the amount of mixing that takes place during an irrigation event.

FUTURE PLANS: Analysis of remaining soil samples will be completed. Additional experiments have been conducted on cotton with longer runs and different soil and on wheat planted on the flat. Samples from those experiments are being analyzed. Similar data sets will be developed for unfurrowed level basins and 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: Mr. Donald Ackley, Program Coordinator, Coachella Valley Resource Conservation District, Indio CA; Dr. Bob Roth, station director, Maricopa Agricultural Center, Maricopa AZ; Dr. Charles A. Sanchez, director, and Dr. Dawit Zerihun, Irrigation Engineer, Yuma Agricultural Center, Yuma AZ; Dr. Pete Waller, Agricultural Engineer, Dept. of Agricultural and Biosystems Engineering, The University of Arizona, Tucson AZ.

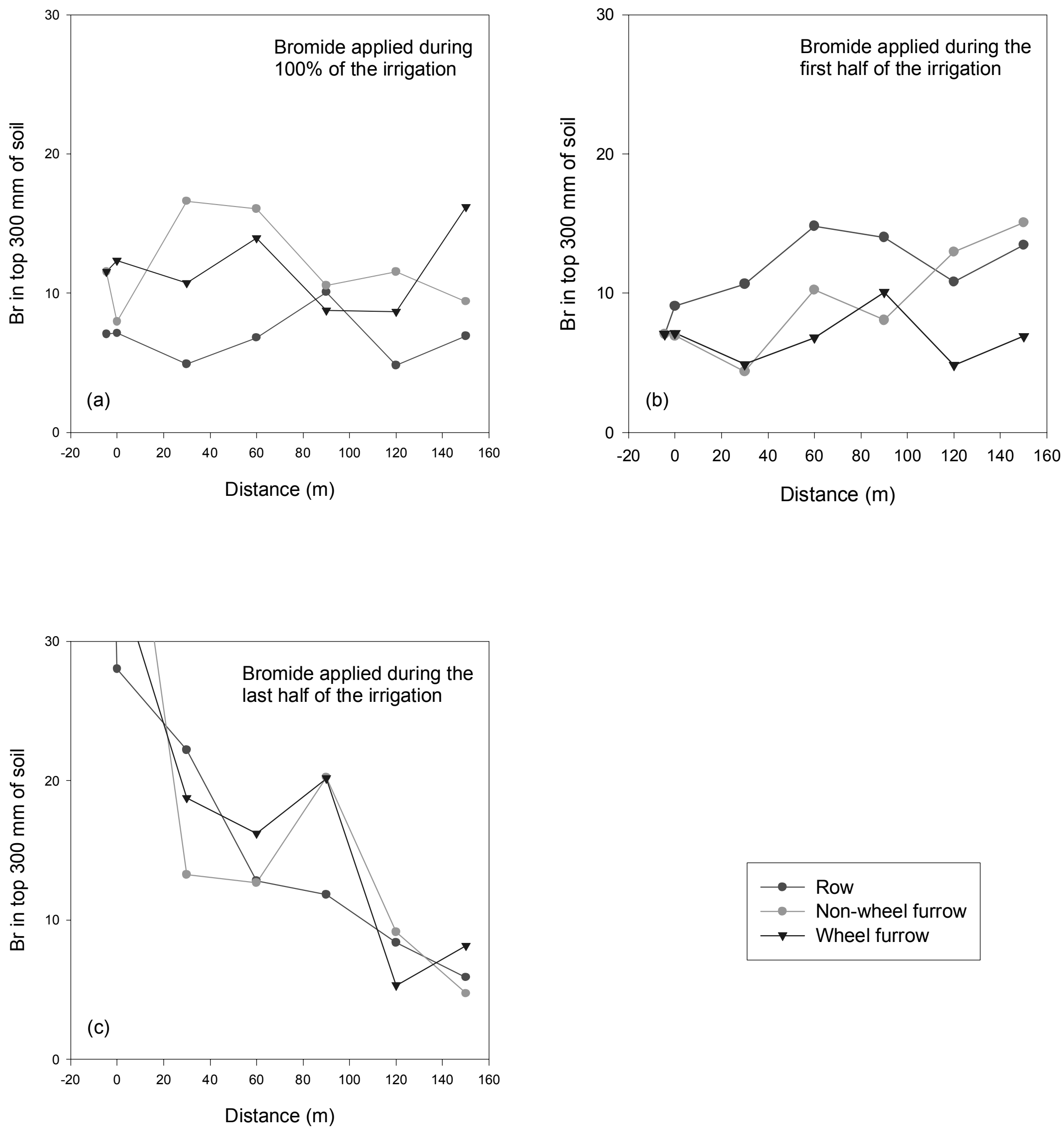


Figure 3. Changes in concentration (mg kg^{-1}) in soil bromide in the top 300 mm of soil from pre-fertigation sampling to post-fertigation sampling for the average of two in row values and for wheel and non-wheel furrow for (a) 100%, (b) first-half and (c) last-half of irrigation injection.

MEASURING SOIL MOISTURE UNDER SALINE CONDITIONS WITH SELF-CONTAINED TDR SENSORS

F. J. Adamsen, Soil Scientist; and D. J. Hunsaker, Agricultural Engineer

PROBLEM: Accurate and reliable soil moisture information is a fundamental requirement in achieving efficient water utilization in irrigated agriculture and in a number of related industries as well. Time domain reflectometry (TDR) and frequency domain reflectometry (FDR) are recognized as established methods for determining soil water content in mineral soils. Both TDR and FDR infer water content from changes in the soil dielectric constant. In the TDR method, this is accomplished by measuring the velocity of an electromagnetic pulse along a pair of rods in the soil. In the FDR method, it is accomplished by measuring the frequency of a tuned circuit which changes as the capacitance of the soil changes due to fluctuations in soil moisture. Initially, the TDR method was considered to be universally applicable over all soil types and soil conditions. However, it is now recognized that widespread application of TDR, and other similar technologies, has been limited due to erratic measurement responses in soils having high salinity. Some success has been made in using TDR signal attenuation to measure soil water salinity, but the technology has not been advanced to the point where this can be accomplished without the use of highly sophisticated and expensive TDR systems.

Soil salinity is recognized as a problem in over one-half of the irrigated lands in the Western United States. It is expected that soil water measurements from commercial TDR and capacitance systems may be used to guide irrigation management on salt affected lands. The objective of this study is to evaluate the effects of soil electrical conductivity on measurements of soil water content by four commercial soil moisture systems (TDR cable tester, two encapsulated TDR systems, and one encapsulated electrical capacitance sensor).

APPROACH: Studies with four commercial dielectric soil moisture systems were conducted in a sand tank in which volumetric soil moisture contents varied from 34 to 12%. The systems evaluated were (1) Trase System 16050x1 (Trase), a TDR cable tester unit with a standard, uncoated, three-rod, "burial-type" probe 0.2 m in length (Soilmoisture Equipment Corp., Santa Barbara, California); (2) Aqua-Tel-TDR (Aqua-Tel), an encapsulated TDR with epoxy-coated multiple probes 0.46 m long (Automata, Inc., Grass Valley, California); (3) Delta-T ThetaProbe ML2x (Theta), an encapsulated electrical capacitance sensor with a four-rod probe 0.06 m in length (Dynamax Inc., Houston, Texas); and (4) Trime-IC (Trime), an encapsulated TDR with a coated two-rod probe 0.11 m in length (Mesa Systems Co., Framingham, Massachusetts).

The tank used in the experiments was a 0.19-m deep tapered masonry trough constructed of high-density polyethylene. The soil medium was a washed sand commercially available for concrete and plaster mixture. Three holes were drilled along the longitudinal center line of the tank bottom. One hole was at the middle of the center line and the other holes were 0.25 m either side of the center hole. The outside holes were fitted with bulkhead fittings and ≈ 0.45 m of tubing attached to the barbed nipple on the fitting. Four pieces of 13 mm diameter cotton-fiberglass wicks 0.2 m long were sewn together to form a double tee pattern. A fifth piece of wick material was attached at the center of the double tee, perpendicular to the plane of the tee. The last piece of wick attached to the system was fed through the center hole and then through a powder funnel with an outlet tube that had been glued to the bottom of the tank with a silicon adhesive. The double-tee pattern was laid in the bottom of the tank extending from either side of the center hole along the longitudinal center line of the tank and forming a tee in each half of the tank. An additional piece of tubing was then forced over the end of the funnel to complete the drainage system in the sand tank. Free water drained from the outside holes, and the wick system drained capillary water from the system and had the effect of creating a water table 0.2 m below the bottom of the tank. The tubes from the three holes were gathered together in a wooden loom and the drainage water was directed into a bucket.

When the tank was filled with sand to a depth of 0.08 m, the three encapsulated systems and the burial probe of the Trase system were placed horizontally across the top of the sand surface approximately 0.10 m apart from one another. Additional sand was then added to the tank, burying the sensors, until the tank was filled to a depth of 0.16 m. Prior to filling, the sand volume within the tank system was estimated by measuring the volume of water required to fill the tank to a depth of 0.16 m. This volume was used to calculate an estimated bulk density of the sand, yielding a value of 1650 kg m^{-3}.

The three encapsulated systems were connected to a data logger and a 12 V DC power source. This configuration allowed simultaneous and automated collection of the mV output from the sensors at desired time intervals. The Trase system provided its own automated logging of volumetric water content measurements.

The soil water salinity of the system was manipulated by adding a range of sodium chloride (NaCl) concentrations to the tank that yielded soil water salinities within the sand bed of approximately 2, 5, 7, 10, 12, and 15 dS m^{-1}. Prior to each test, the sand in the tank was conditioned by leaching it with the desired solution four times to displace any water in the system. After the fourth leaching cycle, sensor testing was begun. After water had drained from the sand tank for seven days the test was ended. At the end of each test, drainage water and soil samples were taken. Holes left from the soil sampling were refilled with new sand.

The output from the Trase system was used to estimate the actual soil water contents of the sand because it was impractical to obtain gravimetric water content samples with sufficient frequency. Salinity level and mV output for each encapsulated sensor were used for the independent variables in multiple linear regression to predict the Trase volumetric water contents over a range of water content data deemed reasonable.

FINDINGS: Including solution salinity along with the sensor output in the regression explained 89 to 93% of the variability in volumetric soil water content for the three encapsulated sensors (Table 1). Negative regression coefficients for solution salinity resulted for all three self-contained sensors, since the outputs for each sensor were increased with increasing salinity.

The deviations from the fitted equations (Fig. 1) indicated that the Aquatel-TDR and Trime sensors both overestimated the soil water contents in the middle of the data range and underestimated the water contents at the high and low ends, whereas the opposite trend was true for the Theta sensor1.

Table 1. Multiple linear regression results for volumetric water content values (θ) as measured by Trase against sensor output in mV and solution salinity in dS m^{-1} (EC_s), where y_0 is the intercept, a is the slope of the sensor output, b is the slope of the solution salinity and R^2 is the multiple coefficient of determination ($\theta = y_0 + a * mV + b * EC_s$).

Sensor	y_0	a	b	R^2
Aquatel-TDR	6.44	0.0074	-0.845	0.893
Theta	-4.46	0.0685	-0.150	0.931
Trime	-2.65	0.127	-0.320	0.886

INTERPRETATION: As a first approximation, a simple multiple linear model fitted the data well. However, because of the systematic deviations of the data from the fitted equations, a more complex model will probably be required to calibrate these sensors in saline soil conditions adequately. The above regressions are also not useful for field use since solution salinity is not an appropriate indicator of soil salinity. What is needed is bulk soil salinity estimates, which can then be used to determine the correction for the sensor output that will yield the true soil water content from the sensor reading. The bulk salinity includes the contribution of the soil matrix as well as the soil contribution.

FUTURE PLANS: We plan to develop a method to estimate the bulk salinity for this data set and to use those values to develop a model that predicts actual soil moisture from the sensor output and bulk salinity. We also plan to determine the response of the sensors to different forms of salt. We will use Mg SO_4 in a similar set of experiments to determine if salt type affects the response of the sensors in addition to salt concentration.

COOPERATORS: Lenny Feuer, Automata Inc., Nevada City CA.

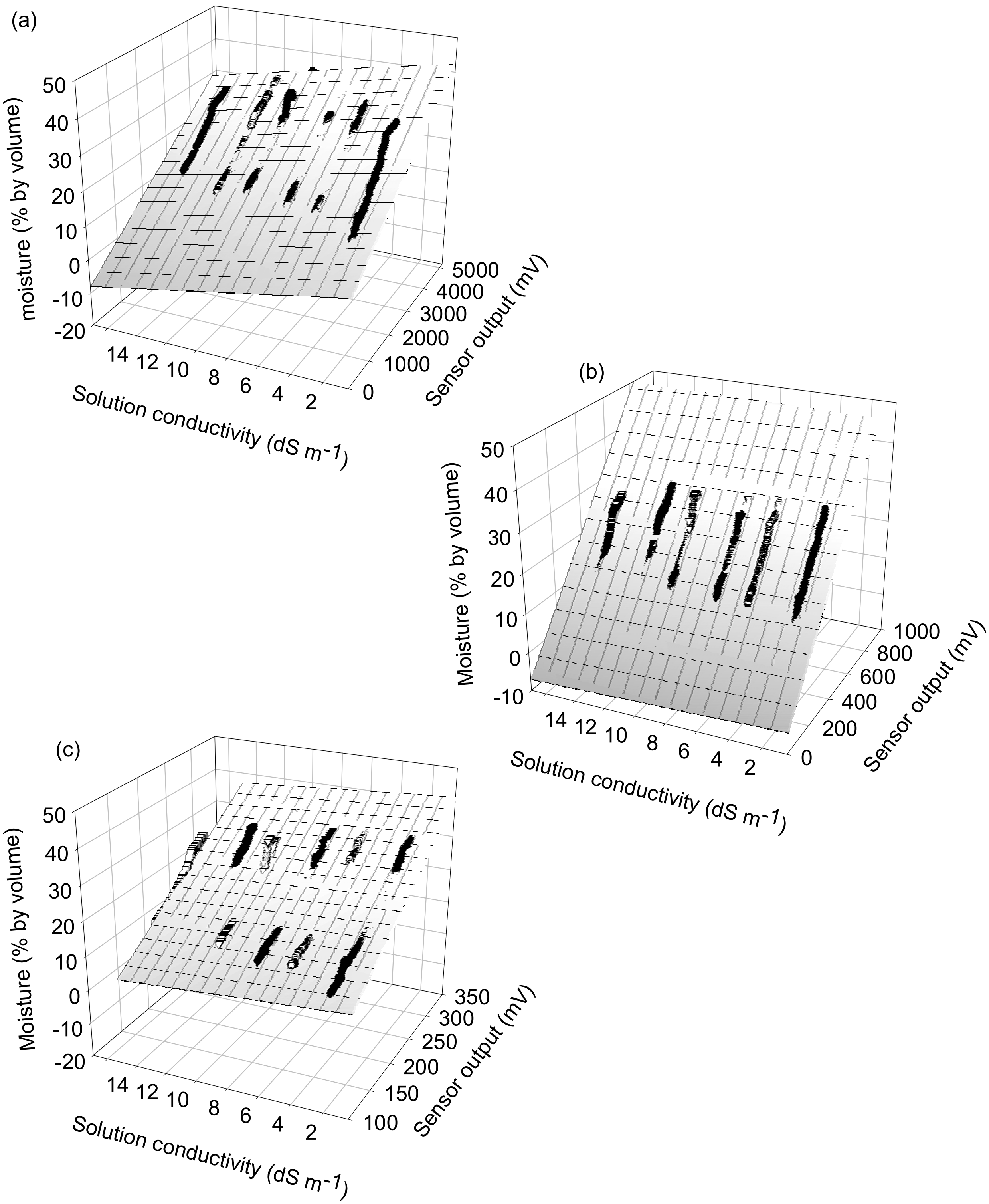


Figure 1. Response surfaces of (a) Aquatel-TDR, (b) Theta, and (c) Trime to moisture content versus solution salinity and sensor output.

SURFACE IRRIGATION MODELING

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

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 headwater and tailwater 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 groundwaters as well as of the field soils. Irrigation streams can be of sufficient power that soil erodes, 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 objectives of current work are 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 has been provided in part by the Natural Resources Conservation Service.

For one-dimensional single-furrow, border, or basin simulation, user-friendly menu-driven data input, as well as output graphs and text, are linked to a simulation engine based on the universal laws of hydraulics 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 toward 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. Apart from the median size of particles in the soil bed and transported in the irrigation water, the mix of particle sizes plays a significant role in the redistribution of soil along the furrow and in the total load transported with the runoff. An especially critical effect of the size distribution has to do with the total surface area of sediment in transport, for that relates directly to the load of chemicals, such as phosphorus, adsorbed to the eroded soil.

Chemical interactions take place between irrigation water in which the chemical may be dissolved, the soil bed on which the chemical may be precipitated or adsorbed, and sediments in transport on which the chemical may be adsorbed. The partitioning of a chemical amongst these media depends on the specific chemical of interest, upon the soil and water chemistry and temperature, and on the surface areas of sediment particles in transport. In the advection-diffusion equations coupled to the hydraulic water-flow equations and describing the fate and transport of the chemical, these interactions lead simply to source/sink terms. Mixing is assumed complete in the transverse direction. Longitudinal dispersion follows from both the transverse turbulent mixing and the transverse velocity distribution, assumed logarithmic. As a first approximation, fate and transport of any chemical is assumed independent of those for any other.

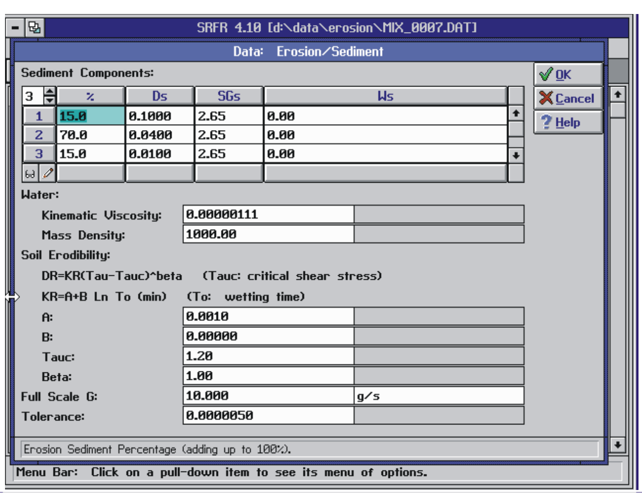


Figure 1 Data-input screen for specifying field data, including particle-size distribution, for erosion computation.

FINDINGS: The SRFR surface-irrigation and erosion simulation model includes three methods to treat particle-size distributions in calculating the flow's sediment-transport capacity. Figure 1 shows the interactive data-input screen for entry of data pertinent to an

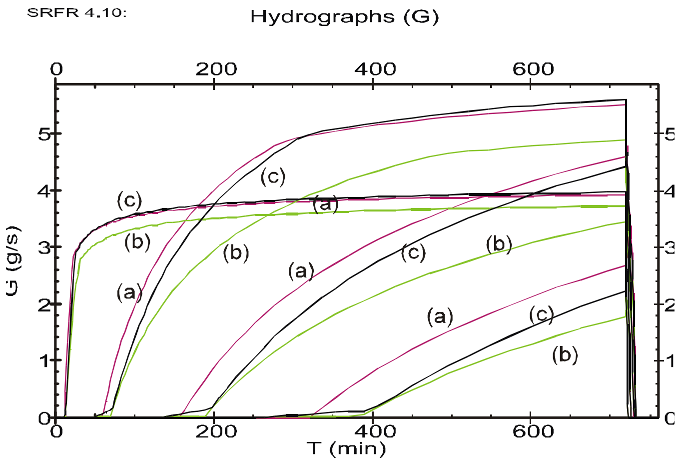


Figure 2 Influence of treatment of particle-size distribution on transport capacity and consequent total sediment load at furrow quarter points; (a) distribution represented by median diameter; (b) as per WEPP (1995); (c) as per Wu and Meyer (1989).

erosion simulation, including the particle size distribution. Figure 2 compares simulated total sediment loads at the quarter points along a furrow's length with the three different treatments of particle-size distribution: (a) a single representative size, the median diameter; (b) weighted in accord with the fraction in the soil mix (WEPP, 1995); and (c) weighted in accord with carrying capacity for the particular size relative to the sum of carrying capacities for each size (Wu and Meyer, 1989; Fernandez, 1997). The particular hypothetical mix of sand (15%), silt (70%), and clay (15%) shown had a mean diameter of 45 microns, a standard deviation of 25 microns and a skew coefficient of 1.2. A less uniform mix with a standard deviation of 33 microns showed considerably more spread in the results.

A pilot two-dimensional model was subjected to intensive validation in a 3 ha irregular basin at the Gila River Farms, which is partially blocked by a raised roadway and irrigated from the center of one side. Figure 3 shows calculated depths after 23 minutes. Monitoring water levels in 26 locations and a land-level survey allowed estimation of the soil infiltration

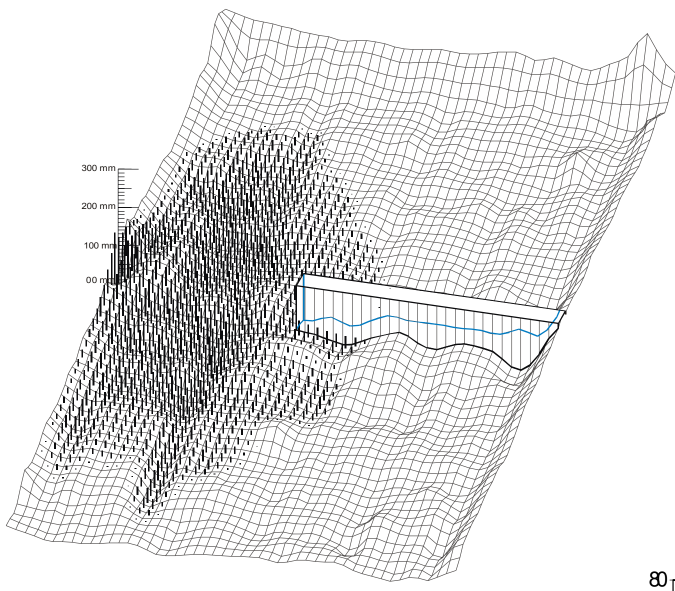


Figure 2 Simulated depths as irrigation stream encounters raised roadway

characteristics. Figure 4 shows comparisons of measured water surface elevations at several locations with those computed in the nearest cells. Computational cells straddle depth-measurement station #4. The computations generally agree with field data.

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

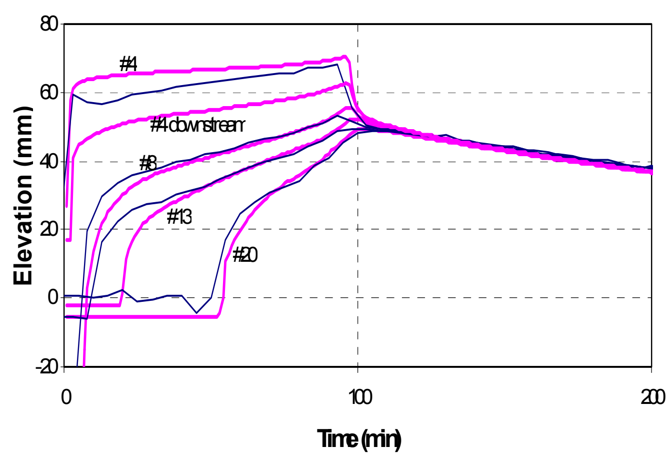


Figure 4 Comparison of simulated (broad grey) and measured (narrow black) depth hydrographs.

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: Individual groups of particle sizes will be tracked through the entrainment/transport/deposition process to yield more accurate estimates of total sediment loads less sensitive to field-data values. A fate and transport of phosphorus component will be added to SRFR (requiring calculated estimates of total surface area of transported particles) under a 3-year competitive grant from NRI-CGP (CSREES).

The opportunity to enter field measurements of surface-irrigation performance (advance, recession, hydrographs, etc.) and plot comparisons with simulations will be added to SRFR. As funding becomes available, coalescing of successive surges will be added to SRFR. Likewise, the two-dimensional pilot model will be reoriented toward 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 recasting the suite of stand-alone DOS-based surface-irrigation software into true Windows programs sharing common input data screens and allowing linkage to common databases. Incorporation of relationships for cohesive soils, a relatively poorly understood area in the field of sediment transport, is envisaged. Incorporation of soil and water chemistry components is contemplated as water and soil salinities play a great role in erosion, especially in clays. Estimates of the pre-wetting effect for surge irrigation should be included. 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, nitrogen 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; Dale Westermann, David Bjorneberg, Rick Lentz, Robert Sojka, ARS Northwest Irrigation and Soils Research Laboratory, Kimberly ID; Thomas Trout, Water Management Research Laboratory, Fresno CA; Charles Sanchez, University of Arizona, Yuma AZ; Marshall English, Oregon State University, Corvallis OR; Roger Stone, Gila River Farms, Pinal County AZ; Rien van Genuchten, Jirka Simunek, Don Suarez, ARS Salinity Laboratory, Riverside, CA.

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.

MEASUREMENT AND CONTROL OF WATER FLOW UNDER DIFFICULT CONDITIONS

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

PROBLEMS: Many flow conditions in irrigated agriculture and watershed studies are not amenable to the use of simple flumes and weirs. Other measurement devices and methods are often more expensive, more difficult to use, or less accurate than needed for field applications. Improvements in these other methods would compliment flumes and weirs. Interest continues in flow profile conditioning in pipes, applications of flow meters to irrigation wells, and automatic regulation of flow to lateral canals. More design information is needed for flap gates, which are sometimes used to prevent back flows in lowland situations. Radial gates are frequently used to control flows in canals. Their hydraulic behavior needs to be simplified, perhaps with simple structural changes.

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. Methods to condition flows and improve the flow profiles would allow the application of many flow metering methods now restricted by these limitations, particularly when short lengths of straight pipe precede the meter.

Even with conditioned flow profiles, some methods experience other limitations. For example, propeller meters readily clog in debris-laden flows and usually can be inserted into trashy flows for only a few minutes. Portable end-cap orifice meters do not attach easily to rusted pipe ends. Pitot systems are considered difficult to apply to discharges from wells without special wall taps and insertion ports. Although effective in solving some pipe and open channel flow measuring problems, ultrasonic flow meters remain too expensive for most irrigation applications.

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. Mechanical-hydraulic mechanisms hopefully can be developed to stabilize the discharge rate through them, regardless of changes in the level of the source canal. Fluctuating flow-rate deliveries increase the difficulty of effective irrigation and may require expensive means to monitor total delivered water volume. Steady flows can use simple time clocks for total volume.

The several ongoing objectives associated with pipe system flows are: (a) to complete papers and technical notes regarding simplifying the use of portable end-cap orifices (previous Annual Reports); (b) to develop practical methods to achieve effective flow conditioning for flow meters installed in difficult short-pipe situations; (c) to evaluate prototypes of clog-resistant propeller meters that have been manufactured to our suggestions; (d) to place current study of the rubberized flap gates into historical perspective with previous flap gate designs, and (e) to modify the edge of a radial gate in attempts to simplify its hydraulic behavior.

APPROACH: Flow-profile conditioning in pipes will include insertion of orifices and sidewall vanes. A special 30-inch diameter pipe facility is being used for conducting these tests. The same pipe system has been modified to allow testing of a pipe flow control concept using the proposed new valving and bag obstruction system.

Testing will continue on the new design of float-operated valves that can be used in combination with a water inflated bag to maintain a desired flow level in a receiving canal. These are cross-referenced to the related "Pipe-Flow" project report for the pipe flow situations. These modifications for channels will be reported herein. The objective is to develop applicable hydraulic flow control devices 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 with a view to generalize the applications and to reduce cost.

Tests on the end-cap orifice system are complete. An alternate pressure tapping method was studied that used 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 was gathered.

A plastic pipe, O.D.= 1 3/8 inches, was fastened to the closing edge of the radial gate model (Fig. 1) in an attempt to make it less sensitive to the angle of the gate face at different gate openings.

FINDINGS: Flap Gate: The rise of the hydraulic grade line for velocities of approximately 5 feet per second was only 0.01 inches of head even with added weights to the gate. The velocity head (h_v) was calculated to be 0.4 feet. For the higher velocity of about 10 feet per second, the difference was even less, about 0.008 inches, for an h_v of 1.5 feet.

Pipe Flow Control System: The new DACL valving system that was developed, because a commercial version did not provide the needed functions, has only been partly evaluated. The new valve appears to be capable of all required functions but needs further laboratory and field evaluation. A small model of the concept operated as hoped. While the bag concept worked on a small model and appeared to function well, a variety of low-cost bag products tried on the full scale resulted in failures from ripping. Different bag materials are on hand but not yet tested.

