ANNUAL RESEARCH REPORT

1990

U. S. WATER CONSERVATION LABORATORY
U. S. Department of Agriculture
Agricultural Research Service
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INTRODUCTION

The U. S. Water Conservation Laboratory (USWCL) Annual Research Report is intended to inform upper level management within the Agricultural Research Service, other ARS research locations involved in natural resources research, and our many collaborators and cooperators about progress made on our research projects in 1990 and plans for 1991. It is our intent to keep the individual reports short but informative, focusing on what is being done and why, specific objectives of the research, the approach to the problem, brief results, what (and so what?) it all means, future plans for the project, and cooperators involved. We want to make sure it is clear what the product of the research will be (or is) and how it contributes to water conservation. For the USWCL staff, it is an opportunity to tell their research story, and in so doing tell the research story for the USWCL as a whole.

The overall mission of the U. S. Water Conservation Laboratory is to conserve water and protect water quality in systems involving soil, aquifers, plants, and the atmosphere. Research thrusts focus on irrigation systems efficiency; management of irrigation systems; methods for scheduling irrigations; remote sensing of crop, soil, and atmospheric conditions; practices for protection of groundwater from agricultural chemicals; introduction of new crops; and the effect of future increases of atmospheric CO_2 on climate and associated yields and water requirements of agricultural crops.

The USWCL program was restructured during 1990. The research programs were refocused on high priority research areas, with emphasis on management of water quality and quantity, changes in the global environment, new crops, and remote sensing. The number of Management Units (MUs) was reduced from four to two. The new Irrigation and Water Quality Research Unit (I & WQ) will focus on water management with emphasis on irrigation and water quality. The new Environmental and Plant Dynamics Research Unit (E & PD) will include work on carbon dioxide-climate change, germplasm development for new crops, and remote sensing. Restructuring allowed us to combine expertise into fewer MUs to provide the necessary manpower to successfully approach research problems.

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 uses holistic approaches to develop concepts and tools for improving the design, operation, and management of both farm irrigation systems and irrigation water delivery systems. In particular, this includes developing best management practices for water and chemical applications, characterizing the movement and degradation of agricultural chemicals below irrigated fields, developing water measurement and control structures, and integrating farm and project operations and management. The research consists of field research studies, laboratory studies, and mathematical/computer modeling. Technology transfer efforts focus on management improvement processes in which users actively participate, thereby expediting acceptance, and on user friendly computer software.

The mission of the Environmental and Plant Dynamics Research Unit is to develop optimum resource management strategies to meet national agricultural product requirements within the context of possible changes in the global environment. Specifically, the unit seeks to develop new methods to assess water and carbon dioxide fluxes in the soil-plant-atmosphere system, quantify plant stress and its effect on crop yield and to predict effects of increasing carbon dioxide and climate change on plant growth and water use; develop suitable new and alternative crops to meet national needs for renewable, agriculturally-based industrial products; and develop remote sensing and related techniques as tools in water conservation, irrigation scheduling, drought prediction and avoidance, and to monitor crop conditions and assess environmental change. The program is designed to meet challenges and opportunities imposed by dynamic environments, particularly those stressful to plants, and their possible effects on crop production. A theme of increasing plant water use efficiency and conserving and improving the quality of agricultural water supplies unites these efforts. To these ends, the organization is closely knit and multidisciplinary, underlain by a philosophy of devising multifaceted approaches to critical problems associated with global environmental changes.

Along with restructuring the USWCL research programs, leadership responsibilities have been realigned, requiring two Research Leaders compared to the previous four. I was appointed Laboratory Director and Drs. Bert Clemmens and Bruce Kimball Research Leaders for the I & WQ and E & PD Management Units, respectively. The organizational structure for the USWCL is shown as Figure 1 and the entire USWCL personnel list as Table 1.

We believe the recently created positions of Chief Scientist and Chief Engineer can serve a very useful purpose to ARS and the Laboratory. The Chief Scientist and the Chief Engineer are responsible for maintaining an active research program while serving as mentors to the entire Laboratory staff on matters ranging from program development and technical and administrative issues to professional ethics, career development, and manuscript writing. They may serve as advisors within ARS and to universities, private institutions, professional societies, and other government agencies. We feel that such positions can help promote ARS in general and the U.S. Water Conservation Laboratory in particular and enhance the research and service capabilities of the Laboratory to user groups, to the general public, and to political entities. They further facilitate the involvement of the Laboratory in research and technology transfer on national and international levels.

We invite you to use this Annual Research Report. Let us know if there are questions or comments; all are invited and will be appreciated.

Allen R. Dedrick
Director

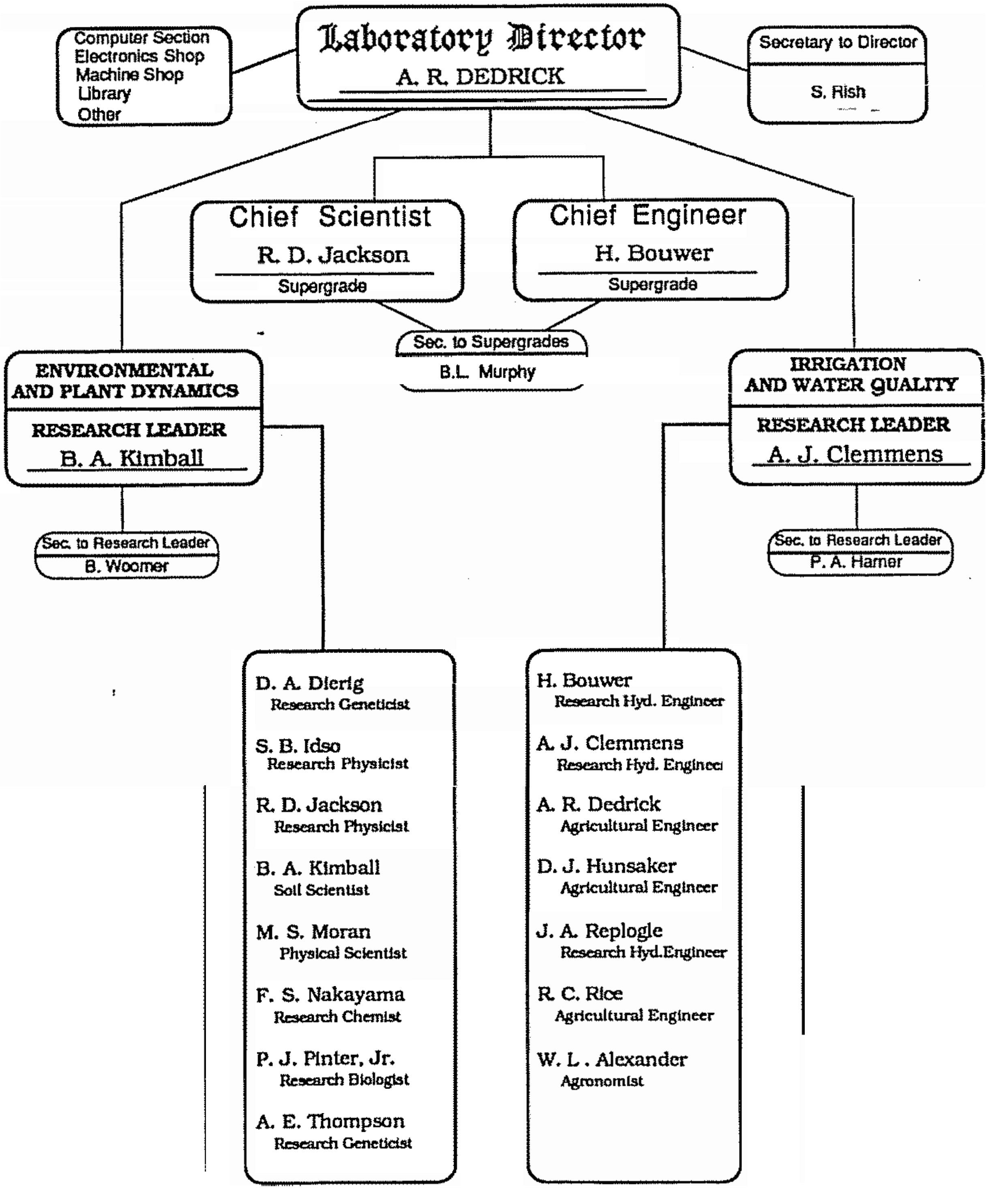

Fig. 1. U. S. Water Conservation Laboratory Organization, December 31, 1990

Table 1. U.S. Water Conservation Laboratory Staff

PERMANENT EMPLOYEES

Name	Title
Alexander, William L.	Agronomist
Allen, Stephen G.	Research Plant Physiologist (resigned 3/23/90)
Anderson, Robert J.	Biological Technician
Arterberry, Carl A.	Agricultural Research Technician
Auer, Gladys C.	Physical Science Technician
Bouwer, Herman	Research Hydraulic Engineer
Clarke, Thomas R.	Physical Science Technician
Clemmens, Albert J.	Research Hydraulic Engineer
Craft, Michael R.	Physical Science Technician
Davis, Sonya G.	Engineering Draftsman (resigned 2/90)
Dedrick, Allen R.	Laboratory Director and Agricultural Engineer
Dierig, David A.	Research Geneticist (Plants)
Gerard, Robert J.	Laboratory Support Worker
Harner, Paulina A.	Secretary
Hunsaker, Douglas J.	Agricultural Engineer
Idso, Sherwood B.	Research Physicist
Jackson, Ray D.	Research Physicist
Jaynes, Dan B.	Soil Scientist (transferred 7/14/90)
Johnson, Earl J.	Agricultural Research Technician (Plants)
Johnson, Stephanie	Biological Technician
Kimball, Bruce A.	Soil Scientist
Lewis, Clarence L.	Machinist
Martinez, Juan M. R.	Hydrological Technician
Mastin, Harold L.	Computer Assistant
Mills, Terry A.	Computer Programmer Analyst
Moran, M. Susan	Physical Scientist
Murphy, Benita L.	Secretary
Nakayama, Francis S.	Research Chemist
Padilla, John	Engineering Technician
Palmer, Joel D.	Agricultural Engineer (resigned 9/8/90)
Peresta, Gary J.	Physicial Science Technician (resigned 6/16/90)
Pettit, Dean E.	Electronics Engineer
Pinter, Paul J., Jr.	Research Biologist
Rasnick, Barbara A.	Physicial Science Technician
Replogle, John A.	Research Hydraulic Engineer
Rice, Robert C.	Agricultural Engineer
Risb, Shirley A.	Secretary
Seay, L. Susan	Publications Clerk
Seay, Ronald S.	Agricultural Research Technician
Thompson, Anson E.	Research Plant Geneticist
Woomer, E. Elizabeth	Secretary

TEMPORARY EMPLOYEES

Aberouette, Maritza	Physical Science Aide
Amthor, Jeffrey S.	Plant Physiologist-Res. Assoc. (resigned 12/90)
Baros, Michael J.	Physical Science Aide (resigned 8/24/90)
Bertrand, Brenda L.	Biological Aide (resigned 8/10/90)
Cho, Hyung-Yul	Soil Scientist-Res. Assoc. (resigned 1/5/90)
Coble, Carrie	Biological Aide (resigned 1/26/90)
Corsnitz, Kimberly E.	Work Study, AZ State University
Domer, Gregory S.	Biological Aide (8/30/90)
Hozhabri, Terri J.	Biological Aide (resigned 8/10/90)
Klosterman, Evelyn M.	Biological Aide
Kracinski, Kevin A.	Physical Science Aide (Exp. of Employment 10/90)
Motle, James S.	Physical Science Aide
LaMorte, Robert L.	Biological Aide
Padilla, Janet R.	Biological Aide
Perschbacher, M.	Biological Aide
Sunshine, Mary J.	Biological Aide (resigned 12/2/90)
Stremel-Schilreff, Susan M.	Biological Aide (resigned 3/10/90)
Strand, Robert J.	Engineering Aide
Wahlin, Brett R.	Work Study, AZ State University

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MANAGEMENT IMPROVEMENT PROGRAM (MIP) FOR IRRIGATED AGRICULTURE

A. R. Dedrick, Laboratory Director, A. J. Clemmens, Supervisory Research Hydraulic Engineer, and J. D. Palmer, Agricultural Engineer

PROBLEM: Improved water management is an essential component of a sustainable irrigated agriculture. Farmer and district operations must change in ways that are consistent with long-term resource management, environmental protection, and social well-being. Across the irrigated West, the most immediate problem farmers face is increasingly scarce water supplies. Many are experiencing a physical shortage, while for others, scarcity takes the form of increased delivery charges. In some areas, supplies are scarce because of regulatory limits on the amount of water farmers can use. And the energy cost of water is increasing for all. These changes are occurring rapidly, and farmers must respond rapidly with improvements in their irrigation systems if their operations are to remain viable. But the performance and even the design of an on-farm irrigation system depend, to a great extent, on the water delivery system. Western U.S. farmers, especially those in irrigation districts, will be forced to reexamine their whole approach to water management. Other changes for farmers include losing control of their own water supply. For example, farmers in central Arizona increasingly have to arrange water deliveries with a district instead of operating their own pumps. Further, flow rates may be several times greater than those from on-farm pumps, creating need for changes in the way water is delivered to individual fields.

But the transfer of new methods and technology in agriculture is traditionally slow, sometimes taking decades or even generations from introduction to full adoption. Most western farmers will not have the luxury of waiting to see what their neighbors do since almost all are experiencing the same pressures to improve their operations. If government agencies and research and technology transfer organizations are themselves to respond to this urgent need for changes in irrigation, they must develop new approaches to making lasting improvements.

The purpose of this work is to carry out a demonstration Management Improvement Program (MIP) for irrigated agriculture within one or more irrigation districts through a coordinated interagency effort. The MIP, a management process not unlike that commonly applied in the management of business organizations, but in this instance applied to an irrigation system (district) to evaluate water resources management in the district with respect to economics and environmental quality; identify opportunities for improvement on farm, district, and government operations; and implement and evaluate appropriate changes. The general approach to the MIP is illustrated in Figure 1. Program participants will evaluate the MIP process as a tool for improving resource management and implementing organizational change. Specific objectives include 1) improved communication and collaboration among farmers, districts, and government agencies, which will strengthen working relationships and eliminate duplication of roles among agencies; 2) better understanding of the current status of, and problems and opportunities in, water resources management, including irrigation district operations and on-farm water management and similarities and differences between districts; 3) identification, selection, and implementation of alternative actions (research/educational programs) to improve irrigation management, farm irrigation system, and water delivery system operations and management; 4) increased farmer profit/benefit; and 5) increased understanding of the MIP process as a tool to apply in a range of situations.

APPROACH: A workshop for planning an interagency management improvement program was held on April 10-12, 1990. A list of participants and affiliation is shown as Table 1. The objectives of the workshop were to 1) reach a common understanding of the purpose, outcomes, and approach of a management improvement program; 2) clarify the roles, responsibilities, and interests of the range of stakeholders involved in the MIP; 3) develop an overall strategy and an action plan for initiating the MIP, identifying participants, activities, resource needs, etc.; 4) identify needs for interagency agreements and plans for addressing these agreements; and 5) strengthen the cooperators' ability to work effectively as a team. The overall purpose of the MIP program, as described in the previous section, was an important outcome of the planning workshop.

An MIP Coordinating Group (* in Table 1 indicates MIP Coordinating Group [MIP CG] member) was organized to provide overall leadership to the demonstration MIP. The MIP CG met three times during 1990, focusing on 1) selection of an irrigation district; 2) preparation of a general work agreement for the MIP; 3) development of funding strategies and associated reimbursable cooperative agreements; and 4) development of a guideline for completion of the MIP.

FINDINGS: A reimbursable cooperative agreement (RCA) was developed among the six cooperating agencies. Companion documents to the RCA include a general work agreement and planning guidelines for the MIP. Cooperators intend to provide funding for costs of outside consultants (about $147,000) and travel and per diem expenses for ARS personnel (about $12,000). A tentative breakdown for funding is: U.S. Bureau of Reclamation (BOR) 80% of the cost to complete the MIP, Soil Conservation Service (SCS) $10,000, and Arizona Department of Water Resources (ADWR) $20,000. At the end of 1990 the RCA was yet unsigned, and funding transfers had not been completed.

Criteria for irrigation district participation in the MIP were developed based on, but not limited to, the following: 1) the district desires to participate, or has special circumstances or incentives (e.g., increasing scarcity or cost of water); 2) farm water supplies are entirely controlled by the district; 3) the district is within the state of Arizona and has a water delivery contract and/or Small Reclamation Project Act loan contract with the Secretary of the Interior; 4) there are significant opportunities for improvements within the district; 5) the district is in an area where the ADWR or the BOR can make financial and in-kind contributions to the MIP; 6) the district is of "manageable" size or can be conveniently subdivided into smaller study areas; 7) the MIP results from the district can be expected to relate to other districts; 8) there is a perceived high potential for the district to successfully implement a management improvement program; and 9) the district delivers the major part of its water to agricultural users.

Fourteen districts in Arizona met these criteria and were invited by letter to participate. Six did not respond, three responded hy letter, and the remaining five by telephone. All but one (Yuma County Water Users) declined for various reasons. A meeting was held on December 12, 1990, with the management staff of the Yuma County Water Users to discuss possible participation in the MIP demonstration project. Subsequent to the telephone declination from the Maricopa-Stanfield Irrigation and Drainage District (MSIDD), we met with the district manager and engineer to further discuss the district's participation. The MSIDD Board of Directors approved MSIDD participation in the MIP demonstration project at their board meeting on December 13, 1990. The MIP Coordinating Group selected MSIDD as the irrigation district in which the MIP will be demonstrated.

INTERPRETATION: Major changes will be essential for irrigated agriculture to survive. The demonstration Management Improvement Program is an attempt to respond to these challenges. The MIP is explicitly designed to respond to the needs of farmers and districts and to create appropriate solutions. The MIP will bring to bear the combined expertise of the Agencies on problems that each would otherwise approach separately. The MIP emphasizes team-building and organizational changes that promote coordination and cooperation among many stakeholders in irrigation water management issues.

FUTURE PLANS: The demonstration MIP will be initiated in the Maricopa-Stanfield Irrigation and Drainage District during 1991.

COOPERATORS: Maricopa-Stanfield Irrigation and Drainage District, U. S. Bureau of Reclamation, Soil Conservation Service, The University of Arizona Cooperative Extension, Arizona Department of Water Resources, and Arizona Department of Environmental Quality.

Table 1. Participants, Interagency Management Improvement Program Workshop, April 10-12, 1990.

* Allen R. Dedrick (MIP Coordinator)
Laboratory Director and Agric. Engr.
USDA, Agricultural Research Service
U.S. Water Conservation Lab.
Phoenix, AZ

Andrea Jones, Prog. Ldr.
(MIP Mgmt. Planner)
International Development Mgmt Center
University of Maryland
College Park, MD

Wayne Clyma (MIP Specialist)
Agricultural Engineer
Dept. of Ag. & Chem. Engineering
Colorado State University
Ft. Collins, CO

<u>U. S. Bureau of Reclamation</u>

Bob Johnson, Regional Supervisor
Water Land and Power
Lower Colorado Region
Boulder City, NV

* Stanley G. Conway, Chief
Irrigation Mgmt. Services Br.
Lower Colorado Region
Boulder City, NV

<u>Soil Conservation Service</u>

Donald W. Gohmert, State Conservationist
Phoenix, AZ

Leland A. Hardy
Water Management Engineer
Midwest Technical Management Center
Lincoln, NE

* Robert B. Crawford, State Resource Cons.
Phoenix, AZ

Harry Millsaps
Hydraulic Engineer
Phoenix, AZ

<u>University of Arizona</u>

* Thomas S. Scherer
Extension Irrigation Specialist
Cooperative Extension
Maricopa Agricultural Center
Maricopa, AZ

<u>Arizona Department of Water Resources</u>

* Thomas G. Carr, Director
Pinal AMA
Casa Grande, AZ

<u>Arizona Department of Environmental Quality</u>

* James F. DuBois
Hydrologist
Tucson, AZ

Melanie Redding
Hydrologist
Phoenix, AZ

<u>USDA/Agricultural Research Service</u>

Joel D. Palmer, Research Hydraulic Engr.
(formerly) U.S. Water Cons. Lab.
Phoenix, AZ

Albert J. Clemmens, Research Leader and
Research Hydraulic Engr.
U.S. Water Conservation Lab.
Phoenix, AZ

* MIP Coordinating Group Member

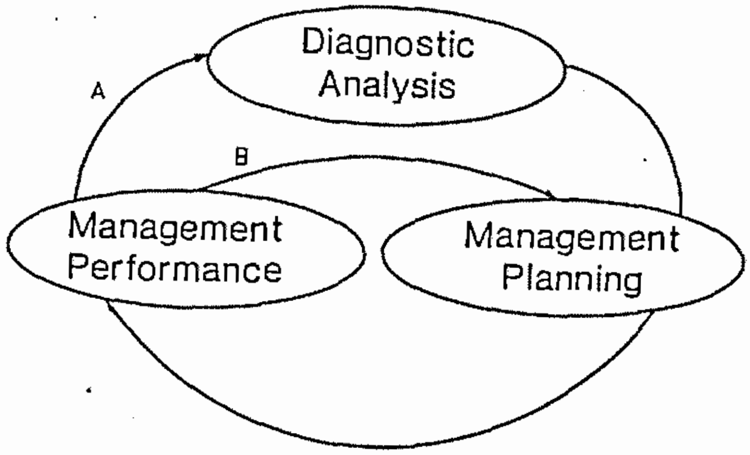

Figure 1. Management Improvement Process phases for improving the performance of irrigated agriculture.

MONITORING AND EVALUATION OF IRRIGATION CANAL DELIVERIES

A. J. Clemmens, Research Hydraulic Engineer, A. R. Dedrick, Agricultural Engineer
and J. D. Palmer, Research Hydraulic Engineer

PROBLEM: The rate of water delivery from an irrigation district to a farmer's field via open channels is inherently nonuniform because of the transient nature of open channel flow. In general, the more flexible the delivery of water, in timing, rate, and duration, the more transient the flow. These variations in delivery flow rates have caused considerable difficulty in the automation of farm irrigation systems and generally cause farmers problems in handling these flows. This is particularly a problem where siphon tubes are used to transfer the water from the farm canal to the field because the number of tubes must be varied as the flow changes. In terms of farm water use, these varying flows cause farmers to apply different amounts of water to different fields, thereby affecting the overall farm application efficiency. In addition, the variations in flow bring into question whether the farmer is being charged for the correct volume of water where only periodic flow rate measurements are taken.

The objectives of this research were 1) to quantify the magnitude of the flow fluctuations and their impact on farm irrigation operations, 2) to identify the causes of delivery flow fluctuations and possible methods for mitigating them, and 3) to determine how accurately water is delivered and accounted for within irrigation districts.

APPROACH: In 1985, we started a program of intensively monitoring lateral canals within an irrigation district in the arid southwest U.S. We installed flumes in the laterals at the canal headings and at a point in the laterals beyond which typically only one delivery was made and in the farm canals just downstream from the farm turnout from the lateral. Thus, we were able to monitor all inflows to and outflows from each lateral. We installed instrumentation on each flow measuring device to measure the water level, which can be translated to flow rate. Instrumentation was also used to monitor canal water levels both upstream and downstream of all check gates and at each turnout and to monitor check gate openings. This allowed us to obtain a relatively complete picture of what occurred on the lateral.

One lateral was monitored nearly continuously from July 1985 to December 1988. A second canal was monitored from July 1987 to December 1988. In addition, district records on water ordered and billed were collected for 1987 and 1988. Several farmers' canals were monitored in 1987 and 1988 to determine the distribution of water to basins within the fields and to determine the impact of fluctuating flows on this distribution.

In December 1988, a rapid diagnostic analysis (DA) was performed on the district and farm operations to determine some of the causes for the observed performance and possible impacts on farm operations. This DA consisted mostly of interviews with district personnel (at all levels from manager to ditchrider) and with farm personnel (owner, manager, irrigator, etc.).

FINDINGS: Fluctuation in delivery flows was expressed in terms of the coefficient of variation (CV) (standard deviation divided by means). For the 286 measured deliveries from July 1985 to June 1987, the CVs ranged from 0.01 to 0.5. They were approximately log-normally distributed with 75% having CVs < 0.14. The uniformity of delivery was slightly better in spring than in the fall and better when the delivery started during the day than during the night. Deliveries were slightly more variable at low flow rates than at high flow rates. Duration of delivery did not impact variability. Flow variability increased slightly with distance from the head of the lateral canal but was influenced more by site conditions. Fluctuations were greater at turnouts that did not have a canal check structure (i.e., in the middle of a pool between two check structures) than those immediately adjacent to a check structure. Variability in delivery was not affected by relief ditchriders when compared to regular ditchriders.

The fluctuating flows affected the distribution of water to individual basins. These data have not been completely analyzed, but it appears that the farmers were not able to mitigate the effects of the fluctuating flows.

Data over two 3-month periods indicated that of the deliveries measured, more than half were not ordered according to official policy (four days in advance), and about one in six deliveries was not billed (Fig. 1). Of the deliveries officially ordered, the district delivered about three out of four within one day of the day ordered (as allowed by official policy), with more of the remaining deliveries late than early. Farmers were more likely to place official orders in the late summer than early spring, and deliveries were more often late in the late summer.

On the average, the district delivered the duration ordered but delivered slightly less than the ordered rate. Examples of ordered, measured, and delivered hydrographs are shown in Figure 2. The district delivered within 10% of the ordered duration 87% of the time, while it delivered within 10% of the requested flow rate (on the average) 33% of the time. The district was more apt to deliver the ordered duration than to bill the actual delivered duration. The district billed within 10% of the delivered duration about 50% of the time (down from 87% for actual versus delivered). Actual flow rates were within 10% of billed flow rates 43% of the time. There was a tendency to bill for a flow rate between that originally ordered and that actually delivered.

The district operates a very flexible delivery system without the aid of a supervisory control system and without off-line storage. They had been able to unofficially relax the official rules to provide more prompt service and had been ordering extra water from the river to provide for late requests. Unofficial policies appear to put extra stress on operating personnel who are on call 24 hours a day.

INTERPRETATION: Conservation of water in irrigated agriculture must be viewed from district, project, and river basin perspectives if it is to have any real impact on water supplies. This study indicates that even in a well-run district, water delivery is imprecise. This study provides some understanding of the nature of the imprecision and some of the reasons behind it. At this point, these results cannot be generalized to all districts but simply identify water delivery characteristics that were measured in one irrigation district. Further, the study emphasizes the need to understand how the system is managed and operated rather than relying on data collected. In many districts, such as the one studied here, this imprecision in delivery may have little negative impact on either farm profit or the environment. However, in other districts, such information might be useful in improving delivery and on-farm performance. As the competition for water supplies becomes greater, the results of this study can be used as a guide for districts to view their own water delivery performance.

FUTURE PLANS: The project has essentially been completed. The field data collection was completed in 1988, with the DA continuing into early 1989. The final manuscripts on the project were submitted for publication in 1990, the results of which were discussed extensively with irrigation district representatives. The DA and monitoring results potentially could be used as guides for initiating some program changes by the irrigation district. If such program changes are initiated, we would cooperate by evaluating the impact of the changes made.

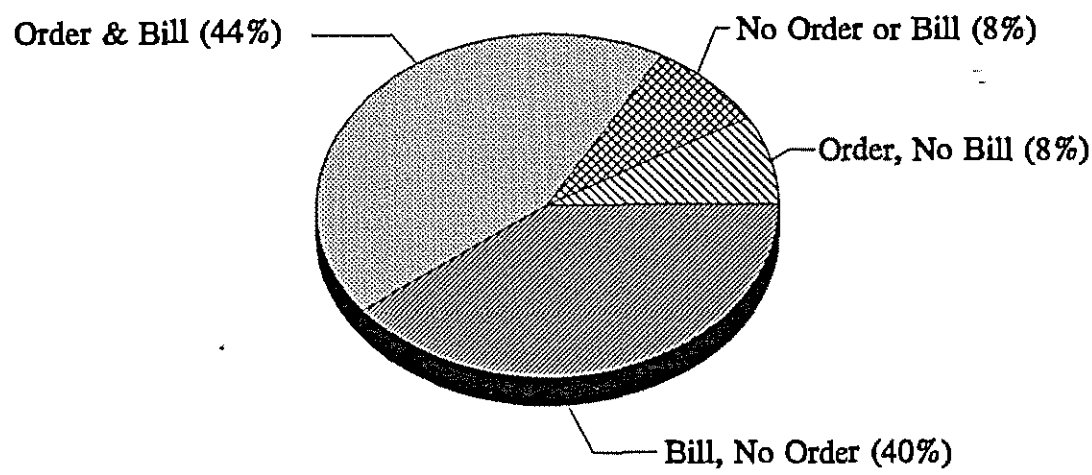

Figure 1. Portion of measured deliveries with corresponding orders and/or bills.

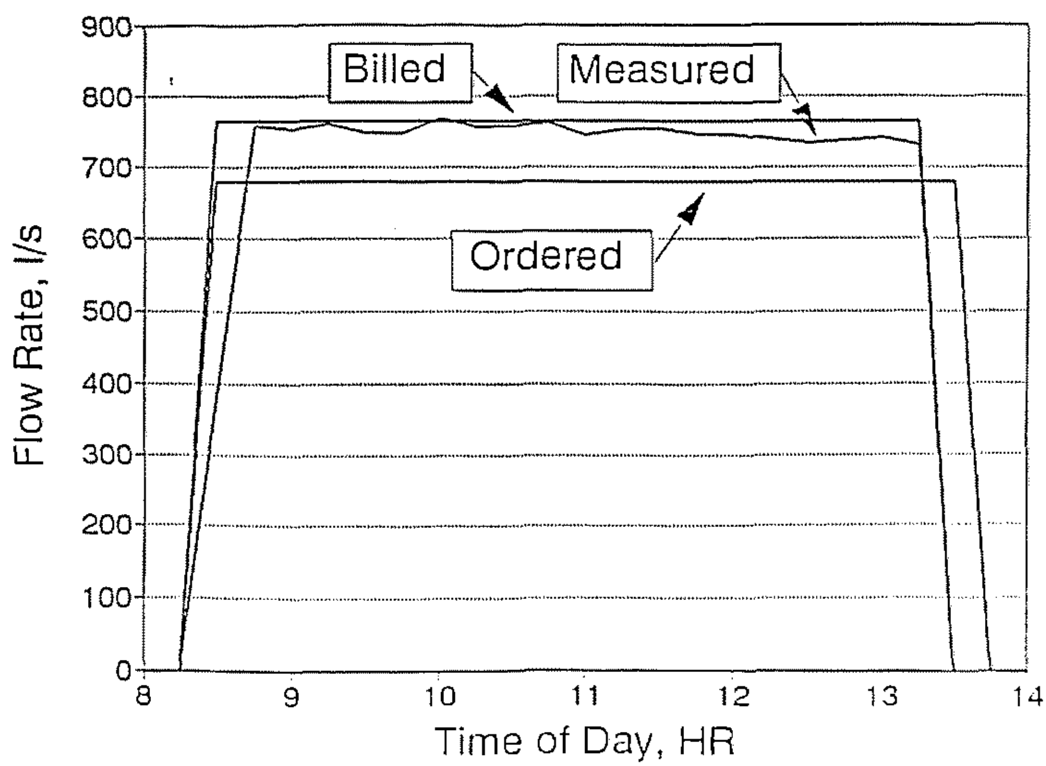

Figure 2. Ordered, measured and billed hydrographs for a single farm delivery.

