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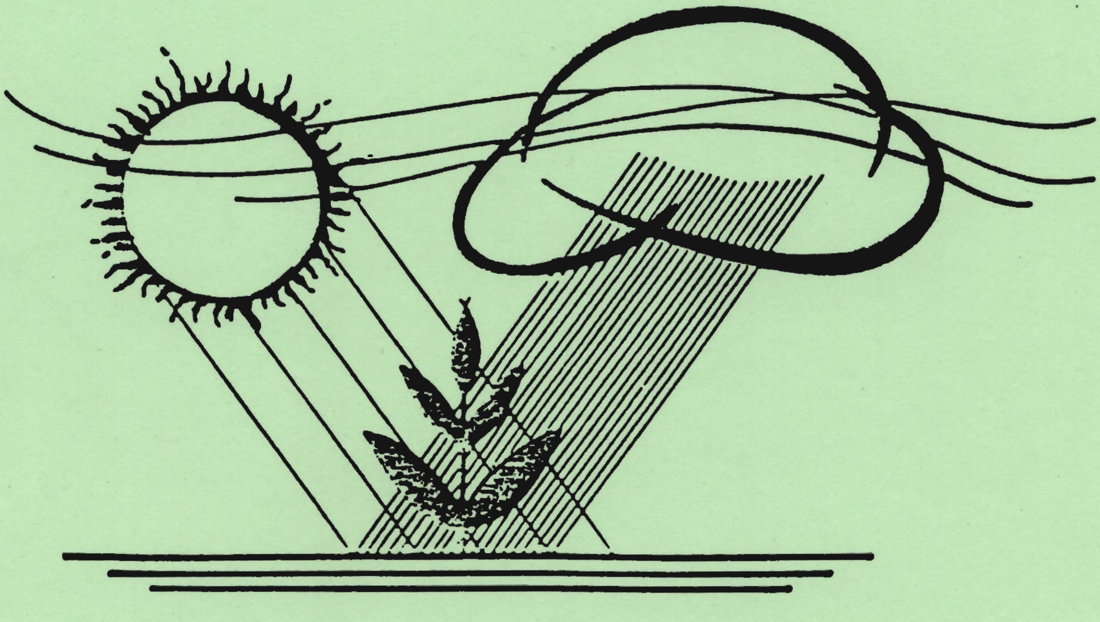
1988

CALIFORNIA PLANT
AND
SOIL CONFERENCE

Agriculture: Changing Realities



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February 3-4, 1988
Piccadilly Inn - University
Fresno, California

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HYDROLOGIC PROCESSES AFFECTING THE DISTRIBUTION AND MOBILITY OF SALINITY AND SELENIUM IN SHALLOW GROUND WATER, WESTERN SAN JOAQUIN VALLEY, CALIFORNIA

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Chemical data for soil and ground water collected throughout the western San Joaquin Valley, California, provide important information about the hydrologic processes that affect salinity and selenium. On a regional scale, spatial distributions of natural soil salinity and present-day ground-water salinity were evaluated in relation to the alluvial-fan geomorphology. This evaluation shows the probable interaction of natural soil salinity and leaching and irrigation practices on the salinity distribution in shallow ground water. The distribution of selenium in ground water is affected by similar factors.

Soils of the upper and middle parts of alluvial fans deposited by the major intermittent streams of the area (Little Panoche, Panoche, Cantua, and Los Gatos Creeks) were naturally low in salinity. Relatively large quantities of water flowed through these fan deposits, leaching substantial amounts of soluble salts and selenium from the soil. Much less water flowed through material deposited by smaller ephemeral streams (1). Soils in the upper and middle parts of alluvial fans deposited by ephemeral streams were more saline than soils deposited by intermittent streams.

Fine-textured soils at the distal margins of the alluvial fans deposited by ephemeral and intermittent streams were the most saline under natural conditions (2). These saline soils exist on the valley trough and the alluvial-fan margins, where Mendenhall et al. (3) reported flowing artesian wells. Flowing artesian wells indicate that hydraulic pressures in deep aquifers were sufficient to cause ground-water discharge at land surface. Ground-water discharge and evapotranspiration in the valley trough and at the margins of the alluvial fans, which resulted in a build-up of salts in the root zone, probably was the principal process that led to historically saline soils.

---

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The present distribution of salinity and selenium in shallow ground water is the result of decades of irrigation of the alluvial-fan soils, which has leached soluble soil salts, including selenium, into the ground water. Low-lying areas along the margins of the alluvial fans had the most saline soils. These areas were most recently developed for irrigation and are underlain by the most saline and selenium-rich ground water. Ground water in the middle parts of the ephemeral-stream fans generally is more saline and higher in selenium than in the middle parts of adjacent fans, which were deposited by intermittent streams.

Stable isotopes of oxygen and deuterium in shallow ground-water samples were collected throughout the western valley. These data show that partial evaporation of water that has leached selenium from saline soils has resulted in the highest concentrations of selenium in shallow ground water. Oxygen-18 and deuterium enrichment in samples collected from wells at higher altitudes where the water table is more than 3 meters below land surface (59 to 100 meters above sea level) generally resembles that of meteoric water. The isotope enrichment of ground-water samples collected at the lower altitudes is characteristic of water that has been partially evaporated. The water table is shallow (less than 2 m below land surface), and salinity and selenium concentrations in ground water are high in the lower altitudes.

Two tile-drained agricultural fields have been studied at locations where evaporation from a shallow water table before drains were installed resulted in evaporative enrichment of selenium concentrations. Both fields, which have been irrigated for 40 years, exemplify how local flow systems induced by subsurface drains affect the movement of shallow ground water with high selenium concentrations to the drains. In both fields studied, saline, isotopically enriched water with high selenium concentrations is being displaced by less saline irrigation water that has percolated through the root zone. The extent and direction of this displacement is affected by the time since installation of the drainage system and the drain lateral spacing.

In one field, drain laterals are spaced 60 meters apart and were installed about 17 years ago. Most of the water high in selenium concentrations is moving toward these drain laterals at pore-water velocities of a 1.0 to 5.0 meters per year. Simulation of ground-water flow to one drain lateral in this field provides estimates of travel times for water particles that entered at the water table. A water particle beginning at the surface of the water table near midway between two drains would take about 10 years to reach the drain lateral.

The regional ground-water-flow system exerts a hydraulic influence on the ground water associated with this and other drainage systems. The hydraulic conductivity and gradients measured in a sand layer 14 m below land surface in this field indicate that in the 15 years since the drainage-system installation in this field, ground water from the outside the field could have moved into the field.

In the second agricultural field, drain laterals are spaced 100 meters apart and were installed 7 years ago. Water movement in this field also is affected by subsurface sand layers, which captures substantial quantities of water. Because of the subsurface sand layers and larger drainage lateral spacing, less water with high selenium concentrations is moving toward the drain laterals in this field. Vertical pore-water velocities determined using tritium data ranged from 1.2 to 3.0 meters per year. This has resulted in water with high selenium concentrations at depths as much as 15 meters below land surface.

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Reactivity and Mobility of Selenium in Soils

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The mobility of selenium in soils has become an important issue in recent years, particularly in the seleniferous agricultural soils of the San Joaquin Valley. In order to attempt an understanding of the mechanisms which influence the behavior of this element in soils, it is necessary to first investigate the interactions between the various forms of selenium that exist in soil systems and the soil itself.

The distribution of selenium in the soil profile is influenced by a number of factors which include: the nature of the parent material, organic matter content, pH, the presence of iron-based compounds, and oxidation-reduction conditions. The oxidation-reduction conditions of a soil depend on the presence of oxygen and may, therefore, be affected by a number of external factors, including water content, which will be governed in the San Joaquin Valley primarily by irrigation practices supplemented by rainfall. All of the above factors will have some influence on the forms of selenium that exist in soils, and these largely determine its mobility and reactivity in the soil profile.

The oxidation-reduction (redox) potential of a soil system combined with its pH status plays an important role in the speciation of selenium (Se). Figure 1 (2) illustrates the aqueous species of Se that would be expected to occur in solution at a concentration of 1mmol m^{-3} under varying pH and redox conditions (pE = Eh / 59.16, where Eh is the conventional electrode potential in millivolts). The shaded portion of the diagram indicates the pH and redox environments typically found in soils. Neutral, aerobic soils, such as those found in the western San Joaquin Valley, generally have a pE value >+7, and thus transformations between selenite and selenate species are of more concern in these soils than precipitation of elemental Se or metal selenides. Selenite, which exists in the the form of two species SeO_3^{2-} and $HSeO_3^-$ depending on the pH of the system, and selenate are the aqueous oxygenated forms of selenium, and are primarily responsible for the reactivity of this element in soil systems. Relative to sulfur, elemental selenium is the more redox-stable element, and for the oxyanions selenite is the favored form over selenate, whereas sulfate is the favored form of S. Concentrations of these oxyanions in soil, surface and ground waters are controlled by the solubilities of selenium in soil. A recent study by Elrashidi et al. (1) indicated that, in general, metal selenate and selenite minerals are too soluble to be stable in soils, and that the formation of selenides, such as Cu_2Se(c), PbSe(c) and SnSe(c), under reduced conditions would prevent the precipitation of elemental Se. It is possible that $MnSeO_3$, $PbSeO_3$(1) or $CaSeO_3.2H_2O$ (3) may be the controlling selenite solubility in acid soils, but their solubility increases with decreasing pH. Iron selenites were not expected to exist in soils, although the formation of ferric oxide-selenite complexes should not be excluded. A similar complex involving gypsum ($CaSO_4$) and selenite may also attenuate soluble Se concentrations, but these coprecipitated complexes are difficult to identify or characterize at present.

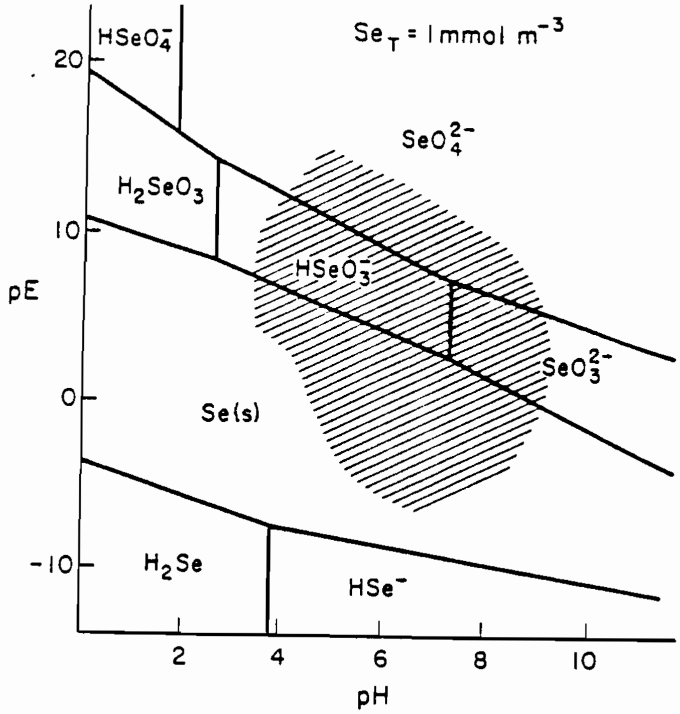

Figure 1. pE-pH diagram for the Se-H_2O system, showing the environments typically found in soils.

The reactivity of Se in soils is, therefore, determined by the chemical species in which it exists. The chemistry and resulting transport behavior of selenate and selenite oxyanions differ significantly, and this serves to emphasize the importance of identifying which species prevails in a system in order to ascertain its potential mobility and environmental fate. Adsorption of ions onto soil surfaces offers a mechanism by which a compound may be retained by soil, or its progress through the soil profile attenuated. The general consensus is currently that selenite is adsorbed to a greater extent than selenate owing to different mechanisms. Selenite is adsorbed by a mechanism involving the exchange of a ligand, usually a hydroxyl group, which resides on the surface of clay particles or metal hydrous oxides. This mechanism is thought to be similar to those involving ions such as phosphate and arsenate. This mechanism is highly dependent on pH, since the presence of hydrogen ions will affect the ability of the surface to attract the negatively charged ion and, as a result, the amount of selenite sorbed by a soil decreases with increasing pH. This is in direct contrast to cations, which become more unavailable with increasing pH. Selenate, on the other hand, behaves in a manner similar to non-specifically adsorbed ions such as chloride, and is, therefore, readily displaced into solution by more strongly adsorbing ions (4,5). In realistic terms this means that selenite will be retained by soils in favor of anions such as selenate, sulfate, and chloride, but may be replaced by, say, phosphate, indicating that the application of phosphatic fertilizers to seleniferous soils may result in increased Se availability. Increasing pH through soil amendments may also result in increased Se levels in soil waters, although this may be of greater significance in acid rather than alkaline soils. Figures 2 and 3 illustrate how changes in pH and the addition of solution amendments may affect the sorptive behavior of selenite and selenate in a soil system, and hence affect their mobility in the soil profile. As shown in figure 2, the addition of calcium ions to the system, e.g., in the form of gypsum, increases the attenuation of selenite, thus decreasing its concentration in solution. In contrast, however, selenate sorption is not changed by this addition.