End-cap Orifice: The end-cap orifice data have been examined and the data appear consistent. The orifice system calibrated as expected from theory and is more repeatable than corner-taps on a pipe of uncertain end quality. The convenience aspects of the system were demonstrated.

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.

Pitot-tube system for irrigation wells: Second report has been published (Reference.)

Radial Gate: Laboratory testing on the first edge modification involving attachment of a round pipe on the gate edge are completed, but the data have not been fully evaluated.

INTERPRETATION: Flap Gate: While the analysis is still incomplete, preliminary findings are that free discharging flap gates cause negligible increased back pressure on pipelines that are flowing full. This is in contrast to their presence if submerged. Mathematical analysis from historical literature has been only partly successful in describing their behavior. Because design information is not readily available for the free outfall or the submerged gate situations, the current results are being reported in the historical context of some limited previous studies in order to make the information more readily available to designers.

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.

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. Indications from limited test runs 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 (Fig. 2 and 3).

Pitot System: The rugged compact system can be constructed using common shop techniques and standard small pipe fittings, is portable, and disassembles to fit into a standard business brief case. The device can be quickly attached to the flowing well pipe to determine well discharges to within plus or minus 3 to 5 percent. This research facilitates the measurement and management of irrigation wells, providing needed tools for irrigation project technicians worldwide to measure flow from wells and to check the condition of existing meters.

FUTURE PLANS: A report on End-Cap Orifice will be prepared and a technical note on the Flap Gate to make it more available to designers in water resources incorporating some limited historical data. We will continue the laboratory study phase and improve instrumentation for faster data collection on flow velocity distribution and evaluate current data on the Radial Gate to assist in redesigning the lip attachment to a structural angle.

COOPERATORS: Robert Gooch, Salt River Project, Phoenix AZ; John Dickerman, Global Water, Fair Oaks CA ; and John Vitas, Plasti-Fab, Inc., Tualatin OR.

REFERENCE: Replogle, J.A. and Wahlin, B. 2000. Measuring irrigation well discharges. Journal of Hydraulic Engineering, ASCE. 126(5) 335-346.

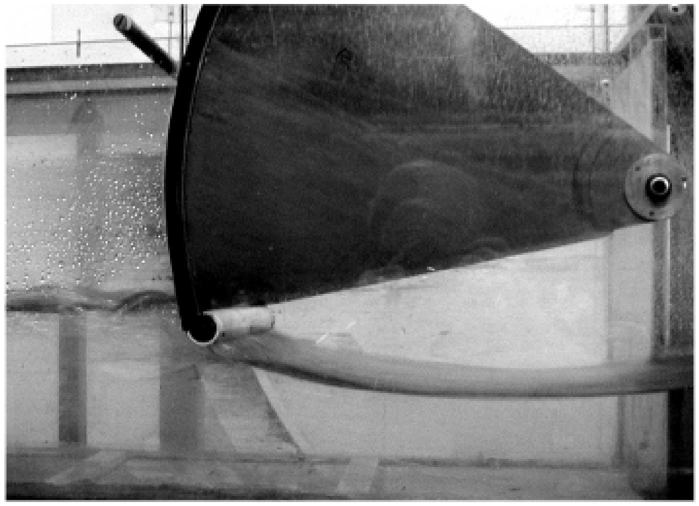


Figure 1. Radial gate with the gate-closure edge modified by attaching a pipe along the edge.

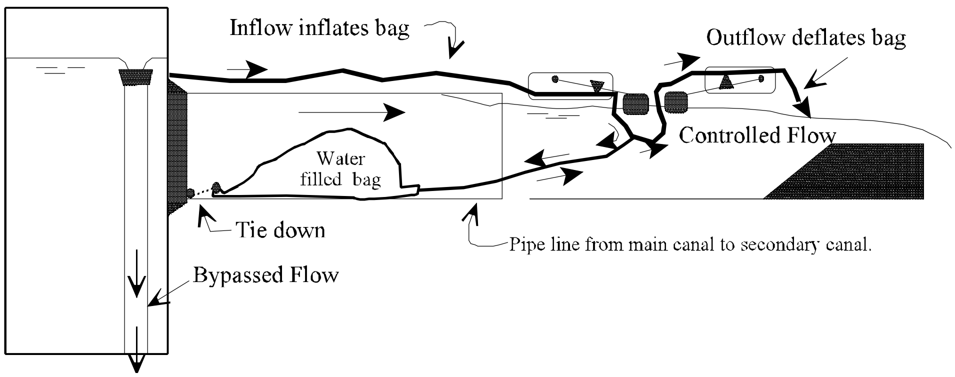


Figure 2. General laboratory set-up for evaluating valve and bag system for flow level control.

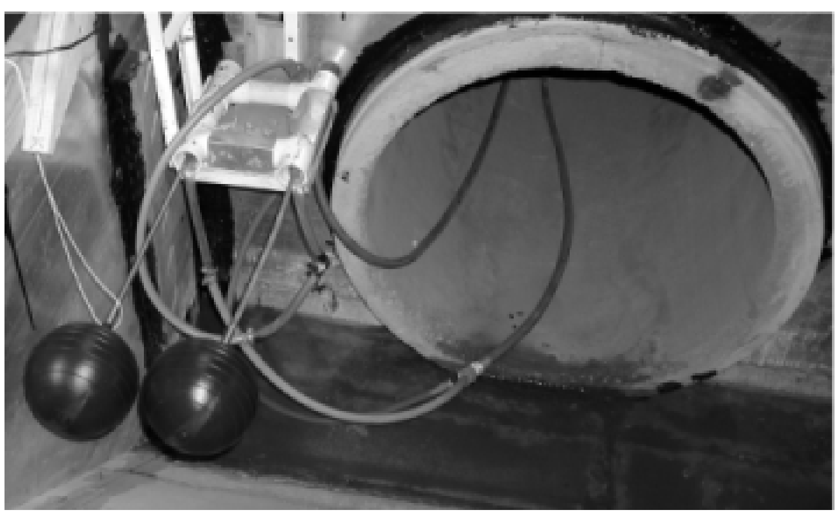


Figure 3. Low-cost float valve system in a pipe outlet channel.

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 connected 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.

- 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 did not run well with computer systems using Windows operating systems. A revision of the original flume book is needed and should include experiences and construction techniques accumulated over the last decade.

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) and has been in operation for over 3 years. The objective was to evaluate the idea of the self-calibrating flume system and to determine its operational limitations in situations where sediment flows ordinarily spoil measurement attempts. 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 was 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.

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 previously reported, the California Water Quality Control Board used the flume data from last year to demonstrate the severity of the cinibar (mercury ore) tailings problem to EPA.

Based on that, emergency super-fund money ($2.5 million) to stabilize the mine tailings was authorized. More data have been collected to verify the initial findings and to evaluate progress in the effectiveness of the clean-up.

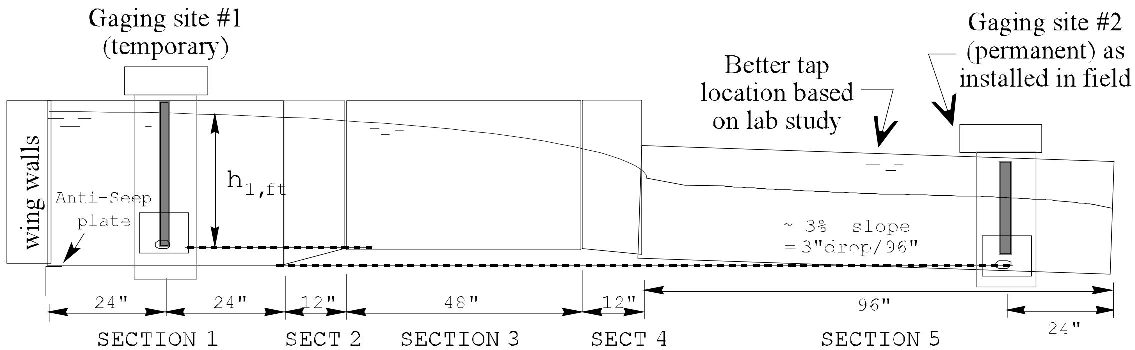


Figure 1. General layout of sediment resistant flume as installed.

The model study of the system showed that 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 of 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. The speculation is that the chute will need to transition gently to its final slope in order to provide a smooth surface drop. The slight drop provided in the original design caused undulations that made depth measurements difficult. This has not been tested.

As previously reported, 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 continue to find the devices easy to install and able to meet their operating requirements. Widespread acceptance appears to be growing, as is interest in 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 final versions to over 490 users from 40 countries.

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.

FUTURE PLANS: Design, installation and application changes for adjustable flumes, including evaluation of field performance, will continue. Recent design assistance included changes to accommodate stilling wells to be attached to the smallest flume size. Kits of a possible recording instrumentation system have not been selected or assembled in any kind of final design format. Such a system seems economical and feasible. This system will continue to be investigated to see if it indeed can be demonstrated and evaluated.

Because the WinFlume program has been distributed, we will write a new book/users manual for the WinFlume Program.

COOPERATORS: Informal cooperation exists among: Tony Wahl and Cliff Pugh, US 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 Steward, 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.

Figure 1. Flow in discharge chute attached to a long-throated flume. The flow calibration is stable despite the rough flow appearance.

SEEPAGE CONTROL WITH MUDDY WATER

H. Bouwer, Research Hydraulic Engineer

PROBLEM: Seepage from ponds, reservoirs, lagoons, wetlands, or other water impoundments often needs to be controlled, usually with earth or plastic linings. Where earth linings are used, the soil material is placed on the bottom and banks and mechanically compacted when the impoundment is dry. However, the soil can also be applied dry or as a slurry to the water itself. The question then is: what gives more seepage control, a compacted soil layer placed on the bottom where the soil is thoroughly mixed, or a soil slurry applied to the water where the coarser particles sink faster than the finer particles, thus creating a lining layer on the bottom that is coarser at the bottom and finer at the top? Another question is: can additional seepage reduction be obtained by applying sodium carbonate or other chemicals that will disperse the clay in the liner?

APPROACH: The effect of placement of an earth lining in an impoundment for seepage control was evaluated in four laboratory columns in 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 carefully 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 in which they reached well-defined final values. After the slurries had been applied and the infiltration rates had become essentially constant for at least 20 days, a solution of sodium carbonate was applied to see if further infiltration rate reductions could be obtained by the clay dispersing action of the sodium. Earlier work at the U.S. Water Conservation Laboratory (USWCL) showed that sodium carbonate additions to the water were effective in reducing seepage rates in stock ponds. Using the dose recommendations resulting from that work, each column received 17 grams of sodium carbonate dissolved in 500 ml water. The salt solutions were placed deep into the water so that they would be close to the infiltrating soil surface.

FINDINGS: Table 1 shows the final infiltration rates at about 40 days after the soil liners had been placed. The rates ranged from 0.85 cm/day for the 15 split slurry applications to 2.7 cm/day for the compacted soil. The infiltration rate for column 1 (compacted earth layer) started at about 3.7 cm/day for the first 10 days then decreased gradually to about 2.7 cm/day in the next 20 days, where it remained for the duration of the test (next 15 days). The split slurry applications produced continued declines, as shown in Figure 1. Since the seepage rate for the silica sand alone was 9.6 to 11.1 m/day, 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 reductions 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 achieved with slurry applications gave better seepage control than a uniform compacted liner. In practice, slurry applications can be repeated until an acceptable seepage level is reached.

After the sodium carbonate solutions had been placed in columns 1, 3, and 4 (column 2 was not used because the soil lining had cracked), infiltration rates began to decrease very slowly. After 150 days, they had reached values of 0.49 cm/day for column 1, 0.25 cm/day for column 3, and 0.19 cm/day for column 4. This amounts to additional infiltration reductions of 82%, 75%, and 78%, respectively.
Because of the slowness of the process, the continued reduction must have been caused mainly by clay dispersion rather than by microbiological action. Regardless, the final infiltration rates of about 0.2 cm/day in columns 3 and 4 were much less than the infiltration rate of about 1000 cm/day for the silica sand alone before the soil liners were placed. This is a very significant seepage reduction which may well be a lot less expensive than plastic or other artificial liners.

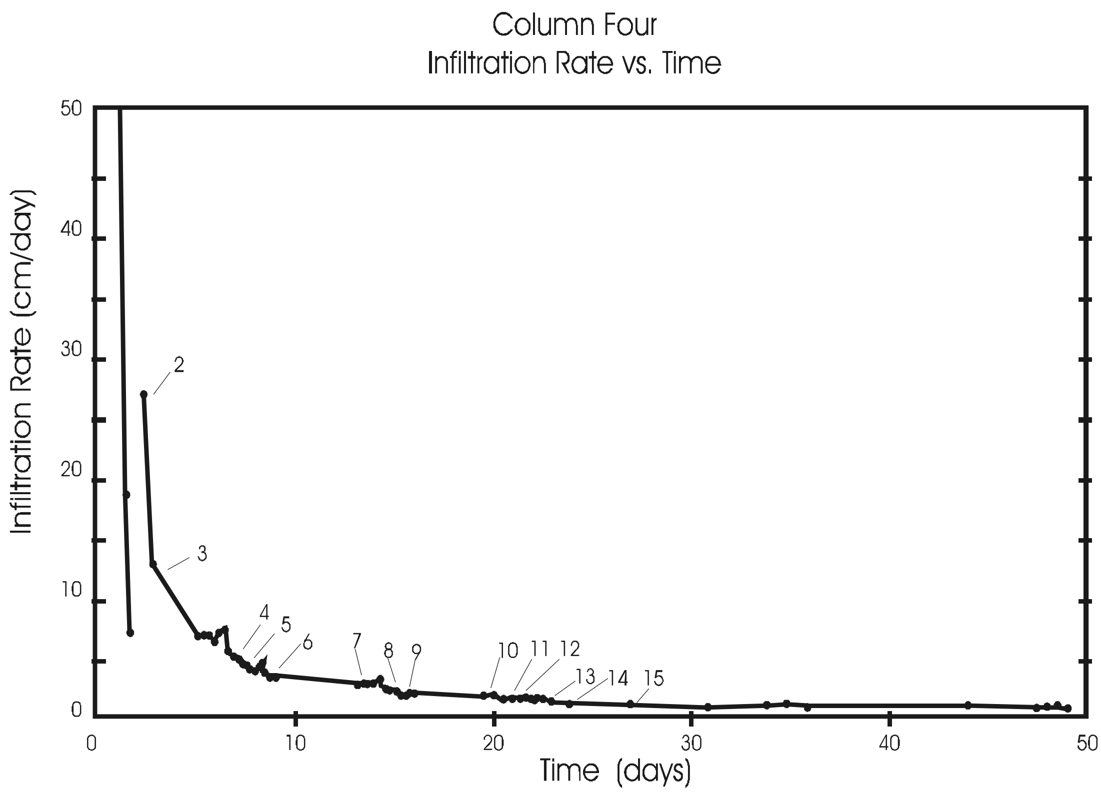


Figure 1. Infiltration rates for column 4 with 15 split slurry applications (indicated on curve).

Table 1. Effects of earth liners and sodium carbonate on seepage rates in soil columns.

	Column 1	Column 2	Column 3	Column 4
	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
Infiltration rate in cm/day after sodium carbonate addition	0.49		0.25	0.19

INTERPRETATION: For the same amount of soil used, earth linings gave lower infiltration rates and, hence, better seepage control when applied as a slurry in split applications to a water filled pond than when applied dry on the bottom of an empty pond and mechanically compacted. Further reductions in seepage losses were obtained by applying sodium carbonate to the water. Repeated slurry applications are naturally achieved in wetlands or other impoundments that receive periodic inflows of muddy water. This is beneficial where seepage losses are to be minimized, but undesirable in infiltration basins for artificial recharge of groundwater. Such basins should then be designed and managed for minimum erosion or other introduction of fine particles into the water.

FUTURE PLANS: The results will be used in interpreting infiltration behavior of impoundments to see what best management practices should be used to maximize infiltration rates (recharge basins) or to minimize infiltration rates (wetlands, ponds, etc.).

FORMATION OF CLOGGING LAYERS IN RECHARGE BASINS

H. Bouwer, Research Hydraulic Engineer; and N.L. Duran, Microbiologist

PROBLEM: Clogging of soil surfaces in infiltration systems for artificial recharge of groundwater or for soil-aquifer treatment is the main problem in maintaining adequate infiltration rates. Even if all clogging parameters like suspended solids, nutrients, and organic carbon are removed, clogging layers may still form on the infiltrating surfaces due to growth of chemotrophic microorganisms. Also, dissolved air in the water may come out of solution as water pressures decrease when the water moves into and through the soil. Other gases, like nitrogen, methane, and hydrogen sulfide may also accumulate due to microbiological processes in the soil.

APPROACH: To evaluate these processes, four plastic columns 10.4 cm in diameter and 90 cm in length were set up in the laboratory. They were packed with four different soils: flint sand, #90 sand, loamy sand of the old Flushing Meadows project in the Salt River bed, and the Mohall-Laveen soil used in the 1 ft x 8 ft stainless steel columns in the greenhouse for studying effects of irrigation and recharge with sewage effluent on groundwater. A coarse sand and gravel layer for drainage was placed at the bottom of the column. Each column was packed with 30 cm of soil. The soil was flooded with Phoenix tap water to a constant depth of 60 cm. The pressure head at the bottom of the soil column was maintained at 60 cm water, thus creating an initial hydraulic gradient of one in the soil column to represent the gravity flow that dominates in actual field systems. The bulk density and saturated hydraulic conductivity of the soils as packed in the column and determined from dry weight and soil volume, and flow rate and head loss, respectively, are shown below.

Soil	Bulk Density, g/cm^3	K, m/day
flint sand	1.50	53.0
#90 sand	1.50	8.5
Flushing Meadows soil	1.54	2.0
Mohall-Laveen	1.74	0.3

RESULTS: Infiltration rates as a function of time for the four columns receiving tap water are shown in figure 1. The infiltration rate started to decrease almost immediately in the two sand columns. The relative infiltration rates (infiltration divided by the initial infiltration rate) are shown in figure 2. The rate at which the infiltration decreased was much faster with the coarser sand columns. The infiltration rate for the fastest three soils approached a common value of about 1 m/day after 45 days. After 95 days, the three columns had an infiltration rate of about 0.7 to 0.8 m/day. The initial rate for the least permeable, Mohall-Laveen soil, was 0.3 m/day and decreased to 0.12 m/day after 95 days. The reduction in infiltration rates could be caused by autotrophic bacteria and/or by formation of entrapped air. Tapping the columns and disturbing the soil surfaces with a rod did not produce ebullition (release of air bubbles) from the soil material, indicating that formation of entrapped air did not contribute to the decline of infiltration rates. However, the soil surface in all four columns was covered with a brown, soft organic layer about 1 mm thick. Stirring up this layer with a rod produced small, sludge-like flocs which, for a while, remained suspended in the water. Undoubtedly, these were flocs of a brown mat of bacteria that grew on the soil surface and their metabolic products like polysaccharides, despite the fact that the water was regular drinking water with some residual chlorine that was given in the water treatment plant to prevent regrowth of microorganisms in the water distribution system. The clogging layer was disturbed for only a small area (about 0.5 cm^2). Nevertheless, infiltration rates immediately increased, but decreased rapidly to the low values before the columns were checked for ebullition (air bubbling). A similar loose, brown deposit of bacterial growth accumulated on the plastic bottom of the constant head reservoir used to maintain constant water levels in the columns, indicating that soil and infiltration played no essential role in the microbiological activity.

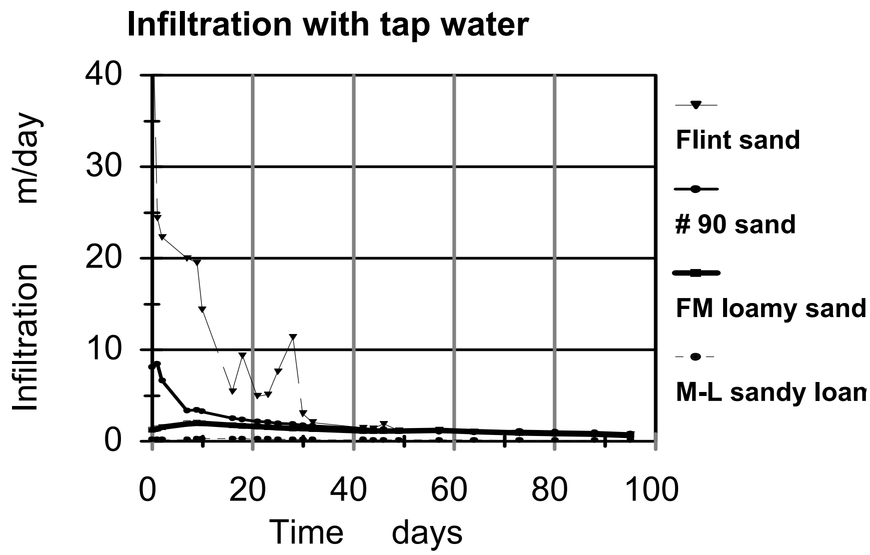


Figure 1. Infiltration with time for columns irrigated with tap water.

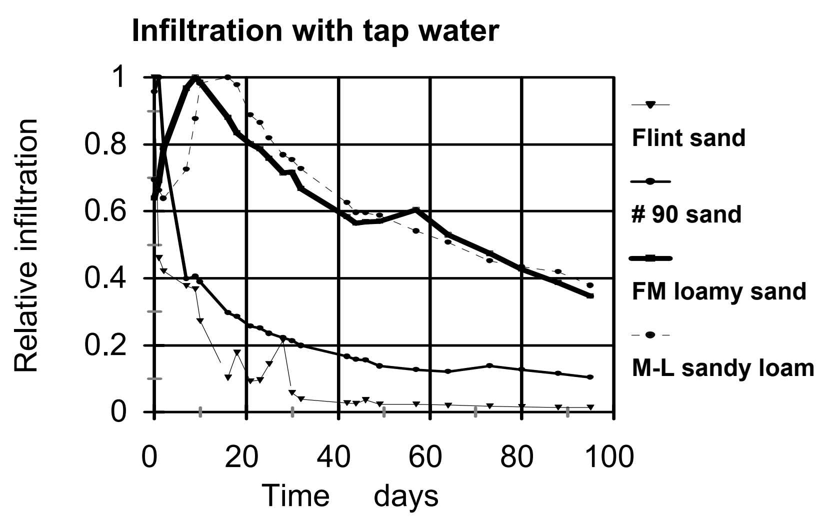


Figure 2. Relative infiltration with time.

Samples were taken from the clogging layer at the top of the columns and analyzed by direct epifluorescent microscopic counts using the nucleic acid fluorochrome stain, acridine orange (AO). Samples were stained with 0.1% acridine orange, filtered through a 0.2μm polycarbonate black filter, and examined with a Nikon epifluorescent microscope equipped with a 410-485 nm excitation filter, an auxiliary excitation filter at 460nm and an absorption filter at 515nm at 100 times magnifications. The biofilm observed on top of the columns appeared to be composed of bacterial cells, dead cell debris and large round cells, possibly aquatic protists. Photomicrographs of spirochetes and bacilli morphologies were taken.

INTERPRETATION: The results show that permeable soils with initially high infiltration rates of finished municipal drinking water clogged faster than less permeable soils, and that eventually all four soils had about the same infiltration rates as controlled by the clogging layer which consisted primarily of bacterial cells and cell debris. Thus, pretreatment of natural water for recharge to remove suspended solids, nutrients, and organic carbon as the main clogging agents will not eliminate clogging problems. Regular drying, cleaning, and disking of the infiltration basins will still be necessary to maintain high infiltration rates. The challenge then is to find the optimum combination of pretreatment of the water and basin maintenance procedures (drying, cleaning, disking) to give the best combination of recharge capacity and operating costs. Where land is scarce, maximizing recharge capacity will be the dominating objective.

FUTURE PLANS: The results of the column studies will be used in developing design and management plans for existing and planned groundwater recharge basins.

WATER REUSE

H. Bouwer, Research Hydraulic Engineer

PROBLEM: Increasing populations and finite water resources necessitate more water reuse. Also, increasingly stringent treatment requirements for discharge of sewage effluent into surface water make water reuse more attractive. The aim of this research is to develop technology for optimum water reuse and the role that groundwater recharge and 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 to treat sewage for reuse. These methods include lagooning, groundwater recharge, and intermittent sand filtration.

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 in soils of phosphate, metals, and strongly adsorbed organic compounds, and in groundwater of salts, nitrate, toxic refractory organic compounds, and pathogenic microorganisms. Water reuse for irrigation is a good practice, but it should not ruin the groundwater. Long-term salt build-up in groundwater will occur 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 can damage buildings, pipelines, landfills, cemeteries, parks, landscaping, etc. The salty water removed from the underground environment must be properly managed to avoid problems. Solutions include disposal into evaporation lakes, membrane filtration for water reuse, and disposal of the salty groundwater and reject brines in the ocean. The latter option is feasible only for areas not too far from a coast.

APPROACH: Technologies based on previous research at the U. S. Water Conservation Laboratory (USWCL) and more recent other 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. Ten soil columns in 8 ft x 1 ft stainless steel pipes have been set up in a laboratory greenhouse at the USWCL to study movement of pathogens and chemicals (including trace organics) in systems involving irrigation with sewage effluent, artificial recharge with sewage effluent, and recharge and irrigation with Colorado River water. The columns were filled with a sandy loam from the McMicken Flood Control reservoir northwest of the City of Surprise. This is a desert soil in the Mohall-Laveen Association that has had no agricultural use. The hydraulic conductivity of the soil was determined with a laboratory permeameter test as 28 cm/day, using a disturbed sample. To avoid particle segregation, the soil was placed in the columns in air-dry condition, lowering it in a container and tipping the container when it rested on the bottom of the pipe and then on the top of the soil as the column was filled. The new soil was then compacted with a rod.

Arrangements were made with the Central Arizona Water Conservation District to obtain Colorado River water from the Central Arizona Project (CAP) Aqueduct at a point where the canal has 100% Colorado River water. The CAP water was applied in a recharge mode to one column, starting February 10, 2000.

The sewage effluent to be used in the column studies should be representative of typical treatment for irrigation. As a minimum, the effluent should have had primary and secondary treatment followed by chlorination. Coagulation and granular medium filtration before chlorination removes essentially all microorganisms and makes this so-called tertiary effluent essentially pathogen free and, hence, suitable for unrestricted irrigation. This includes irrigation of lettuce and other crops consumed raw or brought raw into the kitchen, and of parks, playgrounds, golf courses and residential yards. Also, the effluent should primarily be of residential origin with not much industrial input. Proposed irrigation and recharge studies of the 10 columns are shown in Table 1.

Since the U.S. Water Conservation Laboratory does not have analytical capability for the detection of trace amounts of synthetic organics such as pharmaceuticals and other pharmaceutically active chemicals contributed to the effluent by human and industrial waste, samples of sewage effluent were sent to the laboratory of the Civil and Environmental Engineering Department at the University of California at Berkeley, California, where Dr. David L. Sedlak has an active research program on pharmaceuticals in sewage effluent. The first sample was taken from the Goodyear treatment plant because the effluent there was also used for landscape irrigation and artificial recharge of groundwater. The treatment train consisted of primary and secondary treatment, nitrification-denitrification, filtration, and UV disinfection. The sample was taken in mid-August in the late morning when the sewage flow was still relatively small. The results showed very low concentrations of pharmaceuticals, about an order of magnitude less than what is found in San Francisco Bay area sewage effluents, and close to detection limits, which are normally in the 5-10 ng/L range. A better effluent for the column studies may be from the Tolleson sewage treatment plant, which also receives mostly residential sewage and gives only conventional primary and secondary treatment and chlorination. A sample has been sent to the University of California Berkeley for analysis of pharmaceuticals.

FINDINGS: Flooding of the Colorado River water recharge column was started on February 10, 2000, with a 2-week inundation period during which the infiltration rate dropped from 20 to 11 cm/day. The water depth in the column was maintained at 10 cm. When water was first applied to the dry-soil column, it took the wetting front two days to reach the bottom of the column and for outflow to commence. The accumulated infiltration at the time was 75.3 cm, so that the fillable porosity of the air-dry soil in the column was 0.33. This is 84% of the total porosity of the soil, which was calculated as 0.39 from volume and weight of the dry soil in the column. After the first flooding period, drying of the column caused further settlement of the soil. This reduced the length of the column by 11 cm, which decreased the porosity to 0.36. Further settling was not observed. Subsequent infiltration rates were taken as the outflow rates at the bottom of the column. The decline in infiltration rates during the first flooding period may be due to the advance of the wetting front in the column, at least during the first few days of the flooding period. The continued decline may be due to the formation of a clogging layer on the soil surface.