SURFACE IRRIGATION FEEDBACK CONTROL

A. J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Application efficiencies for surface irrigation systems continue to be poor despite advances in irrigation modeling and science. Efficiencies continue to be poor for a number of reasons. In many cases, the irrigator or farmer has not chosen the correct flow rate or does not have sufficient control over flow rate. In other cases, the wrong application time is used, or a combination of wrong flow rate and application time are used. Proper design can sometimes greatly improve attainable efficiencies. In still other cases, proper scheduling and knowing the correct amount to apply are sufficient. However, because infiltration and roughness can change dramatically over the season, it may be difficult for irrigators to correctly adjust flow rate and time to account for the conditions during the irrigation. While experience is useful, it often leads to suboptimal performance. The objective of this research is to develop feedback control methods for surface irrigation basins and borders.

Mathematical models of water flow in surface irrigation have been developed over the last two decades. These are predictive models; that is, the user supplies the actual conditions, and the model determines the results of the irrigation. For optimal control of a surface irrigation system, two procedures are needed. First, one must be able to estimate the infiltration and roughness conditions during the irrigation (estimation). Second, one must be able to determine the best combination of flow rate and application time to achieve the objectives of the irrigation (optimization). Estimation/optimization is particularly well suited for sloping borders, and to a lesser extent, level basins. For sloping furrows, other methods are probably more relevant, particularly where continuous adjustment of inflow rate is made.

APPROACH: The basic mathematical solution procedures for solving the continuity and momentum equations for determining advance distance and time from known infiltration and roughness were modified to solve for infiltration or roughness parameters from known advance distance and time (inverse problem solution). A sensitivity analysis indicated that this procedure was not always adequate for determining the needed parameters. Search procedures for estimation were found to be more useful in application, with the first guess coming from the direct inverse problem solution. Optimization results had been previously developed for level basins and were available in computer software. Optimization for sloping borders would require a complete solution to advance and recession with a search procedure to determine the best combination of flow rate and time. Such a procedure has not been adequately developed.

In 1989, a field demonstration project was undertaken to test the feasibility of using feedback control on an operational basis. A 32-ha (80 ac) field with eight level basins at the Maricopa Agricultural Center was chosen. The field was irrigated by farm personnel for the first six irrigations of the year, and performance was closely monitored. The last four irrigations of the year were controlled with the feedback control system. Under feedback control, water advance was monitored manually to three-fourths of the field length. Flow rate measurements were made with a long-throated flume and collected and totalized with a data logger. These data were entered into a microcomputer, and the application time was determined by the feedback control program. A statistical procedure was developed and used to combine information from prior irrigations to improve estimation from observations. The intent was to remove systematic errors in estimation procedures. Data from prior basins irrigated within the same field were also used to improve estimation.

During 1990, several irrigations were monitored to determine whether data on water levels within the basin could be used to aid estimation.

FINDINGS: With only advance time and distance measurements, estimation procedures are capable of determining only one infiltration or roughness parameter. The statistical procedures developed to aid estimation were able to provide a reasonable estimate for two infiltration and roughness parameters. Data on water levels within the basins did not appear to improve estimation.

Measured values of infiltration (Kostiakov k) and roughness (Manning n) over the 1989 season are given in Figure 1. There was enough variation in these parameters to affect the irrigation performance and potential efficiency. There was considerable error in the estimation of parameters at the three-fourths field length compared to the full field length. The statistical procedures removed some of this bias. Surprisingly, data from prior basins irrigated did not improve parameter estimation in later basins. It was found that at lower target application depths, the potential efficiencies predicted from theory were not attainable in the field. This was attributed primarily to surface undulations that prevented advance after cutoff.

When the required application amount was above 150 mm (6 in), the irrigator did as well as the feedback control system. However, when the required application depth was less than 100 mm (4 in), the feedback control system adjusted the application time and thus reduced the volume applied better than tbe irrigator (see Fig. 2). Application efficiencies were improved from 5 to 10% for these lesser application depths.

INTERPRETATIONS: Feedback control is potentially useful for estimation of parameters and for control. For the particular example, higher efficiencies could have been achieved with better field design than with feedback control. Control, based on parameter estimates from prior irrigations, was almost as good as that from feedback estimation. However, on this field of mature alfalfa, one would expect conditions not to change much. The contribution from feedback control (and correlation with basins already irrigated) is more significant when conditions are changing significantly. This form of feedback control is probably most applicable to sloping border systems, rather than level basins, where adjustments in flow rate may be needed (e.g., one-time adjustments and not continual adjustments as in furrow feedback control systems). Optimization results for sloping borders need to be available before this method can be applied in practice. Also, the procedures, data collection, and programs must be made available to irrigators (or at least farm managers) in a usable form. Thus, a considerable effort is still needed to make these results usable.

FUTURE PLANS: The next step would be to try the methodology on sloping borders. Since this requires optimization results, which would require a considerable effort to produce, further work in this area will be deferred until some of the other needs in irrigation modeling have been addressed.

COOPERATORS: N.D. Katopodes, University of Michigan.

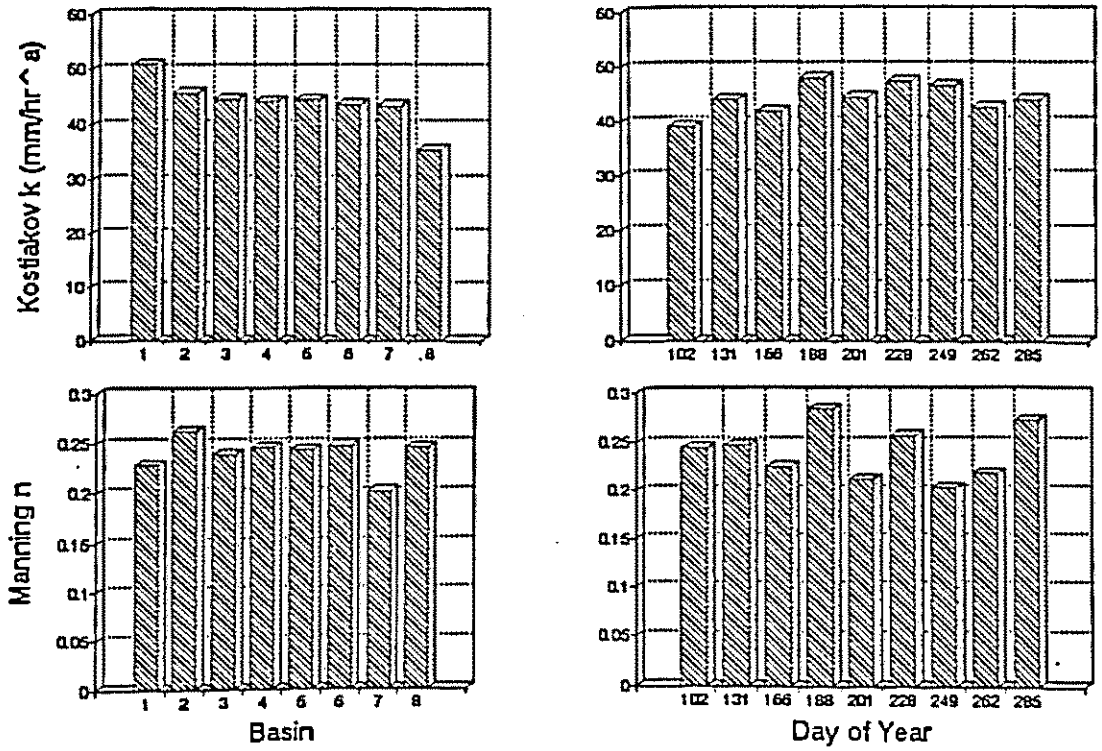

Figure 1. Histogram of historical data for Kostiakov k and Manning n from MAC farm field #13, 1989.

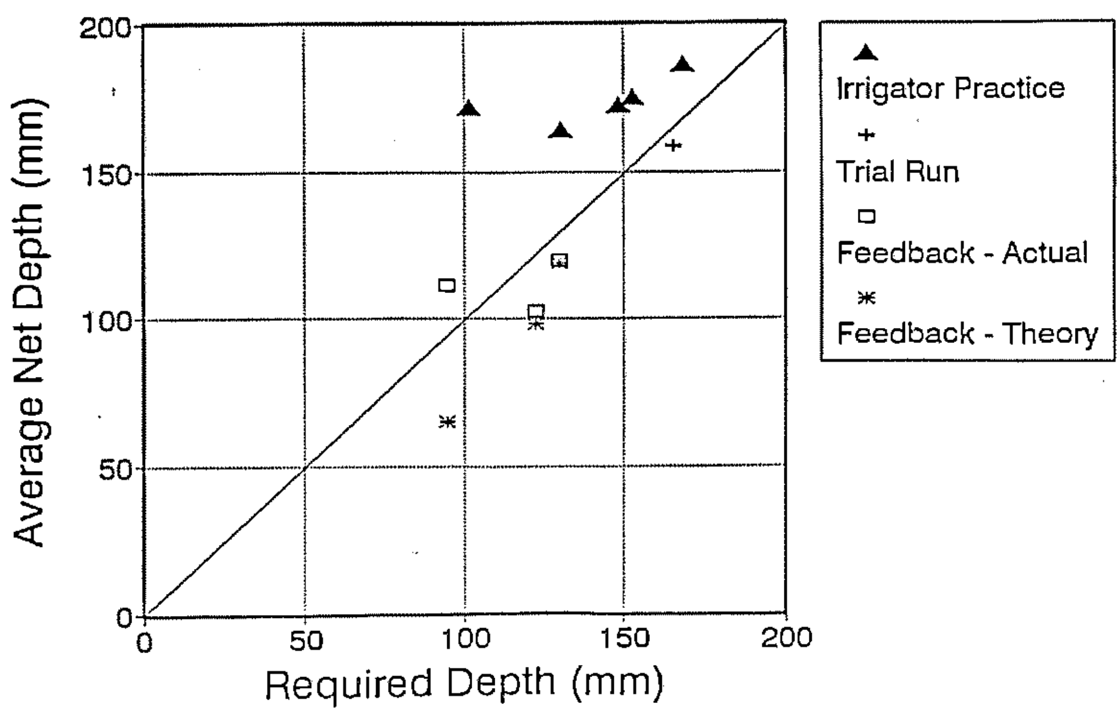

Figure 2. Average actual net (minimum) depth infiltrated as a function of required depth for standard irrigator practice and for feedback control (from theory and as actually used by trained technicians) from MAC farm field #13, 1989.

SURFACE IRRIGATION SYSTEM DESIGN, EVALUATION, AND MODELING

A. J. Clemmens, Supervisory Research Hydraulic Engineer
and A. R. Dedrick, Laboratory Director

PROBLEM: The application efficiencies for surface irrigation systems continue to be poor despite advances in irrigation modeling and science. Efficiencies continue to be poor for a number of reasons. In many cases, the irrigator or farmer did not choose the correct flow rate or does not have sufficient control over flow rate. In other cases, the wrong application time is used, or a combination of wrong flow rate and application time are used. Proper design can sometimes greatly improve attainable efficiencies. In some cases, proper scheduling and knowledge of the correct amount to apply are sufficient. However, because infiltration and roughness can change dramatically over the season, it may be difficult for irrigators to correctly adjust flow rate and time to account for the conditions during the irrigation.

Mathematical models of water flow in surface irrigation have been developed over the last two decades. These are predictive models; that is, you supply the actual conditions; and the model determines the results of the irrigation. In many cases, the infiltration and roughness conditions are not known. While a number of evaluation techniques are available, different techniques are appropriate under different situations. Even when conditions for one irrigation are determined, they may be quite different for other irrigations under different crops and tillage conditions. Design should consider performance over the full range of expected conditions. The idea is that if the design is functional over the full range of circumstances, the irrigator need make only minor adjustments from one irrigation to another. More detailed feedback control is being developed under a separate research project.

Most predictive models do not consider such things as soil spatial variability and field surface irregularities or undulations. These become more of an issue as farmers move toward higher application efficiencies.

The objective of the project is to develop user friendly software for the evaluation and design of surface irrigation systems that is usable in differing irrigation settings.

APPROACH: Reliable predictive models are the first step in the development of surface irrigation software. Model development and working cooperatively with others has been a major effort at the U.S. Water Conservation Laboratory over the last decade. Progress continues with these models, but synthesis and use are now possible.

Generalized design and management guidelines must yet be developed from the models. These guidelines can be in the form of tabulated results, regression equations, or procedures for systematically applying the predictive models. This step is necessary for practical application of these predictive models. Several approaches will be taken in the development of these design guidelines. They include the development of 1) nondimensional solutions for general problems (e.g., optimal design) that can be computer coded, 2) search procedures for more specific problems, 3) design procedures that take into account the changes in field parameters that occur over the season, and 4) sensitivity analysis of design input.

In addition, one must be able to include other factors which affect uniformity and efficiency, namely, soil spatial variability, surface irregularities, nonuniform inflow streams, etc. Various studies will be conducted to assess the impact of these conditions. Procedures will then be developed to account for these in the design and operating procedures.

One limitation of existing programs is that the user must be able to quantify field conditions for infiltration and roughness. There is a need for a general program on field evaluation procedures to assist users in determining field conditions for input into these design and operation programs.

FINDINGS: In 1985, the Border Flow (BRDRFLW) program became available for modeling border irrigation systems. It has become the standard program for border irrigation applications. The University of Melbourne, Australia, has developed a menu-driven program around BRDRFLW that also includes approximate design results and procedures developed from BRDRFLW in the form of regression equations.

These design results are applicable only over a specific set of circumstances representing common conditions in parts of Australia.

The program Surface Irrigation (SRFR) was completed in 1990 and is available for distribution. SRFR is a general program for surface irrigation which includes furrow, basins, and borders. It can also handle variability in parameters over space and time. SRFR has been tested and debugged by a number of individuals over the last few years. SRFR should eventually replace BRDRFLW.

The nondimensional design results for level basins were coded into a menu-driven design program. This program, BASIN, is intended to replace the SCS design charts. Programming and debugging are near completion. BASIN should be available for distribution in early 1991.

The effects of furrow elevation differences, caused by tillage operations, on the uniformity of water distribution in level basins were studied both in the field and with the SRFR program. The study, conducted by Dr. Pedro de Sousa from the University of Lisbon, Portugal, demonstrated the influence of tillage precision on irrigation uniformity.

Studies were initiated to evaluate the "completion of advance" concept for design and management of level basins in the absence of water control, first introduced by Wattenburger and Clyma in 1989. We were able to show a relationship between their results and our design results (published in 1982). Thus "completion-of-advance" criteria can be added to the BASIN program with minimal effort. The field work was done with visiting scientist Dr. A.G. El- Gindy of Egypt. Additional tests are needed.

It has been shown that statistical procedures can be used to combine the factors that influence uniformity and that all of this variability need not be simulated with the predictive irrigation models. Statistical procedures have been developed that can be used with the predictive models.

INTERPRETATION: While noteworthy advancements have been made on the development of predictive models, significant impact will occur when these models can be incorporated into some form of user-friendly software. Only in this way will these models impact water use efficiency in irrigated agriculture.

FUTURE PLANS: Work will continue on the program SRFR. A menu-driven program is planned to simplify data input. A number of minor changes in SRFR are also planned to enhance or simplify the way infiltration into furrows is handled and to improve its application to surge irrigation.

A proposal has been developed with the International Institute for Land Reclamation and Improvement (ILRI) to 1) expand the BASIN program to include field evaluation procedures, 2) include design based on cutoff at completion of advance (or some portion of advance distance), and 3) include statistical procedures to account for spatial variability and surface leveling precision. A book on level basins will be written to accompany the new program, BASIN2, which will take several years to complete.

Long range plans are to develop a general software package for surface irrigation systems along the lines of BASIN2 but expanded to include sloping borders and furrows and to include the actual simulation model as well as generated design results.

COOPERATORS: T. Strelkoff, Consultant, D.D. Fangmeier, W.E. Hart, The University of Arizona, P. de Sousa, The University of Lisbon, T.A. McMahon, The University of Melbourne, M. Jurriens, International Institute for Land Reclamation and Improvement, The Netherlands, W. Clyma, Colorado State University, A.G. El-Gindy, Agric. Mech. Res. Inst., Cairo, Egypt.

SOFTWARE FOR DESIGN AND CALIBRATION OF LONG-THROATED MEASURING FLUMES

A. J. Clemmens, Supervisory Research Hydraulic Engineer
and J. A. Replogle, Research Hydraulic Engineer

PROBLEM: Flow measurement in irrigated agriculture continues to be a difficult problem. Flow measurements are frequently inaccurate, and structures are often improperly installed. Over the last decade, the long-throated flume has been developed as a very useful tool for improving water measurement in irrigation canals. One of the advantages of this device is that it can be custom designed for each installation, thus better meeting the needs of the measurement site. This can be a disadvantage in that it gives the user so much flexibility that an optimum structure may not be selected.

A computer program, FLUME, has been available since 1987 for the calibration of these flumes. It is not very user friendly, as users frequently make errors in data input, and laboratory personnel spend a significant amount of time answering user questions. Thus, there is a need for a more user friendly flume program that can aid the user in design of these flumes.

APPROACH: A menu-driven program, FLUME3.0, is being developed to aid in the design and calibration of long-throated flumes for irrigation canals and natural channels. The program will include design procedures developed over the last few years. The user will input the conditions of the canal and select the type of contraction desired. Then the program will select and present a structure that meets the channel conditions. The program also has graphic data input which shows the flume profile and cross sections so that when the user enters flume dimensions, the changes can be viewed immediately. This should greatly reduce the chance of user error. The project is being sponsored by the International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands. A software programmer from Wageningen is under contract to ILRI to write the menu-driven program.

FINDINGS: The major subroutines have been written, and a main operating program has been completed. This has been demonstrated to users and is currently under review. The manual has been completed and is also under review. The program should be available for distribution by mid-1991.

INTERPRETATIONS: This program should transfer technology to users and make these flumes an even more valuable tool for improving water management in irrigated agriculture.

FUTURE PLANS: Completion and maintenance on the computer program FLUME3.0.

COOPERATORS: M.G. Bos, Internation Institute for Land Reclamation and Improvement, The Netherlands, and J.M. Groenestein, consultant.

ACCOUNTING FOR SOIL AND IRRIGATION SYSTEM VARIABILITY IN CROP MANAGEMENT

D. J. Hunsaker, Agricultural Engineer,
A. J. Clemmens, Supervisory Research Hydraulic Engineer,
and W. L. Alexander, Agronomist

PROBLEM: Spatial variability of soil properties and nonuniform water application limit crop yields and water-use efficiencies in irrigated fields. Soil physical properties are known to vary widely in space, even over short distances. Both small- and large-scale variability in infiltration and soil wetting can profoundly alter the supply of water and nutrients to plants within a field. As a result, plant growth and yield can be expected to vary spatially. Accounting for soil and irrigation system variability is required for optimum crop water management. However, knowledge and description of the effects of this variability on crop yields and water-use efficiencies are presently inadequate to establish appropriate water management practices.

The objectives of the research are (1) to study and describe the impact of spatial variability in soil and irrigation on crop water management and production under farm-scale, surface irrigation conditions, (2) to develop irrigation management practices that minimize the effects of field variability, and (3) to develop management aids that include the effect of this variability, which can be used to help make irrigation decisions, e.g., to maximize profits or increase crop water-use efficiencies.

APPROACH: A series of experimental studies have been conducted from 1985 through 1990 on a 4-ha, sandy loam field site to assess the field spatial variability and its influence on the water use and yield of several crops grown under various managements of applied water. The field site is located at the Maricopa Agricultural Center in central Arizona. Level basin irrigation was used, and water was applied individually to 12 basins within the site. Crops studied were wheat (1985, 1986 and 1990), cotton (1987 and 1988), and grain sorghum (1989). Experimental treatments consisted of seasonal irrigation water applied, irrigation water quality, and basin length. Primary data collected included inflow rate and volume of water applied during each irrigation, irrigation advance and recession, soil infiltration rates, soil water contents, soil texture and bulk density, soil salinity, soil surface elevation, and crop yield. Yields were measured in small areas where soil texture and water content data were measured so that variability in yield could be related to soil texture and water use. Both conventional and geostatistical approaches are being employed in the analysis of data.

In prior years, procedures were developed to statistically combine the factors which affect the uniformity of water distribution under surface and trickle irrigation. For surface irrigation, these include soil infiltration variability, advance time, surface leveling precision, variability in advance, etc. This allows individual evaluation of these different factors and determination of the contribution of each factor to the overall uniformity.

FINDINGS: Analysis of the 1985 and 1986 wheat experiments was completed in 1990. Results from these studies indicated that the relative variability (as measured by the coefficient of variation) in grain yields was affected by the amount of seasonal irrigation water applied, ranging from 26 to 28% under reduced irrigation (dry-treatment, 50% evapotranspiration deficit) to 12 to 15% under full irrigation (wet-treatment). The variability in seasonal crop evapotranspiration accounted for 28 to 46% of the variability in yield with reduced irrigation but only 7% with full irrigation. However, under all irrigation treatments, the spatial variability in soil texture and crop root zone soil water contents played a major role in determining yields. Figure 1 shows the average grain yields obtained for the three predominant soil textural classes (sandy loam, sandy clay loam, and loamy sand) within the experimental site for each irrigation treatment (wet, medium, and dry). Crop production functions (grain yield versus seasonal infiltrated water depth) developed from the field data are presented for the three soil classes in Figure 2. Maximum grain yields obtained under full irrigation varied as much as 34% among the soil textural classes, while grain yield per unit water infiltrated varied as much as 59%. Grain yields per unit of water consumptively used (water use efficiencies) were nearly the same for the three soil types, with the loamy sand having slightly lower water use efficiencies than the other two textures. It is not known whether leaching of fertilizer could account for these reduced yields.

A method was developed for expressing the tradeoffs between irrigation efficiency, area adequately irrigated, storage efficiency and distribution uniformity. The method allows rational decisions regarding the amount of water to apply to a field and can be used in combination with the prior statistical procedures for quantifying the effects of different variability factors on uniformity. This method can be combined with other information (e.g., crop sensitivity to stress, economics, etc.) to make meaningful management decisions.

INTERPRETATION: Optimal use of irrigation water is limited by the effects of spatial variability which presently defy adequate accountability on crop yields. Progress has been made in quantifying the interactive effects of irrigation and soil properties on yields grown under surface irrigation. Data sets that are presently being analyzed will increase our understanding of the effects of irrigation uniformity and deep drainage on crop water management. The primary product of this research will be to provide growers a means with which to more accurately account for crop and soil variability conditions in water management decisions. This will increase irrigation management capabilities for obtaining more profitable crop production.

FUTURE PLANS: Spatial variability research will be expanded to include two new areas in the future: 1) macropore, or small-scale variability, and 2) optimization of fertilizer applications. It is recognized that the effect of macropore flow can radically alter irrigation uniformity. However, we have little knowledge of the effect of small-scale soil water variability on crop yields or the ability of plants to integrate this variability within the root zone. The application of chemical fertilizers is also subject to the effects of both small- and large-scale spatial variability. Future research will study the effects of spatial variability on distributed applications of water and nutrients and on crop response. Strategies will be developed for optimum timing and amount of fertilizer application for higher efficiency of crop utilization. Development of management or decision aid will be delayed until more basic information is available.

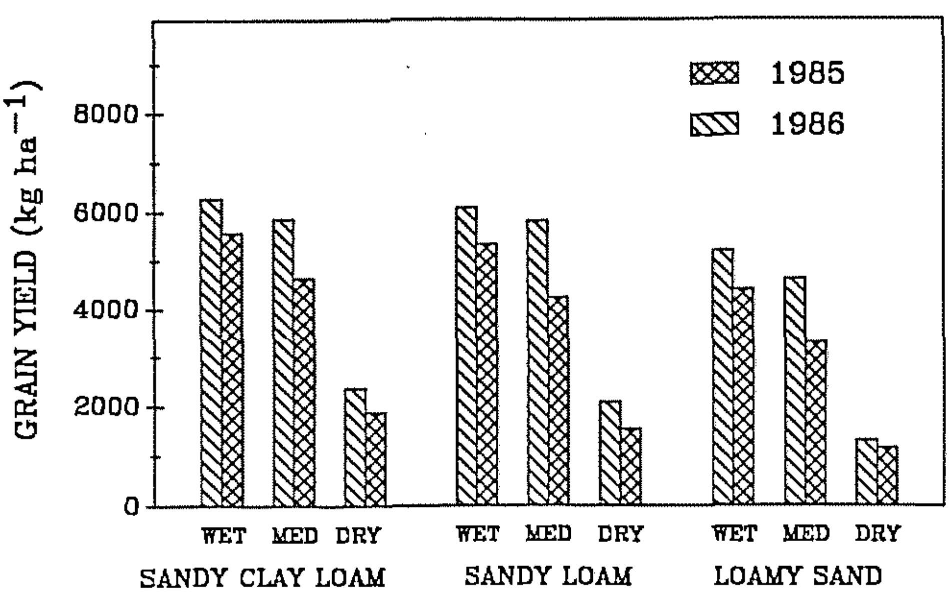

Figure 1. Average grain yields as affected by soil texture in 1985 and 1986.

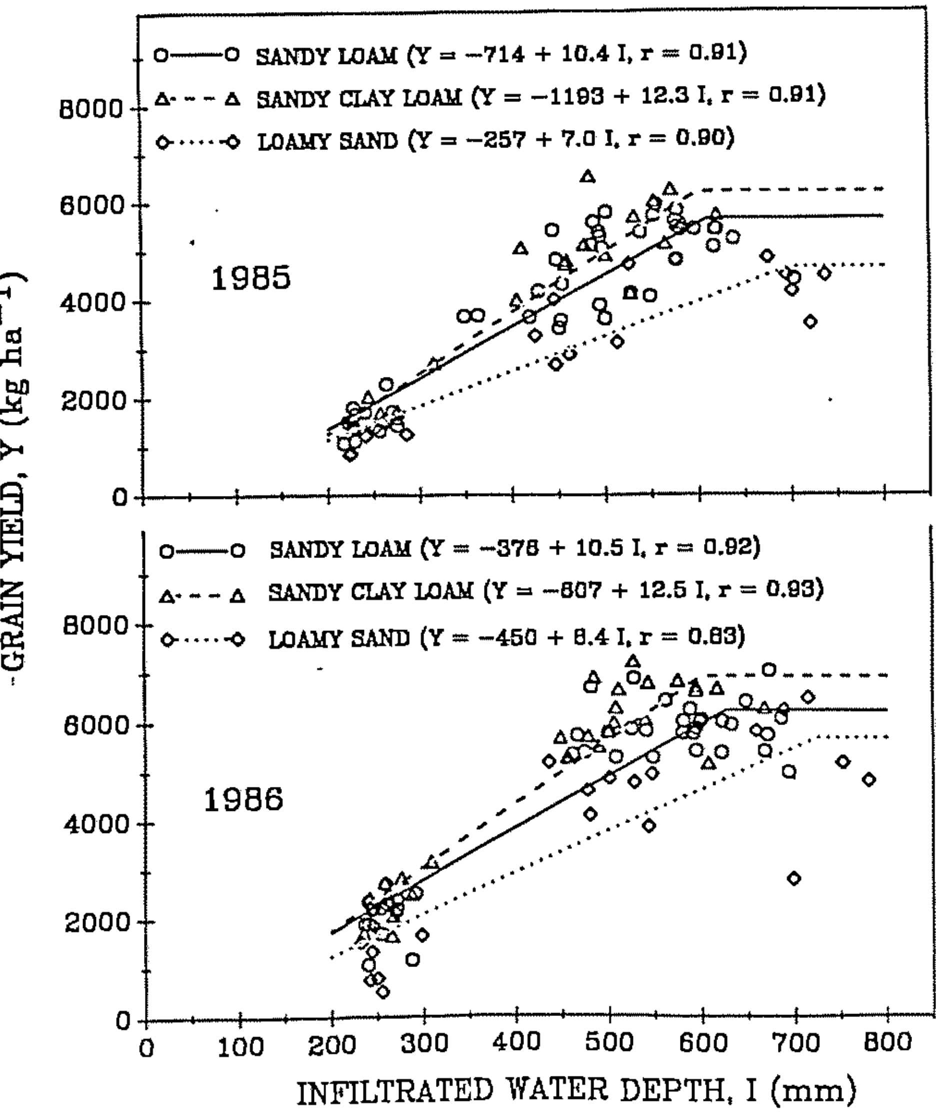

Figure 2. Relationship between grain yield (y) and infiltrated water depth (I) as affected by soil texture.

IRRIGATION FLOW MEASUREMENT STUDIES

J. A. Replogle, Research Hydraulic Engineer

PROBLEMS: A major tool for improving management and conserving water in irrigated agriculture is the measurement of water flow rate. Problems with flow rate devices include their relative complexity, required training level of field users, and economics of installation and operation. Emphasis continues on the development of flow measurement technology and equipment to include improving their usefulness, reducing the training requirements, evaluating the statistical construction tolerances necessary for acceptable accuracy, and re-visiting past techniques for updating in the light of more recent understandings of fluid dynamics and advances in the economics of secondary instrumentation.

APPROACH: Promising measurement and control methods were, and are, evaluated for theoretical limitations. One continuing effort is the development of several construction configurations for a new vertically-movable-sill flume to accommodate large flow rates. Small sizes currently being evaluated are limited to about 4 cfs. Older techniques to be re-visited are the Venturi meter and the float methods. For the Venturi meters, the question , as posed by the Soil Conservation Service (SCS), is whether the reducer fittings currently marketed for their irrigation plastic-pipe standards can be used to field-construct Venturi devices with sufficient consistency. This will require about a dozen constructions of the same size, symmetrical from end-to-end so that they can be reversed, to provide the desired statistics.

Concerning float methods, literature studies of velocity profiles in trapezoidal, semi-circular, and rectangular channels of concrete, would indicate that there may be a consistent ratio of maximum surface velocity to the average velocity. Handbook recommendations on the use of single floats indicate that the average velocity varies from 0.80 to 0.95 times the surface velocity in a vertical section of the channel. Single floats are thus marginally acceptable. A proposed alternate approach, based on computer modeling of velocity profiles in channels of various shapes and roughnesses, would use multiple floats to define the maximum surface velocity in the whole channel, with the expectation that it may provide a narrower band of multipliers. Methods for conveniently finding that maximum surface velocity will be evaluated using comparison flows from existing flow-measuring flumes located in Arizona irrigation districts and at the Maricopa Agricultural Center. Low head loss and quick survey methods are anticipated results.

Other efforts included evaluation of flumes which test the limits of the computer model for flumes. These are usually built by industry and are checked in our facility only if there may be a question of extrapolated results.

Evaluations of measurement and control devices are sometimes made for other federal and state agencies on a case-by-case basis, particularly if they may affect irrigation flow measurement or regulation.

FINDINGS: Movable-Crested Flume: The movable crested flume, Figure 1, was successfully used in field trials in the fall of 1989. Laboratory calibrations indicated that it performed as predicted. Several field user conveniences are incorporated. These include small trays into which water can be splashed to assist in leveling the device; convenient translocated stilling well to make leveling less critical and to improve the readout accuracy; and a hinged-parallelogram structure for the throat that can be easily elevated or lowered to allow accurate flow measurement of each flow rate, using minimum head loss. Previous devices provided minimum head loss only at selected flows, usually the maximum, while lower flows used higher overfalls than otherwise required.