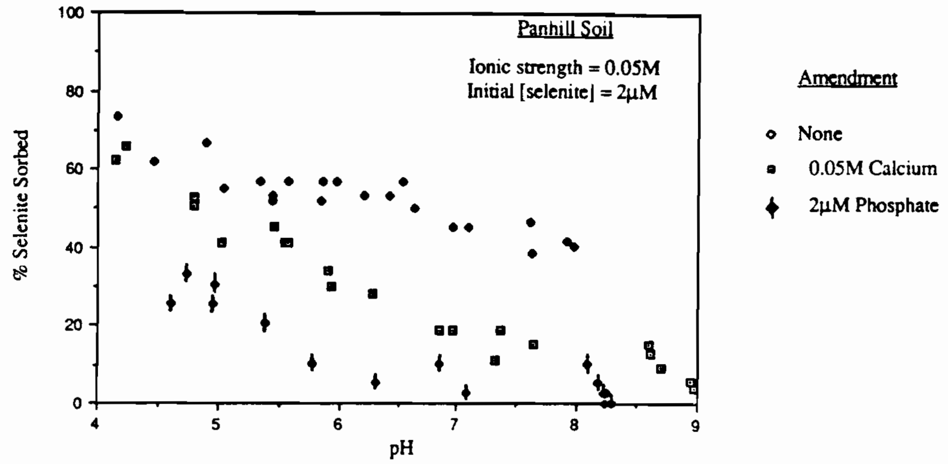

Figure 2. Selenite adsorption by a San Joaquin Valley soil, and the effect of amending the system with (a) 0.05M $CaCl_2$ and (b) 2µM Na_3PO_4. Background electrolyte = 0.05M NaCl.

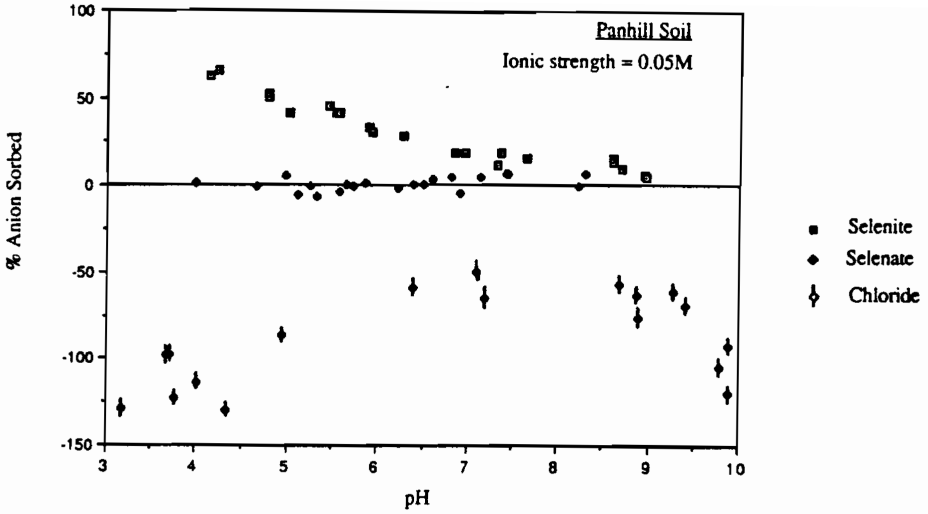

Figure 3. A comparison of the sorptive behavior of selenite, selenate and chloride by a San Joaquin Valley soil. Background electrolyte = 0.05M NaCl.

Clearly, therefore, the pH and redox status of a soil system will have considerable influence on the speciation and hence sorptive behavior of selenium. Selenate attenuation is unlikely to occur in any significant amount unless reduction to selenite renders it more reactive. Under these conditions the chemical nature of the the soil system will affect Se mobility and it may be manipulated using soil amendments to enhance Se attenuation. These chemical interactions must be put in perspective insofar as mobility in a soil profile is concerned, however. Many physical characteristics of an irrigated soil profile will impose upon the behavior of selenium, including soil structure and the rate at which water moves through the soil. Soil structure will determine the amount soil adsorbing surfaces that are exposed to selenium, and thus the potential for sorption and/or precipitation to occur. Structure, and its relation to pore size, the presence or absence of cracks, and the nature of plant roots, if present, will also affect the rate at which the selenium-bearing water passes through the soil profile and the path that it takes. If the transport of, say , selenate is rapid enough that there is insufficient time for a reduction transformation to occur, then it is probable that selenate will be leached directly into drainage water. The slower and more tortuous the passage of selenium through the soil profile, the more likely it will be that a kinetically determined transport/transformation event may take place. These events could be in the form of selenate reduction, selenite sorption onto soil surfaces, or microbial transformation in biologically active zones.

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Health Risk Assessment of Selenium in Food Crops

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Introduction

Selenium is found naturally in coal, sandstone, limestone, shale, soil, plants, vegetables, fruits, and surface water. It exists in different oxidation states and chemical forms, is produced industrially, and is used for manufacturing and veterinary therapeutic purposes, among others. The main source of human exposure to selenium in the general population is through food with the major sources being meat, cereal, and seafood.

The objective of this investigation is to assess whether selenium found in California grown food crops presents a health risk to the public.

Selenium content in food crops

In food crops, selenium is usually found at low concentrations of less than 1 ppm, wet weight. Wide variation in selenium content is typical of many plant foods even among different samples of the same foodstuff. Fruits and vegetables generally contain very low levels of selenium (<0.1 ppm) though garlic and mushrooms contain moderate levels. The concentrations reported for selenium in food crops in different parts of the world are shown in Table 1.

Health considerations

Selenium is a component of the enzyme glutathione peroxidase and plays a role in the cellular defense mechanisms against oxidative damage. This trace element is an essential nutrient for animals and humans. It is effective in preventing selenium deficiency diseases in livestock and farm animals. White muscle disease in sheep and cattle, hepatosis dietetica in swine, and exudative diathesis in poultry are economically significant problems in some parts of the world where selenium levels in soil available for plant uptake are low. In humans, selenium supplementation has beneficial effects in preventing endemic Keshan disease (cardiomyopathy) and Kashin Beck disease (osteoarthropathy), and case reports have linked muscle pain or weakness or cardiomyopathy to selenium deficiency (Levander, 1987).

On the other hand, high exposure to selenium can lead to toxicity in animals such as alkali disease, blind staggers, and reproductive/developmental effects. In humans, high selenium intake can cause gastrointestinal disturbances, loss of hair and nails, skin lesions, and nervous system effects (peripheral anesthesia, acroparaesthesia, pain in the extremities, hyperreflexia, convulsions, paralysis, and motor disturbances). Hepatotoxicity observed in laboratory animals was not seen in humans. Tooth decay in humans has been implicated but it may be due to interference by other environmental factors. The relationship between low selenium intake and high cancer incidence is not confirmed. A major finding from the examination of health data is that the margin of safety between physiologically beneficial levels and toxic levels is very narrow.

Dietary selenium intake

Human intake of selenium from food crops depends on several factors such as the soil-selenium content and the associated availability for plant uptake, food distribution and consumption patterns, and chemical forms.

In animal species, the minimal dietary level to prevent selenium deficiencies is in the range of 0.02-0.05 ppm, even in the presence of adequate amounts of vitamin E (NAS, 1980). A selenium concentration of 0.1 ppm in the diet is adequate for optimal growth and reproduction in animals. No standards or action levels have been established for selenium in human food items in the U.S. Formulated foods for humans used for more than one month with the exclusion of conventional diets should furnish at least 50 μg/day of selenium (NAS, 1980). Worldwide, nutritional surveys provided extreme mean values for dietary selenium intake by adults ranging from 11 to 5000 μg/day, but they usually fall within the range of 20-300 μg/day (WHO, 1987). Comparative dietary selenium intake values are shown in Table 2.

Selenium in food crops obtained or grown in California and human intake

Data available on selenium concentrations in California food crops are limited. Analysis of food crops (fruit, vegetables, nuts, corn, rice, oats) consumed by two individuals residing in Southern California and participating in a study on dietary selenium intake showed selenium concentrations of 0 to 0.5 ppm (Schrauzer and White, 1978). A few samples of crops (cotton seed, barley heads, sorghum heads) collected in California were reported to contain 0.16 to 0.61 ppm of selenium, but no replication of sample analysis was done and the data are not representative of the area studied.

More recent data (University of California, 1987) on selenium in California agricultural crops are available through the research studies conducted under the U.C. Salinity/Drainage Task Force contracts. The selenium concentrations reported for cantaloupe, tomato, honeydew melon, almond, walnut, pistachio, pecan, barley, beets, celery, cauliflower, wheat (grain), broccoli, and Swiss chard ranged from 1.1 to 940 ppm, depending on the study conditions, such as varying concentrations of selenium in agricultural drainage water used for irrigation and time of harvest. Experimental greenhouse experiments using selenium added to soil resulted in higher selenium concentrations in crops such as tomatoes, barley, beets, and Swiss chard. Human dietary intakes of selenium from consuming the food crops studied and the associated public health implications are assessed and reported by Fan and Jackson (1987).

Based on limited available data on field crops, the daily intake values from individual crops were estimated to range from <1 to 20 μg of selenium. Compared to the EPA (1984) acceptable daily intake of 210 μg, the NAS (1980) adequate and safe range of 50-200 μg, and the daily intake range of about 60-200 μg reported for individuals or the general population in the U.S., these intakes from the California crops are not considered to constitute a health hazard. Data from the experimental greenhouse studies showed selenium contents suggestive of a potential health concern, but these resulted from addition of selenium to soil in which the crops were grown, and did not represent selenium contents in actual field crops. On the other hand, available data are limited for an adequate assessment. Additional information is needed to identify the conditions leading to elevated concentrations seen in the research studies as compared to the levels published in the literature. Potential future increases in concentrations that may lead to a hazardous level of human intake should be monitored for.

Health assessment of selenium in food crops considers the availability of information on aspects such as selenium concentration in edible portions of food crops at time of consumption, adequate sample size, food crop consumption rate, total diet composition, food source, consumer population, general dietary selenium intake, and toxicologic and beneficial effects of selenium in animals and humans. Presently, available data on selenium in food crops and food consumption pattern, particularly those specific for California, are limited. As health effects data are being accumulated, quantitative information relating to low-level, long-term exposure is still lacking.

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COMPILATION OF SELENIUM CONCENTRATIONS REPORTED IN FOOD CROPS

Geographical area	Food crops	Concentration ppm, ww
1. Worldwide	Food crops	<1 ppm
	Fruits, vegetables	<0.1 ppm
2. England	Vegetables, fruits	<0.01-0.10[a]
3. Canada	Vegetables, fruits	0.002-0.13[a]
4. Japan	Vegetables, fruits	0.006-0.24[a]
5. Venezuela High Se area	Corn, rice	14-18
6. China		
• High Se area, chronic selenosis	Corn, rice, soybean	4-11.9
• High Se area, no selenosis		0.34-0.97
• Se adequate area		0.035-0.069
• Low Se area		0.009-0.022
• Low Se area, Keshan disease		0.005-0.01
7. United States High Se area; Wyoming, South Dakota, Nebraska	Wheat, corn, barley, rye	0.87-18
8. United States East-central South Dakota	Vegetables, fruits	0.32-0.26[a]
	Nuts	0.32-29.6
9. United States Ohio	Vegetables, fruits	0.004-0.38[a]
10. United States Total Diet Study	Grain/cereal products, vegetables, fruits	0.01-0.45
11. United States Total Diet Study	Grain/cereal products, vegetables, fruits	0.01-0.38[b]
12. United States	Vegetables, fruits	0.002-0.249
	Nuts	0.03-0.68
13. United States Market Basket	Grains, vegetables, fruits	0.0033-0.2[b]
14. United States Maryland	Vegetables, fruits	0.003-0.276[b]
15. United States New Hampshire/ Vermont	Cereals, grains, vegetables, fruits	0.01-1.11[b]
	Nuts	0.02-1.03[b]
16. United States San Diego	Fruits, vegetables, nuts, corn, rice, oats	0-0.5
17. United States San Joaquin Valley	Fruits, vegetables	0.0025-0.940
	Nuts	0.014-0.163

[a] Some higher values reported for cereal, grain, and their products, but most are <1 ppm.