Table 1. Proposed schedule for irrigation and artificial recharge simulation with sewage effluent and Colorado River water for the 10 soil columns in the greenhouse.

Irrigation with Effluent		
COLUMN	**COVER**	**IRRIGATION EFFICIENCY**
1	grass	50%
2	grass	70%
3	grass	90%
4	alfalfa	50%
5	alfalfa	70%
6	alfalfa	90%
7	bare soil	70%[1]
Irrigation with Colorado River Water		
8	grass	70%
	Groundwater Recharge	**Water**
9	bare soil	effluent
10	bare soil	Colorado River water

During the first drying period, the surface soil shrank enough laterally to separate from the pipe, so that it was carefully packed against the pipe again. The second and third flooding periods, which were 21 and 30 days, respectively, showed infiltration rates of around 7 cm/day; but at the end of the third flooding period, an increasing trend developed which continued in the fourth flooding period until infiltration rates reached about 15 cm/day and leveled off at that value. The length of the fourth flooding period was 50 days. During all inundation periods, the Colorado River water above the soil column remained quite clear. A brown mat developed on the bottom, especially in the fourth flooding period, but apparently had no clogging effect. A sustainable infiltration rate of about 15 cm/day is typically achieved in infiltration recharge basins in desert or light agricultural soils. Considering the many factors that affect the relation between infiltration rates and time, the results of the column study did not come as a surprise. The total infiltration amount for the four flooding periods was 12.1 m. Samples of the inflow and outflow were taken for analysis of DOC (dissolved organic carbon) by the Environmental Engineering and Water Resources Department of Arizona State University.

[1] Since evaporation from bare soil will be less than evapotranspiration from a vegetated surface, the bare soil column will be irrigated to give the same volume of leachate as the grass column with 70% irrigation efficiency.

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. The column studies on underground fate and transport of pharmaceuticals and other organic compounds will shed more light on possible effects of both irrigation and artificial recharge on groundwater quality.

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: Dr. P. Fox, Dr. P. Westerhoff, and Dr. J. Drewes, Arizona State University, Department of Civil and Environmental Engineering and National Center for Renewable Water Supplies, Tempe AZ; Dr. R. Arnold and Dr. M. Conklin, The University of Arizona, Tucson AZ; Dr. David Sedlak, University of California, Berkeley CA; J. Swanson, The City of Surprise, Surprise AZ; Fort Huachuca AZ, United States Army Garrison through ASU, Tempe AZ; M. Milczarec of GeoSystems Inc., Tucson AZ; and the City of Tolleson AZ.

IRRIGATION CANAL AUTOMATION

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

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 may 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. Computer models of unsteady canal flow are very complex and expensive because they are 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.

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 are currently using a commercial SCADA package, FIX Dynamics from Intellution, Inc. Originally, standard MODBUS communication protocol was used to communicate between FIX Dynamics and Automata's Base Station, and the base station communicated with the field equipment using Automata's proprietary protocol. All communications in the system now use MODBUS. The USWCL canal control scheme logic (USWCL controller) is interfaced with FIX Dynamics. The research approach will be to use simulation models to test and further develop various control schemes for the proposed automation

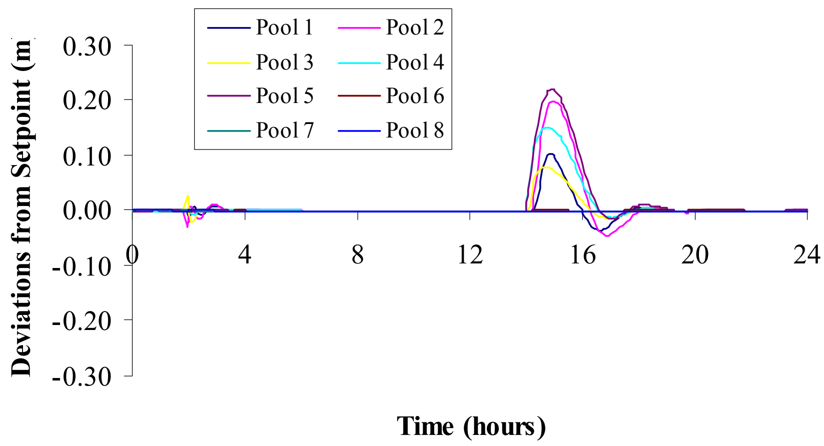


Figure 1. Setpoint deviations for a series of PI controllers on ASCE test case 1-1 (no gate constraints and tuned conditions).

system. The combined hardware and software automation system will be field tested on the WM lateral canal of the Maricopa Stanfield Irrigation and Drainage District (MSIDD).

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 the 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 family of controllers, including a series of simple local PI controllers. Selections of controllers to test on the WM canal are based on simulation tests of controller performance on the American Society 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.

<u>Simulation studies of downstream-water-level feedback controllers</u>: Last year a comprehensive set of simulation tests was performed on the ASCE test canal 1. The feedback controllers used ranged from a series of simple, local downstream PI controllers to a fully centralized downstream PI controller. These controllers were tuned using optimization techniques and the integrator-delay model. This year focus shifted slightly, and the tuning method was examined more

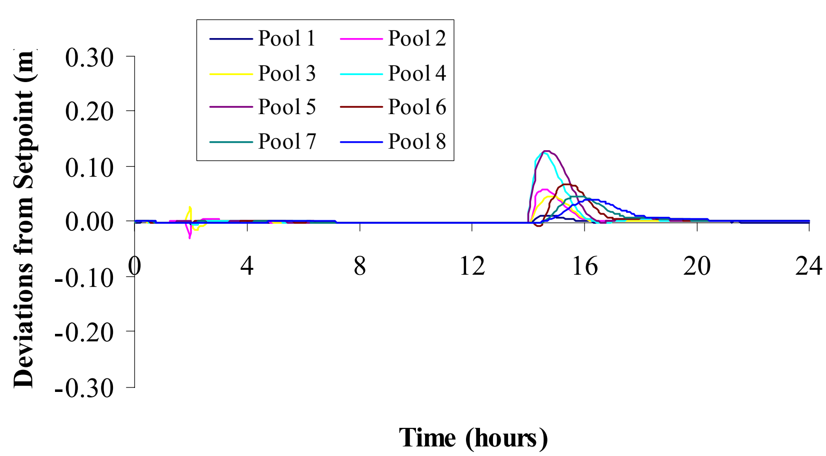


Figure 2. Setpoint deviations for the fully centralized PI controller on ASCE test case 1-1 (no gate constraints and tuned conditions).

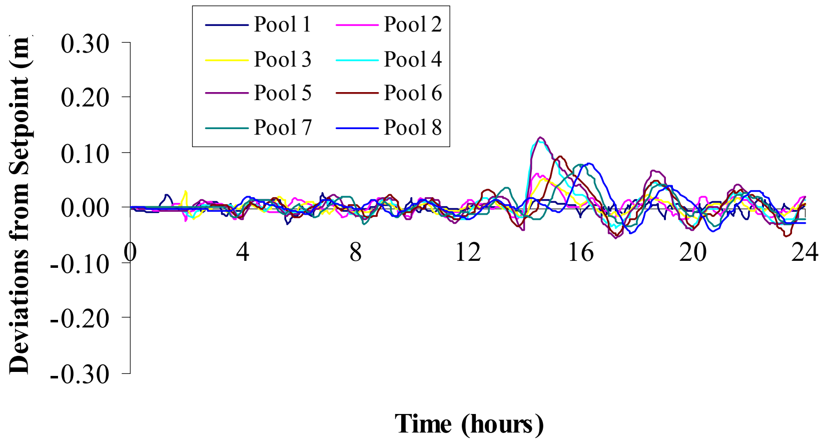


Figure 3. Setpoint deviations for the fully centralized PI controller on ASCE test case 1-1 (gate constraints and tuned conditions).

closely. Specifically, the weights used to penalize water level errors and control actions in the optimization routine were examined. In the initial simulation studies, some of the feedback controllers became unstable when they were run under untuned conditions. This poor performance arose because the controller was fairly aggressive and because of uncertainties in the wave travel time prediction. To avoid this problem, the controller was made less aggressive by increasing the penalty for control actions in the tuning process. Figure 1 shows the simulation results for a series of local PI controllers for the ASCE test case 1-1, while Figure 2 shows the results for the fully centralized PI controller. The minimum gate movement constraints introduced sustained low amplitude oscillations in the water levels (Fig. 3). Most of these optimal controllers were robust enough to handle the untuned conditions without much degradation in performance (Fig. 4).

Also, most of the simulation studies done to this point have been for downstream control of sloping canal systems that are not completely under
backwater. Initial work was done with Jan Schuurmans, Peter-Jules van Overloop, and Charles Burt to convert the downstream tuning procedure into an upstream tuning procedure. The initial work indicates that upstream and downstream control require quite different weighting factors on the control actions. In addition, work was also done on adding a high frequency filter to the tuning procedure to account for the resonance problems that may occur in pools that are completely under backwater. Schuurmans and van Overloop have written an initial optimal tuning method in MATLAB that will add a filter to a series of local PI controllers and allow the user to choose either upstream or downstream control. We are in the process of reviewing that code now, and no simulation tests have been performed yet.

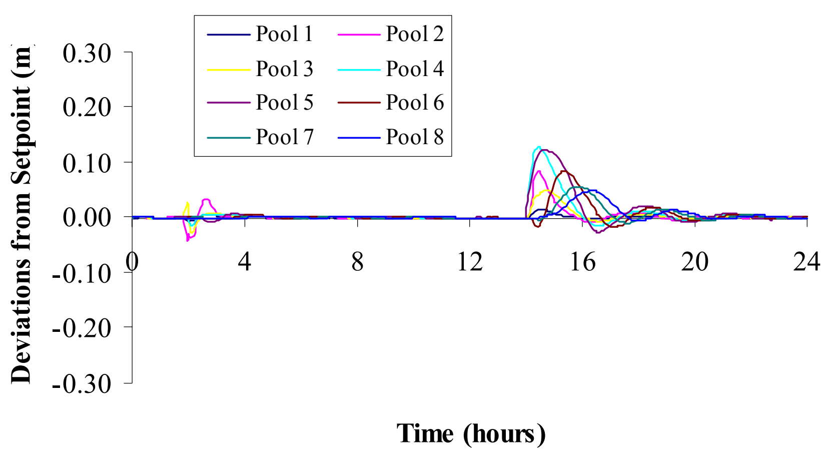


Figure 4. Setpoint deviations for the fully centralized PI controller on ASCE test canal 1-1 (no gate constraints and untuned conditions).

One of the drawbacks to the USWCL controller is that it is applicable only to a single inline canal system. In other words, it cannot be applied to branching canal networks. In reality, canal operators would desire to automate an entire canal network and not just a single branch of that network. Work was done on the USWCL controller to modify it to be able to handle branching canal networks. The method has been developed and it appears to give reasonable controller constants; however, no simulation test has been performed because CanalCAD cannot handle branching canal networks. To overcome this obstacle, the hydraulic simulation package SOBEK was obtained from Delft Hydraulics in the Netherlands. This Windows-based program is capable of handling branching canal networks and the USWCL controller can be programed into it.

MSIDD Field Hardware Modifications and Software Upgrades: As part of the CRADA with Automata, the control sites on the WM lateral were equipped with Automata's "Field Controller" (FC) Remote Terminal Unit (RTU). This unit uses Automata's proprietary communications protocol. To reduce the RTU firmware programming effort, a translator was used at the base station to translate standard MODBUS communications to Automata's protocol. The FC units have been replaced with a new 10-bit version of Automata's Mini RTU. This unit provides functionality similar to that of the FC unit and uses MODBUS as its native communications protocol. This eliminates the need for the intermediate translator. Originally, communication was over narrow-band FM radios. Interference from repeaters in the Phoenix and Casa Grande areas of Arizona have hampered the performance of the control system. To eliminate the interference problem, the FM system has been replaced with a 900 MHz spread-spectrum radio system.

The control software has been upgraded to improve user access to control actions proposed by the system. There are two modes of operation. In "Automatic" mode, control actions are sent automatically to the RTUs. In "Review" mode, the operator is given an opportunity to modify or delete the proposed control actions.

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: Additional simulation studies need to be performed using the controllers developed from Schuurmans and van Overloop's new tuning program. These simulations will include tests to determine the appropriate weighting on the control actions in the tuning program as well as test to determine if the high frequency filter works properly on pools that are completely under backwater. Also, the USWCL controller will be coded into SOBEK and simulation tests will be performed on branching canal networks.

COOPERATORS: Lenny Feuer, Automata, Inc., Nevada City CA; Gary Sloan, MSIDD, Stanfield AZ; Jan Schuurmans, University of Twente, The Netherlands; Peter-Jules van Overloop, van Overloop Consultancy, The Netherlands; Cliff Pugh, USBR, Denver; Charles Burt, California Polytechnic State University, San Luis Obispo CA; Bob Gooch, Salt River Project, Phoenix AZ; Victor Ruiz, IMTA, Cuernavaca, Mexico; Pierre-Olivier Malaterre, CEMAGREF, Montpellier, France.

CANAL AUTOMATION PILOT PROJECT FOR SALT RIVER PROJECT'S 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 and 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 by 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.

As indicated in the 1999 Annual Report (Bautista et al., 2000), SRP has been upgrading their Supervisory Control and Data Acquisition System (SCADA) and their computer systems. Consequently, many aspects of the automation project have been delayed until the upgrade is complete. There are other items on which we have been able to continue our research and development efforts.

(1) A computer program has been under development to carry out the feedforward control calculations. Testing of the program is currently underway.

(2) A study was initiated in 1999 by Jan Tel of Delft University of Technology in cooperation with the USWCL and SRP. The objective of the study was to obtain a more accurate head-discharge relationship for SRP's radial gates. Simulation tests have previously demonstrated that performance of the control system will improve with improved gate flow predictions. These predictions are currently very uncertain, with likely errors of 10% under free-flow conditions and 30% under submerged flow conditions. Even if SRP ultimately does not adopt the proposed automation system, improving gate discharge predictions will improve their canal flow control capabilities.

(3) Prior to field testing, we will need to conduct extensive simulation tests with the automatic control system. The control algorithms were coded into the unsteady flow simulation software Mike 11 during Phase I of this project. That code was developed to handle a specific segment of SRP's delivery system and does not provide the flexibility needed to conduct control tests with the entire Arizona Canal or with other canal systems. Thus, the control algorithms in Mike 11 have been under further development.

FINDINGS: (1) A working version of the canal scheduling program is currently being tested by our cooperators in SRP. The program utilizes water order information compiled through SRP's water accounting database, WTAP. Extensive programming has been required to ensure that WTAP data is properly retrieved and the integrity of all input data is preserved. Also, various elements of the interface have been modified to improve the program's user-friendliness.

Tests are being conducted to compare the program's output with SRP canal operations. These tests will help us assess the potential for implementation. SRP canal operations are complex. Operators receive next day's orders through WTAP and by phone. Based on these demands, they develop a schedule of flow changes. The scheduling process is based on experience. In addition to the known demands, operators take into account possible canal losses or gains (from canal infiltration, gate leaks, return flows, rainfall etc.) and trends in water levels. For example, if water levels are increasing throughout the canal (i.e., supplies exceed demands), they will service some demand increases without scheduling them in the expectation that those unscheduled changes will compensate the excess flow in the system and stabilize the water levels. Operators realize that flow predictions through their check structures is imprecise and, therefore, they do not attempt to develop very detailed schedules. Furthermore, they seek to minimize the number of scheduled changes, which they perform manually through the SCADA system.

In addition to the scheduled changes, operators often try to respond to same-day requests for flow cuts or increases (so-called red changes because they are not scheduled). Operators try to satisfy these red changes by finding an increase or cut of similar magnitude to counteract the requested change. Also, they may observe increasing or decreasing trends in pool levels and try to use the requested change to balance the flow. In other cases, if pump capacity is available, the operators will try to respond by turning pumps on or off. Still, in other cases operators will borrow from pool storage to accommodate these short-notice demands. In addition to red changes, canal flows are subject to other unanticipated conditions, such as partial or total shutdown in water treatment plant operations, flushing of water treatment plant filters, unexpected opening of turnouts, storm runoff, etc., all of which impact flows and levels. Clearly, there is a lot of guesswork involved in the operation of the canal. Because of all of this uncertainty, the schedule developed during the previous day is used only as a guide and may depart substantially from actual operations.

Testing of the scheduling program will be conducted in three stages. During the present initial stage, we are comparing the program's output with the planned schedules and the actual system flows. These tests will be conducted over several weeks to identify conditions that are not being accounted for by the scheduling program. These tests will also help us determine the extent to which operators' schedules depart from actual daily flows. We expect the program output to bear some similarities to both the operator-computed schedules and the patterns of daily flows. If this assumption proves true, then these tests should also help us convince the operators to test the program-generated schedules as their daily operating plan. The second testing phase will consist, therefore, of manual implementation of the program output. After SRP completes its SCADA upgrade, we will request SRP's approval to implement flow control on their check structures and to automate the execution of the computed schedules. Thus, the last testing phase will consist of automatic control in real time.

Figure 1 is an example of scheduled and actual discharges at the head of the Arizona-Grand Canal system based on data collected for October 13, 2000. Because of water travel time, flow rate changes for a given day need to be initiated the day before. The program and operator schedules are quite similar except for the initial flow condition used by the operators and the magnitude of a major flow cut occurring at midnight. The actual flow through the headgate is less than the scheduled values, and it appears that throughout the day operators were trying to catch up with the requested system flow. These discrepancies are thought to be related to the fact that data were collected following a period of intense rainfall and runoff into the canal. According to the operators, there was excess volume of water in the system that they were trying to eliminate. Water level data for the illustrated test period have not been analyzed to verify this statement.

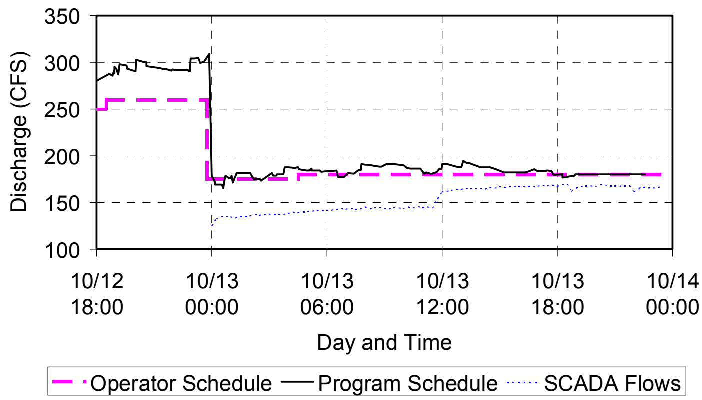


Figure 1. Scheduled and actual flows at the head of the Arizona Canal for schedule date 10/13/2000.

(2) Results of the SRP radial gate study were partly inconclusive (Tel, 2000). The analysis under free-flow conditions produced a relationship for the contraction coefficient that fits data from this and previous studies as well or better than a commonly used relationship proposed by Henderson (1966). These results are illustrated in Figure 2. The analysis also concludes that small energy losses occur under free flow. An energy loss coefficient is proposed for discharge calculations but an approach for computing the value of that loss coefficient is not

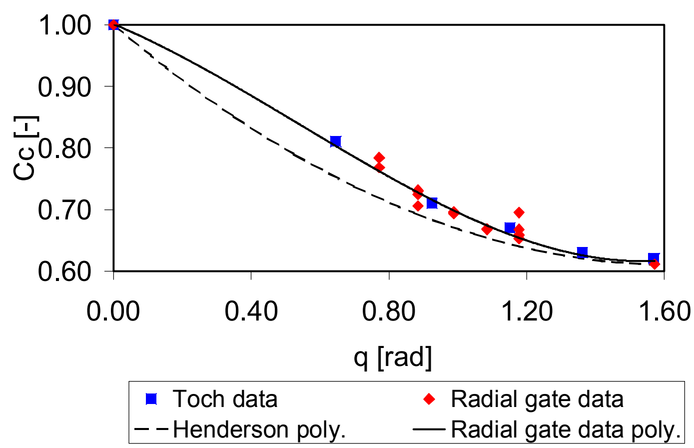


Figure 2. Contraction coefficient for radial gates under free flow conditions; experimental data and best fit polynomials.

provided. From the submerged flow analysis it was concluded that important flow parameters could not be measured with sufficient accuracy. Thus, the study did not suggest ways of improving the accuracy of the radial gate head-discharge relationship under submerged flow conditions.

(3) Development of the Mike 11 automatic control code continued intermittently during 2000 and is expected to be completed early in 2001.

INTERPRETATION: Initial testing of the scheduling program suggests that there is some uncertainty in the available data and that operators rely on experience to compensate for this uncertainty. Despite this, results suggest that the computed schedule can assist operators in developing their daily operational plans.

FUTURE PLANS: A report is under preparation summarizing the Phase II activities and accomplishments. At this time and because of the delays with SRP's SCADA system upgrades, the future of Phase III, testing in real time, seems uncertain. SRP operators remain interested in testing the feedforward control program and so we expect to begin manual implementation of schedules in 2001. At the same time, operators have manifested skepticism of the feedback control component and, thus, there is less enthusiasm to test that part of the control system. We plan at least to conclude the control system simulation tests.

COOPERATORS: Robert Brouwer and Jan Tel, Delft University 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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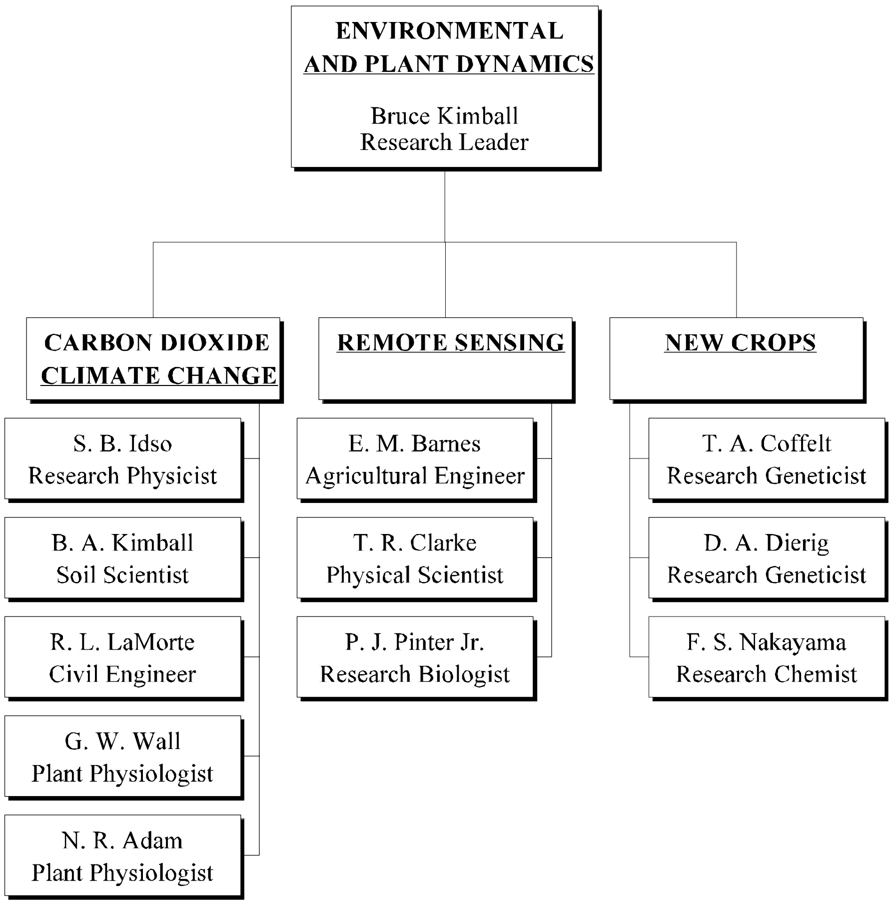
E&PD Management Unit

E&PD Organization



Mission

The Environmental and Plant Dynamics Research Group 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 which 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.

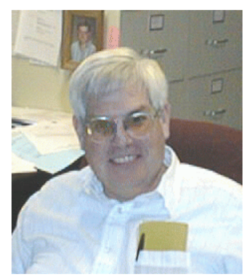
E&PD RESEARCH STAFF

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.

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 and by-product uses 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
Applications of remote sensing technology to management of agricultural resources and research in plant sciences; effects of elevated CO_2 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, Supervisory Soil Scientist; P.J. Pinter, Jr., Research Biologist;
G.W. Wall and N.R. Adam, Plant Physiologists; R.L. LaMorte, Civil Engineer;
M.M. Conley, Physical Science Technician; J. M. Triggs and T.J. Brooks, Research Technician

PROBLEM: The CO_2 concentration of the atmosphere is increasing and is expected to double sometime during this 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 three experiments were conducted on cotton from 1989-1991(Hendrey, 1993; Dugas and Pinter, 1994). Then, from December 1992 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. Another two FACE wheat experiments were conducted on wheat from December 1995 through May 1997 at ample and limiting supplies of soil nitrogen. Over 50 papers have been published (e.g., Kimball et al., 1995, 1999; Pinter et al., 1996) or are in press from these wheat experiments, and more are being prepared.

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 USWCL and one to The University of Arizona) from the NASA/NSF/DOE/USDA/EPA (TECO III) Program, we conducted two more FACE experiments on sorghum during the summer-fall growing seasons of 1998 and 1999. Our hypothesis was that there would be only a small enhancement of growth due to the FACE treatment when the plants have ample water; but under water-stressed conditions, there would be a substantial growth enhancement resulting from the water conservation due to the partial stomatal closure.

Similar to the previous FACE experiments, measurements with the sorghum included leaf area, plant height, above-ground biomass, morphological development, canopy temperature, reflectance, chlorophyll, light-use efficiency, energy balance, evapotranspiration, soil and plant elemental analyses, soil water content, photosynthesis, stomatal conductance, 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: Grain samples from the final FACE wheat harvests were subjected to a battery of nutritional and bread-making quality tests, as described in more detail by Kimball et al. (2001). The water stress treatment improved quality slightly with grain protein concentrations increasing relatively about 2% and bread loaf volumes about 3%. In contrast, a low soil nitrogen supply decreased quality drastically with protein decreasing about 36% and loaf volume about 26%. At ample water, elevated CO_2 from FACE decreased quality somewhat with protein decreasing 5% (relatively) in the irrigation experiments; but in the nitrogen experiments at ample N (which had a higher level of nitrogen than in the irrigation experiments), there was no effect of CO_2 on grain quality. Loaf volume was similarly decreased 2% by elevated CO_2 in the irrigation experiments and not affected at high nitrogen in the nitrogen experiments. Elevated CO_2 tended to make the deleterious effects of low nitrogen worse, with for example, protein decreasing 33% at ambient CO_2 and 39% under FACE. Loaf volume similarly decreased 22% at ambient and 29% under FACE.

As reported in more detail by Ottman et al. (2001), stover yield from the FACE sorghum experiments responded slightly to CO_2; and over the two seasons and over the Wet (ample) and Dry (water stress) irrigation treatments, it averaged 848 g m^{-2} for the control and 928 g m^{-2} for FACE (+9 %). In the Dry plots, grain yield increased due to elevated CO_2 from 472 to 553 g m^{-2} (+17%) in 1998 and 106 to 142 g m^{-2} (+34%) in 1999. In the Wet plots, however, grain yield was not influenced by elevated CO_2 in 1998, but decreased due to elevated CO_2 from 476 to 424 g m^{-2} in 1999 (-12%). Sorghum phenological development was not affected in a consistent manner by elevated CO_2. Elevated CO_2 had the general effect of slowing growth in the Dry plots and accelerating growth in the Wet plots during the vegetative stages, but causing the reverse after anthesis during grain fill. Leaf senescence was accelerated in the Wet plots and may have been partially responsible for the lack of grain yield response to CO_2 with ample water. In water-stressed sorghum, stomatal closure due to elevated CO_2 had a negative effect on growth early and only later in the growth cycle were the positive benefits of soil water conservation realized.

INTERPRETATION: The FACE wheat grain quality data suggest that future elevated CO_2 concentrations will exacerbate the deleterious effects of low soil nitrogen on grain quality; but with ample fertilizer nitrogen, the effects will be minor.

The FACE sorghum data suggest that under conditions with ample water, the higher future atmospheric CO_2 concentrations may cause a slight decrease in sorghum yield due to an accelerated grain-filling period. On the other hand, 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 more.