Dole Flow Regulator:
The Arizona Department of Water Resources asked for our assistance to evaluate whether a commercial device (Dole Regulator), would be consistent and durable enough to allow installation on wells that are legally limited to less than 30 gpm in order to avoid the formality of state regulation. A device rated at 25 gpm was tested. Similar devices of different capacity, used in our own experiments over the last 15 years, were provided to them for durability evaluation. The hydraulic evaluation results are shown in Figure 2.

Pipe Venturi:
At the suggestion of the SCS, we constructed and tested the first of several Venturi meters made with nominal 12-inch to 10-inch to 8-inch plastic pipe reducers with a 12-inch-long throat, 7.94 inches in diameter. The approach piping was 11.875 inches in diameter and was 20 feet long with a bell entrance. This first construction was tested in both flow directions. The results are shown in the accompanying figure. The test range was from about 1.1 to 4.4 cfs, Figure 3. The behavior was within the range of expectations for a Venturi without optimum cone tapering. The fittings contracted and expanded more rapidly than an ideal Venturi meter. The agreement of the reverse flow direction with the original flow testing was good. Higher flow rates are planned to verify whether a constant coefficient is ever reached at high Reynolds numbers.

Narrow, Long-Throated Flume:
A flume that appeared to stretch the limits of the flume computer model was proposed by a manufacturer as per specifications of a New Jersey Municipality. It had a throat that was only 2.5 inches wide and 24 inches long. The approach channel was 4 inches wide, 24 inches long and 22 inches deep. The throat was raised 1.375 inches from the approach section floor. The calibration plot and an example of the submergence behavior are shown in the accompanying Figure 4. The calibration followed the computer model fairly well even though there were some problems with standing waves and reliable head detection that result in data scatter. Data for H_1/L above 0.6 are expected to deviate from theory, as in Figure 4.

Float system:
Preliminary tests on the use of floats to measure average channel velocity were conducted in a rectangular channel and in a trapezoidal channel. These flows were measured separately with a triangular weir or a rectangular flume and showed agreement to within better than 5%. These results are encouraging enough to warrant further evaluations.

INTERPRETATIONS: New flow measuring techniques using new principles have a low probability of being discovered because flow measuring methods depend on exploiting a few basic physical principles. Advances in flow metering are likely to involve improved reliability and user convenience. From this standpoint, many of the basic principles are currently ripe to be re-explored with a view to exploiting new electronic secondary devices, new economies in computer interfaces, and simply new ways of combining the basic principles.

The Venturi studies, the movable-crested flume, and the float velocity evaluations are examples of older methods that may now have a niche in modern irrigation flow metering that will contribute to improved water management and water conservation.

FUTURE PLANS: Plans are to continue the three main studies started this past year, the movable-silled flume, the plastic-pipe Venturi, and the multiple-float velocity study. Papers planned include a summary of a book chapter on flow meters for irrigation, featuring advances in flow measurement; a bulletin that will be based on some of the book chapter items but will feature new applications or applications not well documented in standard handbooks; and a manuscript on evaluation of the operation of several large flumes being used in various irrigation districts throughout the U.S. West.

COOPERATORS: Informal cooperation arrangements include the Soil Conservation Service, The U.S. Bureau of Reclamation, The Bureau of Indian Affairs, various irrigation districts; Maricopa Agricultural Center, and other state universities and state agencies.

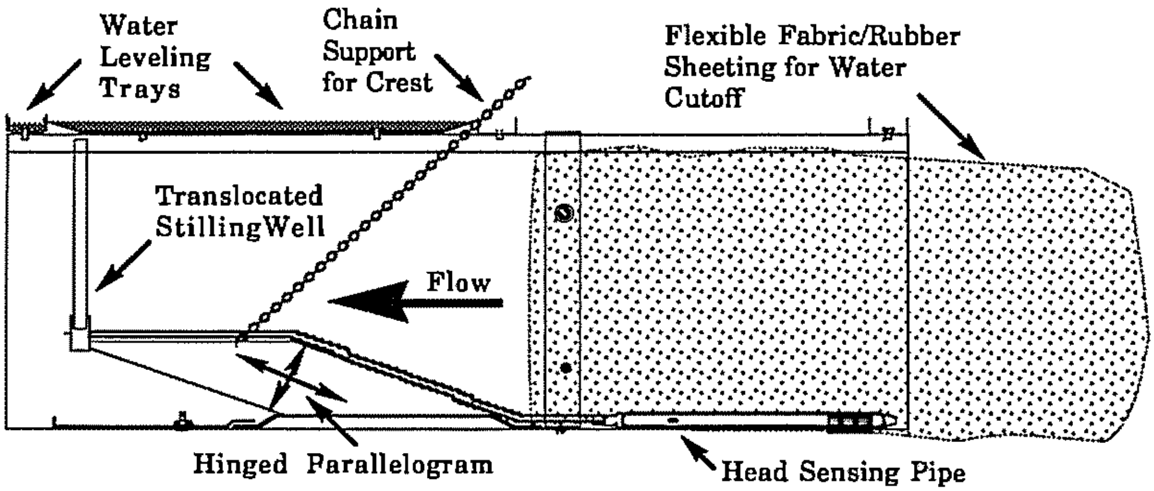

Figure 1. Side View of Movable-Crested Flume for Flow Measurements in Furrows

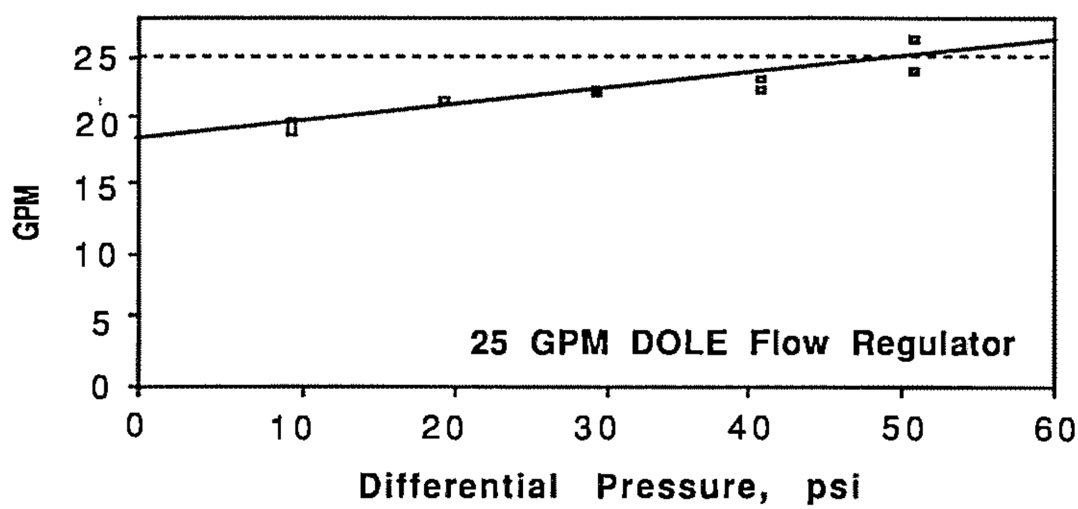

Figure 2. Flow Regulator Manufactured by Dole Company.

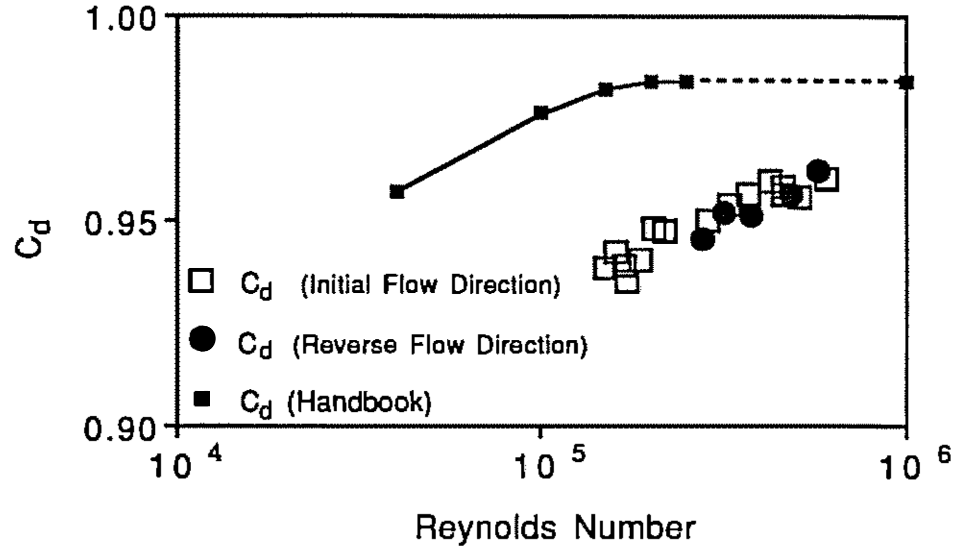

Figure 3. Pipe- Fitting Venturi.

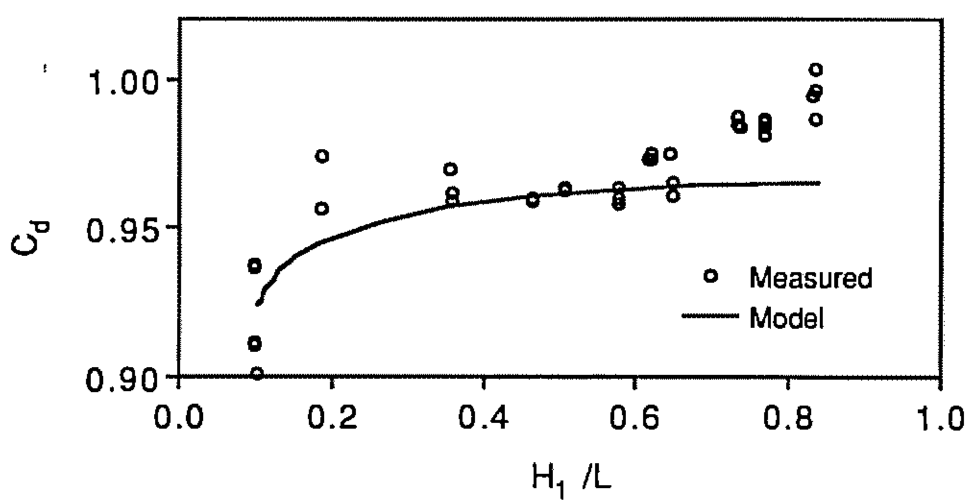

Figure 4. Narrow-Throated Flume

EFFECTS OF PHYSICAL WATER TREATMENT ON TRICKLE IRRIGATION

J. A. Replogle, Research Hydraulic Engineer
and W. L. Alexander, Agronomist

PROBLEM: There are currently several water treatment devices on the market for home and industrial-agricultural uses which claim to solve the problems of scaling, clogging, and deposition of dissolved mineral solids and also to increase crop yields. Most of these claims are anecdotal in nature. Magnetic and catalytic conditioning methods have been in use for at least 30 years and are claimed to replace most of the effects of chemical water softeners. Unlike the chemical water softeners, magnetic and catalytic conditioners do not exchange minerals, but appear to attach electrical charge to the dissolved minerals in the water, rendering them unahle to adhere to the surface of pipes, water heaters, bath tubs, etc. This seems to be the theory behind the magnetic units which generate a DC current in water flowing by them. The catalytic units have yet to be well explained. Their effect is claimed to last for weeks whereas the magnetic unit effects are claimed to last two or three days. One explanation is that they generate tiny seed crystals that are more attractive to scaling chemicals than the pipe walls they protect. Effects on infiltration are also claimed with benefits to nutrient uptake in plants, etc. The prime interest here was to check the anti-clogging effects that these units may have on trickle irrigation tubing. This might allow the use of poor quality water with a relaxation of the management effort required to prevent clogging.

APPROACH: A replicated experiment to evaluate crop effects, infiltration changes, and clogging was attempted with a supply of good quality water and a supply of poor quality water.

FINDINGS: Various mechanical problems, such as broken tubing, loss of saline water supply, and inability to maintain uniform pressures with the equipment available somewhat compromised the desired determinations. The data are presented in the accompanying figure. Infiltration appears to follow the summer air temperatures in most cases with little significant difference. Clogging prevention was not a problem for any of the treatments, so no significant preventative effects could be proven. Crop yields were only marginally different, again with no overwhelming significance. In a parallel experiment on greenhouse cooler pads, the magnetic units appeared to cause some kind of soft precipitate and to clean up deposits on older pads.

INTERPRETATIONS: The physical difficulties with the setup were such that the effects of using treated waters could not be definitively supported one way or the other. This first attempt served as a training period for our technicians and may benefit more definitive testing attempts.

PLANS: The clogging effects need to be accelerated to exaggerate the protective effects, if they exist. This is planned with trickle tubes suspended above a ditch with more frequent wetting cycles used. This will allow the water to be salvaged for other uses. Involvement of others at the Laboratory is planned.

COOPERATORS: The University of Arizona Maricopa Agricultural Center

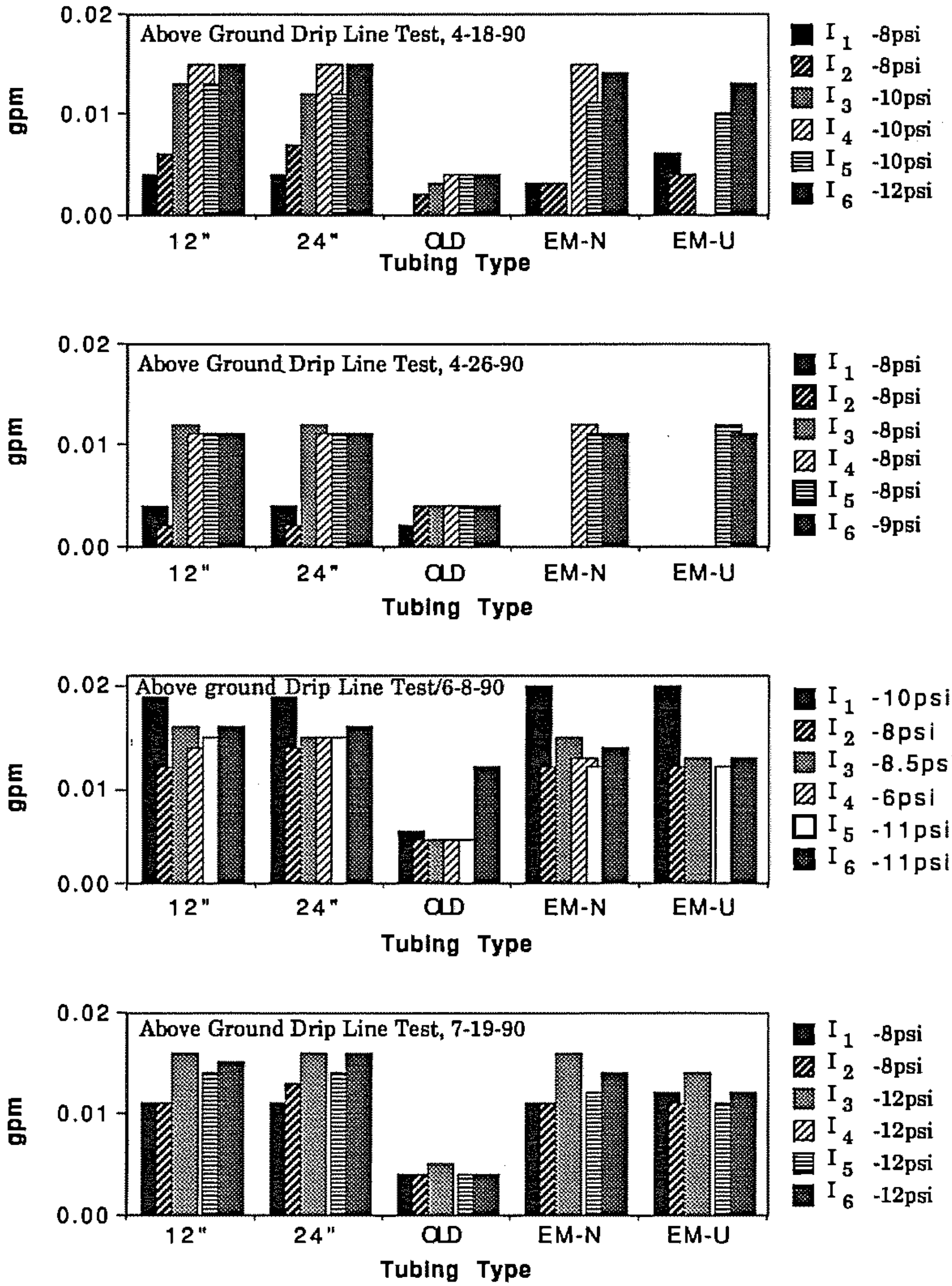

Figure 1. Irrigation treatments : I_1 and I_2, irrigated with water treated by a catalytic type conditioning unit; I_3 and I_4, irrigated with water treated by a magnetic type water conditioner; I_5 and I_6, no water treatment. "EM" refers to Emitter; N = new; U = used.

DERIVATION AND USE OF RETARDATION FACTOR IN PREDICTING CONVECTIVE TRANSPORT OF CHEMICALS IN SOILS AND AQUIFERS

H. Bouwer, Research Hydraulic Engineer

PROBLEM: The retardation factor equation traditionally has been derived from the differential dispersion equation for convective transport of sorbing chemicals in saturated media (aquifers). The resulting equation contains a porosity term, which has caused confusion when applying the equation to unsaturated and preferential flow or similar situations of mobile and less mobile water. In view of tbe many predictive models for underground transport of chemicals, proper use of the retardation equation is required.

APPROACH: The retardation equation was derived using a mass balance approach. The resulting expression for the retardation factor was then applied to a situation of mobile and immobile water (fingering) to show the effect of preferential flow on downward contaminant transport. The expression was also applied to a stratified aquifer model with different hydraulic properties for each layer to demonstrate macrodispersion, predict breakthrough curves, and assess proper volumes of leaching water required to remove pollutants from the aquifer.

FINDINGS: The mass-balance approach clearly showed the roles that porosity, water content, and effective (mobile) water content play, and that porosity in the retardation equation should be replaced by effective water content (mobile water only). Applying this to a situation of preferential flow by instability (fingering) showed that the rate of chemical movement was inversely proportional to the fingering ratio, despite some of the non-linearities involved. Using different retardation factors, hydraulic conductivities, and water contents in a stratified aquifer model showed that the breakthrough curve calculated by assuming piston flow in each layer produced the characteristic "tailing" at the upper end, rather than the symmetrical sigmoid curve obtained theoretically for homogeneous media. This tailing has been observed in practical situations, and it shows the role of aquifer heterogeneity and the futility of predicting breakthrough curves using "a" dispersion coefficient and vice versa. For the same model, aquifer leaching to remove chemicals from the stratified aquifer system required considerably more water than the design number of pore volumes. This was due to the larger flow through the more permeable layers and confirms why passing a prescribed number of pore volumes of clean water through an aquifier system often is insufficient to produce the proper remediation of the entire aquifer.

INTERPRETATION: The analyses provide a better understanding of chemical transport through vadose zones and aquifers. This should enable better prediction of movement of pesticides and other chemicals in the underground environment and of cleanup of polluted aquifers by leaching with clean water.

FUTURE PLANS: Some of this work may be used in planned research to detemined best management practices for irrigation and chemical use to protect groundwater quality.

ROLE OF GROUNDWATER RECHARGE IN TREATMENT AND STORAGE OF SEWAGE FOR REUSE

H. Bouwer, Research Hydraulic Engineer

PROBLEM: Many areas experience water shortages, and municipal wastewater has to be reused. This means that the sewage must be treated so that it meets the quality requirements for the intended reuse. This can be expensive, especially when the sewage is recycled into drinking water or used for unrestricted irrigation.

APPROACH: Cost estimates have been made for post-treatment of water from a soil-aquifer treatment (groundwater recharge and recovery) system for secondary sewage effluent so that the water meets drinking water quality standards. These costs were then compared with the costs of complete advanced wastewater treatment where secondary sewage effluent is directly converted into drinking water.

FINDINGS: Water from previously operated soil-aquifer treatment systems met agronomic and health requirements for unrestricted irrigation. To use the water for potable purposes, it would need additional treatment which consists of activated carbon adsorption for the entire flow, reverse osmosis for half the flow, and disinfection for the entire flow. This additional treatment would cost about $280 per acrefoot (amortization and operation and maintenance costs, 1988 dollars) for a large plant (about 100 mgd). The cost of soil-aquifer treatment, as such, is on the order of $30 per acrefoot (depending on depth to groundwater), so that soil-aquifer treatment and post-treatment to convert secondary sewage effluent to drinking water would cost about $310 per acrefoot. Complete in-plant treatment to produce drinking water from secondary sewage effluent, as done in the Denver Potable Water Reuse Demonstration Project, consists of lime clarification, recarbonation, filtration, ultraviolet irradiation, activated carbon adsorption, reverse osmosis (for the entire flow), air stripping, ozonation, and chloramination. This entire process costs about $730 per acrefoot.

INTERPRETATION: Including soil-aquifer treatment in the treatment process reduces the cost of recycling secondary sewage effluent into potable water from about $730 to $310 per acrefoot. In addition, soil-aquifer treatment systems are robust and fail-safe, offer storage to absorb differences between sewage supply and drinking water demand, and enhance the aesthetics and public acceptance of potable reuse of wastewater by breaking the pipe-to-pipe connection of direct recycling. For crop irrigation, including sprinkler irrigation of crops consumed raw or brought raw into the kitchen, soil-aquifer treatment, as such, is sufficient. Thus, soil-aquifer treatment can play an important role in the reuse of wastewater for potable and irrigation purposes.

FUTURE PLANS: Continue working as consultant to Salt River Project funded research at The University of Arizona to further study the efficacy of soil-aquifer treatment for potable reuse of municipal wastewater, particularly the fate of synthetic organics (including chorination byproducts) in the underground environment and their significance as trihalomethane precursors in the recovered water.

COOPERATORS: Salt River Project, The University of Arizona, Tucson Water Department, Denver Potable Water Reuse Demonstration Project.

PREFERENTIAL FLOW AS A FUNCTION OF APPLICATION METHOD

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PROBLEM: To develop better management practices (BMPs) we need the ability to accurately predict the transport of agricultural chemicals through the soil. Preferential flow has a number of implications. First, most of our present solute transport models do not account for preferential flow. Because of the complexity, it is very difficult to determine when preferential flow will occur. In a number of previous studies, preferential flow was observed under intermittent flood irrigation. Under continuous flooding, however, preferential flow was observed only near the surface. In field studies, preferential flow was observed under both sprinkler and flood irrigation on sandy soils. If preferential flow is the rule rather than the exception, it may not possible to develop BMPs that will reduce the transport of pesticides and fertilizers below the root zone to the groundwater. The method of fertilizer or pesticide application may also affect the transport of chemicals below the root zone. If preferential flow occurs because of macroflow, applying the chemical with the water (chemigation) may result in accelerated flow. The objectives of the studies were (1) to investigate solute transport under continuous drip irrigation and (2) to determine the effect of application method on solute transport.

APPROACH:

Drip irrigation. The experiment was conducted on a plot that had been used in previous experiments under intermittent and continuous flood. A drip irrigation grid of 15 x 30 cm was installed on the 37-m^2 plot. Drip irrigation was applied continuously at a rate of 5 cm/day. Ceramic soil suction samplers were placed at depths of 0.3, 0.6, 1.0, 1.4, 1.8, 2.4, and 3.0 m and replicated four times. Four neutron access tubes were installed to a depth of 3-m for water content determination. When a stable water content profile was established, a series of four conservative tracers were applied to the irrigation water in a 5-cm pulse at 14-day intervals. Daily solute samples were taken from each suction sampler and analyzed for tracer concentration. The solute velocity for each sampler and tracer was determined from the solution of the one-dimensional advection-dispersion equation.

Chemigation. The effect of application method on solute transport was investigated by measuring the leaching behavior of a chemical tracer that had been sprayed onto the soil before irrigation, versus applying a tracer directly in the irrigation water. Potassium bromide was dissolved in water and metered into the irrigation stream during a 100-cm irrigation of a 15.5 by 244-m level basin. Two hours prior to irrigation, a second conservative tracer, *o*-(trifluoromethyl) benzoic acid (*o*-TFBA), was hand-sprayed on 10 2-by 15-m plots distributed across the border. Sixteen days after irrigation, 66 50-mm diameter soil cores were taken to a depth of 2 m from within the 10 plots. The cores were sectioned into 10.25-m long cores from which Br and *o*-TFBA were extracted.

FINDINGS:

Drip irrigation. Estimates of tracer velocity, v_t, were made from the data of each individual sampler. Data from each sampler were treated as independent observations of the solute leaching process. Agreement between the calculated and measured break-through curves was excellent. The solute velocity calculated from the surface flux divided by the water content, v_o, would be the velocity if piston flow occurs or $v_t/v_o = 1$. If the ratio is greater than 1, bypass flow is occurring. Figure 1 shows the mean and 95% confidence limits for the average of the relative velocity, v_t/v_o for each depth. The relative velocity is near 1 for the 30, 60,and 140 depths. For all other depths the ratio is greater than 1.2. The overall relative velocity is 1.19. This is similar to the continuous flood where v_t/v_o was 1.2. The difference is that the preferential flow occurred near the surface under continuous flooding. Under intermittent flooding the relative velocity was 1.7 and occurred throughout the profile.

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Chemigation. Tracer distributions exhibited considerable variability both across the border as well as within a single core, with the *o*-TFBA tracer generally exhibiting less erratic behavior than the bromide. The *o*-TFBA also exhibited less leaching with the mean depth of tracer penetration being 0.4-m deep. Bromide, on the other hand, showed considerably greater penetration of the soil profile with a mean depth of leaching 0.9-m, or about twice as deep as the *o*-TFBA. The magnitude of this difference was unexpected since the only difference between these two tracers was in the method of application. In addition, the deep penetration of the Br indicated that a considerable fraction of the Br traveled along preferential pathways as opposed to the *o*-TFBA.

INTERPRETATION: Preferential flow occurs under a number of different circumstances. Piston flow occurs mainly under steady-state, saturated flow. Preferential flow increases as the degree of saturation decreases and is probably linked to the complex unsaturated flow process and hysteresis. Under intermittent flood irrigation, the bypass flow seems to be greater when the chemicals are applied with the water. This may lead to increased leaching of fertilizers and pesticides to the groundwater. It appears that the transport mechanisms of solutes depend critically on the method by which the solute is introduced to the soil. Developing a comprehensive model of solute transport must include the ability to distinguish between these different mechanisms.

FUTURE PLANS: Studies will continue on the preferential flow process as related to chemigation. The ultimate goal is to develop BMPs that will allow the least amount of agricultural chemicals to move below the root zone to the groundwater and still allow the farmer to earn a profit.

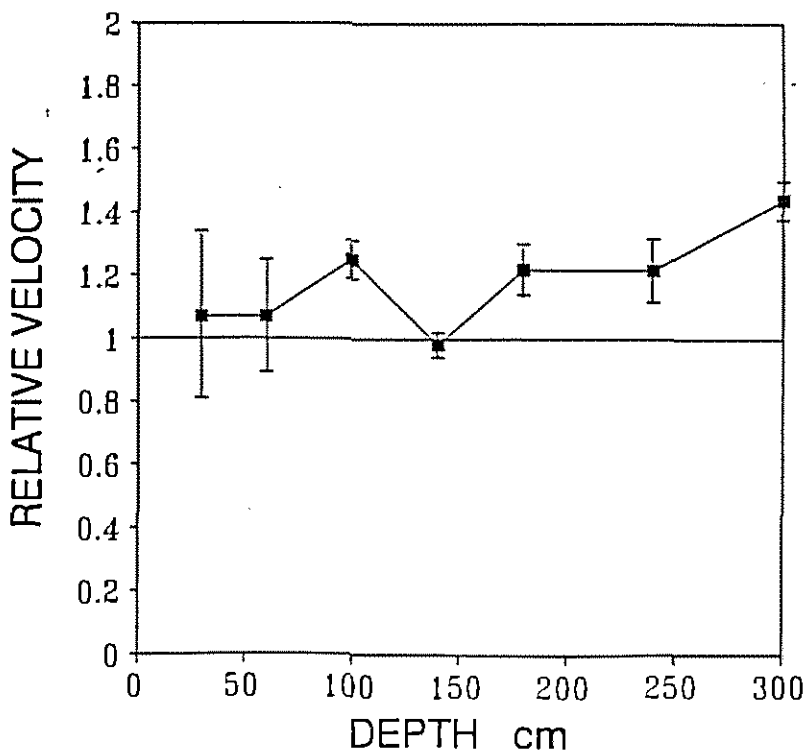

Fig. 1. Relative velocity with depth. Error bars are 95% confidence limits.

TRANSPORT OF AGRICULTURAL CHEMICALS UNDER EXCESS IRRIGATION

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PROBLEM: The objective of this study is to study the effect of excess irrigation on solutes and pesticides transport in the vadose zone and to predict transport from data obtained near the soil surface.

APPROACH: The experiment was conducted at The University of Arizona Maricopa Agriculture Center, Maricopa, Arizona. A 40 m x 40 m-plot was split into three 13 x 40-m borders. Subsurface soil samples were obtained at two locations in the center berm. A drill rig using a hollow stem auger and a 5-cm diameter split sampler was used to take samples. A 45-cm sample was obtained from each 90 cm depth interval. The 45-cm sample was collected in four 10 cm and one 5 cm brass cylinders. A water table was observed at the 14.5-m depth. Five-cm-diameter PVC pipe was installed in the two sample holes before backfilling to serve as monitor wells. The bottom 3 m consisted of perforated pipe. Weekly samples and groundwater depth were obtained.

The pesticides aldicarb, cyanazine, and trifluralin and the conservative tracer bromide were applied to the plots at rates given in Table 1. Approximately 25 cm/wk of water were applied to the plots in two 12.5 cm applications. Irrigation was stopped after 3.2 m of water was applied. Additional soil samples were obtained at five locations to a depth of 12 m. A different conservative tracer was applied to eight 2 m x 2 m plots prior to the last two 12.5 irrigations. Soil samples were taken to a depth of 2.7 m in 30-cm intervals at two locations in each plot. The data from these surface plots were used to predict solute transport to greater depths.

FINDINGS: This report will address only the transport of the conservative tracer. Analysis of the pesticides has not been completed. Texture analysis of the soil samples is shown in Figure 1. The top 3 m consisted of a sandy loam. A gravel layer was present at 4 m. Below 4 m the soil was mostly sand (> 60%). The initial and final water content, shown in Figure 2, was quite variable over the depth ranging from about 2% at the gravel layer to 38% at the water table. The water content paralleled the silt content fairly well in the unsaturated zone. The water table was constant for the first 100 days and then increased in depth by .6 m over the next 80 days (Fig. 3). A rapid rise of about 1 m occurred in the next 20 days. The Br^- concentration fluctuated between .6 and 1 m for the first 110 days and then gradually increased to about 1.2 mg/l at day 180 (Fig. 3). This gradual increase paralleled the rise in water table. At day 180 a sharp Br^- peak occurred. The Br^- concentration had essentially returned to background level before the rapid rise in water table had occurred. This would indicate that the solute was flowing through preferential pathways.