[b] Samples with non-detectable levels of selenium are not listed.

COMPARATIVE VALUES PERTINENT TO HUMAN DIETARY SELENIUM INTAKE

	Selenium, µg/day
Estimated requirement	
North America, men	80[a]
women	57[a]
New Zealand, women	27[a]
China, men	9[a]
men, endemic Keshan disease area	7.7[b]
women, endemic Keshan disease area	6.6[b]
men, nonendemic Keshan disease area	19.1[b]
women, nonendemic Keshan disease area	13.3[b]
Toxicity	
U.S.	
Intoxication, superpotent supplement, 13 individuals, different states	27,000 (single and repeated for 77 days)
Symptoms suggestive but not conclusively identified to be Se related, diet, 100 subjects, South Dakota	60-1,200
Symptoms, drinking water, 1 family, Colorado	18,000 (9 ppm/l, 3 mos.)
Toxic, adequate, deficient	
China, high Se area, selenosis	3,200-6,690
high Se area, no selenosis	240
Se adequate area	42
low Se area, Keshan disease	3
Other comparative values	
U.S., population intake reported	60-216
vegetarian diet	84, 118
Worldwide nutrition surveys	11-5,000, mostly 20-300
Suggested adequate and safe range (NAS)	50-200
Interim acceptable daily intake (EPA)	210
Intake calculated based on California field crop data, by individual crop only	0.02-19.2
Body burden	14,600 (Total in body)

[a] Based on metabolic balance studies.

[b] Based on comparison of dietary intakes.

ROLE OF NATIONAL RESEARCH COUNCIL IN THE SAN JOAQUIN VALLEY PROGRAM

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In response to a request from the Department of the Interior and the Resources Agency of the State of California, a Committee on Irrigation Induced Water Quality Problems was established by the National Research Council of the National Academy of Sciences with the charge to: "Advise the Department.... and the State....with respect to the planned research program" which was to be designed to find solutions to the selenium problem in the San Joaquin Valley. The Committee was to (1) review and advise with regard to the overall research strategy (2) review the research program in progress, and (3) assist in identifying conceptual alternatives available to deal with irrigation drainage problems. The proposal to the Water Science and Technology Board of the NRC acknowledged that: "Although continued operation of the current system appears unacceptable, curtailment appears equally untenable."

The Committee has met regularly almost every three months during the past three years and is now preparing its first major report. It would be premature to summarize the findings of that report, but a number of letter reports have been submitted to the sponsors, representing significant concerns identified by the Committee. The views expressed in this paper are only those of the author and do not necessarily reflect views of other Committee members. We would all agree, I believe, that it is usually very difficult to find technical solutions for political problems.

The first of the letter reports stated, in effect, that there was no research program, therefore it was not possible to review the program and give advice. There were a number of isolated projects, but no overall strategy. This is gradually being corrected and the appointment of an overall project manager has been a major step forward. However, it is this author's perception that there is still no overall research strategy. The major research input has been through the USGS and faculty of the University of California, the latter funded in large part through University funds (Kearney Foundation and Experiment Station).

Since the Kesterson Reservoir is only one in about 20 potential problem sites thus far identified, the Committee has concerned itself with overall strategy which would be applicable for a broader range of problems than just the Kesterson selenium issue. Early in its activities the Committee identified a need for much better Quality Control/Quality Assurance. The different laboratories analyzing for selenium were producing wildly differing results, raising questions about all the basic data. This is now being corrected. We became very concerned with the fact that political decisions as to acceptable solutions to the problem were being made prior to analysis of the problem, with certain options being precluded even from study, e.g., ocean disposal. The Committee has repeatedly urged a systems approach, analyzing the problem from every standpoint, evaluating the costs and benefits of every possible solution and then making the political decision as to which decision is best. While this approach is now given lip-service in some of the documents coming out of the program, little evidence of this philosophy is apparent in the decision making process.

The problem as seen by the governmental agencies involved is simply this: the drainage water is the problem, therefore less drainage water will represent a smaller problem. The solution to the this problem is to increase on-farm irrigation efficiency and reduce the amount to drainage water. Having achieved that reduction, one only needs to determine how to dispose of that smaller amount of drainage water, and who will pay for that disposal. It is obvious that an economic analysis of this solution is essential before one can project its costs. Comparison with the costs of other possible solutions is not being contemplated, insofar as one can ascertain.

It is not appropriate for the Committee to recommend for or against any particular solution, but it examines the research base relevant to that solution. The political process has gone too far for the Committee to have much influence upon the Kesterson issue, but it does hope to contribute to an improved decision making process with respect to future irrigation induced water quality problems. The major threat to irrigation agriculture has always been the specter of salinization. With the urbanization of the west, every successful irrigation project now has an urban population downstream or down gradient with significant political and economic power. Unless agriculture takes the necessary steps to manage its water quality problems, that power will be used to the detriment of the agricultural economy.

PHYSIOLOGICAL ECOLOGY OF THE MYCORRHIZAL-ROOT INTERFACE: FROM CELLULAR TO ORGANISMAL EFFECTS AND PLANT RESPONSES

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The world is divided into two groups of plants: mycotrophs and nonmycotrophs. Mycotrophic plants are those species which are capable of forming mycorrhizal associations. The vast majority of plants fall into this catagory including most plants important to agriculture. The second group are those which do not form mycorrhizal associations. The major plants in this group of concern to agriculture are annuals in the Chenopodiaceae and Cruciferae. Plants in these families are both important crops (e.g., beets, broccoli, califlower, mustard) and aggressive weeds (e.g., russian thistle, goosefoot, pigweed, mustards). As these two groups compete for soil resources, understanding the influence of mycorrhizal fungi on plant growth and physiology is important for weed control and optimizing production.

Vesicular-arbuscular mycorrhizal (VAM) fungi are especially important in cropping or grazing systems. These fungi are important in any description of rhizosphere dynamics. VAM fungi not only alter the physiology of the roots of the host plant, but they can also be a dominant organism by mass in the rhizosphere (up to 50 m hyphae/g soil) and represent a direct carbon drain from the plant to the soil (up to 17% of the fixed C) to the soil. Thus, in any realistic carbon allocation model of rhizosphere activity, VAM fungi must be considered.

One major component of our research has been to describe the physiological interactions between VA mycotrophic plants and nonmycotrophic weedy annuals and how those interactions affect the competitive outcomes between those plants. The data I will present is for a limited number of range grasses and competing annual weeds. However, I suggest that the literature and our own data indicate that the principles might be more general. Therefore, for this presentation, I will concentrate on the interactions between *Agropyron smithii*, western wheatgrass, a dominant rangeland grass, and *Salsola kali*, russian thistle, a common aggressive weed introduced from Eurasia in the mid-1800's.

In a series of both field and greenhouse studies, we have demonstrated that VAM improve the uptake of soil resources (primarily water and phosphorus) in western wheatgrass. In conditions of stress, VAM fungi can also improve grow. VAM also reduced water and nutrient uptake in russian thistle as well as reducing growth and density in the field by > 50%. Thus, simply the presence of the fungi affect the interactions between those plants.

In a general sense, the most important contribution by the VAM fungi to a host plant is to expand, via the absorbing hyphae of the fungus, the surface area for uptake of resources. Indeed, we can account for much of the P uptake increments with VAM simply by the physical structure of the developing, dichotomous-branching hyphae overlapping and expanding to a 4-6 order branching system thereby expanding the depletion zone by 2 to 4 mm per root. Most Chenopodiaceous weeds contain an extensive root hair network presumably eliminating the need for a VAM association.

Specific developmental interactions between plant and VAM fungus suggested that a more detailed understanding of the cell-cell interactions is needed. Weeds responded in a manner totally unpredicted. Not only did the biomass of russian thistle decrease in competition, but also in pure pots when inoculated with VAM fungi. Inoculated plants in the field were severly inhibited by the fungi. Upon close, daily observation in root chambers, we noted that the VAM fungi could invade the root and form arbuscules, the exchange organs between plant and fungus. These arbuscules only had a life span of 1 to 2 days. The root then turned brown developing necrosis regions and, in some cases, the entire root died. The hyphae continued growing in the soil with runner hyphae often moving away from the root into the soil matrix, often to encounter other roots whereupon the process would be repeated.

The grasses responded in a different manner quantitatively but not qualitatively. The arbuscules lived several more days and the browning response was slower and much less severe. Roots were not killed and the fungal runner hyphae continued moving down the main root to continually initiate new infections.

These observations correspond to incompatable and compatable reactions described by Dr. Ann Anderson for ectomycorrhizal fungi (personal communications). Although more work is needed to confirm this mechanism of differential responses, favorable and unfavorable, to VAM by different plants, these compatability reactions are consistent with the molecular biology data of pathogen action (for the chenopod-VAM reaction) and mutualistic interaction (grass-VAM reaction).

Moreover, if these responses are broader than just for the plants we have thus far analyzed, the effects of VAM on host-weed competition could suggest that different management practices need to be undertaken. For example, if the crop is a grass, tree or legume and the weed a chenopod, such as russian thistle, VAM fungi would be highly desirable. Alternatively, if the crop were spinach, and the weed a quack grass (Agropyron repens), VAM would be counter-productive.

An additional perspective on the importance of understanding VAM effects of rhizosphere is suggested by our work on the interactions of the elevated carbon dioxide in the rhizosphere by VAM fungi (Knight et al. in preparation). If soils are relatively high clay, the increased bicarbonate resulting from the increased respiration of VAM roots can result in increased P released from hydroxyapatite. This increased P is potentially available for uptake by the VAM fungal hyphae or by the roots themselves.

However, if the soils tend to be high in Ca, Fe or Al, the P is readily bound, again unavailable for uptake. VAM fungi produce wall-bound crystals resembling oxalates which bind Ca and Fe similar to oxalates. Thermodynamic models suggest that oxalates have the capacity to preferentially bind Ca, Fe and Al to P thereby releasing the P for uptake by the hyphae or root. Importantly, I suggest that this process is relatively limited to the rhizosphere of a VAM plant.

Nonmycotrophic plants in the Chenopodiaceae, especially, are of interest because they tend to produce high amounts of oxalates and are especially prominant on disturbed, finer-textured soils.

They also tend to have rapidly growing roots and high rates of respiration. I suggest that this mechanism is important to P uptake for these plants. The potential interactions between low oxalate-producing VAM plants with hyphae which produce oxalates versus the annuals which have the ability to produce oxalates themselves might be a fruitful area of research.

In summary, both roots and VAM fungi not only absorb nutrients based on their structure, but also alter the rhizosphere chemistry substantially. It is these chemical interactions between host and fungus, non-host and fungus, respiration rates of both organisms, and the micro-domain, rhizosphere chemistry which regulates the production and competitive outcomes of the plants in any given site.

CHEMICAL IMPACT OF ROOTS ON THE SOIL

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A plant root adds some substances to soil and removes others, thus altering the rhizosphere chemistry. Quantitative information about these changes has come as a spinoff from theoretical and experimental studies of nutrient transport to roots, as well as recent studies aimed directly at characterizing the rhizosphere itself. Much of the available information is reviewed by Barber (1984), Nye (1986), Nye and Tinker (1977), and Römheld and Marschner (1986).