FUTURE PLANS: Analyses and reporting of the results from the FACE wheat and especially from the sorghum experiments will continue. Consensus from the participating investigators is that a FACE alfalfa experiment should be conducted next. Specific reasons to focus attention on alfalfa as an experimental crop are as follows: (1) Being deep-rooted, alfalfa could potentially sequester carbon at greater depths below the plow layer where the carbon may be stored for much longer periods than is possible with many other plants. (2) Because alfalfa is a perennial crop that grows the year around with about 8 cuttings per year in our climate, growth observations can be obtained over a very wide range of temperatures and, therefore, the interaction between elevated CO_2 and temperature can be studied. (3) Because alfalfa is a legume, the effects of elevated CO_2 on nitrogen fixation can be examined as can the importance of nitrogen for C sequestration. (4) Alfalfa is an important crop in the U.S. (4th in acreage behind wheat, corn, and soybeans), and it grows well in Arizona. Unfortunately, funding is not currently available to conduct such an experiment; a proposal has been submitted NASA to obtain such funding.

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FREE-AIR CARBON DIOXIDE ENRICHMENT (FACE): EFFECTS ON SORGHUM EVAPOTRANSPIRATION IN WELL-WATERED AND WATER-STRESSED IRRIGATION TREATMENTS

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PROBLEM: The 1996 Intergovernmental Panel on Climate Change (IPCC) projects that, if 1994 CO_2 emission levels are sustained, the global atmospheric CO_2 concentration will reach 500 μmol mol^{-1} by the year 2100. Such an increase in CO_2 concentration is likely to decrease plant evapotranspiration (ET) and increase plant water-use efficiency (WUE).

APPROACH: Eight 490 m^2 rings were subjected to two levels of CO_2 (F = FACE, C = Control) and two levels of soil water supply (W = Wet, D = Dry) as described in detail by Ottman et. al. (2001).

<u>Soil water content measurements</u>: Volumetric soil moisture content was determined with the neutron probe (Hydroprobe Model 503 DR, Campbell Pacific Co., Martinez CA). The calibration equation used was: $\theta = 0.015 + 0.156 * (\text{count / standard count})$ where θ = volumetric soil water content (θ: m^3 H_2O / m^3 soil). Measurements were taken at 0.3 m intervals to either 1.8 m or 3.0 m depths during the 1998 and 1999 seasons, respectively.

Active root depth was determined by estimating the expected water extraction front from 0-1.76 m (Robertson et al., 1993). ET was calculated only for the zone of soil containing active roots. ET was calculated during drying periods by using a soil water balance equation (Jensen et al., 1990).

FINDINGS: <u>Temporal changes in soil water content</u>: During 1998, volumetric soil water content measurements (Fig. 1a) showed two distinct dry-down periods for the Dry plots - the first from day of year (DOY) 228-254 and the second from DOY 275-330. We observed three dry-down periods in the Dry treatment during 1999: DOY 198-218, DOY 228-258, and DOY 268-290. During 1998, periods of plant stress in Dry treatments, as inferred from a 30% drop in soil moisture below field capacity, occurred during DOY 247-253 and DOY 290-325, whereas they occurred from DOY 202-218, DOY 244-258, and after DOY 280 until maturity during 1999 (Fig. 1b).

<u>Evapotranspiration</u>: During the first year (1998), major differences in cumulative ET between Wet and Dry treatments were apparent by DOY 273 (Fig. 2a). Aside from a divergence during DOY 260-290, when plants were undergoing reproductive growth, FD and CD treatments showed similar patterns in cumulative ET. However, significant differences between CO_2 treatments were evident in Wet plots beginning on DOY 260. FW plots evapotranspired 60 mm (±117 mm) or 11% less than CW over the entire growing season. Seasonal ET in the Dry treatment revealed FD evapotranspired 1 mm (±22 mm) or 0% less than CD. During 1999, differences in cumulative ET between Wet and Dry treatments began at DOY 220, becoming more pronounced after DOY 240 (Figure 2b). ET differences between CO_2 levels were evident within the Wet irrigation treatment from DOY 230 through the end of the season when FW had consumed 58 mm (±34 mm) or 9% less water than CW plants. Seasonal ET in the Dry treatment revealed FD evapotranspired 25 mm (±14 mm) or 6% less than CD.

Figure 1: Mean volumetric soil water contents (from 0.0 to 1.8 m depth) in the Control-Dry (CD), FACE-Dry (FD), Control-Wet (CW), and FACE-Wet (FW) plots for the 1998 (1) and 1999 (b) sorghum growing seasons. Bars denote standard errors. Each mean is the average of four replicates. A indicates when only Wet plots were irrigated. B indicates when both Wet and Dry plots were irrigated. NS, *, **, *** = Not significant at P > 0.25 and significant at P < 0.25, 0.15, 0.05, respectively.

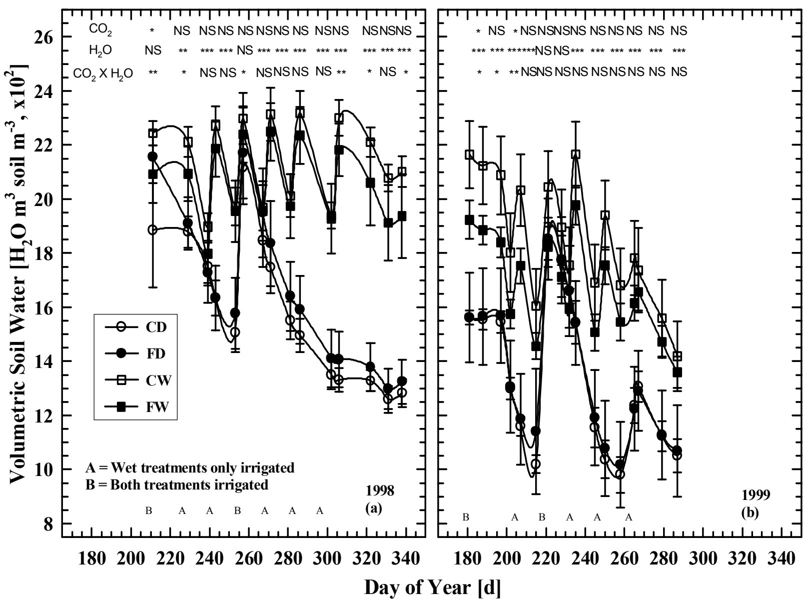
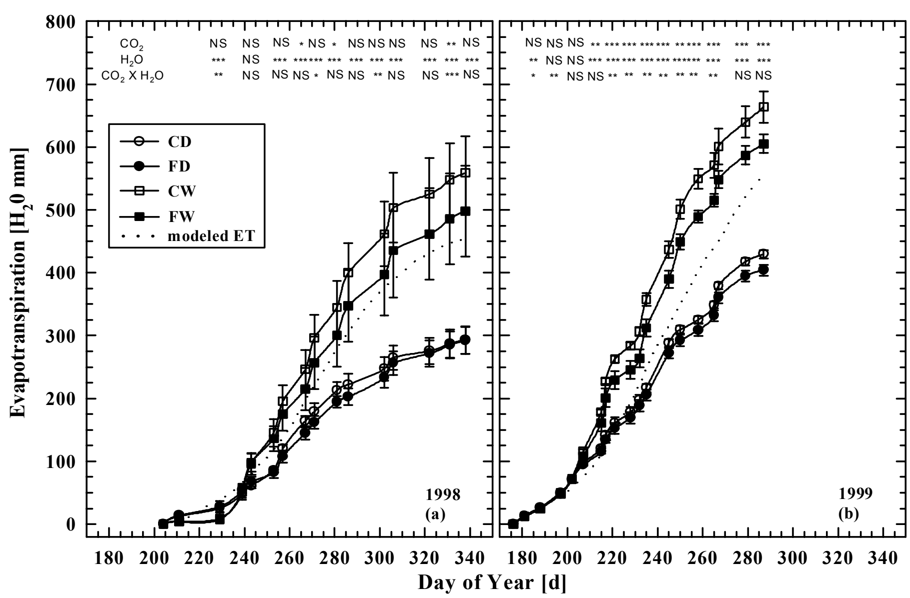


Figure 2: Mean cumulative evapotranspiration (ET) for the Control-Dry (CD), FACE-Dry (FD), Control-Wet (CW), and FACE0-Wet (FW) plots in 1998 (a) and 1999 (b) sorghum growing seasons. Bars denote standard errors. Each mean is the average of four replications. The dotted line represents modeled ET from the Arizona Meteorological Network AZMET (Brown, 1987) adjusted for sorghum. NS, *, **, *** = Not significant at P > 0.25 and significant at P < 0.25, 0.15, 0.05, respectively.



Water-use Efficiency: Grain yield and total above-ground biomass were measured in 1998 and 1999 by Ottman *et al.* (2001). Water-use efficiency based on grain yield (WUE-G) was calculated as the ratio of grain yield per square meter, per mm of ET (Table 1). Water-use efficiency based on total biomass (WUE-B) was calculated as the ratio of biomass per square meter, per mm of ET (Table 2). Based on the two year average, the WUE-G for FD was 0.18 (±0.21) $g/m^2/mm$ or 19% greater than CD, and FW was 0.08 (±0.1) $g/m^2/mm$ or 9% greater than CW; WUE-B for FD was 0.5 (±0.49) $g/m^2/mm$ or 17% greater than CD, and FW was 0.42 (±0.33) $g/m^2/mm$ or 16% greater than FW. This suggests an increasing WUE due to CO_2 enrichment with increasing water stress. Additionally, CO_2 enrichment caused a larger relative increase in grain yield than in total biomass. Such yield increases in grain and total biomass are likely without additional use of water resources at higher than ambient CO_2 concentrations.

Table 1: Sorghum grain yield (Ottman et al. 2001), ET, WUE-G, and the percent difference in WUE-G based on yield and due to FACE enrichment.

	1998			FACE	1999			FACE
	Yield (g/m^2)	ET (mm)	WUE-G ($g/m^2/mm$)	WUE-G % diff.	Yield (g/m^2)	ET (mm)	WUE-G ($g/m^2/mm$)	WUE-G % diff.
FACE-Dry	553 (±30)	292 (±21)	1.93 (±0.24)	15% (±24%)	142 (±33)	404 (±9)	.36 (±.09)	45% (±26%)
Control-Dry	472 (±58)	293 (±22)	1.68 (±0.32)		106 (±18)	429 (±6)	.25 (±.04)	
FACE-Wet	677 (±22)	498 (±72)	1.43 (±0.24)	15% (±21%)	424 (±21)	605 (±15)	.70 (±.05)	-3% (±6%)
Control-Wet	670 (±11)	559 (±58)	1.24 (±0.15)		475 (±13)	664 (±25)	.72 (±.05)	

Table 2: Sorghum biomass (Ottman et al. 2001), ET, WUE-B, and the percent difference in WUE-B based on biomass and due to FACE enrichment.

	1998			FACE	1999			FACE
	Yield (g/m^2)	ET (mm)	WUE-B ($g/m^2/mm$)	WUE-B % diff.	Yield (g/m^2)	ET (mm)	WUE-B ($g/m^2/mm$)	WUE-B % diff.
FACE-Dry	1332 (±80)	292 (±21)	4.64 (±0.61)	12% (±17%)	970 (±69)	404 (±9)	2.41 (±0.22)	26% (±15%)
Control-Dry	1176 (±73)	293 (±22)	4.13 (±0.55)		822 (±58)	429 (±6)	1.91 (±0.16)	
FACE-Wet	1658 (±43)	498 (±72)	3.51 (±0.57)	22% (±23%)	1551 (±54)	605 (±15)	2.56 (±0.15)	8% (±3%)
Control-Wet	1554 (±5)	559 (±58)	2.87 (±0.30)		1566 (±17)	664 (±25)	2.37 (±0.11)	

Increased plant water stress due to increased water demand coupled with decreased total applied water can explain the large decrease in yield, biomass, and WUE in 1999 relative to 1998.

Elevated CO_2 increased WUE-G by 0.13 (±0.16) $g/m^2/mm$ or 14% and WUE-B by 0.46 (±0.41) $g/m^2/mm$ or 16%. CO_2 enrichment caused partial stomatal closure, reduced stomatal conductance, and decreased transpiration per unit of leaf area in both Wet and Dry plots (Wall et al., 2001). Sorghum did not exhibit an increased leaf area in Wet plots (Ottman et al., 2001) so there was conservation of water (Figure 2a,b). In the Dry plots, CO_2-enriched plants had reduced stomatal conductance (Wall et al., 2001), which conserved water and enabled them to grow further into a drying cycle. Cumulative evapotranspiration of FD and CD plants were similar (Figure 2a,b). FD plants grew more (Ottman et al., 2001) and had a greater WUE than CD plants. Therefore, we accept the hypothesis that elevated CO_2 will cause sorghum to decrease ET under wet conditions and to increase WUE under both wet and dry conditions.

INTERPERTATION: Our data show that future water requirements for irrigated sorghum should decrease slightly, provided global warming is minimal. Under rain-fed conditions, where sorghum is more likely to experience water stress, elevated CO_2 will likely cause a productivity increase in total biomass and specifically grain yield. Moreover, under ample-water and, especially, water-limited conditions, increases in CO_2 are likely to cause WUE to increase substantially.

FUTURE PLANS: We plan to run ANOVA analysis of theta by depth using SAS. We will make ET and WUE measurements on alfalfa (Kimball et al, this volume).

COOPERATORS: See Kimball et al. (this volume).

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

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PROBLEM: The CO_2 concentration of the atmosphere is increasing and is expected to double sometime during this 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 and speed were measured adjacent to each FACE ring, and CO_2 concentration was measured at the center of each. 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 semicircular 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, $\boldsymbol{R}_n$, soil surface heat flux, $\boldsymbol{G}_0$, and sensible heat flux, $\boldsymbol{H}$:

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

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.

The instruments were calibrated carefully before the start of the experiments and again between the experiments in early 1999. During 2000, final calibrations were performed, including some comparisons among instruments from various manufacturers to use as reference standards. Analysis of the data from the standards comparisons is completed, and now analysis of the field data themselves is progressing.

FINDINGS: The micrometeorological data have not yet been analyzed, and so no report of the effects of the FACE treatment on the energy-balance-determined **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 and ample nitrogen, the reduction in **ET** was 19.5% (Kimball et al., 1999).

The sorghum growth response to elevated CO_2 amounted to about +9% averaged over two seasons and over the Wet and Dry irrigation treatments (Ottman et al., 2001; Kimball et al., this volume); so, based on the growth and energy balance comparisons from the past cotton and wheat experiments, we hypothesize that there was a slight reduction in sorghum **ET**. However, another basis for this hypothesis is that such a slight reduction was deduced from an analysis of the soil water balance by Conley et al. (this volume). They found that **ET** was reduced about 11% in Wet plots due to the FACE treatment, as averaged over the two growing seasons; whereas in the Dry plots, it was increased an average 3%.

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

FUTURE PLANS: We plan to 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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RELATIONSHIPS OF A-CI PARAMETERS AND ENZYME ACTIVITIES IN SORGHUM EXPOSED TO FREE-AIR CO_2 ENRICHMENT (FACE)

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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 generally, how it will affect plant life. The Free Atmospheric CO_2 Enrichment (FACE) facility at The University of Arizona Maricopa Agricultural Center is helping to determine how plants respond and acclimate to long-term exposure to elevated levels of CO_2 in the field.

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) was measured at a range of intracellular CO_2 concentrations (Ci), which provided information on changes within the photosynthetic apparatus of spring wheat, a so-called C_3 plant. Adam *et al.* (1998) showed that in spring wheat, the slope of the A-Ci relationship at those low values of Ci could be used to assess the changes in the activity and content of Rubisco due to growth in increased levels of CO_2. The work with spring wheat also indicated that, in order to fully assess the response of crop plants to elevated CO_2, various growth stages and canopy, a profile must be measured.

Similar experiments were conducted in 1998 and 1999 on sorghum, a warm-season crop with a different carbon-trapping mechanism, therefore, called a C_4 plant. The carbon-trapping enzyme of sorghum is PEPCase which, unlike Rubisco, fixes only carbon. The product of the reaction catalyzed by PEPCase is then shuttled to Rubisco and into the Calvin cycle. The relationships between the A-Ci curves and metabolic processes of C_4 plants are not fully understood. One objective of these experiments was to investigate the effect of growth in elevated CO_2 on these C_4 pathway enzymes in sorghum, as well as on the A-Ci relationships.

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). Fifty percent emergence occurred July 30, 1998, and July 1, 1999. Following sowing, FACE apparatus was erected on site to enrich the CO_2 concentration of the ambient air (ca. 370 μmol mol^{-1} during daytime) by 200 μmol mol^{-1} above ambient. 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 4th and 5th leaf stages in 1998 and the 2nd through 5th leaf stages in 1999), gas exchange analyses were conducted on the uppermost fully-expanded leaf (referred to as the top leaf) and on the top minus one leaf. Thereafter, measurements were made on the top leaf and the top minus two leaf. Photosynthesis (A) rates were measured over a range of intercellular CO_2 (Ci) 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 were assayed from leaves collected from both years. Parameters estimated from the A-Ci curves were the initial slope, the bend (or inflection) of the curve, and the asymptote.

FINDINGS: The A-Ci curves in the early growth stages (i.e., 2nd and 3rd leaf stages) were found to resemble a C_3-type curve. However, as the plants reached the 4th and 5th leaf stage, the curves were more similar to a typical C_4 curve (Fig. 1a), in that the initial slope of the curve is steeper. We also found that the curves became more C_3-like as water stress became more severe (Fig. 1b) and became more C_4-like after irrigation (Fig. 1c). Step-wise regression showed that the enzyme activities measured explained 50% or less of the variation seen in the parameters of the A-Ci curves (Table 1) and that the initial activity of Rubisco was the enzyme parameter most closely related to all three portions of the curve.

INTERPRETATION: The initial activity of Rubisco was not expected to be related to all three portions of the curve. In addition, PEPCase was expected to be related to the initial slope of the curve. It is likely that factors other than enzyme activity are more important in determining the shape of the A-Ci curve and that the initial activity of Rubisco is responding to the factors that determine the shape of the curve. Although leaf samples from some of the measurement dates remain to be assayed, it appears that factors other than enzyme activity or concentration (for example, water status of the plant) will be more important in determining the response of sorghum plants to future climatic changes.

FUTURE PLANS: Biochemical assays will be conducted on both the remaining samples to determine whether these relationships change. In addition, further analysis of the effects of growth in CO_2 enrichment and water stress on these relationships will be conducted.

COOPERATORS: See Kimball et al., this volume. However, we especially wish to acknowledge the collaborative efforts of Andrew Webber of Arizona State University for helpful advice and the use of his laboratory. We also thank Jonathan Triggs and Jose Olivieri for technical assistance.

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Figure 1. Response of Photosynthesis (A) to Changes in Intercellular CO_2 concentration for the uppermost, fully-expanded leaf of sorghum in (a) pre-water stress conditions, (b) pre-irrigation and (c) post-irrigation conditions.

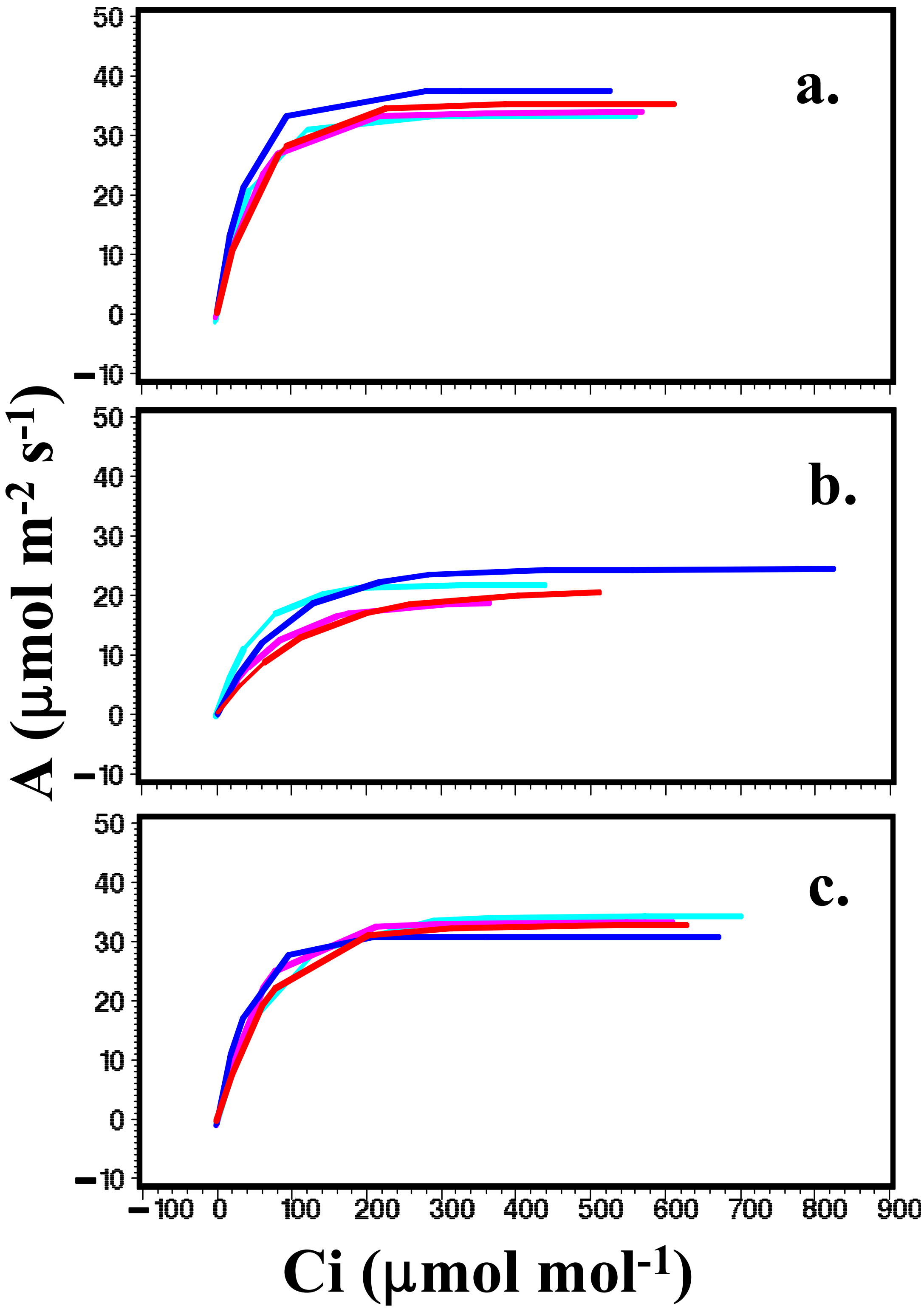

Table 1. Results of step-wise regression analysis of A-Ci curve parameters (Initial slope, Bend, and asymptote) with enzyme activities (Rubisco initial activity, Rubisco full activity, PEPCase optimal activity, PEPCase physiological activity, and PpdK activity).

Parameter	Variable	Model R-Square	Pr > F
Initial Slope	Rubisco Initial Activity	0.5137	< 0.0001
	Rubisco Full Activity	0.5453	0.077
'Bend' of Curve	Rubisco Initial Activity	0.3656	< 0.0001
	PpdK Activity	0.4337	0.0216
	Rubisco Full Activity	0.4779	0.0544
Asymptote	Rubisco Initial Activity	0.3182	< 0.0001
	PpdK Activity	0.4153	0.0075

Effects of Elevated CO_2 and Water and Nitrogen Stress on Phenology of Spring Wheat

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PROBLEM: Terrestrial ecosystems will probably experience a significant increase in atmospheric CO_2 during this century. The potential effect of this change on important food and fiber crops has been the subject of extensive research by U.S. Water Conservation Laboratory (USWCL) scientists for more than a decade. In our research, we have been using Free-air Carbon dioxide Enrichment (FACE) to expose plants to supra-ambient levels of CO_2 because FACE minimizes the microenvironmental and climatic artifacts that are often associated with studies using open-top chambers or greenhouses. Various performance measurements have shown that the FACE facility provides very good temporal and spatial control of CO_2 concentrations and is a cost-effective means for large scale fumigation experiments.

Our strategies for CO_2 exposure and the sophistication of ambient CO_2 control plots have evolved over the years as FACE has been applied to different crops. Modifications have also been made as experimental objectives have changed and as more was learned about system behavior under different environmental conditions (Pinter *et al.*, 2000). When the focus of our FACE project shifted from cotton to spring wheat, a decision was made to enrich the plots on a 24h day^{-1} basis. Because of the extra costs involved, the control plots used during the first two years experimentation in wheat (1992-93 and 1993-94) had dummy plastic manifolds and standpipes but were not equipped with blowers. However, with the new 24h day^{-1} protocol, we began to suspect that the blowers used to introduce CO_2-rich air into the elevated CO_2 arrays was causing some slight additional microturbulence in the boundary layer above the canopy, especially during calm nights. Although subtle and difficult to measure with the mechanical cup anemometers in our micrometeorological instrumentation, the additional disturbance resulted in a slight increase in air and radiant canopy temperatures in the blower-equipped plots at night. We also suspected and later confirmed that the slightly higher temperatures were associated with differences in plant phenology and end-of-season senescence rates.

Wheat FACE experiments were carried out for another two years, through the 1995-96 and 1996-97 growing seasons. For these experiments, however, blowers were installed in the experimental control plots (hereafter called blower plots), and we did not observe differences between FACE and blower plots in nighttime air temperatures, canopy temperatures, plant phenology, or senescence. The objectives of this report are to clarify that CO_2 did not have a direct effect on wheat developmental rates and to discuss the overall stimulatory effect of CO_2 on final grain harvest from all four years of the experiment.

APPROACH: FACE field experiments were conducted at The University of Arizona Maricopa Agricultural Center (MAC). Spring wheat (*Triticum aestivum*, L. cv Yecora Rojo) was sown in mid-December, emerged on or about January 1, and was harvested near the end of May in each year. Irrigation was accomplished via subsurface drip tubing. A split, strip plot design incorporated two levels of CO_2 as the main treatment effect during all four years with levels consisting of ambient Control (~360 $\mu mol\ mol^{-1}$) and elevated FACE (a nominal 550 $\mu mol\ mol^{-1}$)

concentrations. The secondary treatment variable during the first two years (CO_2 by water experiments, 1992-93 and 1993-94) included two levels of irrigation: Wet (100% of consumptive requirements) or Dry (50% of Wet). The secondary treatment variable in the final two years (CO_2 by N experiments, 1995-96 and 1996-97) was applied nitrogen: High (~388 kg ha^{-1} yr^{-1}) and Low (~77 kg ha^{-1} yr^{-1}). More complete details on experimental design and treatment conditions may be found in Kimball *et al.* (1999), Hunsaker *et al.* (2000), and Pinter *et al.* (2000).

Plants were sampled at 7-10 day intervals using similar techniques all four years. Main stems were assigned growth stages according to the Zadoks scale of plant development. Dates when plants reached the midpoint of eight principal growth stages (tillering, stem elongation, booting, heading, anthesis, milk development, soft dough, and ripening) were computed via linear interpolation and then averaged for all replicates within a treatment combination. We computed the difference in chronological time required to reach a specific growth stage between plots with and without blowers (i.e., control minus FACE for 1992-93 and 1993-94) and also between plots having blowers but exposed to either ambient or elevated CO_2 levels (i.e., blower minus FACE for 1995-96 and 1996-97). Paired "t" tests were used to determine the statistical significance of these differences in phenology.

FINDINGS: Qualitative observations of plants growing in the field revealed relatively large differences in phenology (at heading, anthesis, and maturity) between control and FACE plots in the CO_2 by water experiments that were not evident when comparing blower and FACE plots in CO_2 by N experiments. Zadoks growth stage data from the periodic plant samples confirmed these observations. Development in plots with blowers was accelerated by 2 to 5 days compared to plots without blowers. The CO_2 treatment by itself appeared to have minimal effect on developmental rates. Paired "t" test comparisons showed the average differences in phenology between elevated CO_2 FACE plots and the ambient CO_2 control (without blowers) during 1992-93 and 1993-94 were relatively large and highly significant in both the Wet and Dry irrigation treatments (Table 1). The chronological differences in developmental rates between FACE and blower treatments during 1995-96 and 1996-97 were less than 0.5 days and only under deficit nitrogen conditions were the differences between CO_2 treatments statistically significant.

Table 1. Mean differences in the time required to reach each of 8 primary growth stages (tillering → ripening) between different Blower and CO_2 configurations used during the FACE Wheat experiments at Maricopa, AZ.