The Br^- concentration of the five deep holes is shown in Figure 4. These samples were taken on day 250 which was about 70 days after the Br^- peak occurred at the well. On four of the five holes the Br^- peak was between 9 and 10 m in depth. The fifth hole did not show a definite peak indicating that the solute had moved beyond the sampling depth. This hole was located about 2.5 m from the well where the Br^- peak was observed 70 days previous. The deep soil samples indicated that the solute had moved only 10 m compared to 17.5 m at the well.

The projected solute breakthrough curve at the well from samples taken near the surface (3 m) is shown in Figure 3. This projection has the solute peak arriving at the well at 250 days, 70 days after the measured arrival.

INTERPRETATION: Solute transport through the vadose zone is highly variable. Measurements of solute concentration in the groundwater indicated one travel time. Solute concentration obtained from soil samples in the vadose zone indicated a travel time considerably different. Projection of breakthrough curves from samples taken near the surface indicate a third travel time. Because of the highly variable results and the inability of our present solute transport models to account for preferential flow, accurate prediction of solute leaching to the groundwater will be tenuous at best.

Table 1. Application rate, solubility, and adsorption coefficient for applied chemicals.

Chemical	application rate kg/ha	Solubility mg/l	koc cm3/g
Aldicarb	2	6000	17
Cyanazine	1	171	173
Trifluralin	1	0.5	7950
Bromide	130	-	-

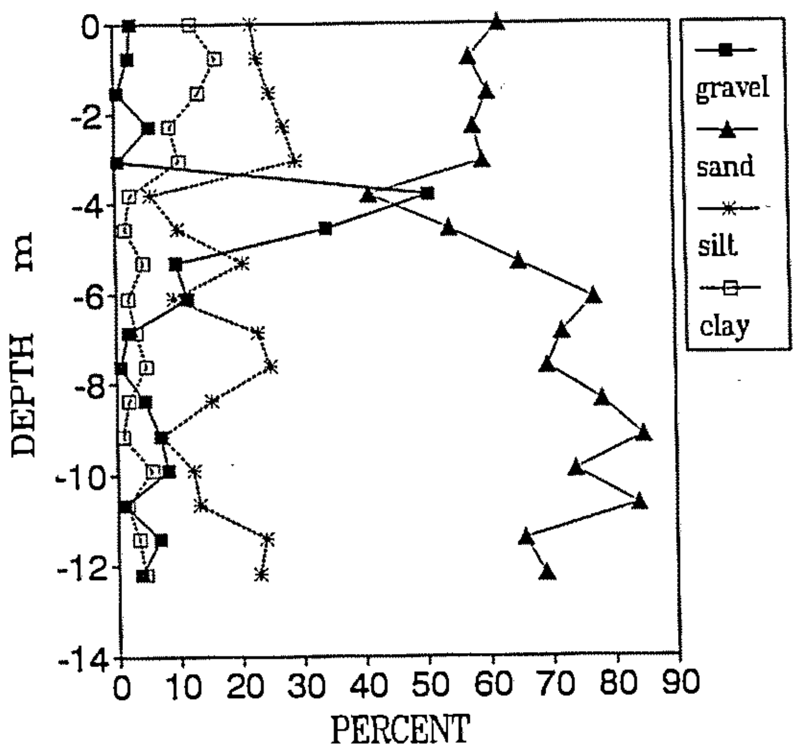

Fig. 1 Texture analysis with depth

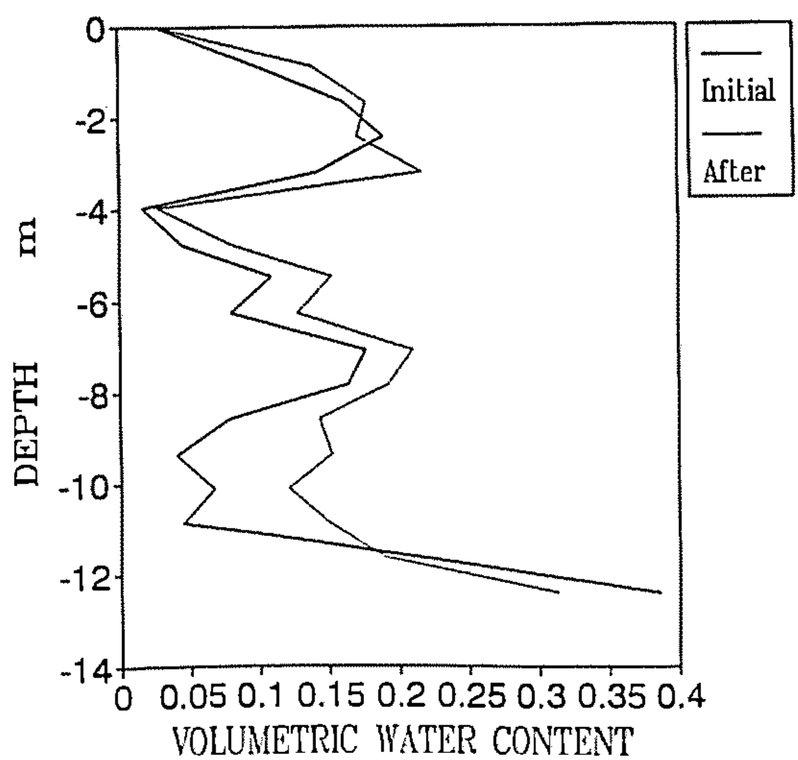

Fig. 2 Water Content with depth

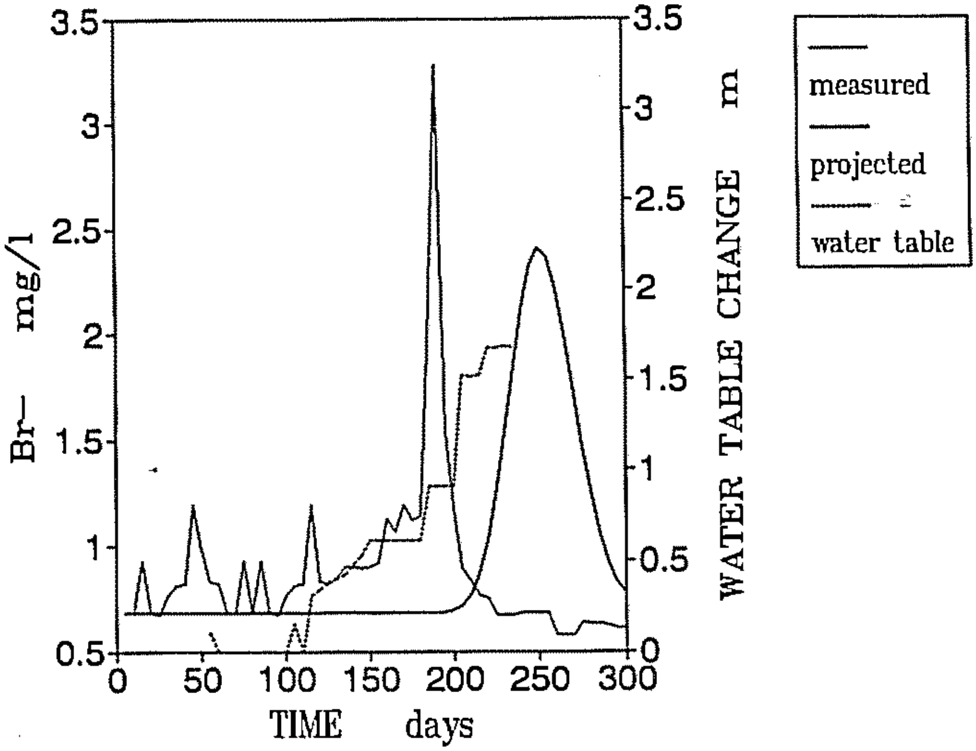

Fig. 3. Measured and projected Br⁻ breakthrough curves and water table changes with time

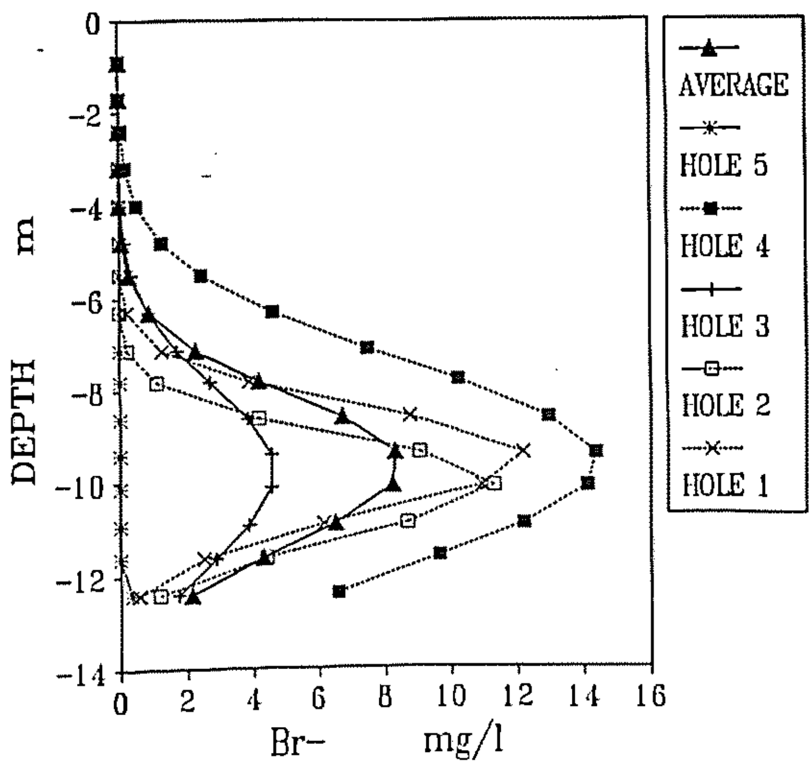

Fig. 4. Bromide breakthrough curves for five holes.

CONCENTRATION AND PREFERENTIAL FLOW EFFECTS ON PESTICIDE FATE AND TRANSPORT IN SOILS

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PROBLEM: The widespread detection of pesticides in groundwater indicates our inability to accurately predict the fate and transport of chemicals in soils. Two factors that have a strong influence on pesticide fate are pesticide concentration and preferential flow. Either factor may result in accelerated chemical transport. High pesticide concentration can occur through misuse of pesticides, excess applications in turn rows, or spills. Preferential flow, which usually is thought to occur in macropores, has been observed in unstructured field soils under unsaturated as well as saturated flow conditions. The object of this project is to determine the effect of high concentrations of pesticides on transport and degradation under field conditions.

APPROACH: Experimental plots were established on uncropped Mohall sandy loam (fine loamy, mixed, hyperthermic Typic Haplargid) at The University of Arizona Maricopa Agricultural Center. The soil had been bare for at least 24 months. The experimental field was divided into sixteen 6 x 6 m plots. All plots and a buffer area were flood-irrigated with two 15 cm irrigations prior to herbicide and tracer application. Three herbicides, bromacil, napropamide, and prometryn were applied at two different rates and replicated three times. The three herbicides were applied in combination to the same plot for both application rates. In addition, each herbicide was applied to three separate plots at the high rate to detect any interference between herbicides at the high rates. The application rates and plot location are shown in Table 1. A conservative tracer was applied to each plot with the herbicide. The tracers used were 2,6-diflurobenzoic acid (2,6-DFBA), pentafluorobenzoic acid (PFBA), o-trifluoromethylbenzoic acid (o-TFMBA), and m-trifluoromethyl benzoic acid (m-TFMBA). A separate tracer/herbicide formulation was prepared for each plot. The four conservative tracers were selected so that no two adjacent plots received identical tracers. The herbicide/tracer solution was sprayed on the soil by making five to six passes with a hand-held spray rig over each subplot. Evaporation was determined using the energy balance method from meteorological data recorded at the site.

Soil samples from three sites in each of the 15 treated plots were obtained during a two-day period commencing 70 days after application. A second sampling was obtained 310 days after the first pesticide application. For the top 90 cm, cores were taken using a 5.0 cm I.D. sample tube equipped with a plastic insert. The sample tube was driven into the soil to a depth of 90 cm and removed. The plastic tube containing the soil core was removed and sealed. Below 90 cm, the samples were taken at 30-cm intervals to a depth of 2.7 m using a 2.0 cm I.D. Veihmyer tube. Each 30-cm sample was placed in a resealable plastic bag and the bag placed in an ice chest. In the laboratory, the 90-cm sample was divided into six 10-cm subsamples (10 to 60 cm) and one 30-cm sample (60-90 cm). All samples were then sub-divided into two groups. One sample was used for water content and tracer analysis and the other sample for herbicide analysis. Potassium bromide was applied to all plots 268 days after the first tracer application. A second soil sampling was conducted 53 days later.

For tracer analysis, a 10-g subsample of each core at field moisture content was extracted with 10 ml of water by shaking for 20 minutes in a 50-ml polypropylene centrifuge tube. After centrifugation and filtering, the tracers were quantified using an HPLC technique. A separate 10-g sample was taken at the same time for gravimetric water content determination. The pesticide analysis was conducted by Robert Bowman at the New Mexico Institute of Mining and Technology.

FINDINGS: Depth-concentration relationships were determined for each hole and each tracer. A typical example is shown in Figure 1 for the three sites at one plot. Velocity and dispersion coefficients were determined for each hole by fitting the data to the one dimensional convection-dispersion equation using the non-linear least squares inversion method assuming resident concentration values for the tracers. The velocity and dispersion coefficients for each site are shown in Table 2. Examples of the fitted curves are shown in Figure 1 as the smoothed curves. The variance in solute velocity was considerably less than in previous experiments located in the same area.

INTERPRETATION: Interpretation of the data is continuing. No conclusions can be made until the pesticide data analysis has been completed. Based on similar findings from previous experiments in the same field, considerable preferential flow did occur. Predicting preferential flow and incorporation into solute transport models will improve our ability to reduce groundwater contamination.

FUTURE PLANS: The field portion of this experiment has been completed. Laboratory analysis of the pesticide data is continuing. Field models of pesticide transport will be calibrated using laboratory data on sorption and degradation. The laboratory-based information will be related to field behavior.

COOPERATORS: R. S. Bowman, NM Institute of Mining and Technology, BARD project.

Table 1. Plot location and application rates for the herbicides and tracers.

Compound	Concentration	Plots
bromacil	high	4, 12, 15
napropamide	high	3, 6, 14
prometryn	high	8, 11, 16
Three herbicides	high	1, 2, 13
All three	low	5, 7, 10
2,6-DFBA	2 g/m^2	1, 3, 5, 7
PFBA	2 g/m^2	2, 4, 6, 8
o-TMFBA	2 g/M^2	10, 12, 14, 16
m-TMFBA	2 g/m^2	11, 13, 15
Br^-	13.5 g/m^2	All

Table 2. Tracer velocity and dispersion coefficients.

plot	VELOCITY cm/day hole 1	hole 2	hole 3	avg.	standard deviation
1	3.56	0.99	3.26	2.60	1.14
2	2.39	2.35	2.91	2.55	0.25
3	3.90	3.03	3.31	3.41	0.36
4	2.37	2.59	3.31	2.76	0.40
5	2.19	3.17	2.97	2.78	0.42
6	1.89	2.51	2.54	2.31	0.30
7	1.90	4.25	2.02	2.72	1.08
8	2.27	2.32	2.74	2.45	0.21
10	2.03	2.31 >	4.06	2.80	0.90
11	1.58	2.44	2.28	2.10	0.37
12	2.86	2.56	2.55	2.66	0.14
13	1.76	3.13	2.41	2.44	0.56
14	2.44	3.27	3.51	3.07	0.46
15	3.05	2.89	3.64	3.20	0.32
16	3.67	2.01 >	3.87	2.52	0.82
	all plots			2.69	0.68

plot	DISPERSION COEFFICIENT cm2/day hole 1	hole 2	hole 3	avg.	standard deviation
1	1.50	2.74	0.96	1.55	0.65
2	2.06	5.90	3.08	3.26	1.42
3	4.79	2.37	3.96	3.53	0.87
4	0.90	2.28	6.26	3.36	1.97
5	3.02	2.07	1.85	2.99	0.53
6	1.56	2.65	2.39	3.15	0.58
7	2.60	19.87	1.46	7.73	7.29
8	0.43	10.69	13.83	8.24	4.96
10	1.88	2.69	----	3.83	1.13
11	4.27	2.02	3.54	5.21	1.16
12	1.35	1.00	1.80	4.04	1.18
13	1.04	4.49	1.30	4.96	1.78
14	0.78	1.20	2.45	4.61	1.49
15	5.52	3.52	3.08	6.78	1.50
16	0.75	0.94	------	11.99	12.02
		all plots		3.86	5.31

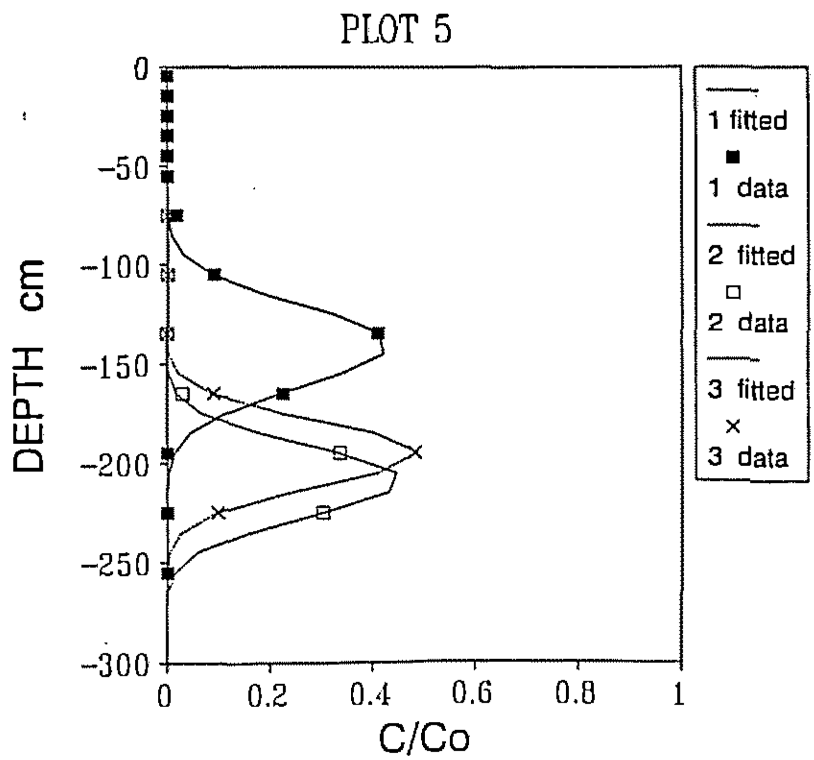

Fig. 1. Tracer distribution with depth for 3 holes in Plot 5.

NITROGEN FERTILIZER AND WATER TRANSPORT UNDER 100% IRRIGATION EFFICIENCY

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PROBLEM: Contributions to groundwater pollution by deep percolating irrigation waters could be minimized and/or eliminated by the development and application of existing and new technologies. However, this requires a better understanding of chemical and water transport in the soil environment. In the arid Southwest more than 75% of the water used is for irrigating crops. Prudent operation of irrigation systems to apply this water can minimize the movement of water and chemicals below the root zone, thus controlling groundwater pollution. Theoretically, irrigating at 100% efficiency will lead to zero deep percolation and keep water and chemicals in the crop root zone. Crop leaching requirements could be met when crops are not being grown, and when most of the applied nutrient chemicals have been used by the crop. However, because of spatial variability and preferential flow of water in the soil profile, 100% irrigation efficiency may still produce some deep percolation and transport of chemicals to the groundwater.

The objective of this research is to determine the movement of water and nitrogen fertilizer in the soil profile when irrigating at or near 100% irrigation efficiency and to develop best management practices to reduce groundwater degradation.

APPROACH: Research will be conducted through a series of experiments to evaluate the 100% irrigation efficiency theory. Corn and wheat crops will be grown using level-basin flood irrigation during the first year. Nitrogen fertilizer will be applied with the irrigation water (chemigation) and broadcast. Future experiments will use drip and sprinkler irrigation techniques. The experimental design will be a complete randomized block with six fertilizer-water application treatments and three replications. Each experimental plot will be approximately 81 m^2 in size. A different conservative tracer will be applied with each N^{15} tagged fertilizer application. This will allow evaluation of a complete water and nitrogen balance, including the amount of nitrogen taken up by the crop and removed from the field by harvest, deep percolation, and denitrification. Nitrogen status of the crop will be correlated with leaf chlorophyll content as determined with a chlorophyll meter. This is a relatively new technique that may allow determination of nitrogen stress in the crop and when and how much fertilizer to apply. Water movement in the soil profile will be characterized with soil water content and tracer analysis. Evapotranspiration will be estimated from energy balance techniques using meteorological data collected at the site.

Experimental treatments will include 1) a "standard procedure" in which irrigation and fertilizer applications are scheduled according to current farm practices with 100% irrigation efficiency, 2) same as treatment 1 except with 80% irrigation efficiency, 3) surface applied fertilizer applications scheduled according to residual soil, petiole NO_3-N feedback, and leaf chlorophyll content with 100% irrigation efficiency, 4) same as treatment 4 except with 80% irrigation efficiency, 5) irrigation water applied fertilizer applications (chemigation) scheduled as in treatment 3 with 100% irrigation efficiency, and 6) same as treatment 5 except with 80% irrigation efficiency.

INTERPRETATION: This research will demonstrate how much of the applied fertilizer can be confined to the root zone under 100% irrigation efficiency during the growing season. The extensive and intensive field measurements will provide information for determining preferential water and chemical flow, spatial variability, irrigation uniformity, efficiency, scheduling, evapotranspiration, and best irrigation management practices to minimize transport of nitrates to the groundwater. In addition, soil solution (nitrogen) and soil air (carbon dioxide) composition measurements will provide data for evaluating chemical equilibrium and for estimating nitrogen and water balances needed in various models under the various irrigation regimes. Although crop production is not part of the primary objective, such information will also be obtained. The combined data can be used to test existing models for water and chemical movement and crop yield.

COOPERATOR: Dr. J.E. Watson, The University of Arizona Maricopa Agricultural Center

GERMPLASM IMPROVEMENT OF GUAYULE

D. A. Dierig and A. E. Thompson, Research Geneticists

PROBLEM: Natural rubber is an important, irreplaceable strategic material imported by the United States at a cost of a billion dollars annually. The source of this material is the Hevea tree, primarily grown in Malaysia, Thailand, and the Philippines. The political climate of these countries and predictions of shortages can cause this foreign market to be unstable. Guayule is a promising source of natural rubber which could be domestically grown in the arid Southwest. The present cost of imported natural rubber is around $0.40 per pound compared to estimated costs of guayule production of $0.85 per pound. Commercialization of guayule will depend on increased yields by plant breeders and development of uses for the by-products. The primary objective of the guayule breeding program is to select high quality, high rubber yielding germplasm with desirable growth, agronomic, and processing characteristics.

APPROACH:

1. Evaluate new selections based on increased rubber content, vigorous growth patterns, and ability to regenerate following harvest by clipping stems above ground level. New selections are compared to standard varieties.

2. An innovative breeding strategy developed in our program is being employed for germplasm improvement. High yielding polyploid selections (apomictic) are crossed to diploids (sexual) to generate variability for desirable traits such as rubber content. Selections are then made from the apomictic progeny. Also, open-pollinated diploids are used as a source for a recurrent selection breeding program.

3. The most promising selections are grown in other locations to determine genotype X environment interactions. Plantings of these new selections are in Texas and California. The third three-year Uniform Regional Variety Trial was planted this year in Arizona, California, New Mexico, and Texas to test advanced lines from breeders in the same replicated trial. This trial is coordinated and analyzed each year by U.S. Water Conservation Laboratory and University of Arizona personnel.

4. Laboratory germination trials of 50 different breeding lines grown in the same environment to determine the amount of variability within and between lines. Selections are being made for seedling vigor.

5. Collections of observational lines with a wide range of variability for various traits of interest are maintained in a nursery.

FINDINGS:

1. New selections evaluated have the potential of producing over twice the rubber, resin, and biomass yield of the older standard varieties. Selections have been identified with the capability of producing sustained rubber yields in excess of 1,000 kg/ha/year.

   New selections have been identified with strong regeneration capabilities and good rubber yields that have the potential of being harvested by clipping after only two years' growth, and therefore on a sustainable two-year harvest and regeneration cycle. These new selections have potential for greatly reducing the high cost of plant establishment and allow amortization of planting costs over a longer period.

2. Progeny of crosses between diploids and polyploids are being field planted for screening.

3. A three-year cooperative study between Arizona and California to determine the nature and extent of genotype X environment interaction of California selections was completed this year and is being analyzed. Preliminary results indicated the newer selections from California, although they had improved yields, were less stable than standard varieties. Twenty-two new selections from this research have been planted in Riverside, California, and at Ft. Stockton, Texas, for evaluation of yield and adaptation. Four of the six new lines in the replicated trial and four of the five observational lines planted in the 1990 Uniform Regional variety Trial III are selections of the Arizona breeding and genetics program.

4. Seed from 50 lines grown in the same environment was collected in two different seasons. Laboratory germination trials from the first season has been completed. Significant differences occurred in the rate and percent of germination.

5. Seed from desirable nursery plants is screened and collected on a continuing basis.

INTERPRETATION: The perennial nature of guayule necessitates a long-range breeding program. Since this program was initiated in 1986, very significant progress has been achieved in the germplasm improvement. The selections resulting from this research because of their high yields and regeneration ability may allow a harvest on a two-year-cycle rather than three years. This would also reduce the cost of stand establishment. Since water requirements are higher at establishment, this should reduce the total amount of water used by the crop. It is apparent that new information on water requirements will be necessary, since these newer selections have characteristics distinct from older varieties.

FUTURE PLANS: New selections will continue to be developed and tested. Advanced generations of selections have been planted for further progress and uniformity. In 1991 an experiment designed to test different lines planted at increased densities to compare harvests of these new lines at two versus three-years will begin. The number of cycles a plant can regenerate with adequate yields will also continue to be studied. The recurrent selection program utilizing a diploid population is in progress with a new round being planted this spring. However, we now feel the strategy developed by our program crossing diploids X polyploids in the greenhouse and then planting the progeny in the field for further selection is a much more effective method. The heterosis effect from this cross would be locked into the apomictic progeny.

COOPERATORS: Dr. D. T. Ray, The University of Arizona, Plant Science Department, Tucson, AZ
Dr. M. A. Foster, Texas A&M Experiment Station, Fort Stockton, TX
Dr. A. Estilai, University of California - Riverside, Botany Department, Riverside, CA

GENETIC AND BIOLOGICAL STUDIES OF GUAYULE

D. A. Dierig and A. E. Thompson, Research Geneticists

PROBLEM: The collective biological, genetic, and cytological properties of guayule are interesting but more complex than most traditional crops grown in the U.S.. It is a facultative apomict, meaning that reproduction can occur sexually or through an asexual process. The nature of the pollination and reproduction results in a natural polyploid series with chromosome counts of 36 up to 144 being reported. Also, extensive aneuploidy and B-chromosomes occur. Self-incompatibility is also present in the diploid population. An understanding of these abnormalities is crucial for manipulation of the plant and improvement of yields in a breeding program.

APPROACH:

1. The inheritance of apomixis is being investigated as follows a) sexual diploids are crossed to apomictic polyhaploids, b) the F1 progeny are screened for reproductive type (sexual or apomictic) by crossing with another species that possesses a distinct leaf shape as an identifiable marker, c) the F1 generation is testcrossed to the apomictic polyhaploids, d) the amount of segregation for sexual and apomictic reproduction from this generation is again determined by crossing to another species with the distinct leaf characteristic, and e) the ratio of the two reproductive types estimate the number of genes involved in controlling apomixis in guayule.
2. Standard cytological microscope counts are being correlated to a technique where the quantity of DNA per cell is measured. This method of flow cytometry enables multiploidy plant species to be screened at a rapid rate. Vegetative plant tissue, such as leaves, can be used instead of reproductive tissue for the determination, therefore allowing any age of plant to be utilized.
3. Seedlings and cutting of the same parent source are being grown together in a replicated experiment comparing four different lines to examine genetic variation. Yield characteristics of both types of plants are being measured.
4. The inheritance of a newly discovered flower trait is being studied by appropriate crossings of plants with this trait.,
5. A sampling method for rubber and resin determinations that would not involve complete destruction of the plant is being studied. Various types of samples have been taken and correlated to whole plant samples.

FINDINGS:

1. The first phase of the apomixis inheritance study has confirmed that sexual reproduction is a dominant genetic trait over apomixis. The number of genes that control this trait is still under investigation.
2. Parent and progeny of 23 lines have been field planted to determine chromosomal variation and the relationship to phenotypic characteristics. Calibration of the flow cytometer to standard pollen mother counts is in progress.
3. Data of two-year-old plants grown from cuttings and seed have been collected and analyzed. Two of the four lines in this study were significantly different in rubber content between the cutting and seed propagated plants. No difference was seen for other traits measured.
4. Crosses between six- and five-flowered diploid plants have been made and the progeny are being grown in the greenhouse. When flowering is induced, plants will be scored to determine the amount of genetic control of this trait.
5. One- and two-year-old plants have been sampled and correlated to whole plant samples for rubber content. Preliminary observations have indicated that correlation between the sample and whole plant have not been proven useful. The problem may be with finding a representative plant part or a problem with the analytical technique for rubber determination. One finding from this study has been that a highly significant difference exists in rubber content when leaves are removed prior to analysis compared to leaves left intact.

INTERPRETATION: *Understanding the inheritance of apomixis is crucial for making meaningful* progress in rubber yields. Advancement in plant breeding is dependent on exploiting variability existing in the germplasm; however, apomixis prevents it from being expressed. Manipulation of this trait would allow heterosis of desirable lines to be fixed while the release of variability in germplasm would also be possible. This has implications not only with increasing yields but also for selections of other desirable traits such as salt tolerance, disease resistance, or water efficiency. Genetic studies such as the inheritance of flower number per capitula are belpful for use as genetic markers to identify crosses. Large numbers of plants requiring considerable time for measurements are necessary in plant breeding programs when screening for desirable traits. This is why a rapid sampling technique for rubber determination or the flow cytometer for measuring ploidy levels would be a tremendous value in saving time. The cutting versus seedling study gives further information on apomixis by comparing differences in phenotypes of plants asexually propagated (cuttings) with plants that reproduce through the asexual process of apomixis (seedlings). Differences between the two types are indicative of genetic variability existing in apomictic plants because the environmental effects of the two would be the same. Germination studies are important to the success of direct seeding guayule. If guayule is to become a commercially acceptable crop, the most economical means for production must be found. Since differences exist for this trait, it should be possible to select lines with high germination rates and the ability to germinated rapidly.

FUTURE PLANS: We are now on the testcross generation in the apomixis study. This study will continue until enough crosses have been made to generate progeny to determine the number of genes in control. Cooperative work is being planned with scientists at The University of Arizona and Arizona State University to elaborate on this study using molecular biological techniques to characterize the difference between an apomictic and sexually reproducing plant. The study would utilize existing crosses, a cDNA library of the egg nucleus in both apomictic and sexual plants for expression of proteins, and flow cytometry to isolate this enlarged cell within the plant ovaries.