Information and Its Sources

a. Modelling. Several models of nutrient uptake from soil indicate the probable magnitude and extent of plant effects on ion concentrations-P, K, Ca, Zn, nitrate - in the rhizosphere. These studies include some experimental validations of model predictions (Barber, 1986; Claassen and Jungk, 1985). In addition, there have been worthwhile efforts to model rhizosphere pH change (Nye, 1986). Less theoretical attention has been given to the release and diffusion of organic matter from roots.

b. Analyses of Rhizosphere Soil. Improvements in analytical sensitivity have relieved the difficulty of getting sufficient samples of rhizosphere soil. (Phosphate and aluminum are important exceptions.) Getting samples of defined position relative to the root remains a problem; two major approaches are current:

1. The "shake" method (rhizosphere soil is that which shakes off the roots with difficulty)
2. The "section" method (a block of soil that has been in contact with a mat of roots is sliced for analysis).

The section method enables clear definition of spatial gradients and time changes, but only in an artificial and two-dimensional rhizosphere. The shake method provides crude arbitrary separations of "rhizosphere" and "nonrhizopshere" soil, depending on how the soil sticks to the roots and coheres; but it is applicable to plants growing naturally in field soils. Rollwagen and Zasoski (1988) used the shake method to get convincing quantitative data on rhizosphere alkalinization with nitrate and acidification with ammonium in tree seedlings. The section method has been used elegantly to determine rhizosphere K gradients as influenced by fertilization (Kuchenbuch, 1985) and salinity (Tyson, 1988).

c. Direct Analysis applied to Intact Root/Soil Systems.

Microelectrode analyses, autoradiography, and direct colorimetric analysis have all been applied successfully, and sometimes nondestructively, although so far only to quite artificial cultures of small plants grown in sieved soil, with their roots trained against a face that can be easily exposed for access. Pioneering use of this method for autoradiography of phosphate, calcium and micronutrients by Lewis and Quirk, Barber's group, Wilkinson and others produced some of the best evidence for chemical changes in the rhizosphere (Barber, 1986). Since then, the accuracy of quantitative autoradiography has greatly improved (e.g. Claassen and Jungk, 1985).

Microelectrodes, despite their fragility, have been used with some success (e.g., Blanchar and Lipton, 1986; Munns, unpublished; Haussling et al., 1985) to show pH variations along roots and crude definition of radial gradients. The gradients are at least qualitatively in agreement with expectations from modelling.

Direct pH-visualization with indicators has succeeded spectacularly (Häussling et al., 1985, and earlier papers from Marschner and Römheld's group). The information shows clearly the effects of nitrogen nutrition on rhizosphere pH, with notable exceptions such as the consistent acidification by chickpea regardless of its mode of N nutrition. And, like the electrode method, it shows major longitudinal pH variations along the root, probably related to differences in ion uptake by roots of different age.

Some areas for Further Research

Chemical effects of roots on the rhizosphere almost certainly vary within the root system of a single plant. Even an initially uniform medium, older roots operate in a different environment than the one explored by the root tips. We know that roots themselves change in nutrient uptake properties during maturation; details are not known (Nye and Tinker, 1977). The differences are clearly documented by electrode and indicator evidence of pH changes; there is strong implication that other rhizosphere effects vary similarly within a root system.

The release of organic compounds and their fate in the soil are difficult to define and to model experimentally. Some of their chemical consequences are now demonstrated, including reduction of manganese oxide by malic and oxalic acids (Jauregui and Reisenauer, 1982), mobilization of manganese and iron oxide in rhizosphere soils (Godo and Reisenauer, 1980; Warden, 1988), complexation of calcium with oxalic acid resulting in P mobilization (Jurinak et al., 1986), and mobilization of iron by organic acids and siderophores (Römheld and Marschner, 1986).

A strangely neglected area, in view of its scientific interest, is the rhizosphere of plants in solution culture, sand culture, and other "defined" simple media. In such media, freedom of solute movement must weaken but not eliminate chemical changes near the root interface. How much "rhizosphere effect" does develop within the apoplast, free space and surface boundary layer separating root-cell membranes from an agitated culture solution? In other words, how really defined and simple are these media? If we wrongly assume that they extend unchanged to the plant's active surface, how misleading are the resulting physiological uptake parameters?

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RHIZOSPHERE EFFECTS ON SOIL PHYSICAL PROPERTIES

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The rhizosphere is the soil volume around roots influenced by root uptake, root exudates, root exchange reactions, microorganisms (symbiotic and other) and by root movement. In discussions of rhizosphere effects on soil physical properties, root movement and the forces exchanged between soil and roots are usually given much less attention than other influences. In this presentation emphasis will be placed on the mechanical interaction between the soil mineral matrix and plant roots.

Soil structure is usually defined as "the combination or arrangement of primary soil particles into secondary particles, units or peds". (Brady 1974). Measures of structure usually relate to the shapes and sizes of peds and their stability under arbitrary treatments. However, this useful focus on ped size and stability is not necessarily enlightening regarding the diameter, length and continuity of the soil pores which govern water penetration and drainage. A sandy soil may be "structureless" in the ped sense, but its pore structure is highly relevant to water transport and root penetration. Roots and the rhizosphere have great influence on both ped formation and stability as well as on the pore structure in both ped-forming and "single-grain" soils.

In an illuminating discussion of soil aggregation, Allison (1968) pointed out that the formation of aggregates requires forces to align and bring particles together as well as material to bind the aggregates into water-stable units. It was on these binding materials that microbiologists had focused much attention, usually neglecting the need for mechanical actions. Prominent among the agents applying the required localized forces to align and bring particles together are those applied by plant roots.

Plant roots exert mechanical forces on the soil as they advance and enlarge (Barley & Greacen 1967, Whiteley & Dexter 1984a). Their extraction of water imposes shrinkage forces tending to draw soil particles together and the aggregations formed may be stabilized by the clay skins formed by pressure and by organic compounds derived from root exudates and residues, perhaps resynthesized into soil stabilizing polymers by rhizosphere microbes. Thus, by their powerful mechanical actions, the creation of high matric suctions and supply of microbial substrate, plant roots have a major role in developing and maintaining a soil structure favorable for water penetration, drainage and gas exchange. Thus, as Allison pointed out,there exist simultaneously in the rhizosphere nearly ideal conditions for aggregate formation and stabilization.

The presence on roots of vesicular-arbuscular mycorrhizal hyphae have been strongly implicated in the development of water stable aggregates in loam (Tisdale & Oades 1979a). These hyphae were covered with amorphous material to which clay particles firmly attached. On the roots of ryegrass the hyphae persisted for several months and continued to bind particles of soil into stable aggregates (Tisdale & Oades 1979b). On the other hand, Thomas et al (1986) found that there was a higher correlation of aggregate abundance with onion root mass than with VAM hyphal density in a silt loam.

While plant roots are major ped forming agents, the root channels themselves can become, upon root senesence and decay, macro pores with a high degree of continuity well-suited to downward conduction of water. On the other hand, where roots are growing through existing pore spaces (Whiteley & Dexter 1984b) they can decrease the fractional volume of macropores and actually cause a reduction in water infiltration rates (Barley 1953). Cyclic changes in infiltration rates resulting from seasonal root growth and decay have been observed in pastures and in laboratory experiments (Barley 1953, 1954). Although this cyclic variation of infiltrability has been documented in sandy soils where both roots and water must be accomodated in the pores between impermeable mineral grains and where the pore volume does not change with water content, it can be expected in a variety of soil textures.

There is some evidence that the high density, particle oriented rhizosphere soil may cause local high hydraulic resistances to water uptake by roots (Huck 1984, Weatherly 1979).

Growing roots exert radial, axial and tangential stresses on the soil. The maximum axial and radial stress exerted by roots have been measured for a few plants and are quite high (0.6 to 2.5 MPa) (Barley & Greacen 1967 cite several sources). Measurements of the tangential stresses are even more difficult to estimate because of the their inhomogeneity, even over short distances. The level appears to be much lower (2 - 60 kPa Stolzy & Barley 1968, Waldron 1980). These tangential stresses in the rhizosphere have important consequences for soil structure and mechanical behavior, however. They provide the reaction force against the root tip pushing downward into the soil. They make it possible for roots to impart cohesion to a particulate matrix of limited cohesion (Waldron 1977). The strength of saturated soil may be limited by the tangential resistance between mineral matrix and roots (Waldron & Dakessian 1980). However, as soil drys the tangential resistance will increase, perhaps to the to the point where root strength is limiting the stability of soil structural units (Stevenson & White 1941).

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ROOT ZONE PATHOGENS: AN ECOLOGICAL APPROACH

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It has become established that most major crops at any given site realize only 50 to 75% of their genetic potential due to crop pests (3). Although yield gains of 100% from pest control may seem like an exaggeration, it must be remembered that crops are subjected to continuous stress from plant pests from the day of planting until consumption. I submit here that a major portion of this stress is placed upon the below ground portion of plants--the roots--primarily because damage to above ground portions of the plant are more readily diagnosed and controlled.

The root-soil interface is a zone of tremendously complex interactions which has been little understood largely because of its inaccessibility. Bruehl (2) maintains that this scientific inhibition is largely psychological but nevertheless real. Plant pathologists, soil scientists, agronomists, ecologists, and physiologists have compiled a tremendous amount of detailed information about roots, the root environment, root physiology, pathogen life cycles, competition, soil chemistry, but as yet we have not fully integrated our information into an ecological approach to studying root zone pathogens. I cannot begin to summarize information about a topic like root zone pathogens--but I can in a short time discuss some ecological approaches for understanding and studying root zone pathogens.

The Dynamics of Rhizosphere Ecology

The study of root pathogens should begin with a thorough understanding of root activity. Fig. 1 represents the dynamics of root pathogens in the rhizosphere of the average citrus tree. Two species of *Phytophthora*, *Fusarium* solani, the citrus nematode, Thielaviopsis basicola, and Pythium spp. occur in regular but seemingly bewildering fluctuations. Further study reveals that P. parasitica populations are correlated perfectly with the dynamics of citrus root growth. P. citrophthora populations are correlated with the dynamics of sucrose movement into roots. F. solani colonizes the rhizosphere and does not infect until stress or death of roots occurs. Thielaviopsis only infects young roots before they become infected with mycorrhizal fungi. Pythium appears to infect roots at periods of maximum root exudation or perhaps maximum exudation of specific compounds. Root growth, root death, nutrient uptake rates, root distribution, root exudate, and root extract fluctuations explain much of the complicated dynamics of the rhizosphere. Indeed the root community in monoculture agriculture can be viewed as a vast competition experiment for a food resource. Roots which generally increase at an exponential rate, the specific compounds in roots, or the even more available root exudates form the central focal point for most microbial activity in the soil (6).

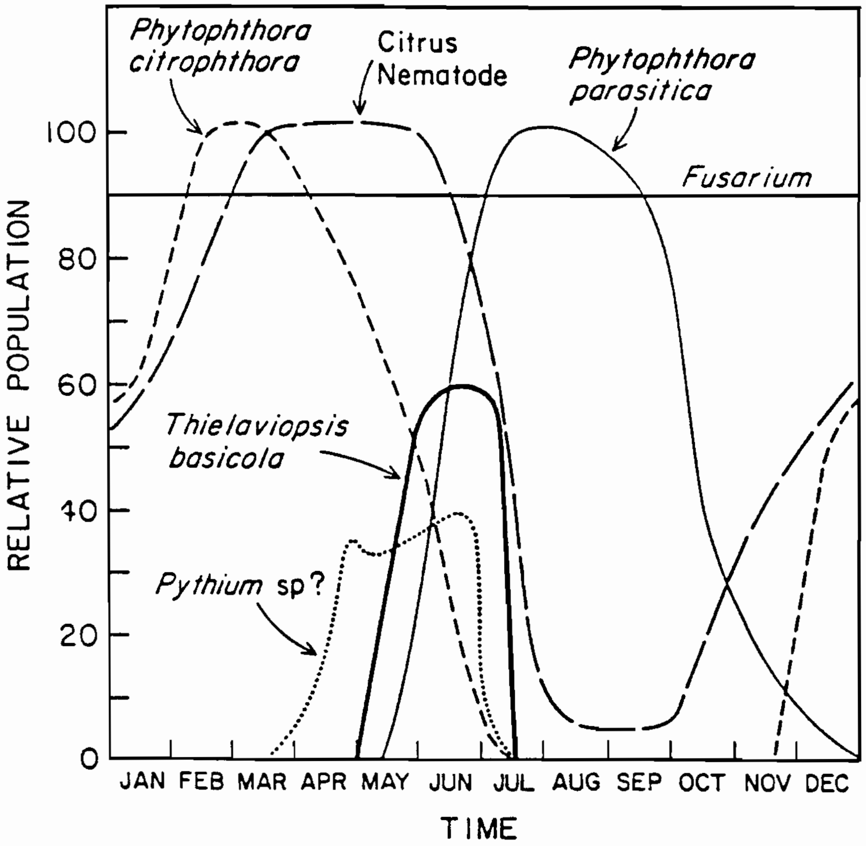

Fig. I. DYNAMICS OF ROOT PATHOGENS ON CITRUS ROOTS

Annual crops are planted into a severely disturbed community and the immense quantity of roots result in a nearly unlimited supply of food (4). Although most root pathogens increase at a slower rate than do many above ground pathogens, most are now believed to grow at an exponential rate and, when unchecked, cause extensive damage. Because of the disturbed nature of the agriculture habitat, pathogen population oscillations are often intense and may result in epidemics (4). It has been commonly shown that more complex environments with more diverse organisms result in a more stable population with fewer soil epidemics and a lower, more constant level of disease (4). The suppressive soil phenomenon, which occurs when annuals are repeatedly planted to an infested field, is a result of smaller, more stable pathogen population fluctuations ocurring from competition and predator-prey relationships (1,2). Pathogen population fluctuations in perennial plants are not nearly so severe since the site is not disturbed each year, the frequency of population oscillitions tends toward equilibrium.