Comparison[†]	Is Blower Present ? ambient CO_2 treatment	elevated CO_2 treatment	*n*[‡]	mean time difference days ± 1 SE	value from paired *"t"* test
CO_2 by Water Experiment (1992-93 & 1993-94)					
CW minus FW	No	Yes	64	3.2 ± 0.33	9.80 ***
CD minus FD	No	Yes	64	2.3 ± 0.23	10.10 ***
CO_2 by Nitrogen Experiment (1995-96 & 1996-97)					
BH minus FH	Yes	Yes	57	0.4 ± 0.31	1.25 NS
BL minus FL	Yes	Yes	57	0.4 ± 0.18	2.20 *

*, *** Significant at the 0.05 or 0.001 probability levels, respectively.
[†] Treatment abbreviations: C, Control; B, Blower; F, FACE; W, Wet irrigation; D, Dry irrigation; H, High nitrogen; L, Low nitrogen.[‡] Refers to the total number of paired observations. Only 3 replicates were available for *t* test comparisons during most of the 1996-97 experiment.

INTERPRETATION: One of the unique findings of the 1992-93 and 1993-94 FACE experiments was the apparent accelerating effect of elevated CO_2 on plant development and rates of canopy senescence (as reported by Pinter et al., 1996; and photograph in Kimball et al., 1995). A reexamination of those data in light of the slight differences in temperature we now know to exist between the treatments and the new phenology results from the CO_2 by N experiments have led us to conclude that the blower effect was sufficient to explain most of the apparent developmental acceleration. The subtle, blower-related rise in nighttime temperatures had cumulative effects on long-term developmental processes of the wheat plant. We now believe that elevated CO_2 *per se* had very little effect on the rates of plant development in well-watered and amply-fertilized spring wheat.

What effect might the blowers have had on CO_2 enhancement of final grain yields? We had originally reported only a 10% increase in yield for wheat exposed to CO_2 at 550 µmol mol^{-1} and supplied with adequate water and nutrients, suggesting that plants in the Control treatment had additional opportunity to "catch up" with the sink-limited FACE plants (Pinter et al., 1996; and Kimball et al., 1995). We now believe that this 10% figure was probably an <u>underestimate</u> of the true CO_2 effect that might have been observed during the first 2 seasons had the controls been properly equipped with blowers and the grain filling duration of both CO_2 treatments been similar. In fact, during the 1995-96 and 1996-97 experiments, grain yields for adequately fertilized and well-watered wheat showed a 15% increase associated with a nominal +200 µmol mol^{-1} CO_2 elevation. This translates into a CO_2 enhancement (β) factor of ~28% for a doubling of atmospheric CO_2 concentrations, an increase which compares favorably with the 33% average for agricultural crops reported by Kimball (1983).

There is little argument that the FACE technique approaches natural conditions more closely than open-top chambers or other means of exposing plants to elevated CO_2. Important advantages include an unmodified light environment, unrestricted rooting volume, and large experimental areas. Despite our results showing that the blowers cause a slight modification of crop microclimate, the advantages of FACE over open-top chambers and greenhouses still outweigh disadvantages by a considerable margin. However, these findings emphasize the importance of equipping control plots in FACE facilities with blowers and point out a disadvantage to nighttime CO_2 enrichment in our region.

FUTURE PLANS: A manuscript dealing with interactive effects of elevated CO_2 and water or nitrogen stress on wheat plant growth and final yields is in preparation.

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LONG -TERM CO_2 ENRICHMENT OF SOUR ORANGE TREES: EFFECTS ON PRODUCTIVITY AND CARBON SEQUESTRATION

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PROBLEM: Many people believe the ongoing rise in the air's CO_2 content is the greatest problem ever to be faced by humanity based on the assumption that it could lead to catastrophic global warming via intensification of the planet's natural greenhouse effect. However, elevated concentrations of atmospheric CO_2 also provide many benefits, some of which tend to ameliorate the global warming problem. Earth's trees, for example, account for approximately two-thirds of the planet's photosynthesis, by which means they remove prodigious amounts of CO_2 from the air and sequester its carbon in their tissues and the soil beneath them, thereby slowing its rate of rise in the atmosphere. Consequently, we seek to determine the direct effects of atmospheric CO_2 enrichment on all aspects of the growth and development of trees concentrating on the long-term aspects of the phenomenon; for until someone conducts an experiment measured in *decades*, we will never know the ultimate impact of the ongoing rise in the air's CO_2 content 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 monthly values of total trunk plus branch volume on the basis of relationships developed specifically for our trees (Idso and Kimball, 1992). 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 minimal 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 the fruit, and calculating the total dry weight of fruit produced in each of the CO_2 treatments from previous determinations of fruit percent dry weight. Also 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 bimonthly assessments of leaf dry weight similar to those of Idso et al. (1993), we calculate the total dry weight of leaves produced 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 five years of the experiment, for example, the values of total aboveground biomass in the CO_2-enriched trees were 107, 90, 95, 116, and 89 kg/tree; while those for the ambient-treatment trees were 62, 51, 57, 61, and 55 kg/tree, producing a five-year-mean CO_2-enriched/ambient-treatment ratio of 1.74.

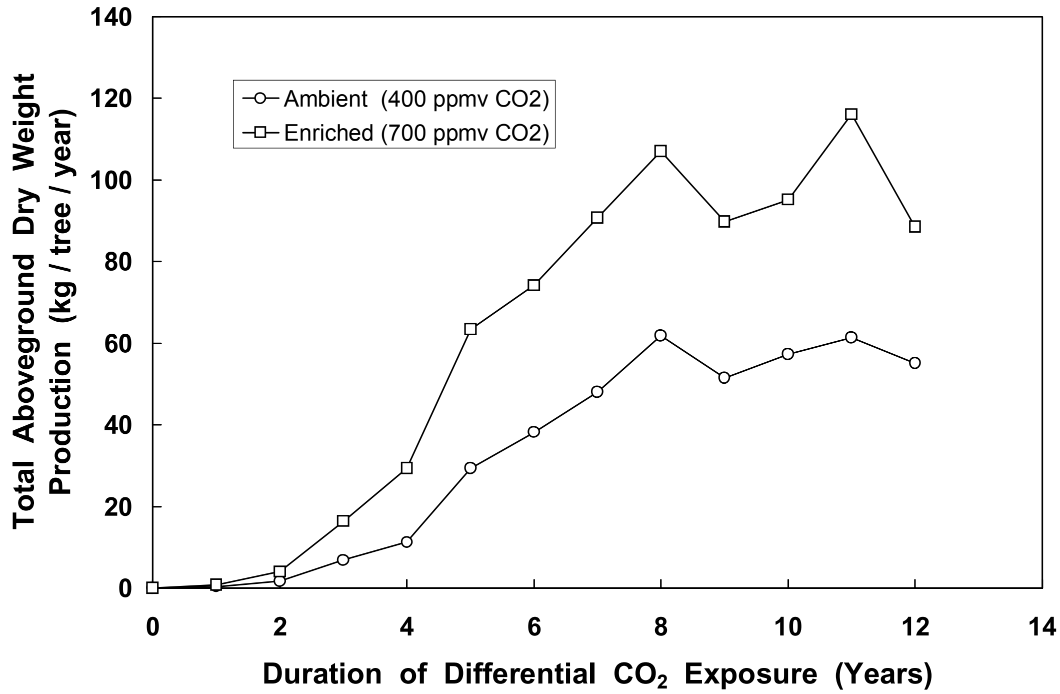

Figure 1. Yearly total aboveground biomass production in the ambient and CO_2-enriched sour orange trees as a function of time since the start of the experiment.

The fruit production component of the total aboveground productivity has been a little more erratic; nevertheless, it too appears to be approaching an asymptotic upper limit (Fig. 2). For the last five years, for example, harvested fruit biomass has been 47, 38, 38, 58, and 36 kg/tree in the CO_2-enriched trees; while in the ambient-treatment trees it has been 25, 13, 23, 31, and 22 kg/tree, producing a five-year-mean CO_2-enriched/ambient-treatment fruit production ratio of 1.87.

We have also 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 to four weeks later, the new branches of the CO_2-enriched trees may be four times more massive than those of the ambient-treatment trees. Furthermore, because there are more branches on the CO_2-enriched trees, they may have as much as six times more total new-branch biomass than the ambient-treatment trees. Shortly thereafter, however, 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 1.74.

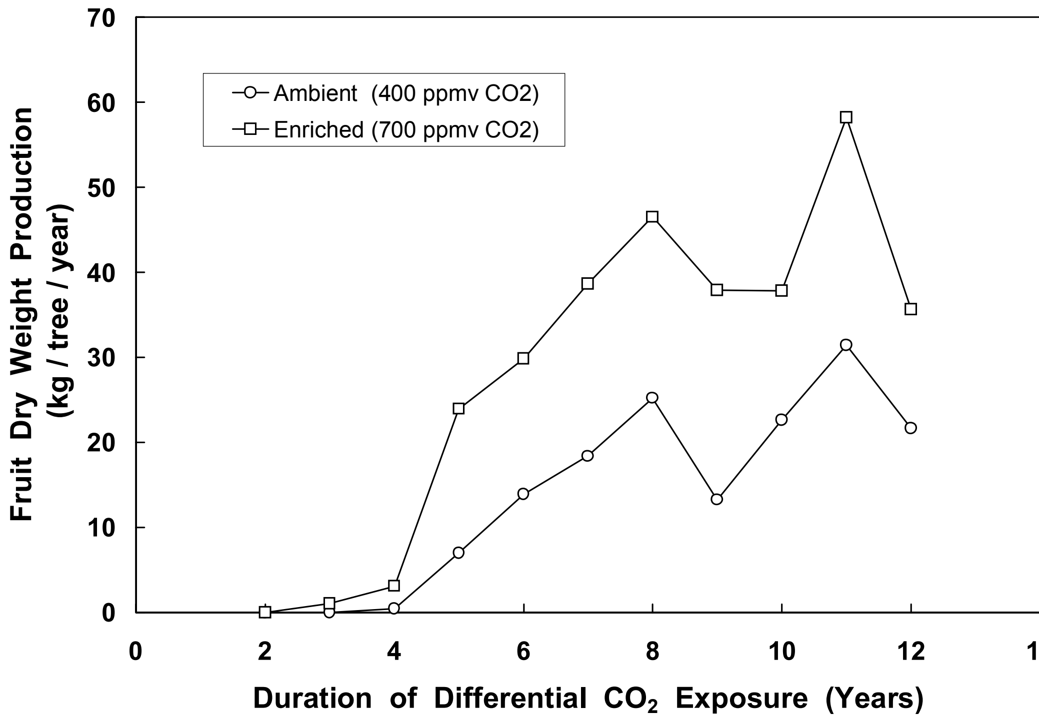

Figure 2. Yearly fruit dry weight production in the ambient and CO_2-enriched sour orange trees as a function of time since the start of the experiment.

INTERPRETATION: What is the ultimate fate of the CO_2 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? The results of our ongoing study provide important insight into these questions and may help our government 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 more of this aerial fertilizer than is normally in the air. It is also possible that this phenomenon may be partially responsible for the progressively earlier occurrence of the spring "green up" of the Northern Hemisphere's vegetation, which has been observed over the past few decades in satellite studies of surface reflectance and in the increasingly earlier occurrence of the spring draw-down of the air's CO_2 content that is evident in studies of the atmosphere's seasonal CO_2 cycle (Idso et al., 2000).

FUTURE PLANS: We plan to continue the sour orange tree experiment as long as it takes to determine if the trees truly achieve steady-state yearly growth rates and if the CO_2-enriched trees are maintaining a growth advantage over the ambient-treatment trees that can reasonably be expected to continue indefinitely. We are also continuing our investigation of the ultra-enhanced spring branch growth phenomenon that we have observed in the CO_2-enriched trees, having just completed three full years of pertinent measurements. In addition, we have initiated several new research thrusts related to the central problem of carbon sequestration. In cooperation with a soil microbiologist, we are investigating the role of atmospheric CO_2 enrichment in stimulating the growth of soil fungi that grow in symbiotic association with the sour orange tree roots and produce a glycoprotein called glomalin, which has been proven to enhance soil aggregation and the stability of soil aggregates. And in cooperation with several scientists who are expert in various types of tree-ring analyses, we are studying cores of the sour orange tree trunks for CO_2-induced differences in cell size, wood density and strength properties. We are also collecting some new data sets that should shed even more light on the effects of atmospheric CO_2 enrichment on the trees' physiology, including weekly assessments of leaf fall and leaf concentrations of chlorophyll, starch and various sugars. Finally, we are entering upon our tenth year of fruit vitamin C measurements and our fourth year of fruit folic acid measurements.

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ELEVATED ATMOSPHERIC CO_2 ALLEVIATES WATER-STRESS-INDUCED MID-AFTERNOON DEPRESSION IN WHEAT CARBON GAIN

G.W. Wall, Plant Physiologist; B.A. Kimball, Supervisory Soil Scientist; P. J. Pinter, Jr., Research Biologist; R.L. LaMorte, Civil Engineer; and S.B. Idso, Research Physicist

PROBLEM: Atmospheric CO_2 concentration is on the rise, which can affect stomatal conductance and water absorption processes in wheat (*Triticum aestivum* L.). Elevated CO_2 also affects internal plant water potential, and as is well known, it also affects photosynthesis. The degree to which each of these processes is affected will determine the overall productivity of wheat in the future. An imperative exists, therefore, to determine the effect that a future high CO_2 -world will have on dawn to dusk trends in stomatal conductance (g_s), total (Ψ_W), osmotic (Ψ_π), and turgor (Ψ_P) leaf potentials and net assimilation rate (A) of wheat grown under elevated CO_2 and adequate and limited soil-water content.

APPROACH: A 2-year field study on a hard red spring wheat (cv. Yecora Rojo) crop was conducted in an open field at The University of Arizona Maricopa Agricultural Center located 50 km south of Phoenix, Arizona. Seeds were sown into flat beds at 0.25-m row spacings on December 15, 1992, (130 plants m^{-2}) and December 7-8, 1993 (180 plants m^{-2}). The crops were harvested on May 25-27, 1993, and on June 1, 1994. Following sowing, a free-air CO_2 enrichment (FACE) apparatus was erected on site to enrich the CO_2 concentration of ambient air (~350 µmol mol^{-1}) to 550 µmol mol^{-1} treatment level (main plots) for 24 h per day from 50% emergence until physiological maturity. A subsurface drip-tape irrigation system provided two soil-water content (I) treatments; 50% (Dry) and 100% (Wet) replacement of potential evapotranspiration (split-plot). Treatments combinations, therefore, consisted of Control-Dry (CD), FACE-Dry (FD), Control-Wet (CW) and FACE-Wet (FW). There were four replications of each treatment combination.

A portable closed gas exchange system (0.25 L transparent cuvette) was used to make in situ measurements of g_s and A on uppermost fully expanded sunlit leaves from dawn to dusk. Leaves were excised approximately 5 mm away from the leaf collar to measure Ψ_W with a pressure chamber. Measurements of Ψ_W and Ψ_π were also made at midday with leaf thermocouple psychrometers using standard psychrometric techniques, whereas turgor pressure (Ψ_P) was derived ($\Psi_P=\Psi_W-\Psi_\pi$).

FINDINGS: FACE reduced g_s by 30% at mid-morning (2.5 h prior to solar noon), 34% at midday (solar noon), and 34% at mid-afternoon (2.5 h after solar noon) (Fig. 1). In Dry compared with Wet, FACE caused less of a proportionate reduction in g_s than Control by 2% at mid-morning and midday, but by 25% at mid-afternoon. Full irrigation increased g_s by 66% at mid-morning and midday and 79% at mid-afternoon. Overall, Ψ_W was less negative by 0.16 and 0.33 MPa at midday in FACE compared with Control, and Ψ_W was less negative by 0.25 and 0.59 MPa in Wet compared with Dry during mild (1993) and severe (1994) drought stress years, respectively. Osmotic adjustment ($\Delta\Psi_\pi$) was 0.73 [Ψ_π MPa (Ψ_W MPa)$^{-1}$] for Control and 0.81 [Ψ_π MPa (Ψ_W MPa)$^{-1}$] for FACE (*P*=0.20), whereas loss of turgor ($\Delta\Psi_P$) was 0.18 [Ψ_P MPa (Ψ_W MPa)$^{-1}$] for Control and 0.16 [Ψ_P MPa (Ψ_T MPa)$^{-1}$] for FACE (*P*=0.20).

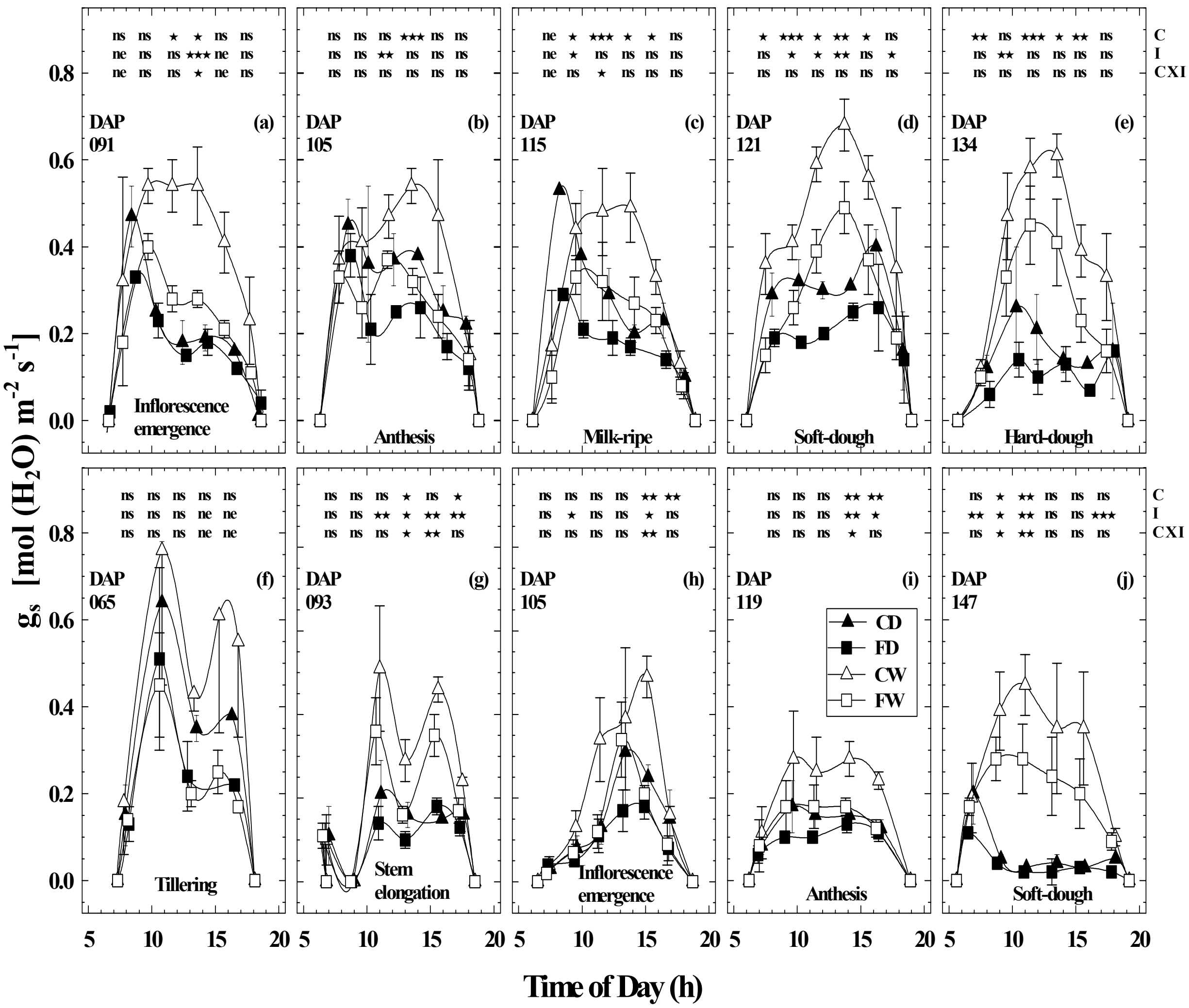

Figure 1. DAWN TO DUSK TRENDS IN STOMATAL CONDUCTANCE (G_S) OF FULLY EXPANDED SUNLIT SPRING WHEAT LEAVES FOR DAY AFTER PLANTING (DAP) AND GROWTH STAGES GIVEN FOR 5 D DURING 1993 (A-E) AND 1994 (F-J). SYMBOLS IN LEGEND REFER TO CONTROL-DRY (CD), CONTROL-WET (CW), FACE-DRY (FD), AND FACE-WET (FW) TREATMENTS. Each vertical bar is one standard error from each datum. Source of variance in ANOVA are carbon dioxide [(C): Control at 370 µmol mol^{-1}, and FACE at 550 µmol mol^{-1}], irrigation effect [(I): Dry at 50% and Wet at 100% replacement of evapotranspiration], and CxI interaction effects. Significance 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 (ne for effect not estimated), respectively. Actual probability of a greater F-value by chance reported if $P \geq 0.10$ and $P \leq 0.25$.

Compared with Control, FACE stimulated A by 32% at mid-morning, 25% at midday,and 23% at mid-afternoon (Fig. 2). The stimulation of A by FACE was greater by 7% at mid-morning and midday and 35% at mid-afternoon under Dry than Wet. Elevated CO_2, therefore, alleviated water-stress-induced mid-afternoon depressions in wheat carbon gain. Full irrigation increased A by 13, 29, and 28% at mid-morning, midday, and mid-afternoon, respectively.

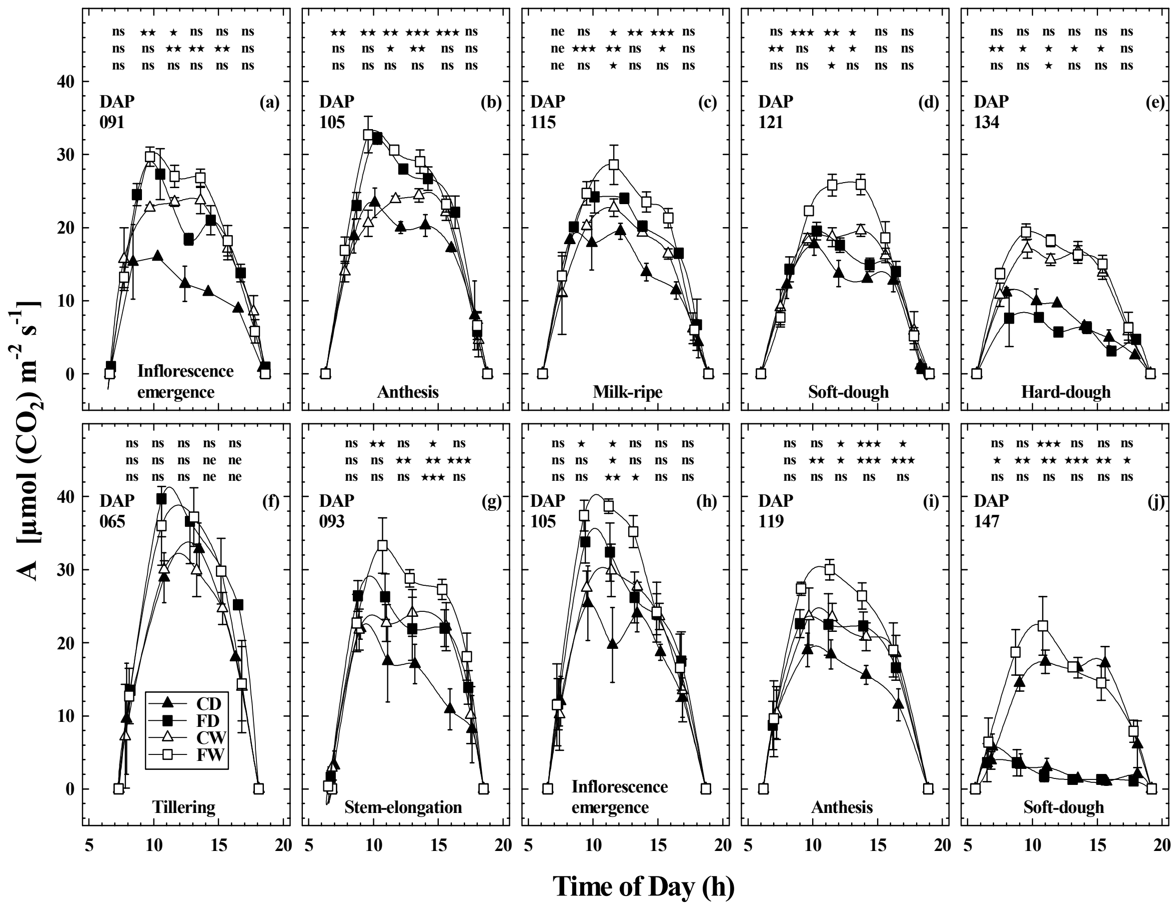

Figure 2. DAWN TO DUSK TRENDS IN LEAF NET ASSIMILATION RATE (A) OF EXPANDED SUNLIT SPRING WHEAT LEAVES FOR DAY AFTER PLANTING (DAP) AND GROWTH STAGES GIVEN FOR 5 D DURING 1993 (A-E) AND 1994 (F-J). SYMBOLS IN LEGEND SAME AS GIVEN IN FIG. 1. SOURCE OF VARIANCE AND RESULTS FROM ANOVA SAME AS DESCRIBED IN FIG. 1.

A hysteresis effect was observed when A vs. photosynthetic photon flux density (PPFD) was plotted from dawn until midday compared to that from midday to dusk (Fig. 3). This hysteresis effect became more pronounced as soil-water content became more depleted. Relationships between A vs. PPFD from dawn to midday and from midday to dusk were normalized (A_n) by dividing each observation of A within a day by the maximum value of A (A_{max}) for that day (usually at mid-morning or midday). Clearly, no hysteresis effect occurred under CW, a slight hysteresis effect was observed under FW, but only a modest increase in this effect was observed for FD. In contrast, a large hysteresis effect was observed for CD (Fig. 3). The smaller the hysteresis effect the greater was daily (A′) and seasonal accumulation (A″) of carbon. Compared with Control, FACE increased A′ and A″ by 25%. However, the stimulation in A″ by FACE over Control was 31% greater under Dry, but only 21% under Wet. This 10% difference in A″ between Dry and Wet can be explained by a proportionate reduction in the hysteresis effect observed for FD compared with CD.

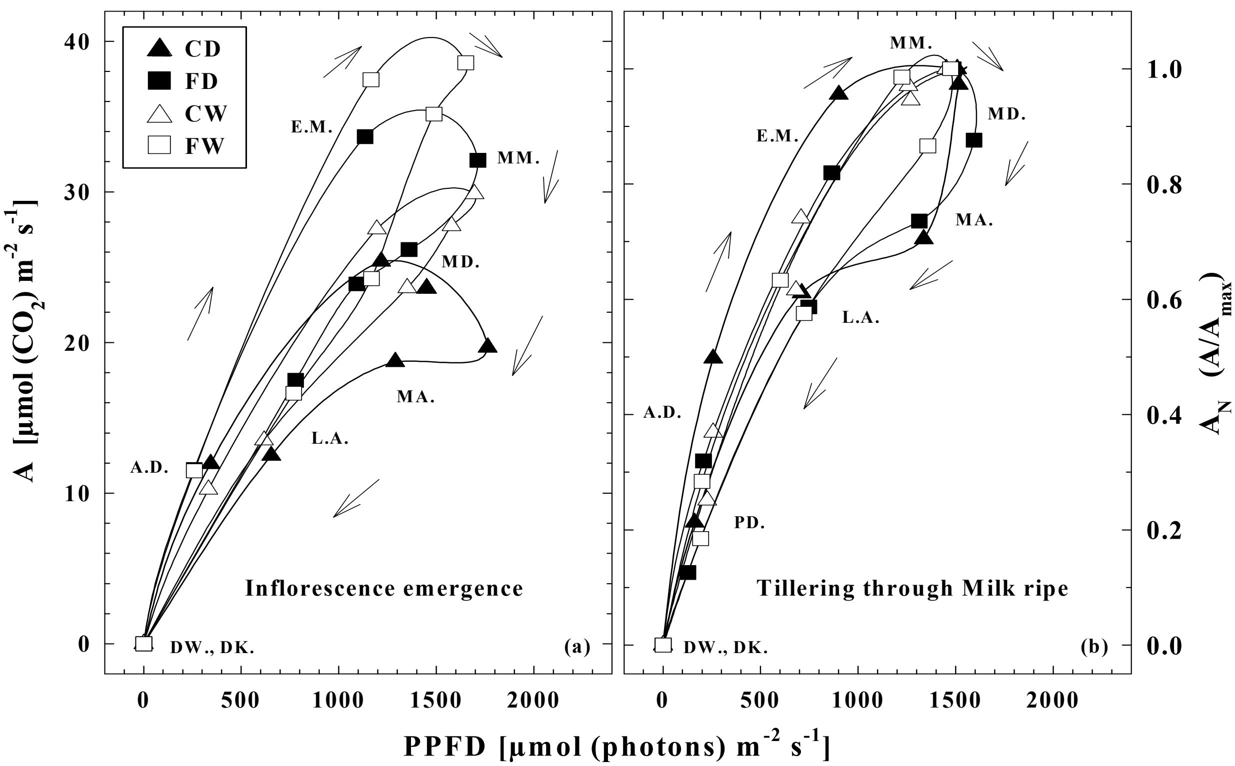

Figure 3: Mean leaf net assimilation rate (A) in response to diurnal course of incident photosynthetic photon flux density (PPFD) during inflorescence emergence on day after planting 105 (replotted from Fig. 2h) (a). Mean normalized leaf net assimilation rate (A_N), across years and growth stages except soft and hard-dough (replotted from Fig. 2a-d and f-i), in response to the diurnal course of incident photosynthetic PPFD (b). Arrows denote direction of hysteresis loop from DW-dawn, AD-after dawn, EM-early morning, MM-mid-morning, MD-midday, MA-mid-afternoon, LA-late-afternoon, PD-pre-dusk, and DK-dusk. Symbol legend same as given in Fig. 1.