COOPERATORS: Dr. D. T. Ray, The University of Arizona, Tucson, AZ
Dr. R. A. Backhaus, Arizona State University, Tempe, AZ

COMMERCIALIZATION OF LESQUERELLA

A. E. Thompson and D. A. Dierig, Research Geneticists
and D. J. Hunsaker, Agricultural Engineer

PROBLEM: Development of new industrial oilseed crops would significantly contribute to the improvement of the agricultural as well as the general economy of the country. The U.S. is completely dependent upon imported castor oil, a strategic material, for its total supply of hydroxy fatty acids, with annual imports of around 40-50,000 MT and a value of about $40 million. Seed oil of lesquerella, a native plant adapted to arid and semiarid areas, holds promise for replacing castor oil and may prove to be useful for developing an even wider array of new, useful industrial products. Preliminary breeding and selection, as well as cultural research, indicates that lesquerella may become a successful new crop with relatively low water requirements. The objective of this research is to evaluate and develop improved germplasm, to develop appropriate cultural and water management practices, and to assess the potential for full commercialization.

APPROACH:

1. Evaluate and enhance germplasm of lesquerella for seed oil yield and hydroxy fatty acid content using appropriate breeding, genetic, and cytogenetic techniques.
2. Make appropriate genetic crosses; select, test, and develop high yielding cultivars capable of full commercialization.
3. Develop and evaluate appropriate cultural and management systems including planting rates and methods, water use, weed and pest management, seed production, and harvesting methods.
4. Work cooperatively with private industry and other public research entities to increase basic and applied research and to increase lesquerella seed for pilot plant oil extractions and evaluations, oil and meal utilization, and new product development for full commercialization.

FINDINGS: Field plot research during the 1989-1990 growing season included experiments on water use and yield tests, on three bulk populations of breeding material. Results on determination of water requirement are summarized within a separate report. In general, extremely high variability in plant stands was observed among the research plots, contributing to high experimental error. Preliminary research conducted on establishment of plant stands on level basins utilizing residual soil moisture indicated that higher seeding rates may be needed. Results from samples sent to NRRC-Peoria, Illinois, for analysis of oil percentage and fatty acid content have not yet been received. Six of the highest yielding half-sib families from single plant selections were propagated in isolation in screened cages containing honey bees. In addition, the six lines were intercrossed with the assistance of honey bees in a large screened cage. Top cross seeds of each line were harvested separately for future yield evaluation. The lysimeter field at the USWCL was uniformly planted in October 1989. Plant stands in separate borders varied considerably, apparently due to differences in amount of soil salinity at the soil surface during seed germination as a result of unequal soil wetting from deeply positioned drip lines. Plots were harvested in June 1990. Detailed spectral measurements made by personnel of the Remote Sensing research group throughout the growing season will be correlated with plant stand and yield of seed, oil, and hydroxy fatty acid. Attempts will be made to construct a crop water stress index for this new crop. Research on the heritable basis of isozyme variation is in progress. Isozyme analysis is being utilized on plant populations grown in 1989 and 1990 to determine the system of mating of lesquerella under field conditions. Such information will be utilized to determine the most efficient breeding system to employ in the future. Three male sterile plants have been identified and appropriate crosses made to determine the nature of their inheritance and usefullness in future breeding and potential for first generation hybrid seed production. Genetic variation for yellow seed coat color has been identified and its inheritance is under investigation.

Cooperative interaction with industry on lesquerella commercialization has been greatly accelerated. Two 230 kg lots of seed were supplied for successful pilot plant oil extractions conducted in cooperation with the USDA-ARS-NRRC-Peoria at two locations; a prepress-solvent extraction at the French Oil Mill Machinery Co., Piqua, Ohio, and an extrusion processing-solvent extraction at the Food Protein R&D

Center at Texas A&M. Funds to help facilitate these trials were supplied by the USDA Office of Agricultural Industrial Materials (OAIM). About 1,600 kg of seeds were made available to two cooperating commercial companies (Jojoba Growers & Processors and Agrigenetics/Lubrizol) for oil extraction and evaluation. Trust fund agreements were entered into with these two companies to cooperatively produce an increased quantity of seed for futher evaluation and product development by industry. Additional funding was received from USDA-OAIM for support of this cooperative effort. About 8 hectares were planted in October 1990 at The University of Arizona Maricopa Agricultural Center. Additional plantings of comparable acreage were made by industry in Arizona, Texas, and Oklahoma with seed provided by the project. Additional cooperative research plantings were made at the Texas A&M Experiment Station at Fort Stockton, Texas.

A split plot (level basin vs. raised, 1-meter wide vegetable beds) experiment with 6 replications was designed and planted with a Brillion seeder on October 10, 1990, to test three seeding rates (4.5, 6.8, 9.0 kg/ha). Excellent plant stands were obtained, and detailed data on plant population and water use are being taken. Harvest by combine is planned for the end of May 1991. A replicated (6) randomized complete blocks experiment was designed and planted on raised beds (2-rows/bed with single row cone seeder) to compare the yields of the 12 breeding populations with that of 3 bulk populations--S0, an essentially unselected base population; S1, a bulk population of selected lines made in 1986; and S2, a new recurrent bulk population arising from field intercrossing of 24 selected, high yielding half-sib families made in 1989. Excellent plant stands have been obtained, and harvest is planned for the end of May 1991.

INTERPRETATION: A report on a favorable assessment of lesquerella's future as a new, domestic hydroxy fatty acid source is expected to be released by the USDA-OAIM in early 1991. The growing interest and cooperative interaction with industry is stimulating a rapid and orderly commercialization of lesquerella. Currently, research is centered on germplasm chiefly adapted to semiarid environments. Prospects are very good for development of a new industrial crop with minimal water requirements, which should result in significant water conservation. As progress continues, other germplasm from different species, which produce two other hydroxy fatty acids of potential industrial utility, may be developed for production over a much wider area of adaptation.

FUTURE PLANS: Current plantings at MAC will be harvested in May or June 1991. Distribution of increased seed will be made to industrial cooperators after appropriate amounts of seed are set aside for future planting stock. Industry will also extract and make available 50 gallons of seed oil for future utilization research at NRRC. All press cake will also be made available to NRRC for future animal feeding trials and other research on seed meal utilization. Continued breeding and genetic research will be based upon results of ongoing research and yield performance in current field experiments to be harvested in 1991. The extent of future cooperative interaction with industry will also be based upon these results and those of industry. Plans are being made to fund and conduct a new germplasm collection within the U.S. About two-thirds of the lesquerella species native to the U.S. have not as yet been collected or evaluated, and several of these are now considered to be rare or endangered. New cooperative breeding and genetic and cultural research is being planned with research scientists at the Texas A&M and Oregon State experiment stations.

COOPERATORS: Mr. J.H. Brown, Jojoba Growers & Processors, Inc., Apache Junction, AZ
Dr. K.A. Walker, Agrigenetics Company, Eastlake, OH
Dr. B. Phipps, Agrigenetics Company, Goodyear, AZ
Dr. M.A. Foster, Texas A&M Experiment Station, Fort Stockton, TX
Dr. R.L. Roth, University of Arizona Maricopa Agricultural Center, Maricopa, AZ
Dr. R. Kleiman and Dr. K.D. Carlson, USDA-ARS-NRRC, Peoria, IL

ESTABLISHMENT OF VERNONIA AS AN EPOXY FATTY ACID OILSEED CROP

A. E. Thompson and D. A. Dierig, Research Geneticists

PROBLEM: No oilseed crop currently produces economic quantities of industrially useful epoxy fatty acids. Existing needs have been met with chemical modification of petrochemicals or epoxidation of fats and vegetable oils, chiefly soybean and linseed oils. Unlike these, vernonia oils have low viscosity, which may prove to be extremely useful in the reformulation of oil-based (alkyd-resin) paints to reduce emissions of volatile organic compounds (VOC), which contibute to production of smog. Estimates for using one pint of vernonia oil as a "reactive diluent" in each gallon of oil-based paint would require at least 73 million kg per year, and create a market for vernonia oil production from at least 145,000 hectares. Other potential markets include toughened epoxy resins, dibasic acids, lubricants, and adhesives. Until very recently, no available germplasm was adapted for culture in the continental U.S. New germplasm collections of Vernonia galamensis from arid regions of Africa, which are currently undergoing evaluation, hold considerable promise for domestication and new crop development.

APPROACH:

1. Evaluate and enhance germplasm of vernonia for seed oil yield and epoxy fatty acid content using appropriate breeding, genetic, and cytogenetic techniques.
2. Make appropriate genetic crosses; select, test, and develop high-yielding cultivars capable of full commercialization.
3. Develop and evaluate appropriate cultural and water management systems.
4. Work cooperatively with private industry and other public research entities to expedite full commercialization.

FINDINGS: A working germplasm collection of 38 accessions of all the available Vernonia galamensis subspecies and varieties has been assembled at the USWCL in Phoenix. Over 800 plants of 18 accessions were evaluated at Phoenix and Yuma in 1989 for flowering response in relation to length of day, seed production, plant growth, and other agronomic characteristics. Seeds from bulk collections and single plant selections were planted by direct seeding in April 1990 in replicated and observational plots at the Maricopa Agricultural Center. Very poor plant stands were obtained for many of the accessions. The accession A399 (V-029) of V. galamensis spp. galamensis var. petitiana was clearly superior to all others tested. This accession does not require a short-day photoinductive cycle to stimulate flowering and subsequent seed set. The plants flowered well, but seed retention was not as good as the original germplasm collected in Ethiopia. Periodic harvests of seeds were made throughout the growing season to have sufficient seed for future research. Seeds of all accessions were germinated for growing representative plants in the greenhouse.

INTERPRETATION: Considerable variation exists among the various accessions from within the Vernonia galamensis species complex. The most promising germplasm so far identified is from accession A399 of the subspecies galamensis var. petitiana from Kenya. It apparently requires no short-day photoinduction cycles for flowering, has good drought tolerance, and produces good biomass and seed under favorable environmental conditions. However, its flowering is indeterminate, and retention of seeds at maturity needs improvement. Sufficient seed was harvested in 1990 to initiate agronomic field experiments, which may lead to the development of an appropriate crop production and water managements system. Hybridization of this promising germplasm with that of the original V. galamensis spp. galamensis var. ethiopica accession and other related material is indicated and will be attempted.

FUTURE PLANS: A field experiment is being designed to determine the effects of planting dates and planting methods-seeding rates on the growth, flowering, and seed yields of the petitiana (A399) germplasm. Initial plantings at MAC will start in mid-February 1991 and proceed at 2-week intervals until mid-April. Three or four seeding rates in single or double rows on raised vegetable beds will be combined with a treatment of cutting back the tops of plants to attempt to induce synchronous flowering. Additional with a treatment of cutting back the tops of plants to attempt to induce synchronous flowering. Additional germplasm will be planted for observation and selection. Samples of seeds from the various treatments will be harvested and sent to the USDA-NRRC, Peoria, Illinois, for oil and epoxy fatty acid analysis.

Plants of the various accessions growing in the greenhouse will be evaluated for growth and flowering response, mode of reproduction, and cytogenetic analysis of chromosome number. A protocol for floral emasculation and controlled hybridization will be developed. Selected plants will be utilized for hybridization among various subspecies and varieties to obtain genetic recombinations of good seed retention, insensitivity to photoperiod, determinate flowering, good water use efficiency, adaptation to conventional agronomic production practices, and high seed and seed oil yields.

Cooperative interaction with industry and other federal and state research scientists will be sought. Assistance is being provided for the development of an 1890 Institution Capacity Building Research Grant at the Virginia State University, Petersburg, Virginia, entitled "Evaluation and Development of Natural Products from Vernonia galamensis." Our project will cooperate closely with this new project, which will also interact with research at NRRC, Peoria.

COOPERATORS: Dr. Michael A. Foster, Texas A&M Expt. Station, Fort Stockton, TX
Dr. Steven J. Knapp, Oregon State Univ., Corvallis, OR
Dr. R. Kleiman and Dr. K.D. Carlson, USDA-ARS-NRRC, Peoria, IL
Dr. A.I. Mohamed, Dr. M.E. Kraemer, and Mr. M. Rangappa, Virginia State Univ., Petersburg, VA

CULTURAL MANAGEMENT OF LESQUERELLA: WATER REQUIREMENT

F. S. Nakayama, Research Chemist; and D. A. Dierig, Research Geneticist

PROBLEM: Agricultural management information is lacking on lesquerella, as a potential new crop for seed oil production. Little is known on its cultural management practices particularly those on water requirement and management under irrigation. Although lesquerella is native to a semiarid environment, improved water management of the crop should increase its yields to acceptable economic levels as has been found for other traditional crops. The objective of this study is to determine the water and fertility requirements of lesquerella.

APPROACH:

1. Determine the water and nutrient requirements for lesquerella under irrigation management by varying the frequency and amount of water and fertilizer application.
2. Develop production functions applicable for economic analysis of the crop.

FINDING: Research began in 1987 when no information was available on the water use and requirements of lesquerella. That year was a learning experience in that poor stand was obtained in October 1987 followed by low yield and water use for the December 1987 replanting. Since then, changes in experimental design and treatments were made as necessary as more knowledge was acquired on the cultivation of the crop. In 1990, an experiment with low and high frequencies with the same total amount of water application was established, since the 1988 and 1989 results showed difference in yields when the method of application was different.

The 1990 data confirmed the earlier 1988 and 1989 results, in that the high frequency irrigation (127 mm/irrigation) resulted in larger yields than the low frequency (63.5 mm/irrigation) at the low total water application rate. Conversely, the low frequency treatment plots had larger yields than the high frequency irrigation at the high total water application rate. Additional information on nutrient status, responsiveness of the crop to water application during various stages of growth, particularly over the fruit forming stage, sensitivity to excess soil moisture during fruit maturation, and others need to be determined before any definitive explanation on the behavior to irrigation frequency can be made. Overall, the water requirement was similar to wheat that is grown in this area.

Data for the composite rotatable design have not been completely analyzed for the water x nitrogen interaction.

INTERPRETATION: Lesquerella has its own distinct response to irrigation. Water use for the crop is on the order of 550 to 660 mm with water application of 650 to 750 mm per growing season. From a practical standpoint, low frequency application would be preferable to the high frequency irrigation practice. Water use is similar to other small grain crops grown in central Arizona.

FUTURE PLANS: Complete statistical analysis of the central composite rotatable design. Continue irrigation studies by increasing replications to reduce variability and to include crop water stress indexing to improve irrigation scheduling and understanding of the crop physiology of the plant relative to stress and seed yield. Determine the salinity tolerance of lesquerella.

COOPERATORS: None

Table 1. Water Use and Seed Yield of Lesquerella - Irrigation Frequency Effects.

1988 (Low frequency)			1989 (High frequency)		
No. Irrig.	Water Use (mm)	Seed Yield (kg/ha)	No. Irrig.	Water Use (mm)	Seed Yield (kg/ha)
3	400	660	4	450	1235
4	550	1060	6	630	1280
5	630	1090	8	565	1130
6	625	1420	10	625	1120

1990 (Low frequency)			1990 (High frequency)		
No. Irrig.	Water Use (mm)	Seed Yield (kg/ha)	No. Irrig.	Water Use (mm)	Seed Yield (kg/ha)
2	360	995	4	480	1125
3	450	1090	6	460	1270
4	530	1250	8	520	1250
5	510	1110	10	550	1160
6	620	1565	12	550	1365

Note: Low frequency treatment received 127.0 mm and high frequency 63.5 mm per irrigation.

GUAYULE RUBBER QUALITY: HARVESTING, STORAGE AND SAMPLE PREPARATION

F. S. Nakayama, Research Chemist

PROBLEM: Rubber degradation in guayule has been observed in the early history of its culture, but adequate information is still lacking concerning how the shrub should be handled prior to processing. Recent reports also indicate a decrease in rubber quantity and quality soon after the shrub is harvested and left in the field. While efforts have been concentrated on trying to understand the post-harvest field storage aspects of rubber quality degradation, one cannot overlook the fact that degradation could also be occurring in the sample between the time it is prepared for analysis to the actual time of rubber analysis. Thus, a laboratory analysis, even though accurate, may not reflect the true nature of what is happening to the field stored materials.

Because of the need to obtain more rubber content data, sample volume has become so large that the rate of analysis cannot adequately keep up with the number of sample being prepared. Thus, samples have been stored in the laboratory or elsewhere for weeks to months before they can be analyzed. The objectives of the study are (a) continue the investigation on the post-harvest changes in rubber content and quality of guayule shrub, and (b) determine the effects of various sample preparation and laboratory storage methods on rubber analysis for developing a standard laboratory procedure for handling samples.

APPROACH: Mature guayule plants of different genetic lines will be harvested and stored in the field and greenhouses for various intervals to follow the progress of rubber content changes. For the laboratory part of rubber analysis, samples will be prepared and stored in various manners (field, greenhouse, laboratory) for different time periods and the rubber content and molecular weight determined.

FINDING: Preliminary results on sample preparation for rubber analysis show that the rubber content of oven-dried materials (55 C) was higher than the air-dried materials; and, contrary to expectations, the rubber content of fresh plant materials was less than that of the air-dried or oven-dried samples. Analyses were corrected for water content. In contrast, the rubber molecular weights were highest in the fresh and lowest in the oven-dried materials. Even at the present time, investigators are reporting rubber content values based either on the air-dried or oven-dried preparations.

Other effects of sample preparation on rubber content have been observed. For example, the rubber content of frozen fresh, ground samples decreased with storage period in the freezer, whereas that of frozen, air-dried samples remained essentially constant over a four-week storage period. An explanation of this behavior is not available at present, but this certainly raises questions as to what is going on with the rubber polymer under various preparation and storage conditions.

Molecular weight distributions with several distinct values (polymodal) are being obtained by further detailed analysis of the size exclusion chromatograms. This type of information would allow us to follow the rubber degradation process more carefully. Previously, most molecular weights of guayule rubber were noted to be a single valued; and occasionally two or bimodal when conditions favor the synthesis of new, low molecular weight rubber polymer molecules. Additional knowledge on molecular weight and its distribution can provide information on the time of year that the shrub was harvested and also a history of its storage.

INTERPRETATION: Differences in rubber contents of guayule reported in the literature could have been caused by the method of sample preparation and storage in the laboratory. Previously, such variations were attributed primarily to the method of analysis. Thus, there is a need to standardize sample preparation so that equivalent comparisons can be made for rubber analysis.

FUTURE PLANS: Continue the study on the effect of sample preparation and storage (field and laboratory) on rubber quantity and quality. Methods for automating the analysis and data handling to speed the rate of analysis will also be investigated. This is particularly important in the determination of molecular weights.

COOPERATORS: W.E. Coates, The University of Arizona

CARBON DIOXIDE FLUX IN NATURAL AND CO_2 ENRICHED SYSTEMS

F. S. Nakayama, Research Chemist

PROBLEM: The increase in the carbon dioxide level worldwide has created concern about how it will affect climate and biological systems. Information on carbon balance is needed and knowledge on the soil component can contribute to the whole picture. More specifically, the exchange of CO_2 of soil with the atmosphere, which is closely related to plant root and soil microbiological activity and chemical composition, can play a significant role in the carbon equation. The objective of the research study is to develop approaches for making soil carbon dioxide flux measurements and to relate the flux so determined to crops and agricultural practices.

APPROACH: Soil carbon dioxide fluxes will be determined in conjunction with the free-air release of carbon dioxide enrichment system (FACE) and also the open-top enrichment chambers. Procedures and equipment needed to make such measurements will be developed as necessary.

FINDING: Numerous measurements of soil carbon dioxide fluxes were made in the FACE experiment at Maricopa, Arizona, with cotton plants. A total of 64 sampling sites were established within the experiment for the check and enrichment plots, which also included "high" and "low" irrigation levels. Weekly measurements showed higher CO_2 fluxes present in the enriched over the untreated plots, but such differences became less evident after enrichment equipment was damaged by lightning (Table 1). Fluxes were similar for the dry and wet plots early in the season, and differences did not become evident until late summer when moisture differences became more evident. Even then, the dry plots could have higher fluxes than the wet plots for a short period soon after the dry plots were irrigated. A single run comparing day- and night-time sampling did not show any differences in flux. High variability was present throughout so that only trends could be interpreted in some cases.

Carbon dioxide flux measurements were also conducted with sour orange trees grown in open top chambers at Phoenix, Arizona. The CO_2 fluxes were higher in the CO_2 enriched than ambient chambers (Table 2) indicating higher root and microbial activities in the enriched chambers. However, negative fluxes were sometimes observed in the enriched chamber samples, which would be an indication that the soil was absorbing CO_2 instead of releasing it. Intensive and continuous two minute sampling showed that such negative fluxes could be the result of fluctuations in CO_2 concentrations occurring in the enriched chambers that shifted the zero-time baseline used to calculate CO_2 flux. This situation would be less noticeable and probably absent in the FACE type experiment and in ambient conditions where gradual changes in the CO_2 concentration is encountered.

INTERPRETATION: Measurements show that soil CO_2 fluxes or respiration under cotton and orange tree cultivation tended to be higher in the CO_2 enriched systems caused by increased biological activities. Large variabilities in fluxes were obtained in the open-air, CO_2 release field experiments, such that the sampling volume should be greatly increased. Even with the existing design, two hours are required to make a complete gas sampling cycle. Obviously, more personnel and improved method of sampling and gas analysis equipment are required.

FUTURE PLANS: Continue cooperative work in determining soil CO_2 fluxes in various enrichment experiments. Develop a self-contained portable flux unit for rapid flux measurement in the field.

COOPERATORS: G. Huluka, Tuskegee University

Table 1. Overall Summary of Soil Carbon Dioxide Flux in the CO_2 Enriched and Ambient Treatments for the FACE Experiment at Maricopa, Arizona - 1990.

SOIL CO_2 FLUX ($mM/m^2/h$)

DATE	CHECK					CO_2 ENRICHMENT				
	Block					Block				
	1C	2C	3C	4C	Avg.	1F	2F	3F	4F	Avg.
21 June	12.8	12.1	18.8	14.8	14.6	22.8	17.7	18.0	16.8	18.8
27 June	12.5	10.2	15.2	7.7	11.4	25.1	25.2	14.4	13.8	19.6
03 July	15.0	7.6	18.0	22.4	15.8	18.7	21.5	22.0	21.5	20.9
12 July	11.5	10.7	14.6	19.7	14.1	12.6	12.9	26.0	24.4	19.0
18 July	22.8	26.7	29.0	38.9	29.4	44.1	36.5	44.2	46.4	42.8
Storm damage										
23 July	20.1	17.3	19.6	20.8	19.4	22.2	19.4	27.6	20.1	20.6
27 July	14.0	19.4	20.2	16.7	17.6	26.0	9.7	18.2	17.7	17.9
31 July	11.3	15.4	11.9	23.6	15.6	19.6	13.2	15.3	10.9	14.7
04 Aug	19.2	14.2	16.5	20.1	17.5	33.9	17.0	18.6	13.8	20.8
14 Aug	7.2	13.8	17.5	20.6	14.8	14.4	17.4	14.8	10.7	14.3
21 Aug(am)	9.2	13.0	15.2	14.1	12.9	17.6	12.9	14.0	11.4	14.0
21 Aug(pm)	15.2	13.7	27.1	19.4	18.8	21.2	22.6	14.1	26.3	21.0
24 Aug	10.6	13.9	12.0	21.8	14.6	15.9	19.2	16.8	11.9	16.0
27 Aug	11.4	10.6	14.7	11.8	12.1	16.1	15.8	10.7	11.8	13.6

Table 2. Soil Carbon Dioxide Flux in Open-Top Chambers with Orange Trees Under Various CO_2 Treatments.

Location	Flux ($mM/m^2/h$)
1. Ambient air	3.30 +/- 0.72
2. Open-top Site (ambient air)	7.98 +/- 1.51
3. Open-top Site (ambient+300 ppm)	11.30 +/- 2.62

Note: Site 1 measurement was on bare soil outside the open-top chamber. Sites 2 and 3 data were from inside the chambers with the sour orange trees.

CO_2 ENRICHMENT OF SOUR ORANGE TREES

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

PROBLEM: The ongoing steady rise in the CO_2 content of Earth's atmosphere is perceived by many environmentally astute people to be perhaps the most significant ecological problem ever faced by mankind. This perception, however, is largely due to a lack of knowledge of CO_2's many beneficial effects in the biological arena. Hence, it is imperative that organizations with the ability to do so should conduct experiments that elucidate this other aspect of atmospheric CO_2 enrichment, so that the public can have access to the full spectrum of information about the environmental consequences of higher-than-ambient levels of atmospheric CO_2. Only under such conditions of complete and wide-ranging understanding can the best decisions be made relative to national and international energy policies.

As forests account for two-thirds of global photosynthesis and are thus the primary player in the global biological cycling of carbon, we have chosen to concentrate on trees within this context. Specifically, we seek to determine the direct effects of atmospheric CO_2 enrichment on all aspects of their growth and development; and we hope to be able to determine the ramifications of these direct effects for global carbon sequestering, which may also be of considerable significance to the climatic impact of atmospheric CO_2 enrichment, as the biological sequestering of carbon is a major factor in determining the CO_2 concentration of the atmosphere and the ultimate level to which it may rise.

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 ppm above ambient -- was begun in November 1987 to two of these chambers, continuing unabated to this day; and except for the differential CO_2 enrichment of the chamber air, all of the trees have been treated identically, being irrigated at periods deemed appropriate for normal growth and fertilized as per standard procedure for young citrus trees.

At the mid-point of every month since the experiment's inception, trunk cross-sectional areas at a height of 45 cm above the ground have been determined for all trees. Leaf net photosynthesis was also measured throughout the daylight hours of six clear days in the summer of 1989 and over ten complete 24-hour periods in 1990. In January and February 1990, we measured the diameters of all of the trees' trunks and every branch of every tree at 20-cm intervals along their entire lengths, so as to be able to compute the trees' total trunk and branch volumes. In July 1990, we also extracted 41-mm-diameter soil cores from depth intervals of 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm, and 100-120 cm at 16 different locations around each tree in order to determine their fine-root biomass distributions.

FINDINGS: Figure 1 depicts the results of the trunk cross-sectional area measurements. The chief significance of these data lies in the fact that the CO_2-enriched trees have not shown any indication of relaxing the degree of growth stimulation observed in the first year of the experiment. The net photosynthesis measurements confirmed this observation: throughout the daylight hours of the summer of 1989 the CO_2-enriched trees exhibited a net photosynthesis rate fully 2.22 times greater than that of the ambient-treatment trees, while throughout the daylight hours of the summer of 1990, the net photosynthetic stimulation of the CO_2-enriched trees averaged 2.23. Nighttime measurements of net CO_2 exchange also revealed the CO_2-enriched trees to be respiring about 30% less on a per unit leaf area basis. Averaged over a 24-hour period, these two effects suggest a near-tripling of carbon sequestering.

Above- and below-ground biomass assessments conducted in 1990 confirmed the reality of this implication. The total trunk-plus-branch volume of the CO_2-enriched trees was found to be 2.79 times greater than that of the control trees at the beginning of the year, while their fine-root biomass was found to be 2.75 times greater about halfway through the summer.

INTERPRETATION: Our experimental results depict a remarkable response of sour orange trees to atmospheric CO_2 enrichment: their growth and sequestration of carbon is actually tripled for a 325 ppm increase in the CO_2 content of the atmosphere, which is less than a doubling of the air's current CO_2 concentration of 355 ppm. If other trees respond similarly -- and there is considerable evidence in the magnitude of the yearly-increasing amplitude of the atmosphere's seasonal CO_2 cycle to suggest that they do -- this finding implies that an approximate 170 ppm increase in the air's CO_2 content may be sufficient to yearly remove from the atmosphere an amount of carbon equivalent to that released to it via mankind's yearly CO_2 emissions. And it suggests that a 340 ppm increase in the CO_2 content of the air could accommodate a doubling of anthropogenic CO_2 emissions. Hence, our work raises the tantalizing possibility that 1) great biological benefits may be obtained from atmospheric CO_2 enrichment, and 2) earth's forests may be capable of removing enough CO_2 from the air to prevent a catastrophic greenhouse warming of the globe if they are not further decimated. On a less general level, but with more certainty, our work suggests that citrus tree growth rates and water use efficiencies may have already benefitted significantly from the historical CO_2 increase of the past two centuries and that these aspects of plant productivity will improve even more dramatically as the CO_2 content of the air continues to rise, greatly reducing the amount of water needed to produce a given quantity of citrus fruit.

FUTURE PLANS: We anticipate continuing the sour orange tree experiment for several years to study very-long-term effects of CO_2 enrichment on growth and fruit production, which should be substantial next year and thereafter. In addition, we plan to begin a similar study of five other tree species to investigate the generality of our observations; and we would like to conduct a larger-scale experiment that would include water, nutrients, and temperature as additional variables.

REPORTS: We have prepared three scientific journal articles that describe various aspects of our findings this year. All have passed peer review and have been accepted for publication. They should appear sometime in the first half of 1991.

1. Idso, S.B., Kimball, B.A. and Allen, S.G. CO_2 enrichment of sour orange trees: Two and a half years into a long-term experiment. Plant, Cell and Environment.
2. Idso, S.B., Kimball, B.A. and Allen, S.G. Net photosynthesis and growth rates of sour orange trees maintained in atmospheres of ambient and elevated CO_2 concentration. Agricultural and Forest Meteorology.
3. Idso, S.B. and Kimball, B.A. Effects of two and a half years of atmospheric CO_2 enrichment on the root density distribution of three-year-old sour orange trees. Agricultural and Forest Meteorology.

COOPERATORS: None

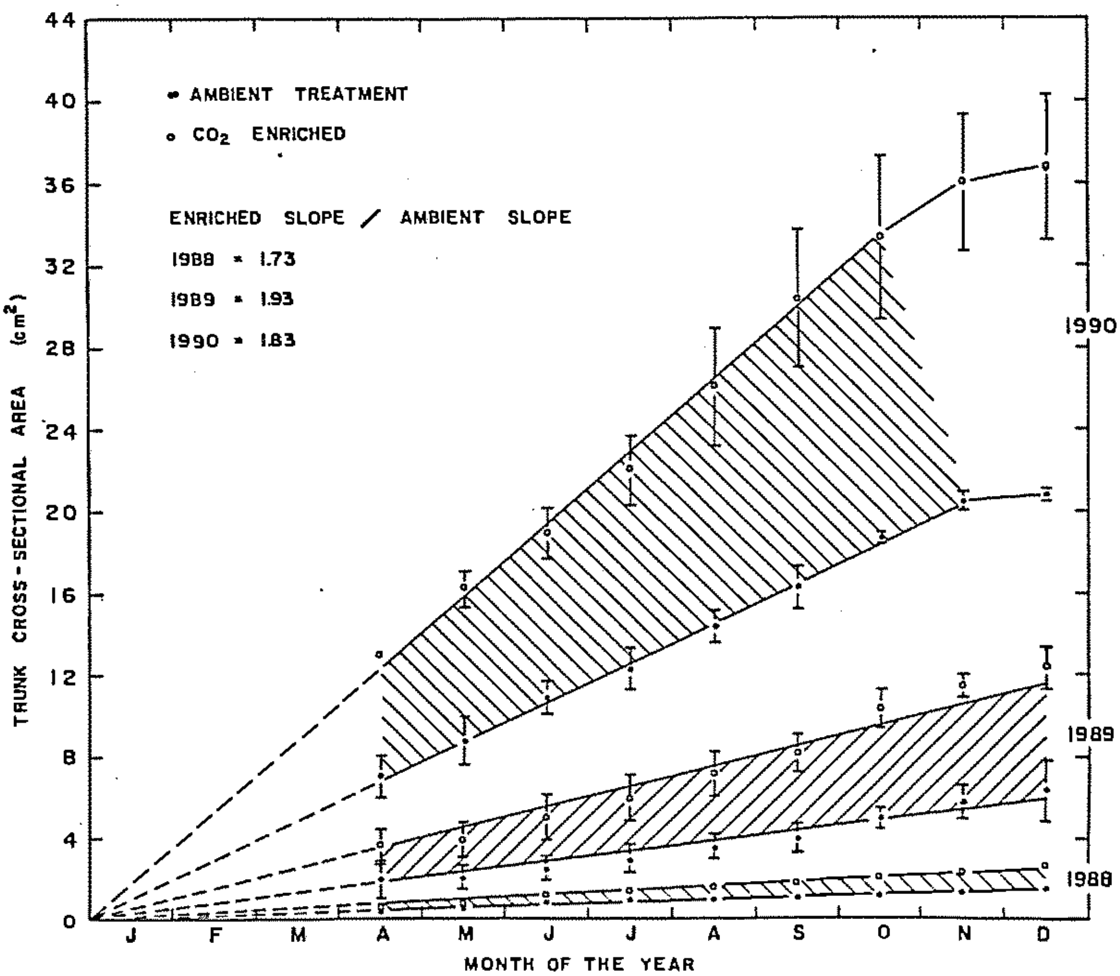

Fig. 1. Trunk cross-sectional area vs. month of the year for sour orange trees growing in clear-plastic-wall open-top chambers exposed to ambient air and air enriched with an extra 300 ppm of CO_2 in the natural environment of Phoenix, AZ. Results for two of the three years also show treatment standard deviations, which were too small to plot for the first year of the study. Cross-hatched areas help to identify the years to which the data pertain and the period of each year over which growth is essentially linear.