Current efforts in biocontrol are an ecological approach toward increasing the diversity of microorganisms in the rhizosphere and increasing the competitors and predators to reduce pathogen epidemics (2,7). However, in most cases, standard ecological competition theories, which could add a great deal to biocontrol experiments, have been ignored. Simple Volterra equations are able to express mathematically several facets of rhizosphere competition (8).

$$\frac{dN_p}{dt} = r_p N_p \left(1 - \frac{N_p}{K_p} - \frac{\alpha Nc}{K_p}\right)$$

Here N_p = number (mass of pathogen)
Nc = number (mass of competitor)
rp = rate of growth of the pathogen
K_p = the maximum number (mass of pathogen) attainable
α = coefficient of competition

With this equation one can measure quantitatively the effect of competition upon the pathogen population at any given time. The factors rp, kp and α can be measures of pathogen activity and ultimately plant disease.

Nich measurement mathematics is another underutilized tool which could be used to select potential biocontrol agents.

The Root As A Food Source For Rhizosphere Pathogens

The root is constantly leaking root exudates into the soil which may amount to 5-40% of the total plant photosynthate (2,5). Presumably the plant benefits from this heavy cost by maintaining a stable root environment and increasing nutrient uptake. Most organisms feeding on root exudates may not be pathogens, but they can become pathogenic by releasing toxic substances, interferring with normal nutrient uptake, or encouraging the root to leak more exudate than normal. These subpathogens are only now beginning to be investigated, but their effect on plant productivity could be enormous. We normally consider plant pathogens to be those which penetrate the root in search of a food source. Many of these plant pathogens only "nibble", that is they are well adjusted to the rhizosphere ecology and the root community and do not overly stress the host plant. These are chronic plant pathogens. They often are root inhabitants that have little saprophytic capability and must exist on a living host. They nevertheless cause crop losses each year, usually causing severe losses only when their populations get out of hand. Other root pathogens, often introductions, are organisms with a wide host range and good saprophytic abilities. These organisms can be responsible for even greater losses. They often kill roots and utilize the dead material. These are often called soil inhabitants because they can grow and reproduce away from their hosts. Many plants have resistance against this type of pathogen.

The root itself presents several niches for pathogens. The root tip is where most of the exudate is released, before the cells are fully formed. This zone presents a unique habitat for fungi which can react quickly to exploit the exudate. Farther back on the root, exudation is reduced but so is competition, and there is a great deal of sloughed root material and dead cells to be utilized by saprophytes or facultative-saprophytes. Still farther back on the root are lignified or woody roots which provide a substrate for strictly pathogenic fungi.

Generalized life cycle of a pathogen

Fig. 2 illustrates a typical plant pathogen. Most pathogens have unique ecological adaptions to their particular niche, but nearly all have these basic attributes.

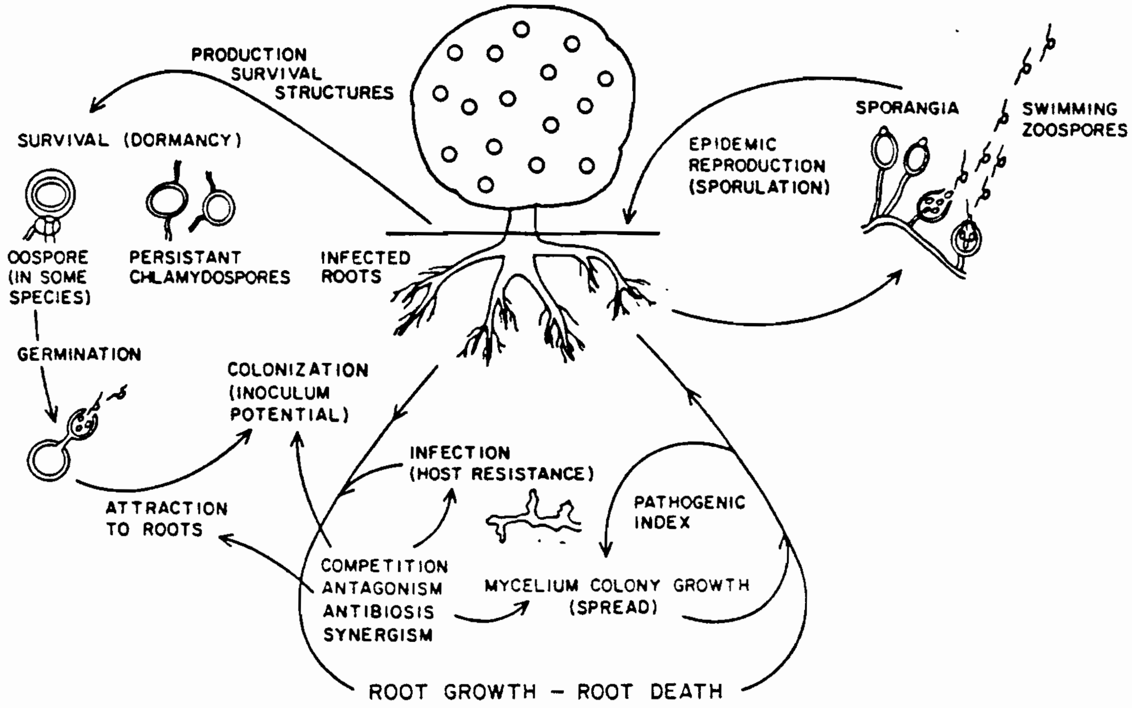

Fig. 2. STANDARDIZED LIFE CYCLE OF ROOT PATHOGEN

"Nuts & bolts" Plant Pathology vs. "Sissy" Rhizosphere Ecology

Although often not fully appreciated by plant pathologists, the study of rhizosphere ecology has made, and will continue to make, many important contributions to disease control. Examples include the advantages of non-tillage agriculture, timing of pesticide applications, identification of the susceptible stages in pathogen life cycles, cultural control measures, and biocontrol strategy.

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INTEGRATING FUNCTIONS OF MICROBIAL ROOT SYMBIONTS IN AGRICULTURE

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The availability of nutrients for plant growth, the health and yield potential of crops, and the decomposition of plant materials as well as many pesticides are all dependent on the activities of microorganisms in the soil. Every handful of soil contains millions of individual organisms each with their own function and ability to increase or decrease plant growth. In a dry fallow soil, most of these microorganisms exist in an inactive state. However, with the moistening of soil and the growth of plant roots from germinating seeds, there is a tremendous increase in microbial activity. The populations of some organisms increase many-fold while others remain virtually unchanged. The microorganisms which subsequently colonize the interior and exterior of roots are the ones which have generated the most interest from researchers and farmers. Although many of these microorganisms have undetermined or plant pathogenic functions in the soil, it is the root symbionts which hold the greatest promise for integration into agriculture.

The Root Symbionts

A microbial root symbiont is a microorganism which forms a relationship with plant roots where both the plant and the microorganism rely on one another and both benefit. Other beneficial associations between microbes and plants include protocooperation (both benefit but nonobligatory) and commensalism (one benefits while the other is unaffected). The emphasis of this paper is on two well-known root symbionts, *Rhizobium* and vesicular-arbuscular mycorrhizal (VAM) fungi, however, important functions of nonobligatory root-microbe associations will also be addressed.

Specialized Structures and Functions

Root nodules formed by the bacterium, *Rhizobium*, on legumes is probably the most studied and easily recognized of all the plant-microbe associations. In the Rhizobium-legume symbiosis, the plant provides the bacteria (bacteroids) with a sheltered environment and photosynthate (carbon) and other nutrients required for growth. The plant, in turn, receives most of its nitrogen (N) through the fixation of atmospheric N by the rhizobia.

Another important root symbiosis is that formed between many crop plants, including legumes, and vesicular-arbuscular mycorrhizal (VAM) fungi. Although no alteration in root morphology is observed with VAM fungal colonization, special structures (arbuscules) are formed by the fungus within roots and serve as the site of nutrient exchange between the plant and the fungus. As with Rhizobium, the VAM fungus receives most of its carbon from the plant. In this association, the plant receives phosphate (P) that the fungus takes up from the soil and transports through fungal hyphae to the roots. Other elements such as N, Ca, Zn, and S have also been shown to be translocated to the plant by hyphae of VAM fungi.

Many other plant-microbe associations are known which are not classified as a symbiosis, but which are very important for crop productivity. Bacteria such as Pseudomonas and Azotobacter live on sugars and amino acids exuded by roots and assist plant growth by performing specialized functions. Some Pseudomonas species assist the plant through antagonism toward certain root pathogens. Azotobacter can fix nitrogen and excrete amino acids and hormones which can be taken up and used by the plant. There are also fungi capable of trapping plant pathogenic nematodes and others that attack fungal root pathogens.

Another function of microorganisms associated with plant roots is that of nutrient mineralization. Protozoa, small unicellular organisms, move about the root surface in water films seeking and consuming bacteria by the thousands. Nitrogen and other elements not required by protozoa are excreted in forms which can be used by the plant or by other organisms.

In addition to the above functions, soil microorganisms can affect the physical and chemical environment of the soil. Microorganisms, including VAM fungi, can improve soil structure by binding soil aggregates together which increases soil aeration and water permeability. Through the decomposition of organic substrates and utilization or excretion of various compounds, soil microorganisms can affect root growth as well as the effectiveness of root symbionts. Understanding the interactions between root symbionts and the soil microflora is necessary in order to integrate their use into agricultural applications.

Integrating Microbial Function in Crop Production

Early knowledge that crops grew better following a legume crop or intercropped with a legume was based, although unknowingly, upon reliance on the Rhizobium symbiont. The improved growth resulted from the adddition of N to the soil from nitrogen fixation. It is now common practice for farmers to inoculate their legume crops with an appropriate strain of Rhizobium. When inoculation is not necessary, then cultural practices, such as little or no application of fertilizer-N or liming low pH soils, are used to encourage nodulation by the rhizobia already in the soil.

The ability of VAM fungi to improve plant P nutrition and Rhizobium effectiveness is well-known but large scale field inoculations are not possible at this time. The reason for this is the fact that the fungi cannot be produced in large quantity in the absence of a host plant. Unlike Rhizobium, more research is required on growing, storing and applying VAM fungi at low cost before wide acceptance is achieved. In addition, little information is available upon which to base predictions of the effectiveness of inoculation.

Once microorganisms have been identified which can improve crop yield under controlled conditions, then the major task of utilizing them in a practical manner becomes very apparent. There are two possible approaches to this problem: either make use of the organisms already in the field, or introduce more effective isolates. Both methods require a high degree of understanding of the nutritional and environmental requirements of the microorganism. Cultural practices such as liming the soil, applying organic amendments, or reducing the fertilizer input may be sufficient to improve the effectiveness of some root symbionts already present in the soil. However, if a microorganism must be introduced, then one must decide on both a mechanism for selection and introduction. The selection process may include an organism which has been genetically altered. But this microorganism, as with any other symbiont, must retain its ability to compete and survive in the soil and improve plant growth without any adverse side effects for people, animals or the environment.