INTERPRETATION: Despite the fact that elevated CO_2 directly reduced g_s (Fig. 1), it indirectly increased drought avoidance (reduced evapotranspiration and increased capacity for absorption of water and nutrients by roots), and increased drought tolerance (xeromorphic adaptations and osmoregulation mechanisms). Consequently, as water stress became more severe, the mitigating effect of elevated CO_2 in alleviating drought actually caused a reduction in water-stress-induced stomatal limitation in wheat carbon gain, particularly at mid-afternoon. Nevertheless, these results also demonstrate that although leaves grown under elevated CO_2 will have less stomatal limitations, regardless of water supply, they will still experience some mid-afternoon depression in carbon gain because of non-stomatal limitations (photoinhibition). In a future high-CO_2 world, therefore, additional carbon uptake at mid-afternoon will increase A' and A''. Presumably, this additional carbon supply will result in an increase in total non-structural carbohydrate pools. Hence, despite any limitations in net primary production because of water deficits, a rise in atmospheric CO_2 will minimize the deleterious effects of drought on physiological function and growth, thereby, expanding the range where a viable crop can be grown, especially under dryland conditions.

FUTURE PLANS: We will continue to analyze, interpret, summarize, and document results from previous FACE experiments on wheat and sorghum. We will also actively plan and seek funding for a FACE alfalfa (*Medicago sativa* L.) experiment (Kimball et al., this volume).

COOPERATORS: See report from Kimball et al., this volume.

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.

REMOTE SENSING CHLOROPHYLL CONTENT IN WHEAT

T. R. Clarke, Physical Scientist; and P. J. Pinter, Jr., Research Biologist

PROBLEM: One of the most important decisions a grower must make is how to manage crop fertilizer inputs in order to assure a profitable yield while preventing groundwater 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 wheat crop's fertilizer needs at critical growth stages and at high spatial resolution is needed for this aspect of precision agriculture to succeed.

A second challenge for precision agriculture is a lack of means by which wheat producers can predict grain protein content before harvest with a high degree of spatial resolution. This ability would provide the option of harvesting the highest quality grain separately with the potential of increasing profits.

APPROACH: A Canopy Chlorophyll Content Index (CCCI) that was previously developed for cotton (1999 Annual Report) was tested for wheat using reflectance data collected during the 1997 Free-Air Carbon-dioxide Enrichment (FACE) experiment. The hard red spring wheat *Triticum aestivum* L cv. Yecora Rojo was sown in mid-December 1996 and harvested in late May. Water and fertilizer were applied through a subsurface drip irrigation system. Each of the eight circular experimental plots was split into halves with each half receiving either an ample amount of nitrogen (N) of 383kg/ha/season or a limiting nitrogen treatment of 45 kg/ha/season. Kimball et al. (1999) provide a full description of the FACE experimental design. Hyperspectral canopy reflectance measurements were made at approximately weekly intervals using a field-portable reflectance spectrometer referenced to a $BaSO_4$ panel of known bidirectional reflectance properties. Spectral bands equivalent to those used in the cotton experiment were extracted and used for analysis. These three 10nm-wide bands were Red (R) centered at 670 nm, far-red (F) centered at 720 nm, and near infrared (NIR) centered at 790 nm. Chlorophyll meter (SPAD) measurements of the uppermost fully-expanded leaves were made at about weekly intervals and were used as an estimate of canopy chlorophyll content. Reflectances of the R, F, and NIR bands were combined to produce two variables. The first was the Ratio Vegetation Index (RVI), NIR/R, which is sensitive to the amount of green vegetation present, and the second was the ratio NIR/F, which is sensitive to the chlorophyll content of green vegetation. These two variables were then used as the two dimensions of a plane, and the maximum and minimum measured values for each variable defined the boundaries of a domain within this plane. The position of a coordinate pair within the domain was then correlated to the chlorophyll content as estimated by the SPAD readings.

FINDINGS: A scatter plot of the two variables revealed good separation between low and high N treatments during the early part of the growing season through early stem elongation, and again during early grain filling. During late stem elongation, head emergence, and flowering, there was a distinct drop in far-red reflectance which rendered the planar domain unusable during this period, as seen in Figure 1. Two planar domains were therefore delimited: one for early season through early stem elongation, and a second for milk through early dough stages of grain filling. The early and late planar domains for wheat were used to develop two separate canopy chlorophyll content indices (CCCIwe and CCCIwl). The CCCIwe showed improving correlation with canopy chlorophyll content, reaching a maximum at early stem elongation (Zadoks 30-34) as seen in Figure 2. The CCCIwl correlated well with final harvested grain quality when two rules were applied to the data. First, phenology must be in the milk to early dough stage (Zadoks 70-85). Second, the RVI must be greater than 8.0 for a datum to be included. With results thus constrained, very good correlation with harvested grain quality as measured by protein content was achieved, as shown in Figure 3.

INTERPRETATION: The three-band, planar domain method of determining canopy chlorophyll content appears effective in this first look. If the technique is verified using existing data from other years, work can proceed on developing nitrogen recommendations based on CCCIwe, and on developing grain quality prediction algorithms based on CCCIwl.

FUTURE PLANS: A second set of wheat data containing nitrogen-limited wheat reflectances from the 1996 FACE experiment will be used to verify the efficacy of both CCCIs. Future experiments in wheat will focus on further verification and development of management tools based on remotely sensed information.

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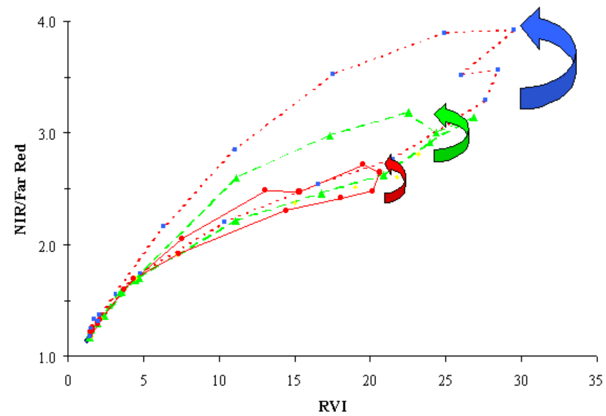

Figure 1. Planar domain of the CCCI applied to wheat. Data from three plots are shown: low nitrogen availability (●), high nitrogen availability (■), and an intermediate level (▲). A shift in the far red band during the late stem elongation and flowering stages of growth resulted in an upward shift in the domain, the location and direction of which is shown by the arrows.

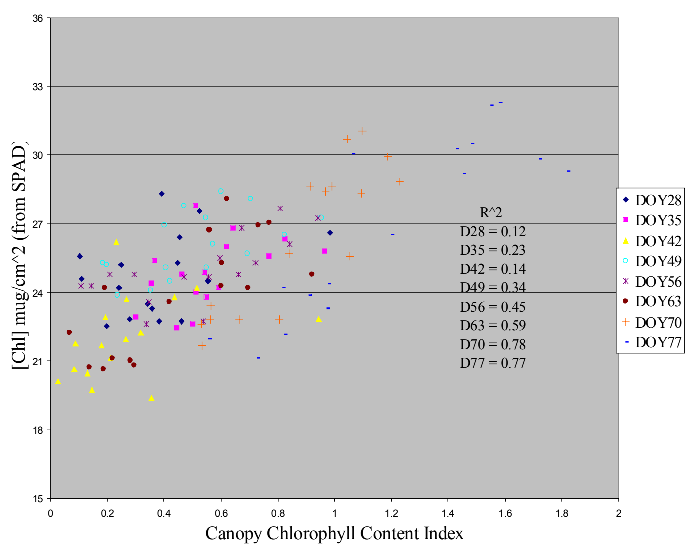

Figure 2. Correlation of chlorophyll content as estimated by SPAD measurement with CCCIwe up to mid stem elongation growth stage.

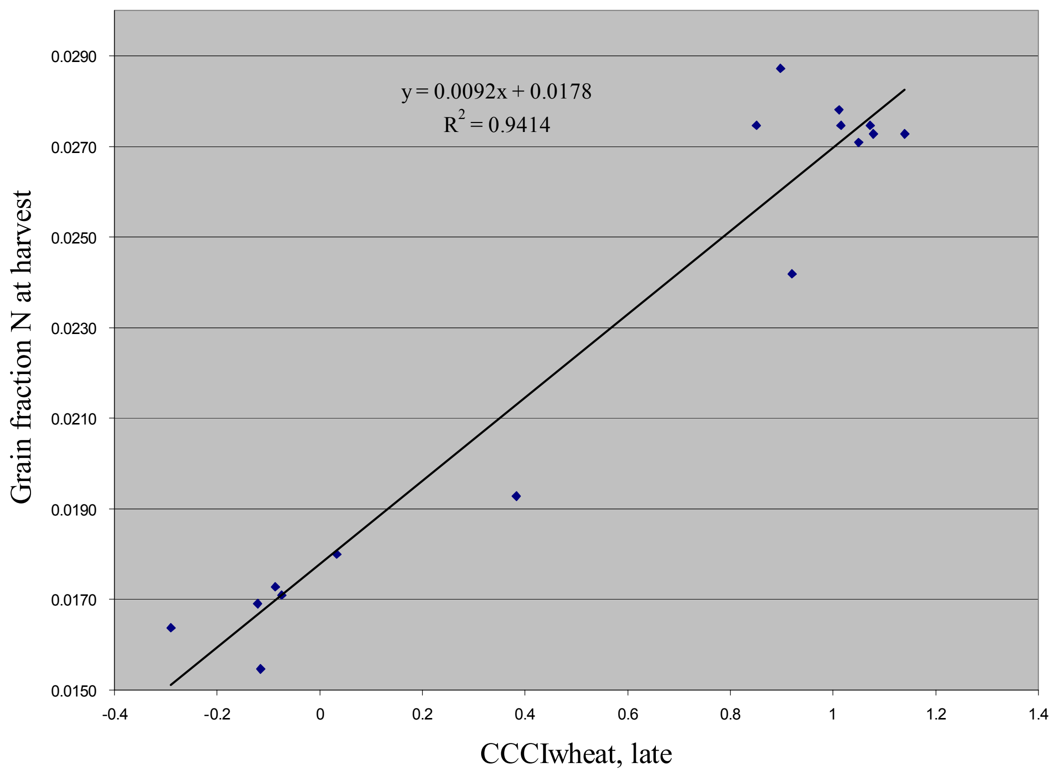

Figure 3. Correlation of grain fraction nitrogen as a measure of protein at final harvest with CCCIwl. Data were constrained to Zadoks growth stage 70 through 85 and Ratio Vegetation Index greater than 8.0.

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

E.M. Barnes, Agricultural Engineer; T.R. Clarke, Physical Scientist; P.J. Pinter, Jr., Research Biologist; S.E. Richards, Research Lab Assistant; W.E. Luckett, Physical Science Technician

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 to manage crop inputs economically 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 between the U.S. Water Conservation Laboratory, the University of Arizona, Texas A&M University, and the Idaho National Environmental and Engineering Laboratory (INEEL). The project is also 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. Concurrent with these experiments, a system was developed to allow the linear move irrigation system to serve as a remote sensing platform (named **Ag**ricultural **I**rrigation **I**maging **S**ystem, AgIIS, i.e., "Ag Eyes"). The 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. 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. The reflective bands were calibrated to units of reflectance by using a plywood panel mounted at the center of the linear move. Periodic radiometer measurements of the panel were taken during the season so that its spectral properties were known.

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 five times during the season); and (4) low water and low nitrogen (wn). Soil moisture levels were monitored in every plot using a neutron probe at a minimum of weekly intervals (two access tubes per plot). Additionally, two plots were heavily instrumented with TDR probes in four locations at four 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 were also 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.

FINDINGS: The data collected during this study are being used to examine issues related to geostatistical analysis of spatial variability in crop condition (Kostrzewski, 2000), and improvement of remote sensing techniques to infer crop nutrient and water status. In order to present examples of some the progress made in these areas, three spectral indices will be used: the ratio vegetation index (RVI = ratio of NIR to red reflectance), a planar domain version of the crop water stress index (CWSI) similar to the version developed by Clarke (1997), and the Canopy Chlorophyll Content Index (CCCI; Clarke and Barnes, 1999). For a more complete description of these indices, see Barnes et al. (2001).

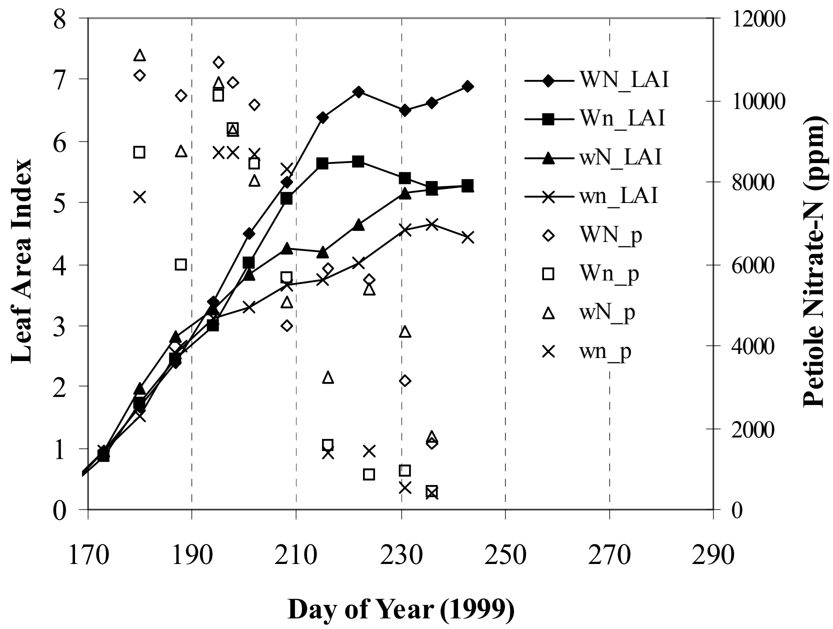

Figure 1. Seasonal trends in treatment average leaf area index (LAI) and petiole Nitrate-N concentration (p).

Figure 1 shows the seasonal trends in leaf area index and petiole nitrate content based on the treatment averages. The difference in water treatments began on DOY 193, after which point there was a definite slowing of LAI accumulation for the low water treatments (wN and wn). By DOY 236 there is little difference in the LAI between the Wn and wN treatments. There was no clear response in LAI to the N treatments until DOY 215 at which point petiole analysis indicate a significant difference between high and low N treatments.

Figure 2 shows the season trends in the stressed treatment averages (Wn, wN, and wn) relative to the control treatment (WN) for the RVI, (1-CWSI) and CCCI. Note that 1-CWSI is used in computing the ratio to the WN treatment in Figure 2c, because under conditions of low water stress, which was common in the WN plots, the CWSI was approximately 0. The relative differences in RVI follow similar trends as LAI with some exceptions (Figure 2a). The sharp relative decrease in RVI on DOYs 194, 202, and 209 was due to a combination of a wet soil background in the high-water treatments (WN and Wn) and some leaf wilting in the low water treatments due to water stress. Note that from DOY 233 to 259 the RVI for the wN treatment becomes higher than the Wn. This illustrates the difficulty in interpreting the differences of simple vegetation indices as a measure of a single stress. Indices based on combinations of the NIR and red areas of the spectrum are strongly correlated with canopy density; therefore, any stress that alters canopy density will impact these indices.

The CCCI begins to show a clear distinction between the low N treatments (Wn, wn) after DOY 214 (Figure 2b), about the same time the petiole data indicated a strong difference between the high and low N treatments (Figure 1). Unlike the RVI, the CCCIs of the low N treatments are consistently less than the control from DOY 214 to 260. While this index does appear to minimize the impact of canopy density, it was sensitive to changes in the wetness of the soil surface background under partial canopy conditions as indicated by the increase in the index on DOYs 198 and 209. On both of these dates, the soil background in the low water treatments was dry, but wet in the high water plots. This resulted in a false indication that the chlorophyll content was higher in these treatments than the control.

In Figure 2c, the periods after which water was withheld (DOYs 194, 202, 209 and to a lesser extent 231 and 245) are identified by the relative decrease in (1-CWSI) in the low water (wN, wn) treatments. While some of these events also decreased the RVI in the low water plots with respect to the high, the RVI trends are not as related to water treatment levels as those in CWSI later in the season, particularly on DOY 251, after the water treatments were purposely reversed (i.e., water was not applied to the WN and Wn treatments on DOY 250). Also note that on dates after all of the plots were irrigated (e.g., DOY 215), there was little difference in the CWSI between water treatments, unlike the RVI.

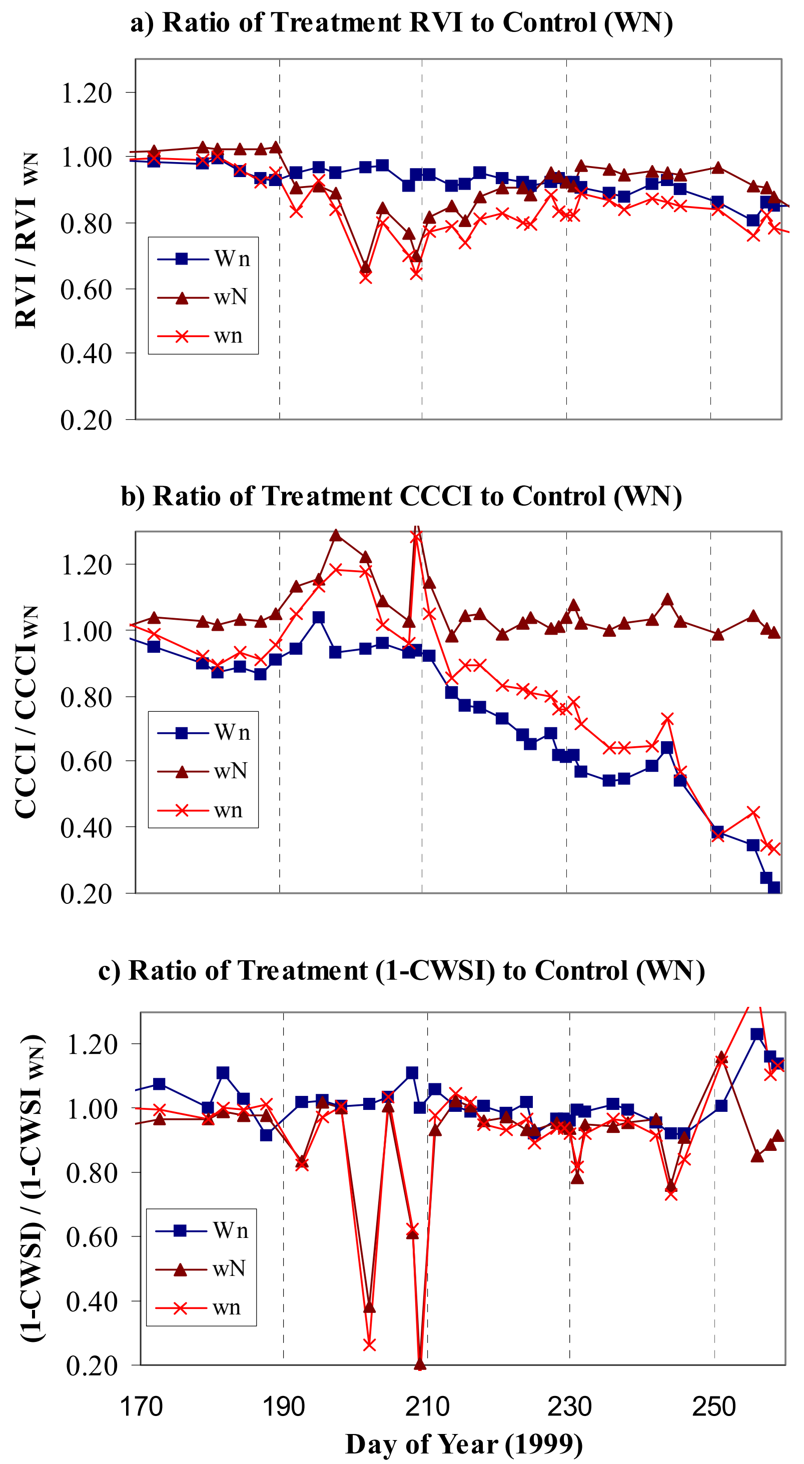

Figure 2. Seasonal trends in the ratio of (a) ratio vegetation index (RVI), (b) 1-crop water stress index (CWSI), and (c) canopy chlorophyll content index (CCCI) in the high water, low N (Wn), low water, high N (wN) and low water, low N (wn) treatments to the respective index in the control treatment (WN).

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 2000-2001 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; Valmont Industries, Valley NE; Jim Stubbs, CDS Ag Industries, CA.

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INTEGRATION OF REMOTELY SENSED DATA WITH CERES-WHEAT

E.M. Barnes, Agricultural Engineer; P.J. Pinter, Jr., Research Biologist

PROBLEM: The development of crop growth models has been progressing since the 1970s and was originally focused on the prediction of average field conditions. More recently tools have been developed to integrate growth models with geographic information systems (GIS) at either regional or field scales. One limitation to simulating spatial variations in crop production is the large amount of input data necessary to accurately characterize the growth conditions. The objective of this study is to determine how remotely sensed observations can be used to improve a growth model's ability to simulate actual field scale variability.

APPROACH: Wheat was selected as the first crop to test methods to integrate remotely sensed observations with crop models due to the extensive growth and remote sensing data set collected during the FACE wheat experiments (Kimball et al., 1999). CERES-Wheat (Ritchie and Otter, 1985) was selected as the crop model to use in this approach because it is a process oriented model capable of simulating different management practices, while maintaining reasonable input requirements that would not prevent its application by a farm manager. Two potential links between CERES-Wheat and remotely sensed data have been identified: the fractionally absorbed photosynthetically active radiation (fAPAR) and crop water status via the crop water stress index (CWSI).

CERES is essentially a radiation use efficiency model, predicting potential carbon accumulation (PCARB, g plant^{-1}) as a function of solar radiation and leaf area index (LAI):

$$\text{PCARB} = 0.5 \ \text{SolarRad RUE} \ [1-\exp(-0.85 \ \text{LAI})] \ / \ \text{PlantPop} \quad (1)$$

where 0.5 is from the assumption that 50% of the total incoming solar radiation (SolarRad, MJ m^{-2} d^{-1}) is PAR, and PlantPop is plant population (plants m^{-2}). The actual amount of carbon accumulation is then decreased if there is water, nitrogen or temperature stress. The model was modified by replacing the [1-exp(-0.85 LAI)] term in the equation 1 with the remotely sensed estimate of fAPAR. Note that by using "observed" fAPAR, the equation provides an estimate of actual carbon production (i.e., it does not need to be modified to account for stress); however, other stress factors in the model that relate to carbon partitioning will not be influenced by these modifications. The remotely sensed estimate of fAPAR was determined as a function of the normalized difference vegetation index (NDVI) using the approach developed by Pinter et al. (1994).

The model predicts transpiration as a function of either the plant available water in the root zone or atmospheric limitations, whichever is smaller. The potential water uptake by the roots (RWU_L, cm^3 water per cm roots per day) in a particular soil layer (L) is calculated by

$$RWU_L = c_1 \exp[c_2 (SW_L - LL_L)] \ / \ [c_3 - \ln(RLV_L)] \quad (2)$$

where c_x are empirical constants, SW_L is the soil water content (cm^3 cm^{-3}), LL_L is the soil water content at permanent wilting point (cm^3 cm^{-3}) and RLV_L is the root length density (cm root per cm^3 of soil). If the sum of RWU_L across the soil profile (TRWU, cm) is greater than potential transpiration for the day, RWU_L is decreased so that the water uptake by the plant is equal to potential transpiration. A soil water deficit factor (SWDF1) is then defined as:

$$SWDF1 = TRWU / E_p \quad (3)$$

where E_p is potential transpiration (cm). SWDF1 is essentially equivalent to the definition of (1-CWSI). Therefore, the model was modified when there was a CWSI observation on a given the day and (1-CWSI) was not within 10 percent of SWDF1. The modification was accomplished by solving equation 2 for SW_L and setting the soil water content distribution in the soil profile so that when the total RWU of equation 3 was calculated, SWDF1 would equal (1-CWSI). A limitation to this approach is that when the model is under-predicting plant available water, the amount of water that can be added to the profile will only be sufficient to bring the predicted levels back to the verge of water stress.

FINDINGS: Figure 1 represents the fAPAR determined by remotely sensed estimates and the model's predicted fAPAR for the 1993-94 and 1995-1996 ambient CO2 treatments. The spikes in the model's predicted fAPAR in the 1993-94 season for the dry treatment are due to the water stress factor, which rapidly returns to one after an irrigation. The remotely sensed fAPAR estimates do not respond to rapidly changing stress conditions caused by short-term water stress between irrigations. However, they do reflect the accumulated effects of the water stress in the later half of the season. For the nitrogen stress treatment in the 1995-96 growing season, the nitrogen stress factor does not change as rapidly, indicating the more sustained nature of the stress.

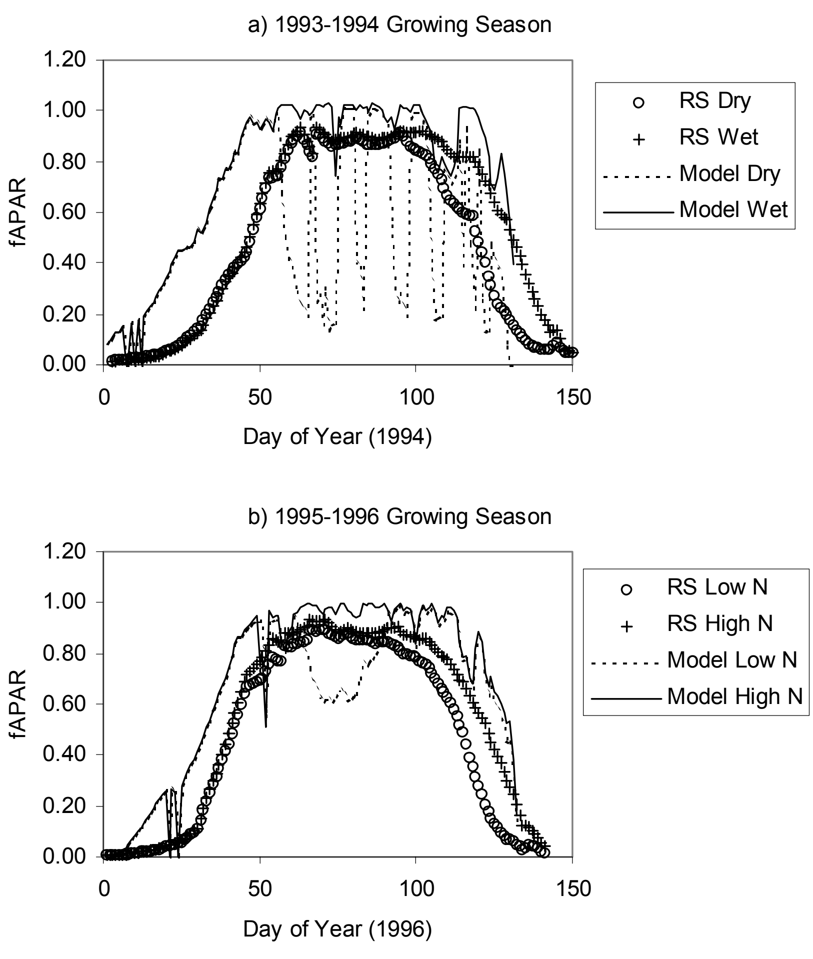

Figure 1. Remotely sensed and model predicted estimates of fAPAR for the 1993-94 (a) and 1995-96 (b) growing seasons.