EFFECTS OF FREE-AIR CO_2 ENRICHMENT (FACE) ON EVAPOTRANSPIRATION OF COTTON

B. A. Kimball, Supervisory Soil Scientist

PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. 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. The objective of this experiment was to evaluate the effects of elevated CO_2 on the ET of cotton.

APPROACH: The evapotranspiration measurements were one component of the much larger Free-Air CO_2 Enrichment (FACE) project, which sought to determine the effects of elevated CO_2 on plant growth, yield, and many physiological processes, as well as water use. Four toroidal plenum rings of 22 m diameter constructed from 12" irrigation pipe were placed in a cotton field at The University of Arizona Maricopa Agricultural Center shortly after planting. The rings had 2.5-m-high vertical pipes with individual valves spaced every 2 m around the periphery. Air enriched with CO_2 was blown into the rings, and it exited through holes at various elevations in the vertical pipes. Wind direction, wind speed, and CO_2 concentration were measured at the center of each ring. A computer control system used wind direction information to turn on only those vertical pipes upwind of the plots, so that the CO_2-enriched air flowed across the plots, no matter which way the wind blew. The system used the wind speed and CO_2 concentration information to adjust the CO_2 flow rates to attain a near-constant 550 ppm by volume CO_2 concentration at the centers of the rings. Four matching control rings at ambient CO_2 but with no air flow were also installed the field. Additionally in 1990, the rings (plots) were split, so half of each ring was well-watered while the other half was water-stressed, the irrigations being applied through a subsurface drip system.

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, the FACE approach offers a unique opportunity to determine CO_2 effects on ET devoid of chamber effects. That said, the determination of ET in the FACE experiment still presented a challenge because most nonwall or micrometeorological methods require a large fetch, and here the plots were only 22-m-diameter semicircles. An energy balance approach was adopted whereby ET was calculated as the difference between net radiation, R_n, soil heat flux, G, and sensible heat flux: $ET = R_n - G - H$. R_n was measured with net radiometers and G 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. The air temperature was measured with an aspirated psychrometer, and the crop surface temperature was measured with infrared thermometers mounted above each plot.

Some difficulties were encountered. The instruments did not arrive until late June; a lightning strike on July 15 damaged the data logger (and the CO_2 control system); and the infrared thermometers were unreliable. Good data were obtained from about the middle of August to the end of the experiment on September 17. To try to remove instrumental differences between plots, the infrared thermometers and the net radiometers were standardized against a hand-held instrument that was carried from plot to plot before dawn and at midday on several days during the season.

FINDINGS: The data are still being analyzed. However, preliminary findings for four September days are presented in Table 1. In the upper half of Table 1, there appears to be little difference among the midday latent heat fluxes measured in the eight plots. Moreover, the larger values are from the dry-control plots, which is rather unexpected for a water-stress treatment. The "background" flux of the surrounding field (ambient-wet conditions) measured with Bowen ratio equipment is slightly higher, but not much.

The daily total evapotranspiration results in the bottom half of Table 1 show differences of 0.2 mm or less among the treatment averages. The wet-control ET of 6.6 mm is only slightly lower than the Bowen ratio ET of 7.2 mm, which gives credence to the methodology. Pan evaporation was 4.9 mm, which seems low, but the pan was somewhat down in the canopy. The reference ET_o from the AZMET system was higher at 7.4 mm, consistent with its location removed from the middle of a cotton field.

INTERPRETATION: Elevated CO_2 concentration appears to have little effect on evapotranspiration rate. Apparently, any decreases in stomatal conductance are being compensated by counter increases in leaf temperature and leaf area.

FUTURE PLANS: Current plans are to repeat the FACE CO_2 by water-stress interactive experiment in 1991 and to install the ET instrumentation as early as possible after planting in order to obtain measurements of ET over the whole growing season.

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with support from the Department of Energy, as well as ARS

Table 1. Midday latent heat flux and daily total evaporation measured on four days during the 1990 Free Air CO_2 Enrichment (FACE) experiment at Maricopa, AZ. The primary method was an energy balance residual technique, with Bowen ratio and pan evaporation measured as "background" in the field and the AZMET reference ET_o measured near the headquarters buildings. Treatments included ambient CO_2 (Control), 550 ppm CO_2 (FACE), well-watered (wet), and water-stressed (dry), with two replicates (1 and 2).

	ENERGY BALANCE RESIDUAL										
	DRY				WET						
	Control		FACE		Control		FACE				
DATE	Rp1	Rp2	Rp1	Rp2	Rp1	Rp2	Rp1	Rp2	Bwn	Pan	AZ-MET ET_o
Latent heat flux from 12:00 to 13:00 (W/m^2):											
9 Sep	670	631	612	617	621	627	623	602	658		
10 Sep	678	626	650	598	576	627	601	618	715		
11 Sep	651	671	638	695	677	622	680	638	796		
12 Sep	655	621	649	596	583	621	626	611	674		
Avg.	664	637	637	627	614	624	633	617	711		
Avg over Reps		650		632		619		625			
Daily Evapotranspiration (mm):											
9 Sep	6.8	6.7	6.9	6.8	6.6	6.6	6.8	6.8	6.9	5.2	7.2
10 Sep	6.7	6.7	7.0	6.6	6.4	6.6	6.8	6.7	7.1	4.5	7.4
11 Sep	6.4	6.8	6.9	7.0	7.1	6.5	7.2	6.8	7.6	4.5	7.6
12 Sep	6.6	6.7	7.0	6.5	6.4	6.5	6.7	6.7	7.0	5.4	7.2
Avg.	6.6	6.7	7.0	6.7	6.6	6.6	6.9	6.8	7.2	4.9	7.4
Avg over Reps		6.7		6.8		6.6		6.8			

EFFECTS OF HIGH-CO_2-GROWN COTTON ON PINK BOLLWORM POPULATIONS

D. H. Akey, Research Entomologist
and B. A. Kimball, Supervisory Soil Scientist

PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Prior work has shown that such an increase in CO_2 concentration markedly affects the growth of cotton and other plants. Moreover, the carbon-to-nitrogen ratio of various organs is affected, which changes the nutritional value to herbivores. In particular, starch accumulates in the leaves of the cotton grown at high CO_2, and our own laboratory experiments have shown that the growth and development of individuals of a leaf-feeder, the beet armyworm Sodoptera exigua, was diminished and survival was decreased. However, the longer duration of the larval stages resulted in an increased population, and the end result was an increase in cotton damage. On the other hand, in earlier work we found that the composition of the seed is only slightly changed by carbon dioxide enrichment. Therefore, the hypothesis was made that the growth and development of individual herbivorous seed-feeders would be little affected by high-CO_2-grown cotton. This hypothesis was validated by results from a field test on one of the most important pests in Southwestern cotton production, tbe pink bollworm (PBW) Pectinophora gossypiella, a seed feeder. However as with the beet armyworm, effects on population numbers are more important than effects on individuals. Importantly, carbon dioxide-enriched cotton plants have much greater numbers of bolls than do ambient cotton plants. Since the PBW is dependant on bolls for seeds, it would be highly desirable to know if populations of PBW would increase with the increase of available bolls present with carhon dioxide enriched cotton. Therefore, experiments were conducted to test the hypothesis that PBW populations would be increased by the increased availability of bolls on host cotton grown at elevated CO_2 concentrations. One uncertainty was the fact that despite more bolls on carbon dioxide enriched cotton, the time period in which the boll is suitable for habitation by PBW larvae is reduced. The experiments were designed to reveal effects on PBW populations from this phenomena also.

APPROACH: This was the second year of a two-year experiment. Cotton was planted normally in a field, and then 3 x 3-m-square by 2-m-high open-top CO_2 enrichment chambers were erected. The chambers consisted of steel posts connected by cables from which walls of transparent plastic were hung. For these insect experiments, the normally-open top was covered by screen, and an additional vestibule was constructed just outside the door to further isolate the subject insect populations. A computer-controlled CO_2 sampling/enrichment system was used to automatically control the CO_2 concentrations in half of the chambers (8 total) to 650 ppm by volume.

For the first part of the 1989 season, the PBW populations did not increase, and a flaw in the experimental technique proved to be the problem. The enrichment apparatus was operating night and day, and at night it apparently was disrupting mating, either by the air movement itself and/or by blowing the insects' pheromones out of the chambers. Therefore, starting about the middle of 1989 and for all of 1990, the CO_2 enrichment and the air flow were stopped at night in order to not disturb the insect pheromone dispersal.

After the first bolls appeared, the chambers were manually infested with equal numbers of PBW adults. In 1989 these adults had been raised from laboratory populations, but there was some concern that these insects conceivably might not behave like their wild ancestors, so in 1990 adults that had been raised from wild parents collected from bolls the previous fall were used.

One night each week, black light or pheromone live traps were used to capture adults, which were released back into their chambers the following morning in order to monitor the PBW populations through the course of the growing season. At the end of the season, all the bolls were harvested and inspected for PBW larvae and damage.

FINDINGS: Statistical analysis of the PBW numbers and boll damage at the end of the 1989 season showed no significant difference between the populations grown on high-CO_2 cotton and those grown on ambient-CO_2 cotton. The data for the 1990 season are still being analyzed.

INTERPRETATION: These preliminary findings support the hypothesis that herbivores that are seed feeders probably will be comparatively little affected by the increasing atmospheric CO_2 concentration. This conclusion contrasts with that obtained from experiments with leaf-feeding insects, which were greatly affected by high-CO_2-grown host cotton, and which did considerably more damage to the cotton. Thus, cotton growers will probably have to be more vigilant against leaf-feeding insects in the future, but fortunately it appears likely that pink bollworm problems will be no worse than they are now.

FUTURE PLANS: There is evidence that the CO_2 response of cotton is strongly affected by temperature, including starch levels in the leaves. Therefore, such a CO_2 x temperature interaction is likely to also affect leaf-feeding insects. A controlled-environment experiment is planned in which cotton seedlings will be grown at two levels of CO_2 and two temperatures, and then the seedlings will be fed to beet armyworm larvae at similar CO_2 and temperature levels.

COOPERATORS: The experiment was partially funded by the Department of Energy.

COTCO2: A MECHANISTIC MODEL OF COTTON PHYSIOLOGY AND GROWTH

J. S. Amthor, Plant Physiologist
and B. A. Kimball, Supervisory Soil Scientist

PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. Both the increase in CO_2 concentration and the possible change in climate are likely to affect the growth of crops, including cotton. In order to predict the effects on future productivity and especially to aid development of optimum future management strategies, a reliable cotton growth model is needed. Because the future CO_2 concentrations are outside the "range" of today's concentration, empirical models that are statistically fit to data collected under today's environment are not reliable. Rather, models are needed that are mechanistic in that they account for the effects of CO_2 and other climate variables on physiological processes and thus can be expected to work over a much wider range of conditions. Moreover, the model should be able to account for such phenomena as the diurnal change of starch and other carbohydrate content of various plant organs in order to predict nutritional value of the material to herbivores, and such as foliage temperatures being progressively below air temperatures as the air becomes drier. There being no such cotton model in existence, a new model called COTCO2 was developed.

APPROACH: Equations or algorithms that describe the physiology and biochemistry for important processes in the cotton plant were extracted from the literature or developed. These processes, which are considered at the level of the individual organ, include organ initiation from meristems, growth of meristems and each organ and stem segment, photosynthesis by leaves and reproductive organs, respiration by all organs, soluble and insoluble carbohydrate pool dynamics, nitrogen uptake and assimilation, translocation of carbon and nitrogen among organs, senescence and shedding, water uptake and transpiration, and sensible energy exchange. Growth is the biochemical conversion of sugars and nitrogen into structural matter in individual immature organs, and the mass of organs is considered in terms of dry structural matter, soluble carbohydrate pools, and insoluble carbohydrate pools. Rate equations are integrated for arbitrary time steps, with one hour being the nominal time step for plant physiology and aboveground environmental processes, and with one minute for the fluxes of water and nitrogen within a two-dimensional soil slab. Soil surface temperature and leaf temperatures are calculated iteratively. The temperatures of all organs are computed individually, and therefore, the rate of processes in that organ are governed by that temperature, not the temperature of the air.

The program has been coded in FORTRAN, a language for which compilers exist for almost all computers, thereby insuring that the program should be transportable from one machine to the next.

FINDINGS: An initial version of the program has been developed, and it appears to "grow" a reasonable cotton plant. Because it considers the energy balance of so many individual leaves and because the time step for soil processes must be so short, the number of computations is enormous, and about five hours are required to run a season-long simulation using a 386 20 MHz IBM-PC-compatible computer. However, the model has not yet been verified by comparison of its predictions with measurements of actual growth or other physiological processes. Neither is the model "user-friendly" because all data are initialized within the program, which does not facilitate running the model with different files of environmental data. On the other hand, the model is well "commented" in the code, and it is also clearly structured so that subsequent users can understand it more easily than most such models.

INTERPRETATION: A large investment of time has produced a simulation model of a cotton plant that ought to be the best plant growth model ever developed. However, the model has not yet been tested to substantiate this claim. Considerable work remains to validate the model and to make it more user friendly.

FUTURE PLANS: A sensitivity analysis needs to be run on the model to test which of the numerous parameters are important (and need precise values) and which are unimportant. And of course, the model needs to be validated by comparing its many predictions against actual measurements of as many variables as possible. It also needs to be made more user friendly and to conform to the IBSNAT standards for input and output files. The departure of Dr. Amthor from the USWCL places this project into considerable uncertainty. Hopefully, however, temporary personnel can do many of the changes to make it more user friendly and even do the sensitivity analysis. However, the validation work, which will involve changes to logic of the model when it does not work will require consultation with Dr. Amthor. Also hopefully, we will be able to hire a new plant physiologist with good computer skills who can make further progress on model validation and development.

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with support from the Department of Energy, as well as ARS

USE OF SATELLITE-BASED SPECTRAL DATA FOR ESTIMATION OF AREAL EVAPOTRANSPIRATION

M. S. Moran, Physical Scientist, and R. D. Jackson, Research Physicist

PROBLEM: Jackson (1985) proposed that remotely sensed measurements of surface reflectance and temperature could be combined with meteorological information (solar and sky radiation, air temperature, wind speed, and vapor pressure) to evaluate the energy balance over agricultural areas and determine surface evapotranspiration. This technique was successfully applied to data obtained using ground-based radiometers by Reginato et al. (1985) and aircraft-based radiometers by Jackson et al. (1987). A logical extension of this work, and the subject of this report, is the use of satellite-based spectral data with ground-based meteorological data to map evapotranspiration on a local scale. This achievement was dependent upon successful attainment of several intermediate goals, including atmospheric correction of satellite-based spectral data in the visible, near-infrared, and thermal spectrum.

APPROACH: An experiment was conducted with the objective of collecting a comprehensive set of atmospheric, meteorological, and remotely-sensed spectral data over large, well-monitored agricultural fields. Over a 15-month period, 12 Landsat Thematic Mapper (TM) images were acquired with coincident ground-based measurements of atmospheric optical depth, energy balance components (net radiation, and soil, latent and sensible heat flux densities), surface reflectance and temperature, meteorological parameters (such as air temperature, wind speed, and vapor pressure), and numerous soil and plant properties. Though not all ground-based data (listed above) were acquired during each of the 12 Landsat overpasses, this experiment provided an excellent data base with which to assess the accuracy of 1) retrieval of surface reflectance and temperature from satellite sensor output, and 2) evaluation of evapotranspiration using remotely-sensed spectral data.

Several atmospheric correction procedures were examined to determine which techniques could retrieve surface reflectance and temperature from satellite digital data with the ease and accuracy necessary for the energy balance model. For the visible and near-infrared (near-IR) spectrum, four radiative transfer codes (RTC) and several experimental correction methods were tested using 7 of the 12 TM scenes and coincident aircraft-based measurements of surface reflectance factors for two sites per scene, one vegetated and one fallow. For the thermal spectrum, one radiative transfer code (RTC) was evaluated and several experimental methods were developed using 5 TM scenes and aircraft-based measurements of surface temperature for large, uniform fallow fields.

Maps of latent heat flux density (λE: a function of evaporation rate (E) and heat of vaporization (λ)) and net radiation (R_n) were produced using atmosphere-corrected Landsat TM data for two dates. On each date, a Bowen-ratio apparatus, located in a vegetated field, was used to measure λE and R_n at a point within the field.

FINDINGS: The results emphasized the importance of using multiple-scattering RTCs for retrieval of surface reflectance factors from satellite-based digital data in the visible and near-IR spectrum. The four RTCs tested in this analysis were all successful in reducing the overall error of reflectance estimation. When care was taken to choose appropriate models for water vapor and aerosol profiles, surface reflectance was evaluated to within ±0.02 reflectance (1 σ RMS). The simplest correction method, termed dark-object subtraction (DOS), was the least accurate method and, in fact, produced greater error in estimations of near-IR reflectance than no correction at all. Two hybrid approaches, which combined the simplicity of DOS with the precision of an RTC, provided sufficient accuracy to warrant consideration for use on an operational basis.

Though RTCs were useful for retrieving surface reflectance factors from satellite data in the visible and near-IR spectrum, they were not practical for retrieval of surface temperatures from satellite thermal data. Results showed that when the Lowtran7 RTC was used to estimate atmospheric conditions, surface temperatures derived from satellite data were overestimated by more than 4° (1 σ RMS). It was apparent that in order to obtain accurate estimates of surface temperature with the Lowtran7 RTC, it would be necessary to obtain local, coincident radiosonde data. On the other hand, a simple linear regression of measured surface temperatures (T_s) and satellite digital numbers provided estimates of T_s to within ±1.2 °C of measured values. Though the regression procedure was accurate, it required concurrent ground-based measurements of T_s and would obviously be inconvenient if it were used on an operational hasis.

Data from the satellite-based TM sensor and ground-based meteorological instruments were combined to produce maps of λE and R_n for Maricopa Agricultural Center, Arizona. The satellite-based estimates of λE differed from coincident ground-based measurements, using a Bowen-ratio apparatus, by 4% in cotton and -6% in alfalfa (Fig. 1). Values of R_n differed from Bowen-ratio measurements by 10% in cotton and 0% in alfalfa. These results were within the suggested accuracy goals for this method, based on a sensitivity analysis of the remote model.

INTERPRETATION: The results reported here indicate that a satellite-based technique will yield values of λE from full-cover cropped fields that compare well with values measured with a Bowen-ratio method (Moran et al., 1989; Moran, 1990a). This outcome was attributable to progress in image enhancement (Moran, 1989), atmospheric correction (Moran et al., 1991; Moran, 1990a) and canopy characterization (Moran, 1990b). Since satellite sensors acquire spatially continuous data over large regions, it is potentially feasible to map evapotranspiration over large areas at frequent intervals with relatively low cost.

FUTURE PLANS: Though substantial progress was made in this research, several aspects of the satellite-based energy balance model need further attention before it can be applied on an operational basis. The atmospheric correction of TM thermal data is presently based on a concurrent set of measurements of T_s over a variety of surfaces. Ideally, a correction technique should be based on information that is readily available from conventional weather stations or from the satellite digital data. In any case, the correction procedure needs to be simplified in order to be incorporated into a convenient operational procedure. Plans are being made to test two innovative correction methods (derived from this data set) on a more extensive data set covering more varied atmospheric conditions.

It should be emphasized that the results presented in Figure 1 were obtained for full-cover canopies. The situation is far more complicated when the soil surface is only partially covered by vegetation (e.g., row crops or rangeland vegetation). Though some progress has been made (Moran et al., 1990c), further research needs to be conducted to provide insight into some of the issues that must be addressed if the satellite-based energy balance model is to be applied to a surface sparsely covered by vegetation. An experiment designed to address these issues was recently conducted at the Walnut Gulch Watershed near Tucson, Arizona; preliminary results and analysis are presented by Moran et al. (1990d, this report).

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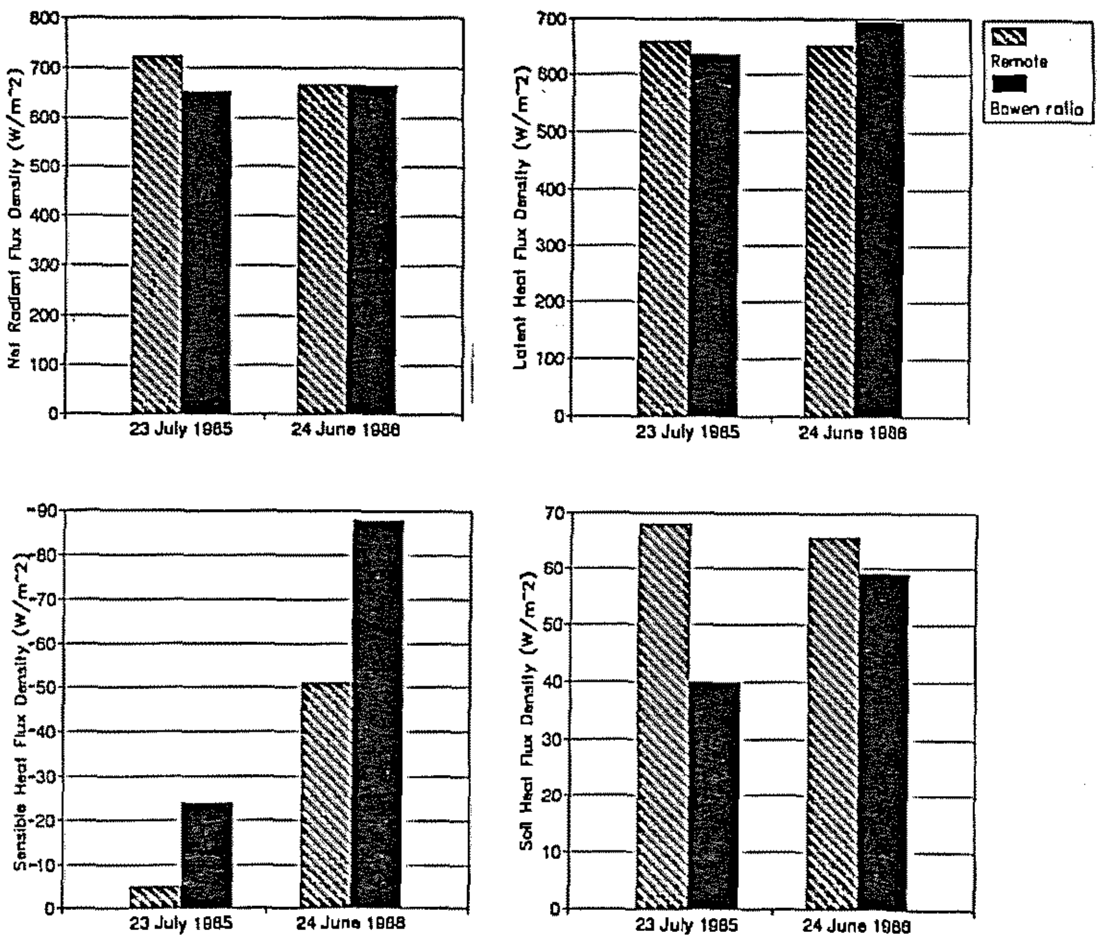

Figure 1. Estimates of λE and R_n (W m^{-2}) at the location of a Bowen-ratio apparatus in fields of cotton and alfalfa on 23 July 1985 and 24 June 1986, respectively.

MULTISPECTRAL MEASUREMENTS OF A SEMIARID RANGELAND FOR STUDY OF ENERGY AND WATER FLUXES

M. S. Moran, Physical Scientist, T. R. Clarke, Physical Science Technician,
P. J. Pinter, Jr. Research Biologist, and R. D. Jackson, Research Physicist

PROBLEM: Arid and semiarid rangelands comprise a significant portion of the earth's land surface, yet little is known about the effects of temporal and spatial change in surface soil moisture on the hydrologic cycle and energy balance. With increasing interest in global surface-atmosphere interactions, these interrelationships have become a crucial research issue. An ARS experiment (Monsoon'90) was proposed to, and funded by, NASA to focus on the utility of remote sensing to provide measurements of surface soil moisture, surface albedo, vegetation biomass, and temperature at different spatial and temporal scales in order to provide a practical means for monitoring some of the more important factors controlling land surface processes (Kustas et al., 1988). The rationale for investigating the use of remotely sensed information in biophysical and geophysical models is because this is the only approach where the computation of the fluxes at catchment and regional scales is attainable on a routine basis.

APPROACH: The experimental plan called for cooperation between scientists from several universities, foreign institutes, ARS laboratories[1] and other U.S. Government agencies to collect concurrent ground measurements of soil moisture, energy and water fluxes and profile data in the atmospheric boundary layer in a hydrologically well-instrumented semiarid rangeland watershed in southeastern Arizona. In addition, data were acquired in the visible, near-IR, thermal and microwave wavelengths using NASA aircraft and, when available, from satellites. The U.S. Water Conservation Laboratory (USWCL) was responsible for acquiring remotely sensed data in the visible, near-IR, and thermal wavelengths from ground and low-altitude aircraft platforms. USWCL ground-based measurements of surface reflectance and temperature, and subsequent evaluation of energy balance, were concentrated at two sites, one shrub-dominated (Lucky Hills) and one grass-dominated (Kendall). A more extensive area was covered by low-altitude aircraft, using several radiometers and a thermal video system. All field experiments were conducted in 1990 during the dry and wet ("monsoon") seasons.

FINDINGS: A detailed description of the cooperative field campaigns, including measurements and some preliminary results is given by Kustas et al. (1991). The results presented here are limited to the preliminary analysis of data collected by USWCL personnel.

Surface reflectance and temperature data were acquired by ground- and low-altitude aircraft-based radiometers on June 5, from July 23 to August 10 and on September 9, 1990, weather and equipment permitting. Unfortunately, many of the dates between July 23 and August 10 had partly-cloudy sky conditions, resulting in questionable estimations of surface reflectance.

At the Kendall site, surface temperature (T_s) and reflectance (ρ_s) measurements were made over a 480 x 120 m target with yoke-based instruments. Using an efficient measurement strategy, 100s of measurements of T_s and ρ_s could be made over the target within a 10-minute period, several times per day. The temperature frequency distribution for the Kendall target on June 5 (dry season) and August 8 (monsoon season) are presented in Figure 1. Though it should be noted that the number of measurements and the target locations were slightly different on the two dates, there is a striking dissimilarity between the trends in the two graphs. On June 5, when the surface was very dry, there was a wide range of temperatures in the morning measurements (8.8h) due to differences in shaded and sunlit surfaces and vegetation. Whereas in August, when the soil was wet and the vegetation was vigorous, the surface temperature was uniform in the morning, and the temperature range increased with time because of soil drying differences.

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[1] Dr. William Kustas, ARS Hydrology Lab, Beltsville, MD, is the principal investigator of the NASA-funded experiment. Co-investigators include scientists from the ARS Aridland Watershed Mgmt. Research Unit, Tucson, Ariz. and ARS U.S. Water Conservation Laboratory.

Energy balance components were computed by combining ground-based measurements of surface reflectance and temperature with meteorological measurements of air temperature, wind speed, incoming solar radiance, and vapor pressure (Fig. 2), according to the method proposed and tested by Jackson (1985) and Jackson et al. (1987). The values appear to be reasonable, considering the grassland cover types and monsoon weather pattern. The accuracy of these values will be assessed by comparisons with measurements using conventional ground-based systems, such as Bowen-ratio and eddy correlation.

INTERPRETATION: It is too early to draw any conclusions about this research, except that the cooperative experiment was successful in producing an extensive data base regarding the hydrologic cycle and energy balance of a semiarid rangeland. To date, the coinvestigators have produced individual reports (available to all participants) summarizing their data collection and preliminary results.

FUTURE PLANS: USWCL coinvestigators in this project foresee that the following research and analysis will be conducted based on the data set collected in the Monsoon'90 experiment:

1) Energy balance components derived from ground-based measurements of T_s and ρ_s and supplementary meteorological data will be compared with conventional ground-based measurements to assess the accuracy of the "remote" method on rangelands. This assessment will address the complications posed by the rangeland site, such as topography, clouds, and sparse vegetation.

2) The accuracy assessment of the "remote" method will be tested again using spectral data from airborne sensors. The issues to be addressed here include atmospheric corrections and scale considerations.

3) A two-part study will be conducted to determine the effectiveness of spectral vegetation indices (VIs) for evaluation of hydrologic parameters in the rangeland. The first step will be to assess the sensitivity of the VIs to parameters other than vegetation, such as topography, soil background, view angle, and atmosphere. Then, based on this knowledge, the correlation between VIs and hydrologic parameters, such as evapotranspiration and soil moisture, will be evaluated.

4) Thermal data from the radiometer and scanner mounted in the low-altitude aircraft will be examined with respect to vegetation type, topographic features, and precipitation patterns during the study.