At this time, many root-associated and root symbiotic microorganisms are known to be capable of increasing fertilizer use efficiency, providing biological disease control, improving plant drought tolerance and improving soil structure, yet only Rhizobium has received general acceptance and integration into production agriculture.

Potential Use in Agriculture

The potential for relying on microorganisms for specific functions in agriculture is great but the progress toward that goal will remain slow for many decades. The principal factor in this slow progress is the lack of sufficient funding from the state and federal governments and excessive delay brought about by regulatory agencies. The understanding and acceptance by the general public of microorganisms is also low. This lack of understanding is partly the fault of microbiologists not communicating with the public, but also the product of sensationalism by the news media when words such as 'man-made bacteria' are suggestively linked to an invasion from outer space or a disease epidemic. On a more down to earth note, the cost effectiveness and risk factor involved with the use of root symbionts or root associated microorganisms is, in some cases, greater than chemical application. Nevertheless, a better understanding and use of plant-microbe associations can produce a safer, less expensive and longer lasting mechanism for crop productivity than relying on chemical measures alone.

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YIELD INCREASES WITH ENHANCED NH_4^+ SUPPLY

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There is interest in NH_4^+ nutrition because it has been demonstrated often in solution culture that plants grow better with mixtures of NH_4^+ and NO_3^- as an N source than with NO_3^- alone. For example, grain, total plant dry matter, and grain-bearing tillers of hard red spring wheat (Triticum aestivum L., var. Len) were greater with 50 percent NH_4^+ than with 100 percent NO_3^- (Table 1, solution).

Table 1. Influence of NO_3^--N/NH_4^+-N on grain, total plant dry matter, and the number of grain-bearing tillers of wheat grown in solution culture and soil. (Unpublished data of F. E. Below and J. A. Heberer, University of Illinois).

Media	NO_3^--N/NH_4^+-N	- - - Dry matter - - - Grain	Total	Grain Bearing Tillers
		g/M²		no./M²
Solution	100/0	494	1,029	396
	50/50	631	1,372	566
Soil	100/0	500	962	462
	50/50	486	935	472

Note: Both N treatments in soil added with dicyandiamide as nitrification inhibitor.

In separate pot experiments with soil in the greenhouse, enhanced NH_4^+ supply consistently increased plant growth (Table 2). Effects of enhanced NH_4^+ supply on grain yield of Len spring wheat were positive and ranged from 1-45 percent, depending on the greenhouse environment and the particular NH_4^+ treatment. The yield increases with enhanced NH_4^+ nutrition were observed over a wide range of N rates, ruling out NO_3^- loss as the reason for lower yields with NO_3^- alone. Environmental variables potentially affecting the magnitude of the response were soil and air temperature, day length, watering regime, soil pH, and initial soil NH_4^+ and NO_3^- levels. Ammonium treatments varied in the proportion of fertilizer N added as NH_4^+ (25, 50, 75, and 100 percent) and the form of N added (urea, NH_4NO_3, and sulfur-coated urea). Although positive response to NH_4^+ was consistent in these experiments, there was no response in another experimental system.

Table 2. Increase in wheat grain yield with enhanced NH_4^+ supply (Yield with NH_4^+-yield with NO_3^-)/(Yield with NO_3^- X 100%) in several greenhouse experiments. (Unpublished data of B. R. Bock and J. J. Camberato, TVA).

Experiment	Grain yield increase with NH_4^+
	%
A	37-47
B	7-17
C	10-19
D	7-16
E	1-15
F	6-19
G	17-19

Note: Soil was Mountview silt loam, limed to pH 6-8, cation-exchange capacity of 8.3 cmol(+)/kg soil, and 1-2% organic matter.

Each NH_4^+ treatment with nitrapyrin compared to yield with $4Ca(NO_3)_2:Mg(NO_3)_2$ as NO_3^- treatment. Inhibitor and fertilizer mixed throughout soil.

In a similar greenhouse experiment with Len wheat grown in soil, there was no growth or yield increase with enhanced NH_4^+ supply (Table 1, soil). In addition to the differences in the environmental variables previously mentioned, there were also differences between the two systems in soil type. The soil was a Drummer silty clay loam, pH 6.0, cation-exchange capacity of 30-40 mol(+)/kg soil, and five percent organic matter. Differences in environment and/or soil type may have contributed to differential response to enhanced NH_4 supply with soil as the growth medium. However, environmental conditions in the Illinois experiment (Table 1) were apparently conducive to yield increases from enhanced NH_4^+ supply as indicated by results from solution culture.

There have been few attempts to pinpoint specific causes of differential response to enhanced NH_4^+ supply occurring in greenhouse experiments. Response to enhanced NH_4^+ supply is more erratic in the field than in the greenhouse, and factors responsible for differential response are more numerous. Not only might temperature, irradiance, and moisture affect plant response to NH_4^+ nutrition, but differences in fertilizer NH_4^+ availability to roots may also occur. Fertilizer NH_4^+ availability to roots depends on the placement of NH_4^+ in the soil and the diffusion of NH_4^+ to the root.

Positional availability of NH_4^+ in soil, as determined by its placement, is critical for conducting relevant field experiments evaluating plant response to enhanced NH_4^+ supply. Identifying soils and environmental conditions in which NH_4^+ diffusion is too slow and therefore detrimental to plant growth also is important.

Ammonium does not move substantially within the soil profile in most soils. Nitrapyrin does not and dicyandiamide (DCD) does move readily in soils. To inhibit conversion of NH_4^+ to NO_3^-, NH_4^+ and the nitrification inhibitor must be in close proximity to each other. Two combinations of fertilizer and inhibitor are suitable: subsurface applications of an NH_4^+ fertilizer plus nitrapyrin, and surface-applied urea plus DCD immediately watered to move the urea and DCD into the desired region of soil. Ammonium fertilizer plus nitrapyrin is most appropriate for preplant applications or early in crop development. Urea plus DCD is suitable for later applications.

Placement or directed movement of NH_4^+ (using relatively mobile urea as NH_4^+ source) should be in soil at a depth accessible to plant roots and in a region of soil that will remain moist. Adequate soil moisture enhances root proliferation and NH_4^+ diffusion. Frequently these conditions are not met in field experiments.

If technology is available to place NH_4^+ where desired, determining what fraction of the soil volume to fertilize is necessary.

Theoretical considerations are similar to those for K placement and involve ion concentration in the soil solution, buffer capacity of the soil, rate of diffusion to roots, uptake kinetics of the root, and the proliferation of roots in the fertilized soil (Kovar, J.L. and S.A. Barber, 1987, J. of Fert. Issues 4:1-6).

In addition to the placement of NH_4^+, the effects of soil factors on NH_4^+ diffusion to the root are also important for determining NH_4^+ availability to roots. Diffusion of NH_4^+ depends on cation exchange capacity, texture, and moisture content. Ammonium diffusion to the root may be too slow for maximum plant growth in some situations such as high cation exchange capacity, sandy texture, or low moisture.

In summary, spring wheat yields were increased by supplying both NH_4^+ and NO_3^- in solution culture. In soil systems, yield increases with enhanced NH_4^+ supply did not occur consistently. Environmental factors such as temperature, irradiance, and moisture, as well as fertilizer NH_4^+ availability to roots, may be responsible for differential response to enhanced NH_4^+ supply. Placement of both NH_4^+ and nitrification inhibitor into moist soil at a depth accessible to plant roots is critical for evaluating plant response to enhanced NH_4^+ supply in field experiments.

TECHNICAL REPRESENTATIVE AND THE DECISION MAKER

BY BRYAN L. RAHN

When I was first contacted regarding this conference, I was informed that the topic of the discussion would be technical problems or questions in the agricultural industry that have not been addressed.

I decided to take an informal poll of smaller acreage growers, most of whom did not regularly use consulting or laboratory services, in the San Joaquin Valley. The idea was to determine if there were specific unanswered questions that several growers might mention that could be addressed with scientific research. Although several growers did indicate problems with crop prices and the weather, the answer to crop prices is more a public policy matter and weather patterns may be a religious item. At any rate, I am limiting the scope of this discussion to questions that can be answered through scientific research.

A large majority of the technical questions asked by those growers had been addressed by previous research or are currently being studied. So, although there are still technical problems yet to be evaluated by researchers, a lot of excellent work is not getting to the people who can use it to make decisions.

I should point out that there are several sources of information provided by the U.C. Cooperative Extension, USDA, farm and home advisors, crop field days, seminars, short courses and trade publications. However, there are a number of growers that are not aware of the available information. The challenge appears to be beyond providing top-notch research, but also distributing the information in a clear, easy to understand and believable format to those decision makers.

A recent court decision indicated that more University of California research efforts should be expended to help the smaller family farms. Some research that is currently underway and most studies that have been previously completed are applicable to both large and small farms. It has been stated that the larger farming operations are receiving the bulk of the benefit. However, it may be that those larger organizations through on staff agronomists and private consultants are getting the information more readily than the smaller growers are. So, do we need to change our research goals or should we evaluate the distribution of information derived from the studies.

Given budget restraints, the ideal system of information transfer may not be easily obtained. I am suggesting, however, that more effort be expended on finding ways to get this information to growers, particularily to small family farms.

As an agricultural consultant, I often find myself relaying research results to my clientele. Since the smaller acreage growers, in most cases, don't have an agronomist or technical representative assisting them, I feel it is that group of growers that should be targeted. One of today's questions is "How do we get this wealth of information to the small family farm?".

Another consideration is the utilization of information and analytical results. First, the analytical results supplied by private laboratories must correspond to the analyses used in the research studies. The growers need similar analyses available to them in order to effectively evaluate how their ranch corresponds to the respective studies. Secondly, there should be more emphasis on the use of the information on small farms. This would allow growers to more efficiently use research results. The demonstration of economic benefits through the use of equipment and manpower commonly available to the small family farmer will provide a feasible answer to some of their problems. So, another of today's questions is "How can we help the small family farmer effectively evaluate and use the research information?".

WATER QUALITY REGULATIONS AND RESEARCH

Gerald E. Johns and Dale A. Watkins[1]

ABSTRACT: Water quality in the San Joaquin River Basin has been adversely affected by reduced flow and increased agricultural drainage over the last 40 years. A technical committee made up of staff from the California State Water Resources Control Board and the Central Valley Regional Water Quality Control Board recently completed a two-year review of water quality needs for the San Joaquin River Basin and how agricultural drainage could be reduced to help meet these needs. This paper summarizes some of the results contained in the Technical Committee's Report.[2] The Central Valley Regional Board will review the information contained in the Technical Committee Report together with other information in their development of enforceable regulations to improve water quality in the San Joaquin River system.

INTRODUCTION

The San Joaquin River Basin is shown in Figure 1. Water quality in the San Joaquin River has degraded greatly since the late 1940's. Salt concentrations in the lower reaches of the River near Vernalis have about doubled since that time due to two primary factors. First, reservoir development on the upper reaches of the San Joaquin River and its east side tributaries has decreased river flow, causing salt concentrations to increase. Second, since the 1960's subsurface agricultural drainage from the west side of the Basin has been discharged into the system in increasing quantities, thus increasing concentrations of salts and other constituents found in agricultural drainage. Also, changes in water

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[2] A report titled "Regulation of Agricultural Drainage to the San Joaquin River", August 1987 with its appendices provide the detailed information developed by the Technical Committee. It is available for a small fee by writing to the Office of Legislative and Public Affairs, State Water Resources Control Board, P. O. Box 100, Sacramento, CA 95801.

management operations by entities on the west side of the San Joaquin River Basin between Mendota Dam and the Merced River during 1983 and 1985 have greatly increased the selenium concentrations in the San Joaquin River.

SOURCES

Initially, twenty-six constituents of concern in subsurface agricultural drainage water were identified. From this group, four constituents were identified as being of primary concern. These constituents are selenium, salts, boron and molybdenum. Special attention is given to selenium because of the possible public health concerns related to the ingestion by humans of fish or waterfowl from the River Basin with elevated levels of selenium in the edible tissues.