For water stress, the CWSI is a more appropriate remotely sensed parameter than fAPAR because it is correlated directly with transpiration. In Figure 2, a comparison is shown between observed extractable water in the top

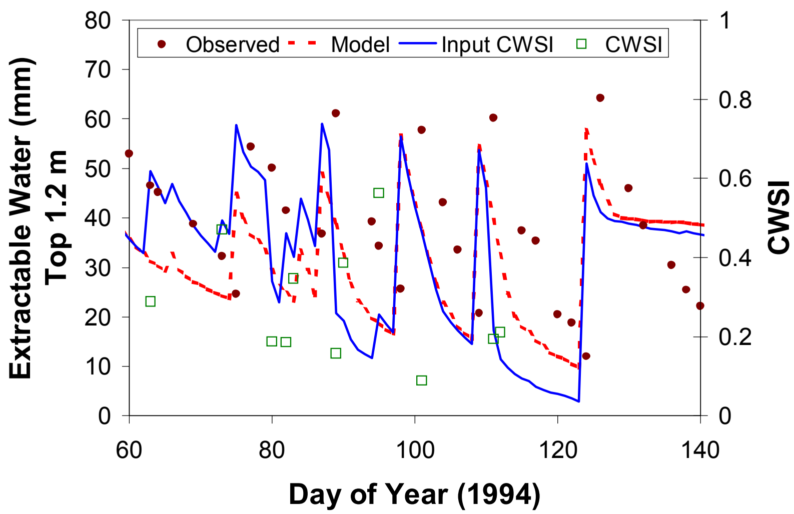

Figure 2. Extractable water in the top 1.2 m of the soil profile as predicted by the model with and without CWSI input. The value of the CWSI input is indicated on the y-axis to the right.

1.2 m of the soil profile with model predictions from CERES with and without CWSI input for the ambient Dry treatment during the 1993-94 season. The squared symbols show when CWSI measurements were made. Early in the season, the CWSI input improved predictions; however, later in the season, CWSI input resulted in under prediction of soil water. This under prediction may have been due to the assumption that the relative distribution of moisture in the soil profile remains unchanged when a CWSI modification is made; however, more investigation is needed. The model alone provided good estimates of soil water content and there were no significant differences in the prediction of yield between the two methods.

Figure 3 shows the results when the 1992-93 ambient Wet treatment was simulated for the first part of the season, and then single CWSI measurements from the Dry treatment were input on selected days and the dry treatment was simulated for the rest of the season. The observed values are for the dry treatment. The different lines indicate the results when the CWSI was input on the day of year indicated. For inputs prior to DOY 90, the CWSI was able to reset soil water to an amount very close to observed. Changes later in the season were not as accurate, but still within 20-mm of the measured value. These test indicate the input of CWSI could be very useful when soil water measurements are not available to initialize the model.

INTERPRETATION: Use of fAPAR estimates from NDVI is best suited for chronic stress conditions (i.e., stress conditions that persist long enough to impact canopy development). Compared to N stress, water stress can develop over much shorter time periods under high evaporative demand, and it can be relieved shortly after an irrigation or rainfall event. Use of the CWSI with the model shows promise as an alternative to measured soil water initial conditions. Dependable methods to forecast yield during the early season would provide a new tool for producers to make informed decisions in the application of precision farming practices. The approaches taken in this study demonstrate that the integration of remotely sensed data and crop models can lead to such a tool; however, improvements in the current methods are needed.

FUTURE PLANS: Further development is need on both approaches, particularly to determine methods to adjust the model's parameters through iteration so that the number of required remotely sensed observations can be minimized.

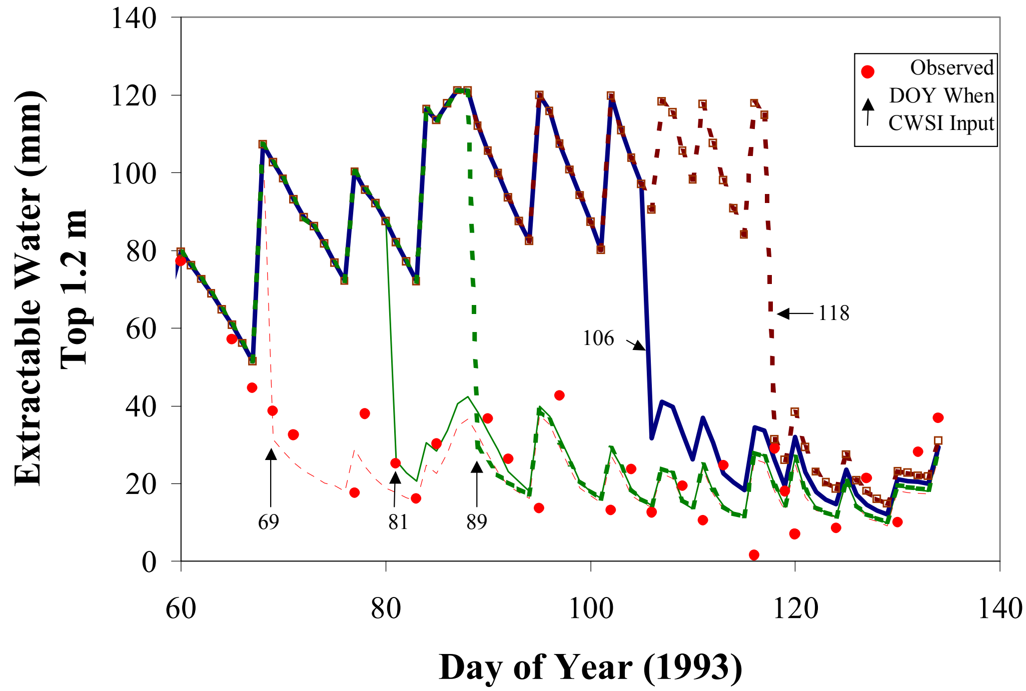

Figure 3. Extractable water in the top 1.2-m of the soil profile predicted by the model when simulating the wet treatment until a day when a CWSI was input and then simulating the dry treatment for the remainder of the season. The observed data points are for the dry treatment.

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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, vernonia, 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: Termite and wood-rot damage are multibillion dollar problems in the United States. Conventional preservatives used to protect wood from insect and microbial damage are presently of major concern to human health and the environment. Finding alternative and economical preservatives has not been successful. The desert-adapted guayule plant has been observed to have both insect and microbial resistant properties. In addition, the utilization of waste plant material or bagasse, approximately 90% of the total biomass following the extraction of latex rubber from the plant to treat wood, would greatly help the economics of guayule culture.

APPROACH: Wood material was impregnated with the resin that was extracted from the guayule plant. Composite boards were fabricated from guayule bagasse material that remained after the extraction of latex rubber. The binders or adhesives used were high density polyethylene (HDPE) and phenolic resin (PR). The two types of wood prepared from guayule were tested for resistance against termite and wood-rot attacks.

FINDINGS: Impregnation of guayule resin into wood at 50% by weight and higher is needed to make the wood resistant to termite attack (Table 1). When the wood was impregnated at the 97% resin content level, complete termite mortality was achieved.

Table 1. Eastern subterranean termite resistance of southern pine treated with resin extracted from guayule.

Amount of resin extract in wood (%)	Observation (after one week)	Rating (ASTM)[a]
0	Termites still alive	No mortality
10.3	Termites still alive	No mortality
51.8	Mildly termite active	Low mortality
97	All termites dead	High mortality
Guayule particleboard (no adhesive)	Mildly termite active	Low mortality
Guayule composite board with 30% HDPE plastic	All termites dead	High mortality
Guayule branch	All termites dead	High mortality

[a] ASTM D-3345 standard

For the guayule composite board with 30% HDPE, 100% mortality occurred. Thus, fabricating composite board directly from guayule bagasse would be a much simpler approach to take than extracting the guayule resin and then impregnating wood to achieve termite resistance.

The guayule particle board without any adhesive had a mild termite activity. Interestingly, the guayule branch material alone was termite resistant causing high mortality. Bultman et al. (1991) had treated wood with a full-strength resin mixture and obtained 100% and higher resin retention in the wood. Their resin-impregnated wood samples were able to resist *Coptotermes Heterotermes* for 71 months in the Panamanian rain forest, and *Reticulitermes* spp. for 62 months in semiarid Arizona.

The decay resistance of composite board made from guayule bagasse is shown in Table 2. Both the composite board with PR and the particleboard without resin were resistant to *G. traveum* and *P. placenta*. The composite board with 30% HDPE as the binder showed resistance to the two fungal organisms. The guayule board made with no adhesive exhibited the largest thickness change for *G. trabeum* (98%) and *P. placenta* (137%). Thus, the guayule bagasse even though it contains resinous material and rubber will need a binder or waterproofing additive to make its wood product water resistant. Unlike the other wood types, the guayule stem alone had moderate resistance to fungi.

Table 2. Decay resistance of guayule composition boards and guayule stems.

Board type and stem	*Gleophyllum traveum*		*Poria placenta*	
	Weight loss (%)	Rating (ASTM)[a]	Weight loss (%)	Rating (ASTM)
PF resin, 10% 14 mm	13.94	Resistant	19.61	Resistant
No adhesive, 8 mm	19.66	Resistant	23.99	Resistant
HDPE, 30% 11 mm	6.46	Highly resistant	5.68	Highly resistant
Guayule stem (with bark & wood core)	30.28	Moderately resistant	12.72	Resistant

[a] ASTM D-2017 standard

The guayule resin extract when impregnated into the southern pine made the treated wood resistant to fungal attack as shown in Table 3. Resistance to *G. traveum* started at 10.3% resin content and 51.8% for *P. placenta*. At resin contents of 51.8% and higher, the treated wood was highly resistant (*G. traveum*). The activities of other types of fungi such as brown-rot (*Gleophyllum traveum*, *Antrodia carbonica*, *Fomitopsis cajanderi,* and *Lentinus ponderosa*) and white-rot (*Dichomitus squalens*, *Trametes versiclor*, and *Ganodermas* sp.) were also observed to be inhibited by the resin extracted from guayule (Bultman et al., 1991).

Table 3. Weight loss and wood-rot rating of southern pine treated with resin extracted from guayule in the presence of fungi.

Amount of resin extract in wood (%)	*Gleophyllum traveum*		*Poria placenta*	
	Weight loss (%)	Rating (ASTM)[a]	Weight loss (%)	Rating (ASTM)
0	58.60	Non-resistant	47.64	Non-resistant
2.6	52.46	Non-resistant	50.98	Non-resistant
10.3	22.42	Resistant	45.00	Non-resistant
51.8	8.69	Highly resistant	36.65	Moderately resistant
97.0	2.95	Highly resistant	11.11	Resistant

[a] ASTM D-2017 standard

The decay resistances of southern pine that was treated with two different types of resin extracts are compared in Table 4.

Table 4. Decay resistance and durability of southern pine treated with two sources of resin extracted from guayule.

Source of resin extract	*Gleophyllum trabeum*		*Poria placenta*	
	Weight loss (%)	Rating (ASTM)[a]	Weight loss (%)	Rating (ASTM)
Acetone extract only	10.48	Highly resistant	4.64	Highly resistant
Bultman resin	12.89	Resistant	8.29	Highly resistant

[a] ASTM D-2017 standard

Our guayule resin extracted with acetone alone showed similar decay resistance as the resin provided by Dr. Bultman, which was extracted from guayule with a solvent system consisting of both acetone and hexane.

INTERPRETATION: The composite board made from 70% guayule fiber and 30% HDPE, the guayule branch, and normally susceptible wood impregnated with 52 to 97% by weight of guayule resin-extract all had antitermitic property. The guayule particleboard with no adhesive showed termite resistant property, but it could not stand high moisture exposure.

The effects of impregnating southern pine wood with the guayule resin-extracts (content of 10.3% and higher) on the decay resistance (10.3% and higher for *Gleophyllum trabeum*, and 51.8% or higher for *Porio placenta*) appeared to be significant. The treated specimens showed greater resistance to *G. traveum* than *P. placenta*. *P. placenta* often causes decay in millworks and in wood situated above ground.

Southern pine wood specimens impregnated with resin derived from either an acetone extract or a combination of acetone and hexane were resistant to the wood-rot fungi. Both the phenolic adhesive bonded and the guayule only particleboard showed good decay resistance property to *P. placenta* and *G. traveum*. The plastic composite board made from 70% guayule and 30% HDPE was highly resistant to both types of wood rotting fungi.

The natural guayule stems and branches with 10 to 15% resin content also exhibited some decay resistance property. Excessive thickness, swelling and specific gravity reduction occurred with the wood made from guayule plant fiber alone where no adhesive was added.

Our preliminary results indicate that the commercial application of the guayule is possible to provide a dependable, renewable, and alternative natural source of wood preservatives. Because the plant is drought tolerant and its derivatives can reduce tree harvest, its cultivation as an alternative crop will help conserve our water and forest resources.

FUTURE PLANS: We will continue to find ways to utilize guayule waste materials for pest control including the fabrication of composite and resin impregnated wood products. We plan to develop cooperative studies with other ARS locations who are working with insect control and to establish Cooperative Research and Development Agreements (CRADA) with private organizations to make use of the waste bagasse for making guayule blends with other waste wood to fabricate high-valued, commercially useful wood products.

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GUAYULE BREEDING AND GERMPLASM EVALUATION

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

PROBLEM: Allergies caused by using latex products from the Heavea source are a serious health problem in certain population groups in the United States, such as health care workers and patients who undergo multiple surgeries. Guayule is the best potential source of hypoallergenic latex to solve this problem. Previous work has shown that natural latex from guayule can be used to make medical products, gloves, and condoms that prevent virus and other pathogen transmission. In addition, guayule can be grown in the Southwestern United States to provide a domestic source of this valuable latex. Currently, the United States imports all of its natural rubber of which about 300,000 metric tons is used for natural latex products. The United States consumes about one third of all natural latex in the world. For guayule to be used in the hypoallergenic latex market, lines with higher latex content that can be harvested in less than three years are needed to replace older lines that require three to five years before harvesting. Thus, high yielding, fast growing, and easy to establish germplasm is needed for guayule to be successful as a viable new crop. Recent research results from this program have also shown that maximum benefits for genetic improvements can be made when selections are done when plants are one or two years old rather than four or five years old. The objective of the current studies was to evaluate the genetic variation among 20 new guayule lines for agronomic and latex characteristics compared to two older breeding lines.

APPROACH: Twenty new guayule germplasm lines and two check lines (11591 and N565) were transplanted at The University of Arizona Maricopa Agricultural Center, Maricopa, Arizona, USA on April 6, 1995. Plots were two rows, each 1 m long and 1 m wide. Transplants were spaced 360 mm apart. A randomized complete block design with four replications was used. Plots were irrigated immediately after transplanting and the soil kept moist with frequent irrigations until plants were established. Plants were maintained each year during the active growing season with approximately biweekly irrigations from February through October. Recommended production practices for row crops in Arizona were used to maintain plots during the experiment.

Percentage of plants surviving per plot and plant height were determined one (1996) and two (1997) years after transplanting. Plant width was determined two years after transplanting. All surviving plants in each plot were measured for plant height and width and the mean for each replicate used for statistical analyses. Changes in survival rate of each plot were calculated by subtracting the survival rates for 1997 from the 1996 survival rates. Changes in plant height of each plot from 1996 to 1997 were determined by subtracting the plot mean heights in 1996 from the plot mean heights in 1997. A plant height to width ratio was calculated in 1997. Two representative plants from each plot were selected in 1998 for determining latex content per plant, wet and dry plant weight, chipping losses, latex yield per plant, and latex and plant biomass yields per m^2. Wet plant weights were taken before and after chipping to obtain plant biomass yields at harvest and plant weight losses during chipping. The weight loss during chipping was converted to a percent loss by dividing the after chipping weight by the before chipping weight to standardize data across plots. Dry plant weight was determined by oven drying a sample of the chipped plant material at 60^0C. The weight of latex per plant, latex yield per m^2, and plant biomass yield per m^2 were calculated for each plot. Data were analyzed using the Proc GLM procedure in SAS (1988) for a randomized complete block design. Replications were considered fixed effects and genotypes random effects. Significance among genotype means was determined by analyses of variance and LSD at the P=0.05 level.

FINDINGS: Significant variation was found among the 20 lines and two checks for all characteristics (Tables 1 and 2). None of the lines were significantly better than the checks for all characteristics, but five lines were identified that merit further study. G7-14 was the fastest growing line (406 mm tall) the first year and had the best survival rate (99%). A higher latex content per plant occurred in two lines, P3-11 (4.1%) and P10-4 (4.2%), than 11591 (2.4%) or N565 (3.1%). G1-16 had the highest wet plant weight (2.7 kg), and was one of the highest for dry plant weight (1.6 kg) and total biomass yield (2214g/m^2). The most promising line was N9-3, which had the highest plant dry weight (1.6 kg), weight after chipping (2.3 kg), latex weight per plant (60.3 g), latex yield per m^2 (83 g) , and total plant biomass yield per m^2 (2259 g), as well as the lowest percentage loss during chipping (14.8%).

INTERPRETATION: Results from this study indicate that variation is available in this germplasm for significant improvements in all characteristics studied through a breeding and selection program. This is the first study on variation present in germplasm lines for chipping loss. Chipping losses can be associated with several factors, but the amount of leaf material in the sample may be the most important. Leaves tend to be lost during the handling and chipping process. Those plants that were higher in percentage of leaf weight may be the ones with higher chipping losses. Another observation that supports this theory is that samples with less leaf material tend to pass more completely through the chipper, thus leaving less residue in the chipper. Data were not collected in this study on leaf weights or residue left in the chipper. Therefore, further tests will be necessary to identify the specific trait(s) responsible for the significant differences in chipping loss observed in this study. Leaves contain very little or no latex. Thus, removal of leaves prior to chipping and/or harvesting may be desirable for a more efficient chipping process that would require less cleaning of equipment. Latex yields reported in this study should be helpful to industry in order to plan the number of hectares to plant for meeting latex production needs.

FUTURE PLANS: An Initiative for Future Agriculture and Food Systems grant was obtained by the USWCL as part of a consortium grant to the University of Arizona. Tests will be initiated in the fall of 2000 and spring of 2001 to study the effects of planting date, plant population, irrigation level, fertility, harvest time, post-harvest/pre-chipping storage conditions, cutting height, and regrowth on latex, seed, and plant growth traits. A cooperative yield test will be established for evaluating promising lines from the breeding program for release and new populations for making selections will be developed. These studies will involve close cooperative work with scientists at the various locations involved in guayule research.

COOPERATORS: D.T. Ray and D. Stumpf, Plant Science Department., The University of Arizona, Tucson AZ; M.A. Foster, Texas Agricultural Experiment Station, Texas A&M University, Pecos TX; K. Cornish, USDA-ARS-PWA-WRRC, Albany CA; F.J. Adamsen and D.J. Hunsaker, USWCL, Phoenix AZ.

Table 1. Plant stands, height, width, and height/width ratio for 22 guayule lines grown at Maricopa Agricultural Center, Arizona, USA in 1996 and 1997.

Line	Stand 1996 (%)	Stand 1997 (%)	Stand (1996-1997)	Height 1996 (mm)	Height 1997 (mm)	Height (1997-1996)	Width (1997) (mm)	Height/ Width
11591	97.00	96.25	0.75	336.50	**547.30**	**210.80**	461.00	1.19
N565	80.00	79.25	0.75	250.50	418.00	167.50	436.80	*0.96*
G1-10	91.25	89.75	1.50	*239.50*	371.30	131.80	313.50	**1.20**
G1-16	86.00	79.00	7.00	290.80	431.30	140.50	398.30	1.09
G7-14	**99.25** [1]	**98.50**	0.75	**405.80**	520.50	114.80	458.80	1.13
N6-2	84.50	77.50	7.00	243.00	352.50	109.50	312.50	1.14
N6-3	91.50	86.25	5.25	269.50	388.80	119.30	347.50	1.12
N7-2	75.00	72.50	2.50	311.80	489.30	177.50	444.80	1.10
N7-5	79.75	72.75	7.00	240.30	*339.50*	99.20	315.50	1.12
N8-1	61.00	58.00	3.00	261.80	427.30	165.50	389.80	1.10
N8-5	75.25	74.50	0.75	*238.30*	351.30	113.00	321.80	1.10
N8-10	90.75	88.50	2.25	270.30	422.00	151.80	387.00	1.09
N9-3	94.00	90.00	4.00	292.50	465.30	172.80	415.00	1.12
N9-4	61.00	61.75	*-0.75*	319.30	510.80	191.50	**473.00**	1.08
N12-18	87.75	80.50	**7.25**	274.00	402.80	129.50	355.80	1.14
N13-1	83.00	82.25	0.75	299.80	468.00	168.30	420.80	1.11
O16-1	82.25	80.50	1.75	291.50	480.50	189.00	431.80	1.11
P3-11	95.50	92.50	3.00	306.00	430.00	124.00	380.80	1.13
P10-3	*56.50*	*56.50*	0.00	250.30	404.80	154.50	371.00	1.09
P10-4	97.00	91.00	6.00	275.50	345.50	*70.00*	*288.50*	**1.20**
P10-5	86.00	82.25	3.75	242.00	367.80	125.80	308.50	**1.20**
P11-1	84.50	78.25	6.25	247.30	380.80	133.50	337.80	1.13
LSD	16.65	18.34	6.00	51.20	63.70	45.90	62.50	0.10

[1] Numbers in bold are the largest values for the column and numbers in italics are the lowest values for the column.

Table 2. Latex content, latex yield, plant wet weight, plant dry weight, chipping loss, and plant biomass of 22 guayule lines grown at Maricopa Agricultural Center, Arizona, USA in 1998.

Line	Wet weight (kg)	Dry weight (kg)	Chip weight (kg)	Chip loss (%)	Plant biomass (g/m^2)	Latex content (%)	Latex plant (g)	Latex Yield (g/m^2)
11591	1.91	1.18	1.57	19.48	1626	2.36	27.95	38.68
N565	2.00	1.23	1.66	15.90	1706	3.09	35.03	48.47
G1-10	1.32	1.02	0.97	27.55	1408	3.24	33.41	46.24
G1-16	**2.70**	1.60	2.18	20.23	2214	*2.19*	35.81	49.56
G7-14	1.72	0.99	1.25	**28.03**	1363	2.26	*22.16*	*30.66*
N6-2	1.31	0.77	1.05	20.43	1059	3.49	27.45	38.00
N6-3	1.55	0.91	1.19	24.10	1263	3.54	31.82	44.04
N7-2	1.85	1.06	1.55	16.68	1470	2.88	29.85	41.31
N7-5	1.33	0.76	1.02	23.65	1052	3.55	26.79	37.07
N8-1	2.20	1.28	1.83	17.25	1775	3.47	45.80	63.38
N8-5	1.36	0.82	1.00	26.63	1128	4.01	32.74	45.30
N8-10	2.43	1.51	1.98	18.10	2090	3.41	49.93	69.09
N9-3	2.64	**1.63**	**2.27**	14.83	**2259**	3.57	**60.34**	**83.08**
N9-4	1.59	0.97	1.22	23.48	1339	3.91	37.67	52.13
N12-18	1.41	0.83	1.10	22.35	1149	3.46	28.74	39.78
N13-1	2.29	1.38	1.84	*14.80*	1910	3.30	44.49	61.57
O16-1	1.76	1.00	1.33	24.80	1387	3.26	32.30	44.69
P3-11	1.48	0.92	1.09	27.58	1270	4.07	38.28	52.98
P10-3	2.13	1.30	1.80	15.80	1799	3.01	39.20	54.25
P10-4	*1.00*	*0.60*	*0.73*	26.08	*830*	**4.22**	25.28	34.99
P10-5	1.44	0.88	1.17	19.60	1221	2.84	26.23	36.30
P11-1	1.58	0.93	1.17	24.89	1287	3.68	34.34	47.52
LSD	0.75	0.50	0.68	9.21	686	0.98	19.03	26.34

[1] Numbers in bold are the largest values for the column and numbers in italics are the lowest values for the column.

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: Seed oil yields of *Lesquerella fendleri* (Gray) Wats., *Brassicaceae*, a potential oilseed crop native to the Southwestern United States, cannot yet compete with similar imported oilseeds. The seed oil from lesquerella contains hydroxy fatty acids (HFA), comparable to castor. Imports of castor oil and derivatives amount to more than 65,000 tons per year at a value exceeding $100 million per year. Unique properties of lesquerella oil along with coproducts are promising for commercialization if yields are improved.

Other species of *Lesquerella* produce higher quantities of HFA than *L. fendleri,* but none are as productive in seed yield. There are more than 70 species from the western half of the U.S. that do not cross-pollinate in the wild. Traits from these species could be incorporated into *L. fendleri* to improve yields. There is also a high amount of diversity within *L. fendleri* that could be utilized for plant improvements. Public releases of seed have been made in the past by this laboratory with higher oil and lesquerolic acid contents and reduced oil pigmentation.

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 utilize these accessions successfully in our breeding program. It is also necessary to make seed available to other researchers through the National Plant Germplasm System.

APPROACH: Hybrids were produced between *L. fendleri* and one of four other species from greenhouse controlled crosses (Table 1). These species were chosen based on a higher HFA content compared to *L. fendleri*. Embryo rescue was necessary since seeds did not form from the crosses. Some plants resulting from these crosses were sterile, possibly due to some incongruity between the two species. Fertility was restored by chromosome doubling using the chemical colchichine. The order of our procedures to obtain plants for greenhouse crossing was embryo rescue, shoot culture, colchicine treatment, and root culture.

Half-sib selections for high oil content were planted at Maricopa Agricultural Center and re-selected for both high oil and seed yield. The number of mass selected individuals was increased this year from 500 to 1300 plants to obtain more variability. The selections originated from a previously released line, WCL-LY2.

Seeds originating from a past collection trip in Mexico were field or greenhouse grown at the U. S. Water Conservation Laboratory (USWCL), Phoenix, Arizona, 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. The pollinators within cages prevented cross pollination with other accessions. Plants were also grown in greenhouses if the accession of a species was not adaptable to an Arizona climate. Flies were also placed in the greenhouses on a weekly basis during the flowering period.

Plant growth measurements were taken throughout the season; and after harvest, seeds from each accession were analyzed for oil content and composition.

FINDINGS: F_1 interspecific hybrids had traits such as leaf shape, trichomes, stem thickness, and flower color that were intermediate of the parental plants. Although parental crosses were done via bud pollinations and siliques formed, less than 0.1% seed amounts were produced. Embryo rescue increased the number to 75%, depending on the cross. Colchicine applied at a rate of 0.1% to shoot meristems and cultured for two days was successful in producing fertile hybrids. When *L. fendleri* was crossed to one of the four species, the F_1 hybrid had the same HFA content as *L. fendleri* maternal parent instead of a mid-parent value. When the reciprocal was crossed, the hybrid had the same HFA content as the other species used as the maternal parent. This indicated that HFA content is maternally inherited.

Table 1. Chromosome number, oil, lesquerolic, and auricolic acids of *L. fendleri* and four 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
pallida	6	na	81.4	3.68
gracillis	6	28.9	68.8	trace
auriculata	8	33	8.1	17.4

Seed oil content averaged 29.0% for the 1300 randomly selected plants. Unselected plants averaged 23.6% for oil contents. The top 150 plants were selected from this population and bulked together for next season planting. This population averaged 34.09% for oil content.

Two new germplasm lines developed here were released to the public this year. WCL-LY2 has high oil content and seed yield compared to the previous released line and WCL-SL1is salt tolerant.

Forty-eight accessions from 12 species were increased this year at the USWCL. Some of these are shown in Table 2. A single plant of *L. fendleri* growing in the evaluation plots, A4005, segregated for cream-colored flowers. This has never been reported for this species. All other flowers are yellow. It could be a useful phenotypic marker for breeding.

Following harvest, seeds of increased accessions were sent to the ARS Curator in Parlier, California, to be entered in the National Plant Germplasm System. A service contract with a cooperator in Mexico provided more accessions from areas that were not able to be collected last year because of lack of seed on plants, or there was not enough rain for plants to reach the full flowering cycle. Seed was obtained from these accessions and other localities not previously visited.

Table 2. Results of evaluation of some of the *Lesquerella* species increased and evaluated at the

USWCL, 1999-2000.