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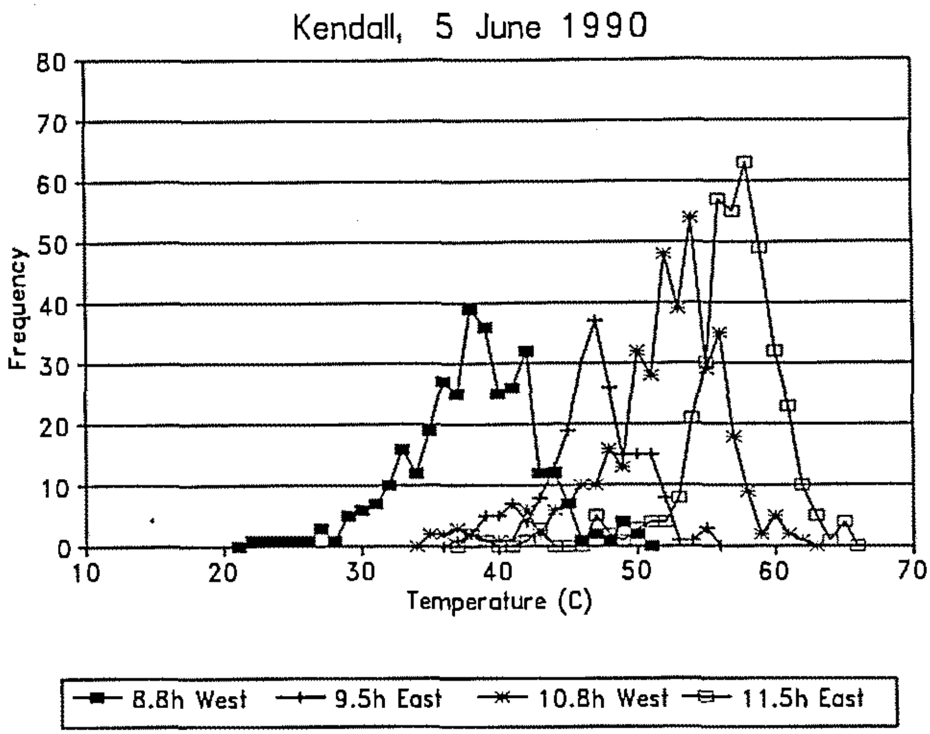
Jackson, R.D., Moran, M.S., Gay, L.W. and Raymond, L.H. (1987) Evaluating evaporation from field crops using airborne radiometry and ground-based meteorological data, Irrig. Sci. 8:81-90.

Kustas, W.P., Hipps, L.E., Jackson, R.D. and Woolhiser, D.A. (1988) Water and energy balance of a semiarid rangeland during the summer "monsoon" season, NASA proposal submitted in response to NRA-88-OSSA-11, 35 p.

Kustas, W.P., Goodrich, D.C., Moran, M.S., Schmugge, T., Stannard, D., Hipps, L., Blanford, J., Jackson, R., and Shutko, A.M. (1991) Monsoon 90: An interdisciplinary study of the energy and water fluxes in the atmosphere-biosphere system over semiarid rangelands, Bull. of Amer. Meteorol. Soc. (submitted for publication).

Moran, M.S. and Clarke, T.R. (1990) Ground-based spectral and meteorological measurements at Kendall and Lucky Hills, USWCL Internal Report, copies available on request from the authors.



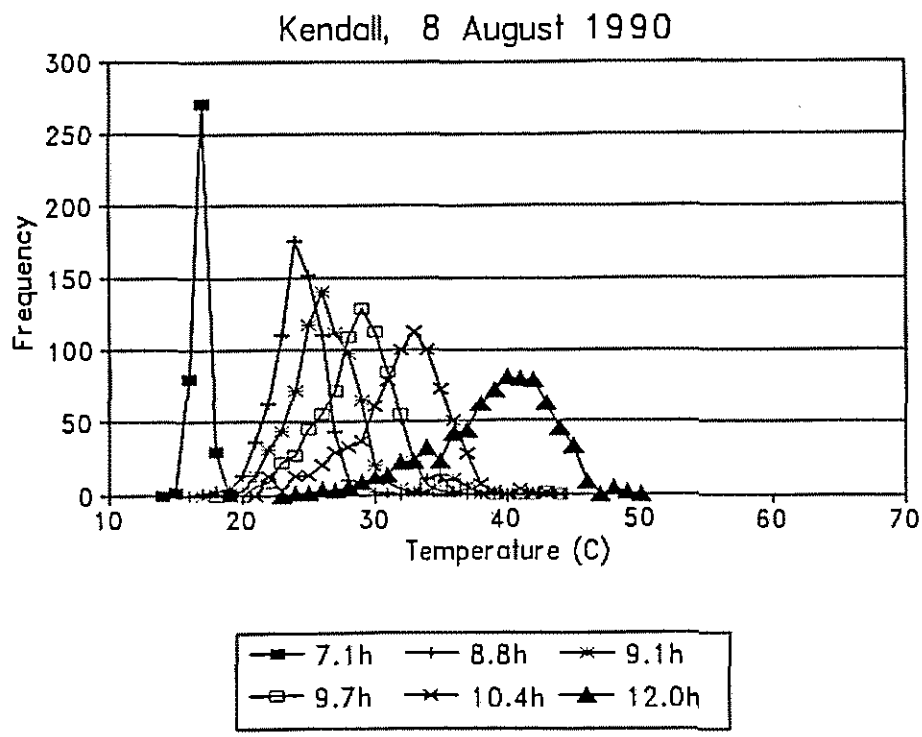


Figure 1. Frequency distribution of surface temperatures at the Kendall grassland site on 8 August and 5 June, 1990. Each line represents the data for the time of day listed in the legend. On 5 June, data were collected on the east and west sides of the wash, respectively, as noted in the legend. On 8 August, data from the east and west sides of the wash were combined in each histogram.

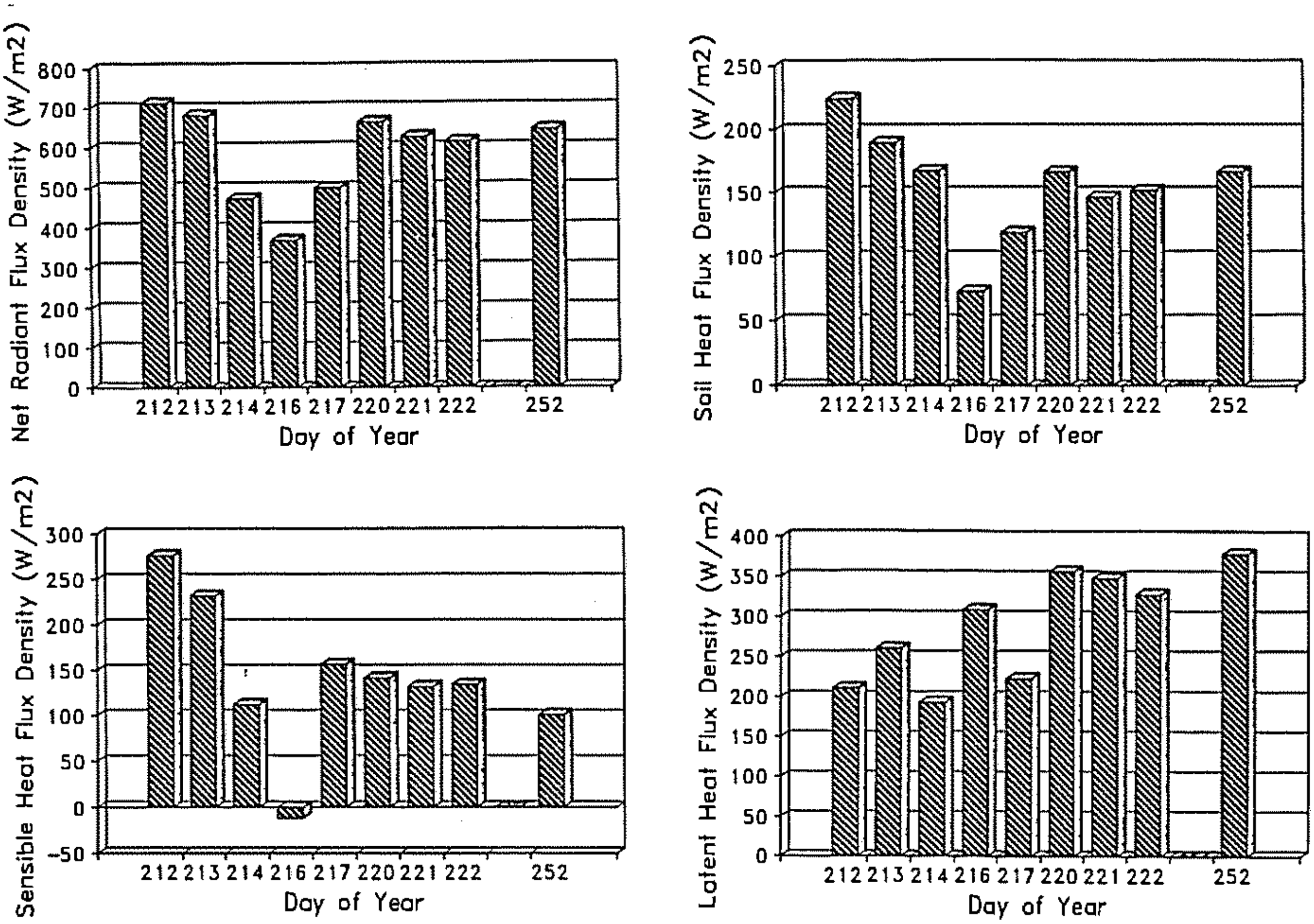


Figure 2. Energy balance components computed for the Kendall site at time of day 9.5h for days of year 212-214, 216-217, 229-222 and 252.

BIDIRECTIONAL REFLECTANCE OF AGRICULTURAL TARGETS

R. D. Jackson, Research Physicist,
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M. S. Moran, Physical Scientist

PROBLEM: The potential for using satellite-based remotely sensed data to aid in making agricultural management decisions has been limited by the frequency that data can be obtained and by the timeliness of delivery of the data. The frequency problem has been partially solved by the ability to point satellite sensors (a capability built into the French SPOT satellites) which allows data to be obtained over a specific target on different orbital passes. This pointability, however, adds problems associated with sensor view angle. Light reflected from non-lambertian surfaces is not only dependent on the solar zenith angle but also on the view angle of the sensor. Most agricultural targets are notably non-lambertian, which makes it necessarv to account for view angle effects if a time sequence of images are to be compared. On the other hand, evaluating the non-lambertian properties, i. e., measuring the bidirectional reflectance factor (BRF) at a number of view angles, can provide important additional information on surface conditions that might not be evident at a single view angle. The objective of this research was to delineate the BRF-view angle relationships for bare soils, wheat, and cotton.

APPROACH: Two experimental techniques were used to obtain BRF-view angle relationships. The first utilized a device that allowed measurements of BRF at 19 view angles in steps of 5° from -45 to +45° from nadir (the radiometer positioned directly above the target), at a fixed azimuth angle (42)*. The second technique required two radiometers mounted on a backpack device that allowed them to be positioned such that one was pointed directly down (nadir) and the second pointed at approximately the same angle as the SPOT satellite sensor was pointing at the time of measurement (65). The first technique allowed rapid measurements at 19 view angles and at a large number of solar zenith angles but for one target area presumed to be representative of the entire area of interest. The second technique allowed a much larger target area to be measured by making transects through agricultural fields, but it was restricted to three view angles and a few solar zenith angles.

Measurements with the stationary device were made over bare soil and a wheat canopy, at a number of different solar zenith angles. Measurements with the backpack device were made over bare soil, wheat and cotton, near the time of the SPOT satellite overpass. The results reported below are for the multispectral bands of the High Resolution Visible (HRV) sensor on SPOT-1. Bandwidths are: HRV-1, 0.50 to 0.59μ (green); HRV-2, 0.61 to 0.68μ (red); HRV-3, 0.79 to 0.89μ (near-infrared). Results are reported in terms of relative BRF, that is, the ratio of the BRF at a particular view angle to that at nadir. When the radiometers were positioned east of a target, view angles were considered negative. Also, for consistency, solar zenith angles were considered negative for times before solar noon.

FINDINGS: Results of BRF measurements at different view angles demonstrated the need to account for non-lambertian properties of surfaces when oblique views were obtained over agricultural targets. Relative BRFs for clay loam soil (Fig. 1) changed by more than a factor of 2 for view angle changes from -45° to +45°, with the positive view angles (forward scattering) always less than at nadir. BRF-view angle relationships were nearly the same for the three bandwidth intervals (green, red, and near-infrared). However, for a wheat canopy, the relationships were considerably different for the three bands (Figure 2). The green (HRV-1) and the red (HRV-2) were considerably greater than the near-infrared (HRV-3) for the backscatter angles (negative view angles). This resulted from the greater transmittance of infrared light through green leaves.

Observations from nadir-pointed radiometers at ground and aircraft altitudes established that reflectance changes over a two-day period for soil, cotton, and wheat were negligible. However, when

*For parenthetical references, see corresponding item number in Appendix A, Manuscripts Published or Accepted for Publication in 1990.

reflectance changes over a two-day period for soil, cotton, and wheat were negligible. However, when these same targets were observed from SPOT on the same two consecutive days using off-nadir view angles, differences in surface reflectance were pronounced. Approximately half of the variation in SPOT imagery was explained by the BRF properties of the surface and changes in sensor viewing geometry.

INTERPRETATION: The relationship between bidirectional reflectance and view and solar angles is different for different surfaces. The relationship for bare soil is much less complex than for vegetative surfaces, but it varies significantly with roughness. The relationship is dynamic for vegetative surfaces because it is related to plant height and density, as well as optical properties of leaves that change with age.

FUTURE PLANS: SPOT data obtained on consecutive days at different view angles will be analyzed to evaluate view and solar zenith angle effects on the imagery. Results will be compared with ground-based data to further delineate the BRF-view angle-solar angle relationship.

COOPERATORS:
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M. F. Jasinski, NASA, Goddard Space Flight Center, Greenbelt, MD
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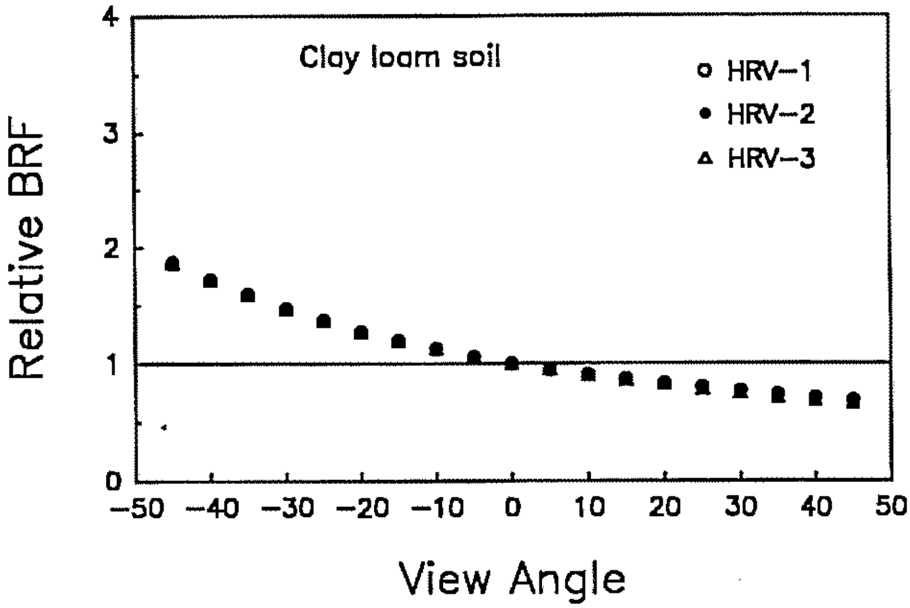

Figure 1. Bidirectional reflectance factors relative to nadir versus view angle for green, red, and near-infrared spectral bandwidths measured over bare soil.

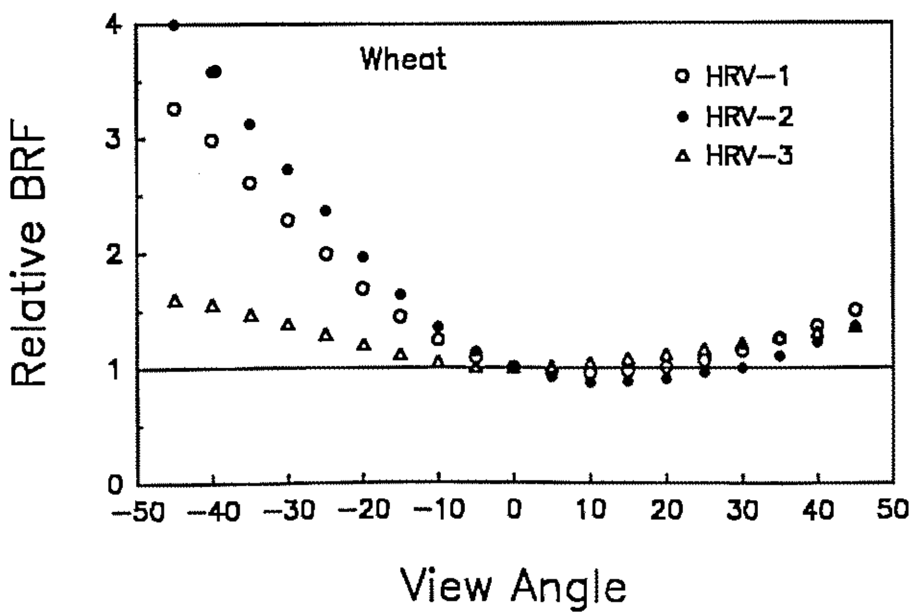

Figure 2. Same as Figure 1 except the measurements were over wheat.

CALCULATING REFLECTANCE, TRANSMITTANCE, AND ABSORPTANCE FROM SPECTRORADIOMETRIC MEASUREMENTS OF SINGLE LEAF SCATTERING PROPERTIES IN THE FIELD

Paul J. Pinter, Jr., Research Biologist

PROBLEM: The spectral properties of individual plant leaves are frequently needed to provide diagnostic evidence of nutrient deficiency or disease, to confirm the effect of experimental treatments on leaf pigment changes and photosynthetic capacity, or as required inputs for complex models of canopy reflectance used for interpreting remote sensing imagery. Portable spectroradiometers provide a viable solution for obtaining high resolution spectra from plants and soils. However, measuring single leaf reflectance (ρ), transmittance (τ), and absorptance (α) in the field without a relatively expensive and cumbersome integrating sphere to control the irradiant environment is difficult. Radiation that is transmitted through semitransparent leaf tissues from the background is included in the scattered signal (σ, reflected plus transmitted energy) measured by the radiometer. Separating desired ρ, τ, and α components from this total σ is not possible. As a consequence, comparisons of spectra acquired at different locations or times of the day becomes very difficult if not impossible to accomplish. Furthermore evaluation of bidirectional reflectance properties of the leaf is not possible with an integrating sphere because the source of illumination is solely hemispheric in nature instead of hemispheric-directional as occurs in the field with hemispheric sky radiation plus direct beam solar.

The objective of this research was to develop a spectroradiometric technique which avoids these problems and permits the separation of visible and near infrared ρ, τ, and α from leaf measurements taken in the field without an integrating sphere.

APPROACH: The method requires the measurement of radiant flux from both the adaxial and abaxial surfaces of leaves under conditions when the background is alternately sunlit and shaded. The technique minimizes the effect of background spectral characteristics by subtracting the energy transmitted through the leaf to the radiometer. Measurements were made using a SE-590 Spectron radiometer with 360 to 1080 nm measurement capability on detached leaves of *Parthenium tomentosum* var. stramonium (Greene), a perennial shrub native to northern Mexico that has relatively large, lanceolate leaves. A circular, spring-loaded, leaf clamp apparatus was developed to hold an individual leaf relatively flat in front of the radiometer, perpendicular to its direction of view and fully illuminated by the sun. With the leaf removed the radiometer had an unobstructed view through the frame to the background target. The radiometer was positioned to provide a 45° difference between its viewing angle and the solar zenith angle using a pin hole, solar sighting device and protractor mounted on its side. The distance between the leaf and radiometer lense was maintained at about 10 cm; the 15° field-of-view optics resulted in a 2.6 cm dia. circular target on the leaf surface.

Observations of σ (w m^{-2}) were obtained for adaxial and abaxial leaf surfaces, with the leaf fully illuminated by direct beam solar radiation and the background alternately sunlit and or shaded using a 75 by 75 cm opaque cardboard screen to block direct beam solar radiation from striking the surface immediately behind the leaf. Each set of leaf spectral measurements was bracketed by measurements of σ sunlit and shaded backgrounds. Four backgrounds were used: a painted, $BaSO_4$ panel; a tray of dry Avondale loam soil, a partly senescent bermuda grass canopy, and a plywood surface painted with 4 coats of Rustoleum[1] flat black paint. Incoming solar and diffuse irradiance (I_o, w m^{-2}) were estimated from frequent measurements over a sunlit, 30 by 30 cm halon reference panel that was positioned normal to the viewing direction of the radiometer and 45° with respect to the sun.

The fraction of light transmitted (τ) in each wavelength through each leaf surface was calculated as the difference between σ measured from leaves having sunlit and shaded background surfaces divided by the differences between σ measured from sunlit and shaded background. For the adaxial surface

$$\tau_{\lambda \ell 1} = [\sigma_{\lambda \ell 2b} - \sigma_{\lambda \ell 2d}]/[\sigma_{\lambda Bb} - \sigma_{\lambda Bd}], \text{ and} \qquad \text{eqn 1}$$

abaxial,

$$\tau_{\lambda \ell 2} = [\sigma_{\lambda \ell 1b} - \sigma_{\lambda \ell 1d}]/[\sigma_{\lambda Bb} - \sigma_{\lambda Bd}], \qquad \text{eqn 2}$$

where the subscripts λ refer to wavelength, ℓ to the adaxial (1) or abaxial (2) leaf surfaces, and B to the background in bright sunlight (b) or darker shaded (d) conditions. Leaf reflectances were computed as

$$\rho_{\lambda\ell 1} = [\sigma_{\lambda\ell 1b} - \tau_{\lambda\ell 2}\sigma_{\lambda Bb}]/I_{o\lambda}, \text{ and} \qquad \text{eqn 3}$$

abaxial,

$$\rho_{\lambda\ell 2} = [\sigma_{\lambda\ell 2b} - \tau_{\lambda\ell 1}\sigma_{\lambda Bb}]/I_{o\lambda}. \qquad \text{eqn 4}$$

Leaf absorptances were then calculated as a residual

$$\alpha_{\lambda\ell 1} = 1 - \rho_{\lambda\ell 1} - \tau_{\lambda\ell 1}, \text{ and} \qquad \text{eqn 5}$$

abaxial,

$$\alpha_{\lambda\ell 2} = 1 - \rho_{\lambda\ell 2} - \tau_{\lambda\ell 2}. \qquad \text{eqn 6}$$

FINDINGS: Examination of data acquired from *P. tomentosum* leaves showed σ was influenced by the spectral characteristics of the background. This was least noticeable in the visible region (~380-700 nm) where leaf transmission was low (Fig. 1A) and exaggerated in the near-infrared where transmission was relatively high (Fig. 1B). The $BaSO_4$ background, with more than an order of magnitude greater reflectance than the black surface, had the greatest effect on σ at all wavelengths. The soil and grass backgrounds were intermediate in their effects. Although the spectral signature of the senescent grass canopy was not particularly pronounced, it had a substantial effect on the first derivative spectra of the leaves (data not shown). Compensating for the fractional portion of light that was transmitted through the leaf tissue, permitted ρ to be calculated from observed σ and significantly reduced the effect of the background spectral characteristics on leaf spectra (Fig. 2A and 2B).

Once the varying background signal had been removed it was then possible to compare the spectral signatures of different leaf surfaces. In the example of Fig. 3A, the average ρ, τ, and α of adaxial surfaces of three normal leaves are compared with those of the abaxial surfaces. Fig. 3B shows similar data for three chlorotic leaves. Large differences between upper and lower surfaces in ρ and α were observed in both the visible and near-IR wavelength regions. It is interesting to note that the τ were similar for both surfaces. This information would have been partially obscured if the measurements on the different leaves had been taken over different soil backgrounds (eg. dry versus wet) or different times of the day. Figs. 4A and 4B show the data for normal and chlorotic leaves for comparison.

INTERPRETATION: An immediate contribution of this simple technique is that it permits ρ, τ, and α spectral components to be separated from measurements obtained in the field without an integrating sphere. This makes results obtained from different field sites and times of day more comparable and gives investigators more confidence in first derivative spectra obtained from single leaf field observations. It provides a method whereby leaf spectral properties can be correlated with experimental treatments, management practices or anticipated changes in global climate and atmospheric conditions. An important potential contribution is that the technique should allow evaluation of spectral components under varying hemispheric-directional irradiance conditions (ie. different solar and view angles) in a manner that cannot be accomplished with commercially available systems.

FUTURE PLANS: Plans for future research include characterization of the effects of CO_2 and water stress on spectral components of cotton leaves throughout the season, correlation of leaf α with leaf pigments estimated with a commercially available "chlorophyll meter" and investigations into the suitability of the technique for estimating bidirectional reflectance factors of individual leaves for input into canopy radiation models.

COOPERATORS: Dr. Alfredo Huete and graduate students (Soil and Water Sciences Department, University of Arizona) provided the SE-590 and basic data reduction programs; Mr. Bob Anderson assisted in field measurements.

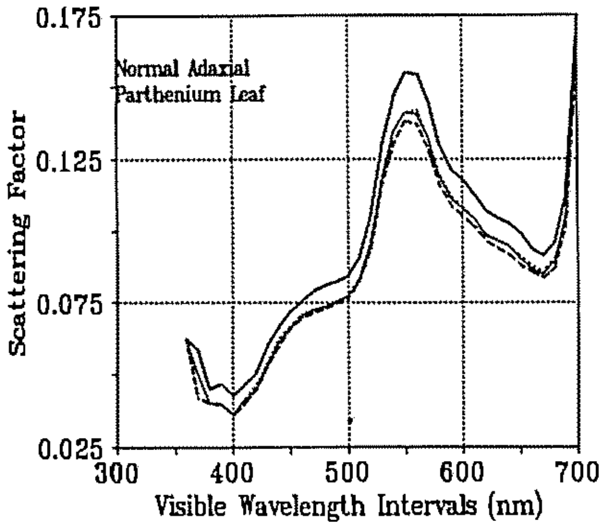

Fig. 1A. Apparent visible scattering factors (σ) of *P. tomentosum* measured over different backgrounds (uncorrected for τ).

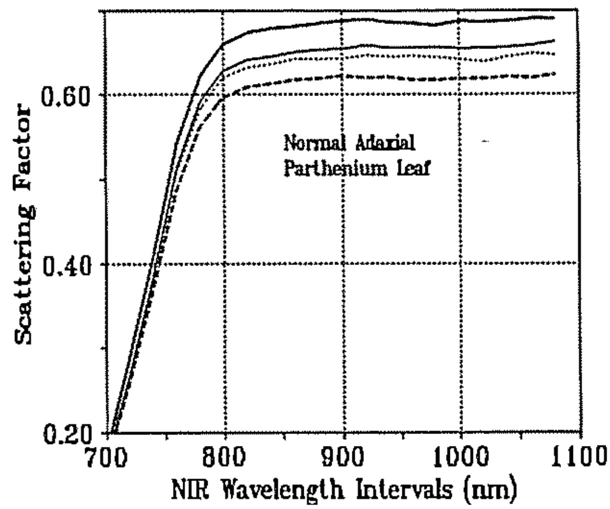

Fig. 1B. Apparent near-IR scattering factors (σ) of *P. tomentosum* measured over different backgrounds (uncorrected for τ).

Background Legend – Applies to all figures on this page
—— BaS04 —— Grass ······· Soil ----- Black

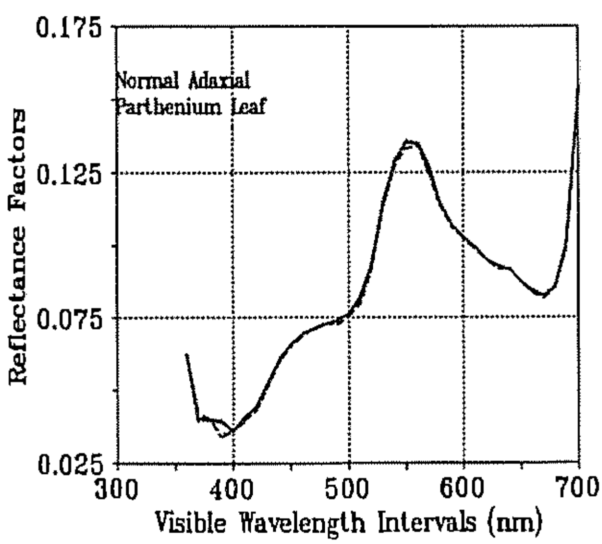

Fig. 2A. Calculated visible ρ of 3 normal *P. tomentosum* leaves measured over different backgrounds (corrected for τ).

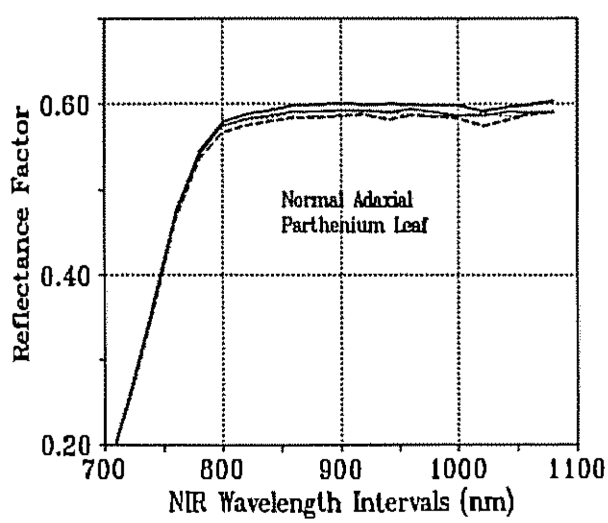

Fig. 2B. Calculated near-IR ρ of 3 normal *P. tomentosum* leaves measured over different backgrounds (corrected for τ).

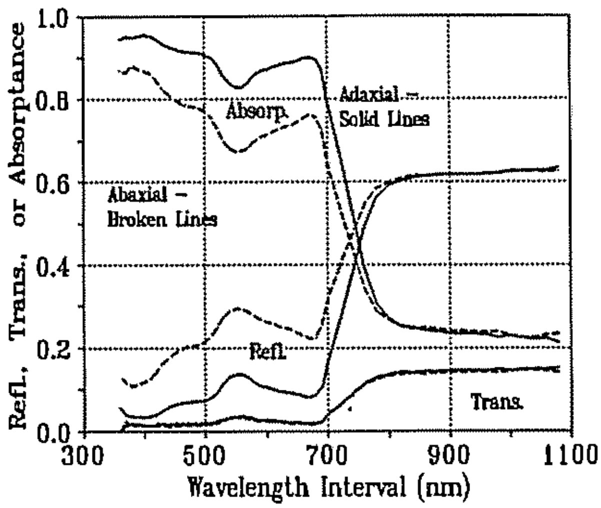

Fig. 3A. Average ρ, τ and α of adaxial and abaxial surfaces of 3 normal leaves from *P. tomentosum*.

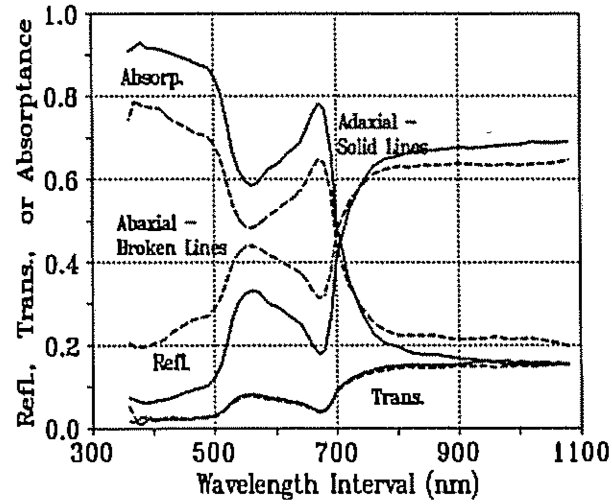

Fig. 3B. Average ρ, τ and α of adaxial and abaxial surfaces of 3 chlorotic leaves from *P. tomentosum*.