The major source of selenium (81%), boron (69%), salt (46%) and molybdenum (44%) in the San Joaquin River is the agricultural area in the Mud and Salt Slough drainage basin which is upstream of the juncture of the San Joaquin River and the Merced River (near Hills Ferry). In 1985, the year for which the loading percentages above are calculated, this drainage basin supplied only 12% of the flow in the San Joaquin River. Control measures focus on a Drainage Study Area (DSA) of 94,480 acres (see Figure 2). About half of the DSA has subsurface (or "tile") drains.

WATER QUALITY OBJECTIVES FOR SELENIUM AND OTHER CONSTITUENTS

Based on today's knowledge of the public health effects of selenium and the adverse effects that selenium can have on fish and waterfowl, an appropriate concentration of selenium in the San Joaquin River at Hills Ferry appears to be 2 ppb (parts per billion which is equivalent to ug/l). This value is based on data on the bioaccumulation of selenium in aquatic ecosystems different from those found in the San Joaquin Valley. Two ppb also generally reflects the selenium levels experienced at this location in the mid-1970's; important because 1975 is a benchmark used for compliance with the antidegradation policy of the Federal Clean Water Act.

Because of scientific uncertainties associated with the applicability of a 2 ppb selenium objective in the San Joaquin River and the large costs to achieve this value at and below Hills Ferry, an interim water quality objective for selenium of 5 ppb was recommended. A long-term objective for selenium has not been recommended at this time.

In order to meet the interim water quality objective of 5 ppb selenium at and below Hills Ferry on the San Joaquin River, selenium loads from the DSA would need to be reduced by about 30 percent. To reach 2 ppb selenium at this location, loads from the DSA would need to be reduced by about 70 percent.

Water quality objectives for boron, salts and molybdenum were also recommended. These recommendations call for general improvement in water quality for these constituents. Table 1 summarizes these recommended water quality objectives for selenium, boron, salts and molybdenum and their proposed compliance dates.

ACHIEVING OBJECTIVES THROUGH REDUCTIONS IN DRAINAGE VOLUMES AND LOADS OF POLLUTANTS

Reduction of subsurface drainage volumes and loads of pollutants through an aggressive program of water conservation can have a dramatic effect on reducing not only selenium concentrations in the San Joaquin River, but also boron, salts and the other elements of concern. The limited data available to the Technical Committee indicate that a reduction of subsurface drainage flows results in an almost proportionate decrease in the load of pollutants like selenium. More information on the relationship between subsurface drainage flow and pollutant loads is needed to quantify this relationship. Deep percolation of irrigation water could be reduced by about 40 percent if better water management practices were employed with the furrow irrigation techniques predominately used in the DSA. The cost of improvements in both water application and drain flow regulation is estimated to be about $16/acre. Better water management techniques are readily implementable. Well managed improved irrigation techniques, which would be significantly more efficient than furrow irrigation as currently practiced, could reduce drainage volumes about 70 percent over those currently generated in the DSA. The costs associated with improved irrigation technology is estimated at about $60/acre. This technology is available but may need to be field tested in this area before being implemented on a large scale.

Improved water management in the entire DSA could save about 46,000 acre-feet of water each year. Well managed improved irrigation technology in the entire DSA could save at least 75,000 acre-feet of water per year.

This water would be available for use in the waterfowl areas in the San Joaquin River Basin, which have been adversely affected by high selenium drainage, or in other parts of the State.

The interim objectives appear to be achievable through better water management with existing irrigation systems. This is a logical first step in achieving the long-term water quality objectives recommended by the Technical Committee. Assuming the long-term selenium objective is eventually determined to be about 2 ppb, both better management and improved irrigation technology will likely be needed to achieve this concentration in the San Joaquin River at Hills Ferry and points downstream. Treatment to remove selenium may not be needed to achieve a long-term selenium objective if better water management and irrigation technologies are implemented. Achievement of the long-term selenium objectives through better water management and increased irrigation efficiency will be an effective first step toward achieving the salinity and boron objectives. However, additional actions in areas outside the DSA may be needed to achieve these water quality objectives.

An aggressive program of drainage reduction through improved irrigation efficiencies is a logical first step toward addressing the agricultural drainage issues in the San Joaquin River Basin. If future studies show that additional actions beyond drainage flow reduction are needed to further reduce the loading of pollutants in agricultural drainage, the costs of these actions will be less than they would be otherwise because there will be less volume to handle. Therefore, drainage reduction through improved irrigation efficiencies is the one alternative that promises rapid, near-term, inexpensive improvements in water quality in the San Joaquin River. It will also be an integral part of any long-term program that may be developed to deal with agricultural drainage in a more comprehensive manner.

BEST MANAGEMENT PRACTICES

The adoption of best management practices should be considered to reduce pollutant loads and achieve the interim selenium water quality objective of 5 ppb at Hills Ferry. Best management practices can be included into waste discharge requirements to aid in their enforceability. One goal of these practices would be for all areas in the Drainage Study

Area and areas upslope to increase their infiltrated water use efficiency[3] from the existing 70 percent to 80 percent. Available information indicates that this could be achieved through best management practices using existing systems. The type of practices that should be employed include (1) better managed preirrigation, (2) better managed initial irrigation through better water scheduling and (3) use of the high ground water table in the summer as a source of water for some crops. The other goal of such practices would be to reduce subsurface tile drainage from existing tile drained areas in the DSA to 0.45 AF/acre. Incremental steps in drainage flow reduction from the existing 0.75 AF/acre, should be considered to achieve the drainage flow reduction goal by October 1991 (e.g., 0.55 AF/acre 1989, 0.5 AF/acre 1990, 0.45 AF/acre 1991).

The drainage flow reduction program goals may need to be revised to 90 percent infiltrated water use efficiency and 0.2 AF/acre in order to achieve the long-term water quality objectives, depending on the outcome of site-specific studies and the exact relationship of subsurface drainage flows to pollutant loads.

CONCLUSION

Based on the available information, it appears that the improvement in water quality resulting from implementation of the interim selenium objective and long-term objectives for salts, molybdenum and boron is necessary to provide reasonable protection to beneficial uses. The economic costs needed to do so appear also reasonable. However, data on the (1) concentrations of selenium which protect aquatic ecosystems in the Basin, (2) concentrations of selenium which protect human consumers of fish and wildlife, and (3) drainage flows and pollutant loads produced in and upgradient of the DSA needs to be developed and reviewed before a long-term selenium water quality objective is implemented.

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[3] Efficiency of infiltrated water use = (evapotranspiration of applied water ÷ depth of applied water infiltrated into the soil) x 100