	Collection number	Species	Date of 1st flower	1000 Seed wt. (g)	Oil (%)	Hydroxy fatty acid (%)	Seeds per silique	Plant height (cm)	Plant width (cm)
1	A3342	*argyraea*	12/09	1.30	18.39	57.84	17.75		
2	A4004	*argyraea*	01/16	0.51	19.29	55.48	18.7	18.4	43.5
3	A4014	*argyraea*	01/25	0.50	20.26	53.18	8.7	26.2	51.6
4	A4030	*argyraea*	12/27	1.05	17.19	59.05	10.7	10.7	57.1
5	A863	*argyraea*	03/30	1.00	26.44	24.64			
6	A2401	*douglasii*	01/18	1.38	19.73	43	2.16		
7	A2402	*douglasii*	01/19	1.20	9.83	38.05	1.12		
8	A2403	*douglasii*	01/18			48.04	1.16		
9	A3343	*fendleri*	01/31		17.64	51.54	3.12		
10	A4001	*fendleri*	01/12	0.69	21.61	55.48	11.7	22.8	46
11	A4002	*fendleri*	01/31	0.56	24.82	54.47	17.7	23.9	45.5
12	A4003	*fendleri*	02/11	0.58		55.07	13.7	23.8	65.1
13	A4005	*fendleri*	01/30	0.71	22.7	55.33	13.4	25.9	51.7
14	A4006	*fendleri*	01/31	0.57	22.69	55.86	14.3	29.3	73
15	A4007	*fendleri*	01/19	0.53	25.1	55.7	16.2	26.5	59.4
16	A4015	*fendleri*	03/09	0.70	21.93	52.28	7.6	18.6	27
17	A4016	*fendleri*	02/17	0.61	20.23	53.05	8.7	18.1	22.7
18	A4024	*fendleri*	01/27	0.63	22.49	56.58	16.7	13.4	33.6
19	A4027	*fendleri*	03/20	0.67	19.99		7	14.3	22.4
20	A2217	*lasiocarpa*	12/10	0.69	27.51	31.51	20.4		
21	A2217	*lasiocarpa*	01/31	0.81	26.10	53.25	22.5		
22	A2228	*lasiocarpa*	01/25	0.46	23.61	50.26	20.7		
23	A2232	*lindheimeri*	12/21	1.00		83.24	12.1		
24	A3344	*mexicana*	03/20	1.22	12.89	56.21			
25	A1859	*pinetorum*	01/31			9.53	1.9		

26	A1853	*purpurea*	01/08			27.21	1.98		
27	A4020	*schaffneri*	02/24					6.7	18.4
28	A640	*wardii*	01/06	1.58	18.08	33.11	1.98		
29	AS741	*wardii*	12/20	1.58	16.21	19.19	4.74		

INTERPRETATION: These are the first confirmed interspecific hybrids of *Lesquerella* species native to the Western U.S. Since hybrids had the same oil profile as the maternal parent, species other than *L. fendleri* with high HFA contents were used. Hybrids have HFA contents of more than 80%. Many of the other traits from these species are not desirable and will need to be bred out. This will be done through backcrossing the hybrid with *L. fendleri* over several generations until the hybrid has most characteristics of *L. fendleri* except for the HFA contents. This has the potential to reduce the cost of the seed oil drastically from about $3 to $1 per pound and to compete with castor effectively in the marketplace.

The 150 selected plants for oil content and seed yields had some plants with oil contents above 39%. This is the first year we have seen plants above 37%. This may be due to recombination of favorable alleles and/or a higher probability of finding those plants with the larger selection of plants. Over an eight-year period, there has been a 10% increase in oil content. With larger sample sizes, we may be able to reach 40% within five years.

Breeding *L. fendleri* with wild relatives may yield offspring that bear bigger seeds with more oil and higher amounts of hydroxy fatty acid. It may also expand the growing region outside the Southwest U.S. 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 National Plant Germplasm System benefits researchers nationally and internationally. It also has a long-term benefit to our breeding program.

FUTURE PLANS: Interspecific hybrids are being backcrossed to *L. fendleri*. High oil lines will be used as the donor pollen parents. We have some hybrid plants that have already been backcrossed once (BC_1F_1) and will be backcrossed again this season. Others will be backcrossed for the first time. Internal transcribed spacers (ITS) molecular markers are being used to confirm hybridity and are especially useful to distinguish at the species level. These utilize the 18S - 26S nuclear ribosomal DNA region. Taxonomic information, such as leaf trichome descriptions, number of ovules, and flower petal length, is also being collected. Chromosome counts of colchicine hybrids have started.

The selection within *L. fendleri* for high oil will continue with increased sample numbers. Further germplasm releases are anticipated. Seed increase and evaluation of seed sent this year from Mexico will be evaluated this coming year.

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Weekly Reports

Support Staff

Cooperators

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PUBLICATIONS SPECIAL ISSUE

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Special Issue on the Management Improvement Program, conducted in the Maricopa-Stanfield Irrigation and Drainage District in Central Arizona from 1991-1994

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Technology Transfer

Following are summaries of the laboratory's major technology transfer accomplishments for 2000.

Irrigation and Water Quality

Scientist: John Replogle - Sediment-Resistant Flume for Measuring Stream Flows
Information on precipitation runoff, particularly from agricultural and mining sites, is important for applying and evaluating best management practices and remedial activities. Most of these sites are on intermittent gravel-bedded streams, which are difficult to measure because of their constant bottom and side-slope changes. Flow measuring flumes are an attempt to stabilize the shape changes, but sand and gravel dune movements quickly spoil attempts to measure storm runoff when they move into the usual flume or weir system. A special flume system devised by John Replogle from the USDA-ARS U. S. Water Conservation Laboratory in Phoenix, Arizona, overcomes these problems by combining his previously-developed computable flumes with a chute outlet that forces the dune sediments into suspended flow, which the chute can handle. Simultaneous measurements in both the computable flume and the chute allow the chute to be field-calibrated for use even after the original flume has been spoiled by dune movement. A recently completed laboratory study verified this concept, which had already been used on a field site in California based on preliminary design concepts proposed and constructed by Replogle.

Scientist: Eduardo Bautista - Release of Beta Version of Canal Scheduling Software
Eduardo Bautista of the U.S. Water Conservation Laboratory, Phoenix, Arizona, released a Beta version of a canal scheduling program to the Salt River Project, a major supplier of energy and irrigation water to the Phoenix area who is a cooperator in the development of this software. The program's purpose is to generate a sequence of canal gate operations (timing of the change and gate position increment) based on the known or anticipated water demands of a water delivery system. Currently, scheduling is done manually based on the field experience of operators. The proposed scheduling program uses a hydraulically-based approach. In addition to automating the schedule calculations, the resulting schedules are expected to provide a more accurate water level control. Furthermore, the program will provide operators an easy means of comparing alternative operational scenarios, especially in situations with multiple sources of water supply and when constraints need to be imposed on those supplies. The software has been programmed in the familiar Windows operating system. Objectives in the Beta testing are to identify program limitations, determine features needed to make the program more robust and user-friendly, and identify and correct programming bugs.

Scientist: Herman Bouwer - National Drought Policy Commission
As a member of the USDA Municipal and Industrial Working Group of the National Drought Policy Commission, Herman Bouwer of the USDA-ARS U. S. Water Conservation Laboratory, Phoenix, Arizona, advised on tools that local entities should have in place to mitigate potential drought impacts and, if necessary, to qualify for drought relief funds. Tools identified by the working group, and for which Dr. Bouwer provided expertise and guidance, included demand management, water conservation, water reuse, and artificial recharge of groundwater or other long–term storage in times of water surplus for use in times of shortage. The working group included municipal and industrial representatives.

Environmental and Plant Dynamics

Scientists: Francis Nakayama & Terry Coffelt - Release of Guayule Latex
Under a Trust Agreement with Yulex Corporation, scientists at the USDA-ARS U. S. Water Conservation Laboratory, Phoenix, Arizona; and Western Regional Research Center, Albany, California; produced and released a large quantity of latex to Yulex. The latex will be used to produce guayule latex products for manufacturer testing and further develop guayule as a hypoallergenic source of latex for fabricating medical products. Techniques developed in producing the latex have been shared with Yulex for their use in developing a pilot processing facility.

Scientists: Terry Coffelt, R.W. Mozingo, & T.G. Isleib - Release of New Peanut Cultivar
Scientists at the USDA-ARS U.S. Water Conservation Laboratory, Phoenix, Arizona; Virginia Tech University; and North Carolina State University have cooperatively developed and released VA 98R, a new Virginia-type peanut cultivar. VA 98R has large pods and seeds acceptable for the export market, matures earlier than current widely used cultivars, maintains its higher yields during the harvest season, and has brighter pod color than other cultivars. Seed have been released to the Virginia Crop Improvement Association for seed increase and is expected to be available to growers this year.

Scientist: David Dierig - Release of Two New *Lesquerella fendleri* Germplasm Lines
Scientists at the USDA-ARS U. S. Water Conservation Laboratory, Phoenix, Arizona; and the USDA-ARS George E. Brown Salinity Laboratory in Riverside, California; have developed and released a new line of *Lesquerella fendleri*, a potential new industrial oilseed crop, that will allow it to be grown on soils with saline irrigation problems. Lesquerella has been identified as potentially able to clean up contaminated soils by accumulating selenium, a harmful trace element found in soils, in its leaves and stems. The oil from lesquerella is used for industrial purposes, and the selenium bioaccumulation would not be transferred to the food chain. This new salt tolerant line allows lesquerella to be grown on more marginal soils where drainage effluents are reused, and it also provides germplasm with high genetic diversity for future improvements. Scientists at the U. S. Water Conservation Laboratory have also developed and released a new line of *Lesquerella fendleri* with improved oil content and seed yield compared to previously released germplasm lines that will significantly advance its commercialization. The new line provides a higher margin of profit for producers of the oil needed for many uses. Seed from these new lines are available upon request. 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 2000. 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.

Scientist: Edward M. Barnes - Precision Farming using Remotely Sensed Information
New tools are being developed to assist agricultural producers evaluate their precision farming practices. ARS scientists at the U. S. Water Conservation Laboratory in Phoenix, Arizona, are refining methods to integrate remotely sensed information from aircraft or satellites with computer models that predict crop growth based on weather and soil conditions. This research is being conducted to help meet the information needs for precision farming. In precision farming, the rate of agricultural inputs is varied according to plant needs at a very fine scale (as small as 1- m x 1-m). Remotely sensed data are used to provide the crop model with information on plant conditions at fine spatial resolution and at select times during the season. The model is then used to test different management scenarios in specific areas of the field.

Scientist: Eduardo Bautista - Large Open-Channel Water Delivery Systems Computer Program
ARS scientists at the U.S. Water Conservation Laboratory, in cooperation with the Salt River Project, a water and power provider in the Phoenix metropolitan area, have been working on the development and testing of a computer program for scheduling the operation of large open-channel water deliver systems. Currently, canal operational schedules are developed manually based on canal operator experience. The expectation is that the computerized scheduling approach will not only reduce the effort required to produce the daily schedules but will also improve the accuracy and flexibility of water deliveries. The proposed approach can be applied to delivery systems with centralized supervisory control capabilities, where changes in water demands are known in advance. Adoption of this technology will require significant buy-in and support from the operators. Therefore, tests are currently being conducted to compare computer program generated schedules with those developed by operators. In a following phase, the computer generated schedules will be implemented manually by the operators. Eventually, the schedules will be fed as a series of commands to the canal's SCADA (Supervisory Control and Data Acquisition) system for automatic implementation.

Scientist: Herman Bouwer - Clogging Layers in the Design and Management of Surface Water Impoundments
Research at the U.S. Water Conservation Laboratory has shown that clogging layers in ponds or basins can be friend or foe to water conservation efforts. Infiltration rates from surface impoundments like storage ponds, wastewater lagoons, wetlands, groundwater recharge basins, and storm water retention basins, generally decline with time as sediment and other suspended solids accumulate on the bottom. These sediments, along with biological and chemical reactions, then form a slowly permeable "clogging" layer. The thickness of this layer may vary from an inch or less if

the water is relatively clear and biological and chemical reactions are the main factors, to a foot or more if the water contains a lot of sediment (clay, silt, fine sand). Clogging layers are desirable where the main function of the impoundment is storage of water, or where the impoundment contains sewage effluent or other wastewater that should not contaminate underlying groundwater. Clogging layers are undesirable where the main function of the impoundment is infiltration for recharge of underlying groundwater or disposal of rainfall runoff. For both types of systems, there can be repeated or periodic inflow events with muddy water. The coarser soil particles will then settle out first, followed by finer particles until the sediment layer is topped with a thin layer of the finest clay or soil particles. This process repeats itself with subsequent inflow events, resulting in a layered sediment accumulation or soil "lining" with each layer also being individually graded from relatively coarse at the bottom to fine at the top. Column studies in the laboratory with silica sand as bottom showed that such layered linings gave greater reductions in infiltration rates than a compacted lining placed on the sand in a dry column using the same amount of soil. Thus, for engineered earth linings, it is more effective to apply the soil as slurries and in split applications to a water filled pond, than placing it on the bottom of a dry pond and compacting it. Also, for wetlands, this indicates that periodic inflows of muddy water can cause large decreases in infiltration rates so that plastic or other linings may not be necessary. The same can be true for storage basins. For recharge basins, it indicates the importance of avoiding sediment in the inflow water as much as possible. Pre-sedimentation or otherwise desilting of the water may then be desirable before it enters the recharge basins. Also, where sediment still accumulates on the bottom of the recharge basin, regular drying and removal of the clogging layer are necessary to maintain high infiltration rates. The clogging layer thus plays a major role in the design and management of surface water impoundments, regardless of whether infiltration into the bottom needs to minimized or maximized.

Scientist: Thomas R. Clarke - Cooperative U.S. - Canadian Experiment Gets Underway
Remote sensing has shown potential as a crop management tool, both as an input to crop management models and as a direct measurement of crop status. ARS scientists at the U.S. Water Conservation Laboratory (USWCL) in Phoenix, Arizona, and the South Central Agricultural Research Laboratory (SCARL) in Lane, Oklahoma, have joined Canadian counterparts at the Horticultural Research and Development Center in Saint-Jean-sur-Richelieu, Quebec, to develop this potential. USWCL remote sensing experts will take measurements on a broccoli crop grown at The University of Arizona's Maricopa Agricultural Center, and vegetable quality experts at SCARL will evaluate harvested broccoli. Their findings will be compared to remote sensing measurements to see if quality can be predicted from the plants' spectral signature. Canadian crop modelers will use remotely-sensed and physical parameters collected in the field to test a vegetable crop management model, developed for northern latitudes, for its applicability to other climates.

Scientist: Albert J. Clemmens - Desert Research Leads to Irrigation of Crawfish in Louisiana
For decades, ARS research scientists at the U.S. Water Conservation Laboratory in Phoenix, Arizona, have been developing methods to improve surface irrigation systems. Prior ARS research that led to application in Louisiana includes laser-controlled land grading, pioneered by ARS scientists in the mid-1970s; level-basin irrigation systems, used as a standard for high irrigation

efficiency in Arizona; and drain-back level basins, which allow lighter water applications and cost less to develop than conventional level basins. The use of these drain-back systems is growing in Arizona, with about 10,000 acres developed over the last four years. The distinguishing feature of drain-back level basins is their ability to drain excess water off the field. Farmers in Louisiana recognized the potential in this concept and, with the help of ARS Scientists and NRCS field-office personnel, developed a new level-basin system with surface drainage. Key features of a surface-drained level-basin system are precision land grading; level slope; and internal drainage ditches, constructed on a grid, that allow water from high rainfall events such as hurricanes to run off quickly. Farmers have found that in addition to achieving excellent drainage, they are able to irrigate more efficiently. Thus far, about 10,000 acres have been developed for rice, corn, wheat, soybeans, duck habitat, and crawfish!

Scientist: Terry Coffelt - Hypoallergenic Guayule Latex
An estimated 20 million Americans are now allergic to Hevea latex products. Guayule is a source of hypoallergenic natural rubber latex suitable for making medical products. Research by ARS and FDA has shown guayule latex to be an effective barrier against disease-causing viruses and bacteria. ARS scientists at the U. S. Water Conservation Laboratory in Phoenix, Arizona, and Western Regional Research Center in Albany, California, in cooperation with Yulex Corporation through a trust agreement are developing methods and techniques to harvest and extract latex from guayule. These tools can be used in constructing a prototype commercial-size extraction plant. Latex from the project will be used for formulation testing in making latex films. Knowledge obtained from this cooperative project will facilitate the commercialization of guayule.

Scientist: David Dierig - The Potential of Lesquerella
Scientists at the U. S. Water Conservation Laboratory in Phoenix, Arizona, and the U. S. Salinity Laboratory in Riverside have developed a new line of *Lesquerella fendleri*, a potential new industrial oilseed crop, that will allow it to be grown on soils with saline irrigation problems. Lesquerella has been identified as potentially able to accumulate selenium, a harmful trace element, from contaminated soils in its leaves and stems. The oil from lesquerella is used for industrial purposes, and the selenium bioaccumulation would not be transferred to the food chain. This new salt tolerant line allows lesquerella to be grown on more marginal soils where drainage effluents are reused and it also provides germplasm with high genetic diversity for future improvements. 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.

Scientist: Douglas J. Hunsaker - NRI Grant Awarded for Nitrogen Fertigation Guidelines
In July 2000, Soil Scientist Floyd Adamsen and Agricultural Engineer Douglas Hunsaker at the USDA-ARS, U.S. Water Conservation Laboratory, Phoenix, Arizona, were awarded a 3-year, $192,000, grant under the USDA-National Research Initiative-Competitive Grants Program to develop management guidelines for fertigation in surface irrigation systems. Proper fertigation practices can save labor, energy, and farm machinery costs. Improper practices can cause nitrate contamination of groundwater and surface water. These funds will be used to determine appropriate timing and duration of nitrogen injection during irrigation events for various surface irrigation

systems.

Scientist: Sherwood B. Idso - Atmospheric CO_2 Enrichment Yields More Oranges with Higher Vitamin C Concentrations

The World Health Organization recently reported that more than half the world's population is malnourished. To help alleviate this problem, agricultural research strives to determine how to boost crop productivity and improve nutrient content. In a long-term experiment, now in its 13th year, scientists at the U. S. Water Conservation Laboratory, Phoenix, Arizona, have evaluated the effects of a 75% increase in the air's carbon dioxide (CO_2) concentration on these two aspects of fruit production in sour orange trees. In years of normal productivity, the 75% increase in atmospheric CO_2 produced a 75% increase in the number of fruit harvested from the trees; and the vitamin C concentration of the juice was 5% greater than the juice of the fruit produced on the trees exposed to normal air. In anomalous years, when elevated CO_2 boosts fruit production by 200% or more, the CO_2-induced increase in orange juice vitamin C concentration can be as high as 15%. It was thus concluded that this dual benefit of the ongoing rise in the air's CO_2 content should be a great boon to humanity as both population and atmospheric CO_2 levels continue to rise.

Scientist: Francis S. Nakayama - Guayule Latex

An adequate supply of guayule latex has been unavailable for industry to fabricate and test hypoallergenic latex products which are sorely needed by the U.S. medical profession. Therefore, ARS researchers at the U.S. Water Conservation Laboratory, Phoenix, Arizona, and the Western Regional Research Center, Albany, California, through a Trust Agreement with Yulex Corporation, have developed a simple process to produce sufficient quantities of latex for expanded research. The technique is expected to provide guidelines for commercial production of latex. Latex was also provided to Yulex to enable them to produce reliable medical products. This work significantly advances the cultivation and commercialization of the water-conserving, arid-adapted guayule plant.

Scientist: Paul J. Pinter, Jr. - Remote Sensing Studies in Free-Air CO_2 Enrichment (FACE) Experiments

A powerful approach for monitoring the effects of global change on vegetation in the future has been developed and tested by scientists at the USDA-ARS, U. S. Water Conservation Laboratory in Phoenix, Arizona. They have observed that the accuracy of satellite estimates of agricultural plant productivity are unlikely to be affected by rising levels of atmospheric carbon dioxide. This work is part of the Free-Air CO_2 Enrichment (FACE) research at Maricopa, Arizona, in which plants growing in open-fields are exposed to levels of CO_2 expected to occur by the middle of the 21st century. Since the FACE technique exposes plants to natural levels of light, water, and nutrients without the complications and measurement problems caused by artificial chambers, it is an ideal approach for use in remote sensing validation studies. The research was conducted using ground-based sensors similar to those on satellite systems. FACE results are applicable to large-scale production agriculture and thus far, the experiments at Maricopa have included wheat, sorghum, and cotton, important worldwide food and fiber crops.

Scientist: John Replogle - Investigation of Flume Calibration Variances
Engineers at the U.S. Water Conservation Laboratory, ARS, Phoenix, Arizona, are addressing reports of a few flumes that have been constructed for measuring water, which, when field calibrated, appear to deviate from expected behavior. While hundreds of thousands of flumes are in use worldwide, such calibration problems have only been experienced with a few. These flumes include a large Parshall flume that deviates from published calibrations by over 20%, and some trapezoidal broad-crested weirs with unusually high overfalls that appear to over-discharge about 6 % at maximum flows. Laboratory studies on models of Parshall flumes fail to reproduce these differences. Thus, the original published calibration may need review. Currently, a trapezoidal broad-crested weir is under study to investigate problems associated with the high overfalls and provide guidance for correcting them. Assuring accurate flow measurements is important to ongoing water conservation efforts.

Scientist: Theodor Strelkoff - Surface Irrigation Software Development
The surface-irrigation software development group at the USDA-ARS, U.S. Water Conservation Laboratory in Phoenix, Arizona, together with the ARS Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho, received a three-year NRI grant from CSREES to incorporate a phosphorus transport and fate component into the existing surface-irrigation simulation program, SRFR. Phosphorus, an essential plant nutrient applied to many crops can be discharged into receiving streams with the irrigation-water runoff, encouraging algal growth and eutrophication of receiving water bodies. Simulation will allow users to test a variety of "what-if" scenarios aimed at reducing phosphorus discharges while maintaining uniform and efficient irrigation. Potential users include NRCS field offices, consultants, extension personnel, and universities.

Sccientist: Gerard W. Wall - Global Change Impact on Wheat Production
Atmospheric carbon dioxide (CO_2) concentration is rising, and little is known about the effects of elevated CO_2 on future world sorghum production. Sorghum grain production is 6th in acreage in the U.S., 2nd in Africa, and 4th in the developing countries as a whole. Because of concerns about food security, sorghum has been identified as high priority for global change research. Scientists from the USDA-ARS, U.S. Water Conservation Laboratory, Phoenix, Arizona, and from The University of Arizona, Tucson, Arizona, as well as others, investigated the relationship between atmospheric CO_2 and growth by exposing a sorghum crop in an open field to about 50% more CO_2 than is present in the earth's atmosphere today. The sorghum was grown with both ample and reduced water supplies. Results indicated that when water was in ample supply, elevated CO_2 had a nominal effect on sorghum growth and yield. In contrast, limited water had a substantial (15%) stimulating effect on the elevated CO_2 yield. Consequently, on a relative basis, the beneficial effect of a rise in atmospheric CO_2 concentration on productivity will be greater for water-stressed than well-watered sorghum. More efficient use of water by sorghum plants in a future high CO_2-world will be beneficial to both producers and consumers, particularly during a drought year.

U. S. WATER CONSERVATION LABORATORY SUPPORT STAFF

PERMANENT EMPLOYEES

Name	Title
Adamsen, Floyd J.	Soil Scientist
Arterberry, Carl K.	Agricultural Science Research Technician (Soils)
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Bautista, Eduardo	Agricultural Engineer
Bouwer, Herman	Research Hydraulic Engineer
Clarke, Thomas R.	Physical Scientist
Clemmens, Albert J.	Lab Director, Res Leader, and Res Hyd Engineer
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Hodge, Vanessa J.	Budget and Accounting Assistant
Lee, Richard E.	Custodial Worker
Martin, Kevin R.	Air Conditioning Equipment Mechanic
Sexton, Judith A.	Purchasing Agent
Steele, Terry L.	Occupantional Safety
Wiggett, Michael R.	Administrative Officer
Worthen, Michelle	Office Automation

TEMPORARY EMPLOYEES

Name	Title
Adam, Neal R.	Plant Physiologist
Amann, Michael A.	Engineer Technician
Bierly, Pierre-Charles	Engineer Technician
Bishop, Lerey R.	Engineer Aid
Chinn, Sarran	Biological Science Aid
Conley, Matthew M.	Billogical Science Technician (Plants)
DeGraw, Christa L.	Office Automation
DeGraw, Lisa L.	Office Automation
Dhalakia, Mital	Engineering Technician
Eshelman, Trathferd G.	Science Technician
Faber, Amy	Physical Science Technician
Gilbert, Kathleen	Biological Science Aid
Jacob, Sally J.	Biological Science Aid
Jacques, Daniel	Physical Science Technician
Kaiser, Aaron R.	Biological Science Aid
Luckett, William E.	Physical Science Technician
Olivieri, Laura M.	Biological Science Technician
Schmidt, Baran V.	Computer Programmer Assistant
VanMeeteren, Kandy K.	Biological Science Technician
Vu, Duong H.T.	Engineering Technician
Waichulatis, Steve R.	Biological Science Aid

TEMPORARY STATE EMPLOYEES

Name	Title
Brooks, Talbot J.	Research Technician
O'Brien, Carrie C.	Research Laboratory Assistant (Staff)
Richards, Stacy	Biological Science Aid
Strelkoff, Fedja	Research Hydraulic Engineer/Research Professor (U of A)

Tomasi, Pernell M.	Research laboratory Assistant
Triggs, Jonathan M.	Biological Science Aid

COOPERATORS

UNIVERSITIES

Arizona State University	Tempe, Arizona
Department of Botany	
Department of Civil and Environmental Engineering	
Department of Geography	
Department of Plant Biology	
National Center for Renewable Water Supplies	
California Polytechnic State University	San Luis Obispo, California
Cancer Research Center	Tempe, Arizona
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
Peter-Gules van Overloop, van Overloop Consultancy	The Netherlands
Royal Veterinary and Agricultural University	Toastrup, Denmark
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
	Yuma, Arizona
University of Arizona - Don Slack	Tucson, Arizona
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 Montana	Missoula, Montana
Division of Biological Sciences	
University of Twente	The Netherlands
University of Wisconsin	Madison, Wisconsin
University of Wyoming	Torrington, Wyoming
Research and Extension Center	
Utah State University	Logan, Utah
Vrie Universiteit of Amsterdam, University of Amsterdam	Amsterdam, Netherlands

STATE, COUNTY, AND CITY AGENCIES

California Water Quality Control Board	Oakland, California Sacramento, California
Imperial Irrigation District	Imperial, California
The City of Surprise	Surprise, Arizona
Coachella Valley Resource Conservation District	Coachella, California

FEDERAL AGENCIES

NASA Goddard Institute for Space Studies	New York, New York
National Germplasm Resources Laboratory	Beltsville, Maryland
Natural Resources Conservation Service	Portland, Oregon; Phoenix, Arizona
National Water and Climate Center	
Oak Ridge National Laboratory	Oak Ridge, Tennessee
U.S. Army Garrison	Fort Huachuca, Arizona
U.S. Department of Energy	Washington, DC
Atmospheric and Climate Research Division	
Office of Health and Environmental Research	
Idaho National Engineering & Environmental Lab	Idaho Falls, Idaho
U.S. Bureau of Reclamation - Hydraulics Laboratory	Denver, Colorado
USDA-ARS Citrus and Subtropical Products Laboratory	Winter Haven, Florida
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 Conservation Laboratory	Phoenix, Arizona
USDA-ARS Water Management Research Lab	Fresno, California
USDA-ARS Western Wheat Quality Laboratory	Pullman, Washington
USDA-Forest Products Laboratory	Madison, Wisconsin

OTHER

Automata, Inc.	Nevada City, California
Brookhaven National Laboratory	Upton, New York
Buckeye Irrigation District	Buckeye, Arizona
Carnegie Institution of Washington	Stanford, California
CDS Ag Industries	Chino, California
CEMAGREF-Irrigation Division	Montpellier, France
Center for the Study of Carbon Dioxide and Global Change	Tempe, Arizona
Citrus Research and Education Center	Lake Alfred, Florida
The City of Tolleson	Tolleson, Arizona
CSIRO Wildlife and Ecology	Lyneham, ACT, Australia
GCTE (Global Change Terrestrial Ecosystems) Wheat Network	Oxon, UK
Gila River Farms	Pinal County, Arizona
Global Water	Fair Oaks, California
IMTA (Mexican Institute for Water Technology)	Cuernavaca, Mexico
Institute of Soil and Water Conservation Chinese Academy of Sciences Ministry of Water Resources Engineering	Shaanxi, China
Instituto de Agricultura Sostenible	Cordoba, Spain
ITESM	Monterrey, Mexico
Maricopa-Stanfield Irrigation & Drainage District	Stanfield, Arizona
McKemy Middle School	Tempe, Arizona
Milczarec of GeoSystems, Inc.	Tucson, 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 High School	Tempe, Arizona
Valmont Industries	Valley, Nebraska
Wellton-Mohawk Irrigation & Drainage District	Wellton, Arizona