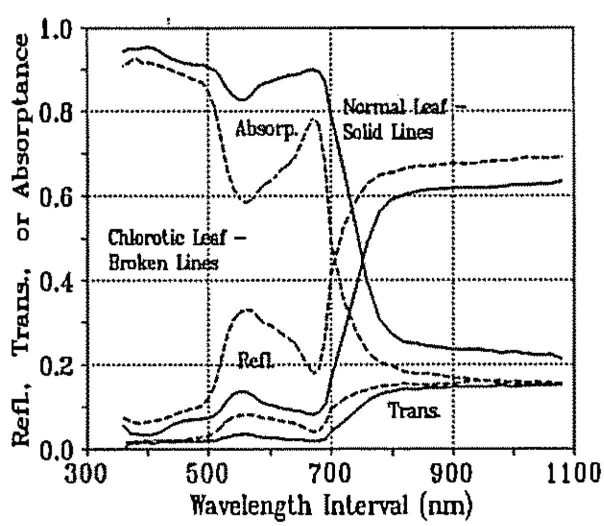

Fig. 4A. Average ρ, τ and α of adaxial surfaces of 3 normal and 3 chlorotic leaves from *P. tomentosum*.

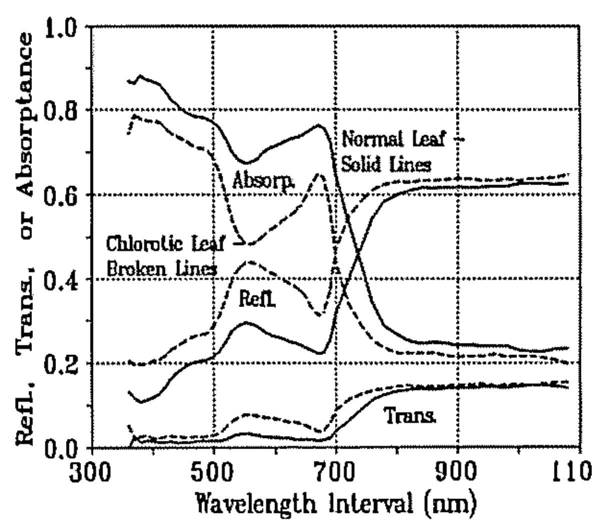

Fig. 4B. Average ρ, τ and α of abaxial surfaces of 3 normal and 3 chlorotic leaves from *P. tomentosum*.

MULTISPECTRAL INDICATORS OF LAI, BIOMASS, AND LIGHT USE EFFICIENCY IN THE FREE AIR CO_2 ENRICHMENT EXPERIMENT ON COTTON IN 1990

P. J. Pinter, Jr., Research Biologist

PROBLEM: Efficient techniques are needed for evaluating plant response to CO_2 enrichment and water stress treatments. Traditional methods for accomplishing these goals are not only labor intensive and time consuming to perform, but are inappropriate for use in very small research plots because they require destructive sampling of individual plants that usually cannot be sacrificed without affecting the remaining population. An equally perplexing problem arises in large-scale field experiments, where it may be unfeasible to obtain a sufficiently large number of samples to characterize all the variation present in the system. Remote sensing techniques which measure the amount of light that is reflected from the plants in visible and near-infrared (NIR) wavelengths can minimize these problems and provide a noninvasive solution for monitoring plant response throughout the season.

Handheld radiometers were used to measure canopy reflectances during the Free Air CO_2 Enrichment (FACE) experiments in 1989 and 1990. Conducted at The University of Arizona Maricopa Agricultural Center (MAC), the FACE experiments are unique in their attempt to evaluate the response of cotton (*Gossypium hirsutum* L., cv Delta Pine 77) exposed to ambient (approximately 370 ppm) and elevated (~550 ppm) concentrations of CO_2 without the confining walls and altered microclimate of glasshouse, or open top field chamber studies. There were several objectives for the reflectance measurements. First, to determine their utility for monitoring plant response throughout the season. Second, to develop correlations between multispectral vegetation indices (VIs) derived from reflectance data and green leaf area index (LAI), biomass and fraction of absorbed light in photosynthetically active wavelengths. And third, to use VIs to determine effects of CO_2 enrichment and differential water treatments on light use efficiency of the canopy during different phenological periods of plant development. Data presented here were collected during the 1990 growing season.

APPROACH: CO_2 enrichment of field grown cotton was accomplished by release of CO_2 into the canopy from 20-m-diameter circular manifolds placed in the field shortly after planting. CO_2 concentrations at the top of the canopy were maintained at desired 550 ppm levels during daylight hours by constant monitoring of CO_2, wind speed and wind direction, and injection of CO_2 into appropriate upwind ports in the array. The ambient CO_2 treatment consisted of similar manifolds (without the gas injection system) in paired locations distant from the enriched arrays. The CO_2 treatments were replicated four times. Different soil water conditions were created in each array using subsurface drip irrigation: a "wet" treatment intended to meet consumptive requirements of cotton and a "dry" treatment approximately 80% of consumptive requirements.

Biomass and green leaf area index were determined from destructive samples taken at approximately 10-day intervals from May 15 until September 20, 1990. Canopy reflectances were measured with an Exotech[1] Model 100A portable radiometer equipped with 15° field-of-view optics and spectral bandpass filters in 3 visible and one NIR wavelength interval. Filters were similar to the blue channel (0.45 to 0.52μm) on LANDSAT 5 and the green (0.50 to 0.59μm), red (0.61 to 0.68μm), and NIR (0.79 to 0.89μm) channels on the SPOT satellite platform. The radiometer was handheld about 1.5 m above the soil surface in both irrigation treatments within the FACE (550 ppm CO_2) and ambient CO_2 arrays. Twenty-four, equally-spaced measurements were taken along a 6-row transect in each treatment. Reflectances were taken two to four times each week from May 17 until September 20, 1989 (44 data sets). The entire measurement sequence required approximately 25-35 minutes to complete. To minimize the effects of changing solar zenith angles on canopy reflectances, observations were centered on a morning time period corresponding to a constant solar zenith angle of 45°. Qualitative observations of weather, sky conditions, and canopy appearance were recorded at time of data collection.

Radiometer voltages were recorded on a portable data acquisition system (Polycorder, Omnidata International, Inc.). Reflectance factors were calculated as the ratio of energy measured over each cotton target to incoming energy in the same wavelength interval as inferred from a time-based linear interpolation of data collected at ~15 min. intervals over a 0.6 by 0.6 m, horizontally positioned, calibrated, painted $BaSO_4$ reference panel. Correction factors were applied to panel data to compensate for non-lambertian properties. The ratio VI was computed as the NIR reflectance factor divided by the red reflectance factor; the normalized difference (NDVI), as [NIR-Red]/[NIR+Red].

FINDINGS: Multispectral VIs computed as either the simple ratio or the NDVI were influenced by the agronomic properties of the cotton canopy and the treatment variables. They were significantly correlated with green leaf area index (Figs. 1A and 1B); similar relationships occurred regardless of CO_2 or irrigation treatment. Although the NDVI responded rapidly to newly emergent vegetation, it saturated when LAI attained approximately 4 units. The ratio was slow to detect sparse vegetation, but retained sensitivity to LAI between 5 and 6. VIs were also significantly correlated with biomass (Figs. 2A and 2B). However, slightly different relationships were observed for control and CO_2-enriched treatments. NDVI saturated at a lower biomass level than the ratio (about 750 vs 1000 g m^{-2}, respectively).

A significant correlation was found between the NDVI and the fraction of absorbed photosynthetically active radiation (APAR) measured at midday using a LiCor line quantum sensor (Fig. 3). This relationship appeared independent of both CO_2 and water treatments. The NDVI provided a mechanism to evaluate PAR absorbed by the cotton canopy throughout the season, using daily estimates of incident PAR derived from global solar radiation at the MAC AZMET station. When combined with biomass produced over growth intervals corresponding to vegetative (emergence to first square, DOY 123 to 156), early reproductive (first square to first flower, DOY 156 to 190), mid-reproductive (first flower to first open boll, DOY 190 to 225), and later reproductive stages (first open boll to mid-September, DOY 225 to 255), the amount of APAR accumulated over the same interval gave estimates of light use efficiency of the canopy that varied with CO_2 level and to a lesser degree with stage of growth and irrigation treatment (Figs. 4 and 5).

INTERPRETATION: Seasonal trajectories of VIs revealed differences between plots that were caused directly by environmental variables and CO_2 enrichment and irrigation treatments. Results were available within minutes after data collection and thus were used by scientists and experiment managers in a near-real time fashion to monitor progress of the experiment. Coupled with estimates of plant biomass, the NDVI provided a mechanism for evaluating the LUE of relatively large undisturbed sections of the canopy. This is the first time that the LUE of CO_2-enriched plants has been evaluated at the canopy level in studies outside of greenhouse or open top field chamber work. In the wet irrigation treatment, the data show an average of about 28% increase in LUE for a 50% CO_2 increase over ambient conditions; the LUE increase was ABOUT 19% in the dry treatment. It is likely that these increases would have been greater if CO_2 enrichment had not been interrupted during a several day period in July because of lightning damage to the control system. It is also significant to note that multispectral reflectance data respond to changes in chlorophyll content of the canopy and thus may be better related to the physiological mechanisms which affect PAR absorption than those measured using the light bar operating on the basis of blocked light in the 400 to 700 nm region of the spectrum.

FUTURE PLANS: Techniques for estimating light use efficiency of the canopy will be applied to reflectance and growth observation collected under different growing conditions during the 1989 FACE experiment in cotton. Plans for future research include continuation of measurements during the 1991 FACE experiment.

COOPERATORS: These experiments were conducted with partial funding from the Department of Energy and in cooperation with personnel from Brookhaven National Research Laboratory and the Western Cotton Research Laboratory. The author extends his appreciation to Mr. Bob Anderson for making many of the measurements of canopy reflectance and Dr. Jack Mauney for providing the agronomic data from destructive samples.

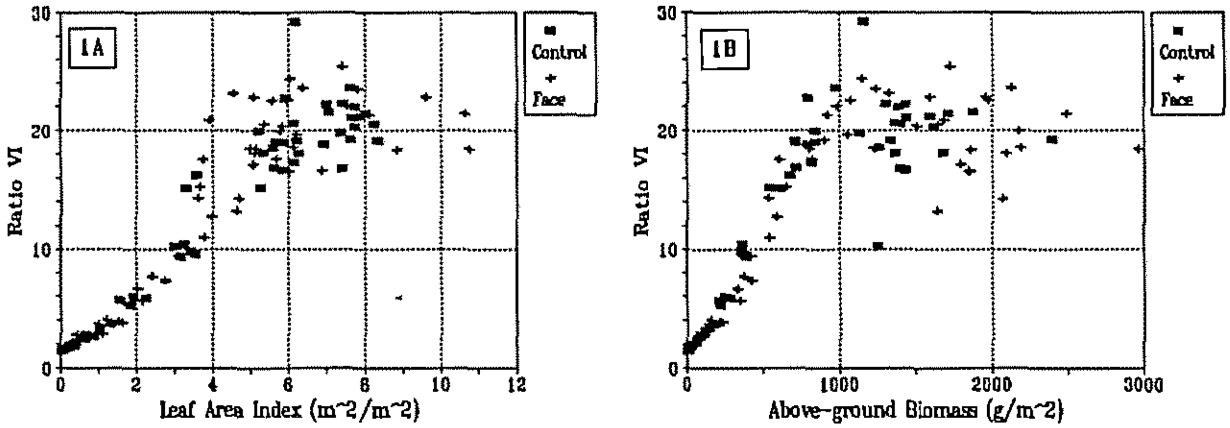

Figure 1. Ratio vegetation index (NIR/Red) versus cotton green leaf area index (m^2 m^{-2}, Fig. 1A) and total above ground dry biomass (gm m^{-2}, Fig. 1B) measured in the wet irrigation treatment during the FACE experiment in 1990. Relationships observed for dry irrigation treatment were similar (not shown).

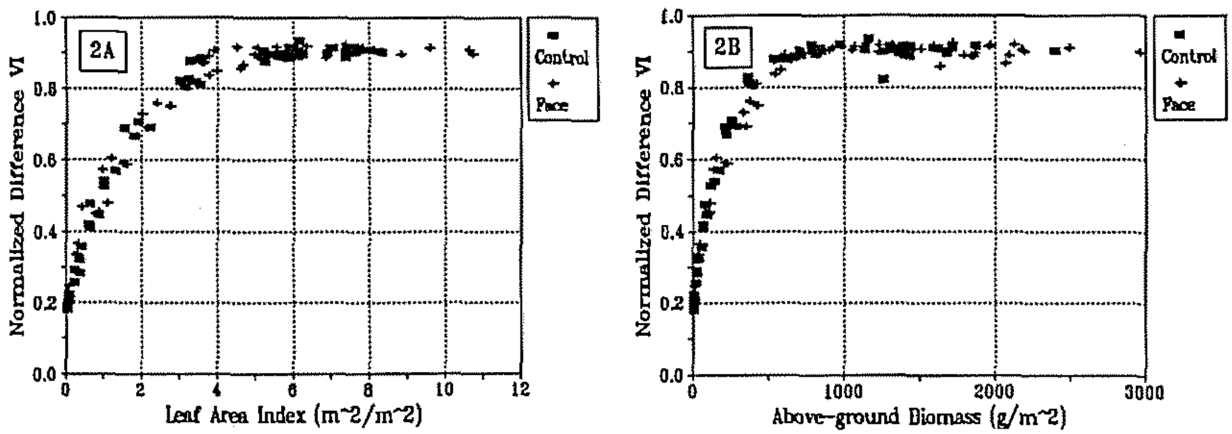

Figure 2. Normalized difference vegetation index [(NIR-Red)/(NIR+Red)] versus cotton green leaf area index (m^2 m^{-2}, Fig. 2A) and total above ground dry biomass (gm m^{-2}, Fig. 2B) measured in the wet irrigation treatment during the FACE experiment in 1990. Relationships observed for dry irrigation treatment were similar (not shown).

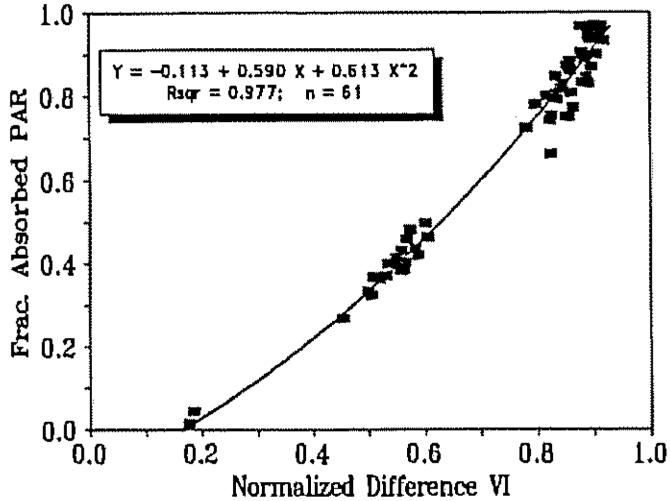

Figure 3. Fraction of photosynthetically active radiation absorbed by the canopy versus the normalized difference vegetation index measured during the FACE experiment in 1990.

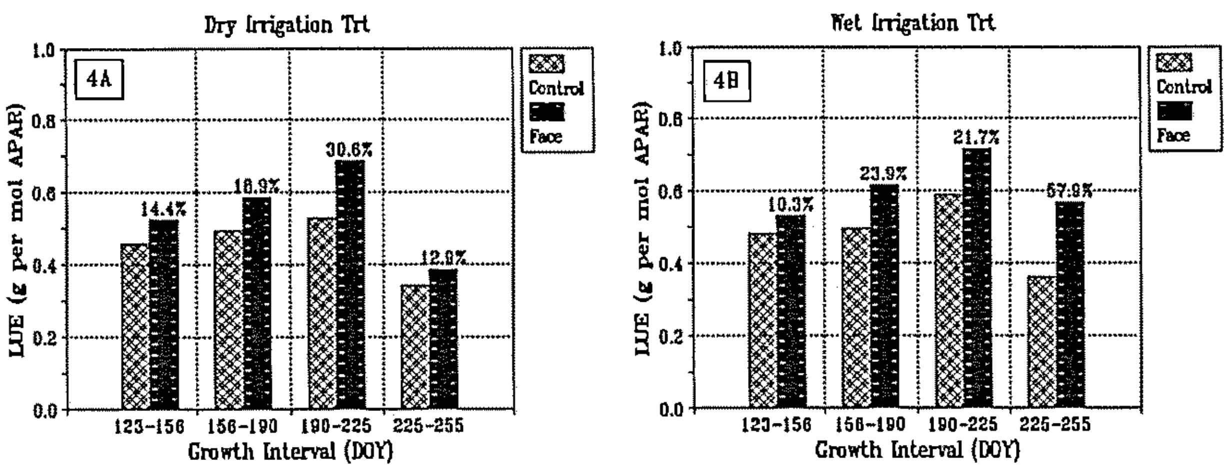

Figure 4. Estimates of light use efficiency (g biomass per mol APAR) of control and FACE cotton in the dry irrigation treatment (4A) and the wet irrigation treatment (4B). Percentages refer to increase of FACE over controls.

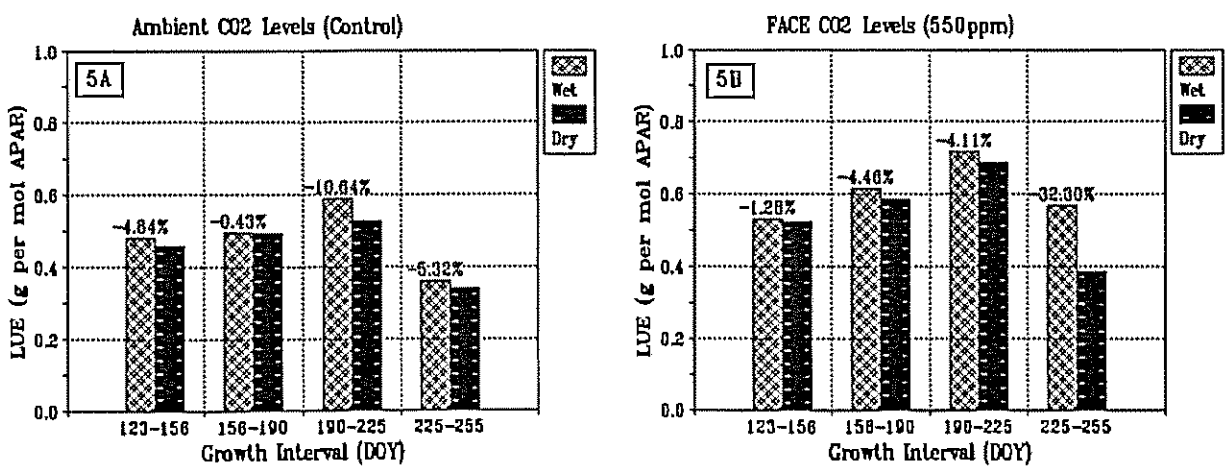

Figure 5. Estimates of light use efficiency (g biomass per mol APAR) of wet and dry irrigation treatments in the control (5A) and FACE (5B) cotton. Percentages refer to decrease in dry compared with wet treatment.

ELECTRONICS ENGINEERING LABORATORY

D. E. Pettit, Electronics Engineer

The Electronics Engineering Laboratory, staffed by one Electronics Engineer, is assigned to design, develop, repair, calibrate, evaluate, and modify electronic equipment in support of U. S. Water Conservation Laboratory research projects.

During 1990, an extensive renovation and modernization of the Electronics Engineering Laboratory was undertaken and largely completed. The project included an electrical static dissipative (ESD) floor, wall-mounted port bins, a new electronic work bench, new lighting, and repainting. The new electronic work bench provides an ESD test station, a repair station, and a general construction station. The entire bench will provide for control of computer automation testing, a general information database, a new improved computer-aided design software package for printed circuit board design, and a schematic design and analysis package. Testing capability now includes RAM testing and inspection of new types of miniature circuits. Parts and tools have been restocked to levels that will expedite many routine repairs and requirements.

Research program support included redesign of a sample-and-hold device that instantaneously captures up to ten channels of output from a multiband radiometer and infrared thermometer and sends the outputs sequentially to a data recording device (see Moran et al., "Multispectral measurements of a semiarid rangeland for study of energy and water fluxes," in this report). The new design reduces the number of chips and components from 40 to only two, thereby reducing unit size, power requirements, and cost while enhancing repairability.

At the beginning of the CO_2 project (see Idso and Kimball, "CO_2 enrichment of sour orange trees," in this report) in 1983 an interface circuit was designed and built that enabled a polycorder to control up to 63 devices with only six control signals. The interface has generally performed well, but occasionally was bothered by noise which resulted in two or more valves being on at the same time. During the past year the interface was redesigned and modified to make it more immune to noise.

Overall Laboratory support included evaluation and implementation of new PC devices, such as a 50 MB removable hard cartridge drive. New IBM-PC compatible computer-based machines were tested and assembled.

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. Following are examples of work orders completed in 1990:

Fabricate a device to position a leaf sample in front of the spectron radiometer to measure leaf spectral properties in the field. The device filled a requirement to provide control over leaf and viewing angle along two axes and is used in remote sensing work (see Pinter, "Calculating reflectance, transmittance and absorptance from spectroradiometric measurements of single leaf scattering properties in the field," in this report).

Fabricate soil sampling tubes from galvanized tubing to take soil samples in open top chambers as part of the CO_2-enrichment work on orange trees.

Mount SC94 interface cards to panel in the data logging system to collect micrometeorological data for calculation of evapotranspiration in the Free-Air CO_2 Enrichment (FACE) experiment at The University of Arizona Maricopa Agricultural Center.

Fabricate an exotech/IRT yoke to suspend a 2-kilogram, 4-channel radiometer and a 1/2 kilogram infrared thermometer about 2 meters above the ground and 1/5 meters away from the carrier's body. The device, along with the reflectance plate stand, was used for intensive "ground truth" measurements to complement aircraft and satellite measurements during the Monsoon '90 Experiment (see Moran, et al., "Multispectral measurements of a semiarid rangeland for study of energy and water fluxes," in this report).

Fabricate holder for neutron access tube cross-piece from channel iron or brass to hold access tube in barrel of water. Device used for calibration of neutron equipment.

COMPUTER FACILITY

T. A. Mills, Computer Programmer Analyst

The computer facility supports all laboratory computer equipment and applications, both scientific and administrative. Support is provided by one fulltime Computer Programmer Analyst and one Computer Assistant. The facility is responsible for purchasing, installing, configuring, upgrading, maintaining (both in-house and by contract), and providing supplies for all computer systems. Systems include a Hewlett-Packard HP 1000, a Digital MicroVax II, personal computers, 4 operating systems, a standard Ethernet network, and all associated peripherals. The Network supports Digital's DECNET, PCSA, and LAT protocols.

During the past year, the Computer Assistant's major effort was installing, maintaining, and upgrading personal computers. Instructing and training users on new and updated products was ongoing. The Computer Programmer Analyst spent most of his time with the two mini computers and the network installation. Standard (thick) Ethernet cable was placed in nearly all buildings that might require some network-type interaction. Digital's PCA protocol was chosen in FY89 to be the base of network communication. In late August of this year, based on a feasibility report by Mr. Mills, the staff decided to begin phasing out the two mini computers.

Major projects for FY91 include transferring the volumes of data from the minicomputers to PC-type media, removing the MicroVax II as a network server, and replacing it with a PC server.

LIBRARY AND PUBLICATIONS

L. S. Seay, 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,[1] as well as for holdings of professional journals and other incoming media. Support includes performance of searches for requested publications and materials for the Staff. Library holdings include approximately 1500 volumes in various scientific fields related to agriculture. Some professional journal holdings in the same fields date back to 1959.

During the past year, the U. S. Water Conservation Laboratory List of Publications, containing approximately 1600 entries, was converted from a manual entry system to PROCITE, an automated bibliographic program. The automated system provides for sorting and printing selected lists of Laboratory publications. Publication lists and most of the publications are available upon request. Entry of Laboratory Library holdings into PROCITE is planned.

[1] Appendix A lists manuscripts published or formally accepted for publication in 1990.

APPENDIX A

APPENDIX A

Manuscripts Published or Accepted for Publication in 1990

1. ALLEN, S.G., IDSO, S.B., KIMBALL, B.A., BAKER, L.T., ALLEN J.R., J.H., MAUNEY, J.R., RADIN, J.W. and ANDERSON, M.G. 1990. Effects of air temperature on atmospheric CO2-plant growth relationships. p. 1-60 IN: DOE/ER-0450T. U. S. Dept. of Energy, Wash. DC. 13 Dec 1989. 5344-11130-004-00D

2. AMTHOR, J.S. and KIMBALL, B.A. 1990. Predicting the growth and productivity of cotton in a future greenhouse world: Development of a physiological model. Proc of Beltwide Cotton Conf. 16 Jan 1990. National Cotton Council, Memphis, Tenn. p. 724. 5344-11130-004-00D

3. BOUWER, H. 1990. Agricultural Chemicals and ground water quality - issues and challenges. Ground Water Monitoring Rev. 10(1):71-79.

4. BOUWER, H. 1990. Irrigation management for groundwater quality protection. p. 395-399 IN: Visions of the Future. ASAE. Proc. Third Natl. Irrig. Symp., Phoenix, AZ. 28 Oct - 01 Nov. 1990. 07 Jul 1990. 5344-13000-002-00D

5. BOUWER, H., DEDRICK, A.R. and JAYNES, D.B. Irrigation management for groundwater quality protection. Irrig. & Drain. Syst. An Int. J. (Accepted by Journal - Nov 90). 5344-13000-001-00D 5344-13000-002-00D

6. BOUWER, H. Effect of water depth and groundwater table on infiltration from recharge basins. p. 377-384 IN: S. C. Harris (eds.) Proc. of 1990 Nat. Conf., Irrig. & Drain. Div. of Am. Soc. Civ. Eng., Durango, CO., 11-13 Jul. 1990. 5344-13000-002-00D

7. BOUWER, H., PYNE, R.D. and GOODRICH, J.A. 1990. Recharging ground water. Civ. Eng. 60(6):63-66. 5344-13000-002-00D

8. BOUWER, H. Research needs in movement of agricultural chemicals to groundwater. p. 168-174 IN: S. C. Harris (eds.) Proc. of 1990 Nat. Conf. Irrig. & Drain. Div. of Am. Soc. of Civ. Eng., Durango, CO., 11-13 Jul. 1990. 5344-13000-002-00D

9. CLEMMENS, A.J. 1990. Feedback control for surface irrigation management. p. 255-260 IN: Visions of the Future. ASAE. Proc. Third Natl. Irrig. Symp., Phoenix, AZ. 28 Oct.-01 Nov. 1990. June 27, 1990. 5344-13000-001-00D

10. CLEMMENS, A.J. 1990. Infiltration or roughness from surface irrigation advance. p. 46-53 IN: S. C. Harris (eds.) Irrigation and Drainage: Proceedings of the 1990 National Conference. Proc. Conf., Durango, CO. 11-13 Jul. 1990. ASCE. 14 March 1990. 5344-13000-001-00D

11. CLEMMENS, A.J. 1990. Understanding delivery performance before rehabilitation. p. 62-69 IN: S. C. Harris (eds.) Irrigation and Drainage: Proceedings of the 1990 National Conference. Proc. Conf., Durango, CO. 11-13 Jul. 1990. ASCE. 14 March 1990. 5344-13000-001-00D

12. CLEMMENS, A.J. A direct solution to the surface irrigation advance inverse problem. J. Irrig. and Drain. Engr. 17 Sep 1990. (Accepted by Journal - 12 Dec 1990). 5344-13000-001-00D

13. CLEMMENS, A.J. and BOS, M.G. Statistical methods for irrigation system water delivery performance evaluation. Irrig. & Drain. Syst. An Int. J. 12 Sep 1990. (Accepted by Journal - 19 Oct 1990). 5344-13000-001-00D

14. CLEMMENS, A.J., BOS, M.G. and GROENESTEIN, J.M. 1990. Menu-driven design program for long throated flumes. p. 527-532 IN: Visions of the Future. ASAE. Proc. Third Natl. Irrig. Symp., Phoenix, AZ. 28 Oct.- 01 Nov. 1990. June 22, 1990. 5344-13000-001-00D

15. CLEMMENS, A.J. Irrigation uniformity relationships for irrigation system management. J. Irrig. and Drain. Engr. 03 Aug 1990. (Accepted by Journal - 08 Oct 1990). 5344-13000-001-00D

16. CLEMMENS, A.J., REPLOGLE, J.A. and REININK, Y. 1990. Field predictability of flume and weir operating conditions. J. Hydraul. Engr. 116(1):102-118. 5344-13000-001-00D

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21. DIERIG, D.A., THOMPSON, A.E. and RAY, D.T. Effects of field storage on guayule rubber quantity and quality. Rubber Chem. and Tech. 02 May 1990. (Accepted by Journal - Nov 90). 5344-13210-001-00D

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23. DIERIG, D.A., THOMPSON, A.E. and RAY, D. T. 1990. Rubber and resin yield evaluation of new Arizona guayule selections. Proc. First Int. Conf. on New Industrial Crops. 9-12 Oct 1990, Riverside, CA. 5344-13210-002-00D

24. DIERIG, D. A., THOMPSON, A. E. and RAY D.T. 1990. Yield performance of new Arizona guayule selections. Proc. Crop. Sci. Soc., Agronomy Abstr. Oct 1990, San Antonio, TX. 5344-13210-002-00D

25. HEERMANN, D.F., MARTIN, D.L., JACKSON, R.D. and STEGMAN, E.C. 1990. Irrigation scheduling control and techniques. p. 509-535 IN: On Farm Irrigation Practice. ASA Monograph, Section VI. August 11, 1988. 5344-13610-001-00D

26. HUNSAKER, D.J., BUCKS, D.A. and JAYNES, D.B. Irrigation uniformity of level basins as influenced by variations in soil water content and surface elevation. Agric. Water Mgmt. 23 March

27. IDSO, S.B. 1990. A role for soil microbes in moderating the CO2 greenhouse effect? Soil Sci. 149:179-180. 22 Aug 1989. 5344-13610-001-00D

28. IDSO, S.B. 1990. Evidence for the reality of Gaian climate control in hemispheric temperature trends of the past century. Theor. Appl. Clim. 42:135-137. 10 July 1989. 5344-13610-001-00D

29. IDSO, S.B. 1990. Interactive effects of CO2 and climate variables on plant growth. p. 61-69 IN: N.J. Rosenberg, L. H. Allen, Jr., G. H. Heichel, C. W. Stuber, D. E. Kissel and S. Ernst B. A. Kimball (eds.) Impact of Carbon Dioxide, Trace Gases, and Climate Change on Global Agriculture. Proc. Symp. ASA Mtg Anaheim, CA, 27 Nov-2 Dec. 1988. 5344-13610-001-00D

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31. IDSO, S.B. 1990. The CO2/trace gas greenhouse effect: Greatly over-estimated? p. 19-26 IN: N.J. Rosenberg, L. H. Allen, Jr., G. H. Heichel, C. W. Stuber, D. E. Kissel and S. Ernst B. A. Kimball (eds.) Impact of Carbon Dioxide, Trace Gases, and Climate Change on Global Agriculture. Proc. Symp. ASA Mtg Anaheim, CA. 27 Nov.-2 Dec. 1988. 5344-13610-001-00D

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56. NAKAYAMA, F.S. 1990. Future plans for the new AAIC journal. El Guayulero. 12(1+2):1. 5344-13210-001-00D

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