FIGURE 1 - SAN JOAQUIN RIVER BASIN

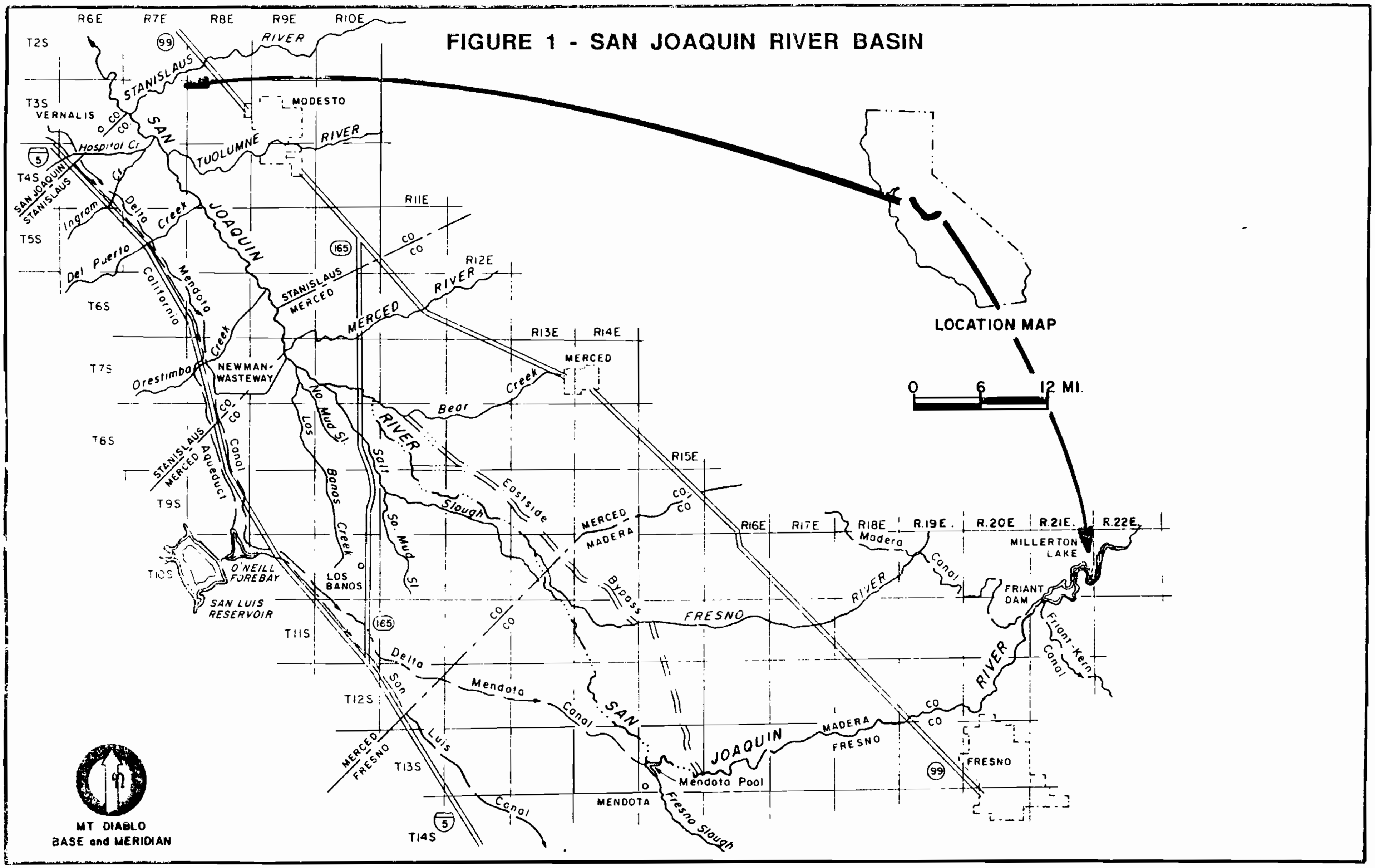

FIGURE 2 - DRAINAGE STUDY AREA

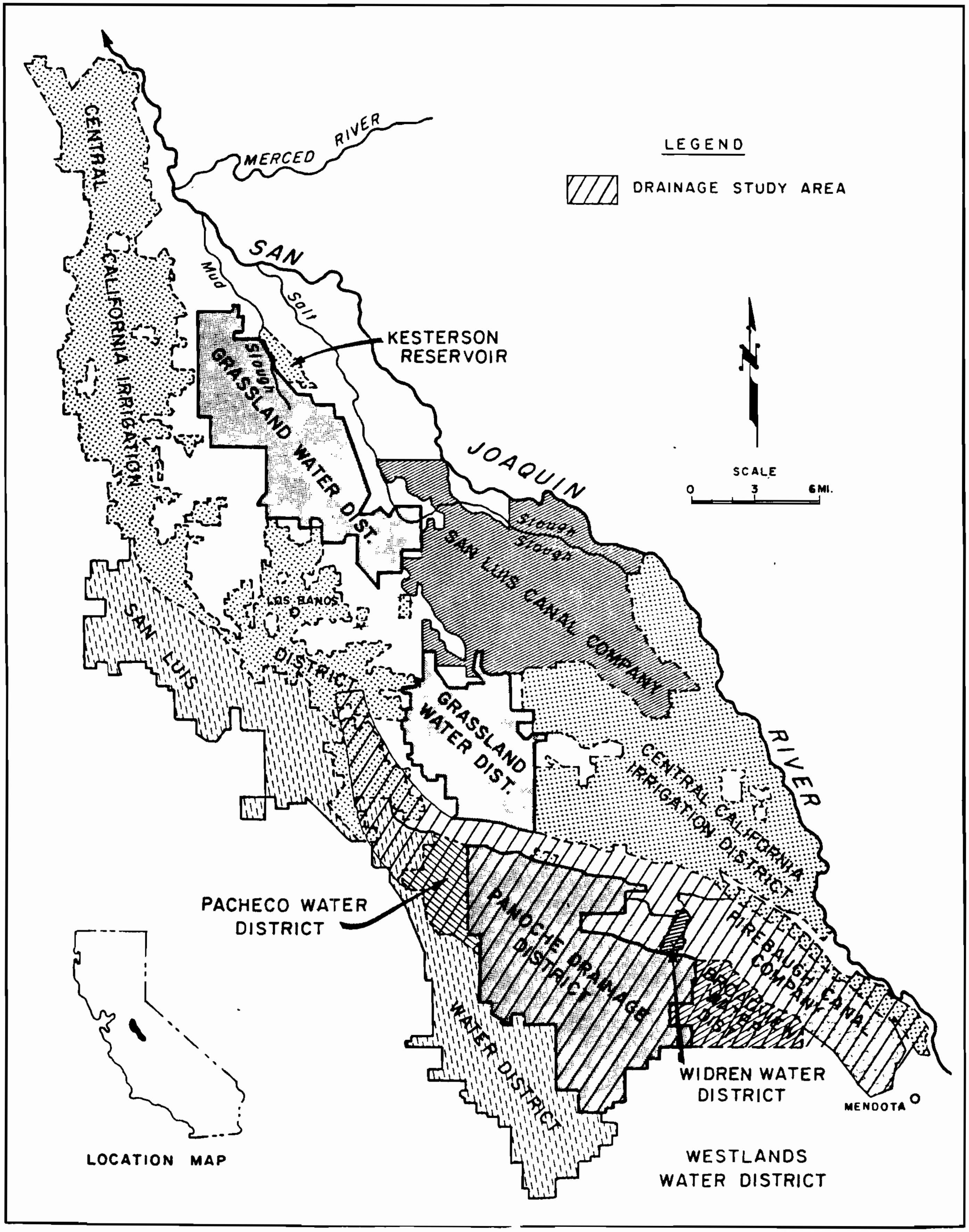

TABLE 1

RECOMMENDED WATER QUALITY OBJECTIVES FOR THE SAN JOAQUIN RIVER BASIN

LOCATION	CONSTITUENT	MAXIMUM MEAN MONTHLY LEVEL	INSTANTANEOUS MAXIMUM	COMPLIANCE DATE
<u>Interim Objectives</u>				
San Joaquin River at Hills Ferry and downstream	Selenium	5 ppb	26 ppb	October 1991
Grassland WD, San Luis NWR and Los Banos SWA	Selenium	2 ppb (can be provided via a substitute supply)[1]		October 1989
<u>Long-term Objectives</u>				
San Joaquin River at Hills Ferry and downstream	Selenium	To be determined based on site-specific data		To be determined
	EC	1.0 mmho		
	Boron	700 ppb	5,800 ppb	
	Molybdenum	10 ppb	440 ppb	
Salt & Mud Sloughs & San Joaquin River Lander Ave. to Hills Ferry	Selenium	10 ppb	26 ppb	To be determined
Salt Slough and San Joaquin River Lander Ave. to Hills Ferry	EC	3.0 mmhos		To be determined
	Boron	2,000 ppb	5,800 ppb	
	Molybdenum	10 ppb	440 ppb	
Grassland WD, San Luis NWR and Los Banos SWA	Selenium	To be determined based on site-specific data (can be provided via a substitute supply)[1]		To be determined

[1] If a substitute supply of 2 ppb or lower is provided, the quantity of this supply should be in a volume equal to the lesser of either (1) the quantity of water (mid-1970's) diverted by these waterfowl areas or (2) the actual flow in the canals available to these areas.

ON-FARM MANAGEMENT PRACTICES AFFECTED BY WATER QUALITY REGULATIONS

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The agricultural industry is increasingly coming under the auspices of federal and state regulations designed to protect environmental quality. Formerly, agricultural management decisions were based almost entirely on productivity with very little concern about environmental consequences. Presently, consideration of environmental quality is being dictated by regulations and prospects for the future are that the regulations will only become more stringent. Several of these regulations have been adopted to protect the quality of surface waters and groundwater. My assignment is to analyze adjustments in on-farm management practices to meet the dual role of high production and low water degradation.

The types of agricultural water pollutants can be generally categorized as: 1) nitrates resulting from fertilizer or animal wastes, 2) pesticides applied to protect crops against disease, insect damage or weeds, and 3) inherent toxic soil elements such as selenium, boron, etc. Pathways by which these pollutants reach surface or groundwaters are: 1) surface runoff from agricultural lands, 2) waters collected in subsurface drainage systems designed to control the water table depth, and 3) downward water migration to aquifers.

Both the source and pathway must be considered in designing management strategies to protect water quality. Nitrogen is an essential plant nutrient and yields of most crops are enhanced by nitrogen application. Protecting water quality by reducing the source (amount applied) represents a definite tradeoff between yield and environmental quality. A variety of options are sometimes available for protecting crops from pest damage. Options which eliminate or greatly reduce the usage of chemicals which serve as water pollutants should be adopted whenever possible. Presence of inherent toxic soil elements is not controlled by the farmer. In summary, protecting water quality by reducing the source of pollutants at the farm level has varying degrees of possibility. In some cases, reducing the source represents a significant tradeoff with crop yields.

Restricting the pathway is an alternative approach to source reduction in protecting water quality. The pollutants are transferred by water from the site of origin to the affected water body. Elimination or reduction of water flow would reduce water degradation.

Letey et al. (1977) measured nitrate-nitrogen in tile effluent waters from drainage systems located in various parts of California. They found that the amount of nitrate in the tile effluent was related both to the amount of nitrogen application and to the tile effluent volume. Of the two, however, there was a higher correlation between the quantity of nitrate and the effluent volume than to the amount applied. Low drainage volumes produced low quantities of nitrate-nitrogen regardless of the application amount. Controlling water pollution by mitigating against the pathway through reduced water flow represents a management option with good possibilities. Indeed, if surface runoff is eliminated and deep percolation reduced to a very low level, the farmer can have a greater degree of freedom in applying nitrogen and pesticide. Without water transporting these compounds, they do not serve as water pollutants even if they are applied at quite high concentrations.

Irrigation, therefore, is the key on-farm management practice to be adjusted because of water quality constraints. Whereas irrigation management formerly was directed towards the objective of high production, irrigation must now be managed to produce high production and low deep percolation.

Can high yields and low deep percolation both be achieved? The answer is yes, if the irrigation system and management meet two criteria. First, water must infiltrate uniformly over the entire field. Second, the irrigator must be able to precisely control the amount of infiltrated water so that it does not exceed the available soil-water storage capacity.

Nonuniform irrigation requires a tradeoff between yields and deep percolation. To obtain the highest yields, enough water must be applied so that even the part of the field with the least infiltrated water has enough for maximum production. In so doing, "excess" water must be applied to other parts of the field, which will lead to deep percolation. On the other hand, if deep percolation is to be held to a minimum, parts of the field must be under-irrigated and thus reduce yields. Without water quality concerns, the former would add rather high amounts of water to achieve high yields. Uniformity was not too important because "over-irrigating" a portion of the field was relatively inexpensive. Presently, either because of regulations and/or high costs of drainage water disposal, application of "excess" water is costly or restrictive.

In summary, water quality regulations dictate a modification of on-farm management practices. A shift in irrigation technology and management provides the most effective means of meeting water quality objectives. The reports by other individuals at this conference on various aspects of water management are timely and critical to the future challenges facing the California farmer. The agricultural industry must clearly recognize, if it does not already, that farm management is no longer free from external constraints. Adjustments will be required and the innovative and progressive farmer will meet this challenge by making the appropriate adjustments.

REFERENCE

Letey, J., J. W. Blair, Dale Devitt, L. J. Lund, and P. Nash. 1977. Nitrate-nitrogen in effluent from agricultural tile drains in California. Hilgardia 45(9):289-319.

Economic Aspects of Irrigation System Improvements

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There can be little doubt that water quality regulations will have significant effects on water management practices. It is likely that reductions in drainage flows will be required to meet regulatory standards. This can be accomplished by building evaporation ponds, reusing drainage water, reducing per acre water applications, improving application efficiency, or changing cropping patterns. Estimating the economic impacts of changes in water management practices is difficult because such changes depend on other economic variables. The cost of reducing drainage flows depends on crops grown and irrigation technologies used. Cropping patterns and irrigation methods will be determined in part by the prices of water, energy, and drainage flows. Water district pricing of water and/or drainage will therefore have both a direct and indirect effect on drainage flows. However, if it is assumed that farmers are presently operating in an efficient fashion, any change will decrease profits. Cropping patterns might change, some land might go out of production and other land would be less profitable. These changes would affect land values and owner wealth and have a ripple effect throughout the community.

This paper examines the economic aspects of irrigation system improvements as a means of reducing drainage flows to meet regulatory standards. Irrigation system improvements reduce the amount of water applied through increased investments in equipment, training and energy. Such investments may reduce application costs, increase the productivity of other inputs (e.g. fertilizer, labor, etc), and increase irrigation efficiency.

Returns will vary depending upon the quality of the soil and the efficiency and uniformity of the current system. It is recognized that a number of problems arise in attempting to measure improved application efficiency. These problems as well as those arising from uncertainty regarding the institutional milieu (water district pricing, drainage district formation, etc) are ignored for the moment to develop some general principles.

A spreadsheet template of the irrigation system investment decision is used to analyze the economic effects of choosing between alternative irrigation systems. Four irrigation system improvements (drainage water reuse, shorter runs, sprinkler, and drip) were compared on three different types of soils (poor, medium, and high quality) with three different types of crops (low, medium, and high valued). The economic effects are measured in terms of reduced profitability. While the outcomes in this paper are based on assumed values of certain parameters, the methodology employed can be used with greater confidence given site specific information.

Modern irrigation technologies are sometimes referred to as land quality augmenting. Water holding capacity is determined by soil characteristics. Given the interaction between water availability and crop yields, water holding capacity is an important soil quality. Modern irrigation systems augment this water holding capacity and thereby increase soil productivity-thus the land quality augmenting nature of modern systems. Irrigation efficiency (that portion of applied water used by the plant) is determined by the water holding capacity of the soil and the irrigation method. The price of effective water (that which is actually used by the plant) is the delivered price divided by the irrigation efficiency coefficient. Switching to a modern system increases irrigation efficiency and decreases effective water prices. Such changes will be larger on those soils with less water holding capacity (poorer quality soils). Therefore, the relative gain in switching to a modern system is greater for the lower quality soils. Increased capital and energy costs must be balanced against the increased irrigation efficiency to determine whether or not such a system is economically justified. Since modern systems use capital and energy and "save" water and land, high capital and energy prices will lead to higher effective water prices for modern systems while such prices may well be lower if poor quality land is involved (more land is being "saved") or if water prices are high.

Under the assumption that farmers are currently operating in an efficient fashion, changes to modern systems for purposes of reducing drainage flows will decrease profits. That is, the decreases in effective water prices will be more than outweighed by the increased capital and energy costs. The reduction in profits will be less however on the poorer quality soils other things being the same. The goal will be to choose that system which meets the reduced drainage standard and decreases profits least. Since system benefits and costs will accrue over time, a capital budgeting approach is required to accurately measure the increases in costs expected. Table 1 contains data on each of the four systems to be evaluated. Salvage values are assumed to be 10% of system costs. Irrigation efficiencies are probably the best that can be expected under the various systems. It is assumed that all water is ditch water so pumping is only required for pressurization. Water is priced on a fixed per acre and a variable per acre foot basis. Variable production costs that vary by system are noted. It is assumed that a $60 per acre downpayment is made in each case and that the investment is depreciated using a double declining balance approach.

Table 2 shows the assumed differences in irrigation systems and soil qualities. Tailwater recovery systems are assumed to have no impact on yields on good quality soils but negative impacts on moderate to poor quality land.

This might be the result if soils with poor water holding capacity are also somewhat saline and the addition of slightly more saline water decreased yields. This assumption is used to show what happens if changes in irrigation systems decrease yields and is not intended to be indicative of actual experience. The other three systems have increasingly positive impacts on yields as they are applied to lower quality land. Three different crop values are used ($500, $1000, and $1500 per acre returns) but water needs are not varied.

A spreadsheet template is used to calculate the net present value of all costs associated with each irrigation system for each crop value and soil quality over the life of the system. These costs are annualized so that investments of differing useful lives can be compared. Table 3 shows the annualized present value of the cost per acre of each system for each crop value and soil quality. The numbers shown include the effects on yields (and hence revenues) of shifting to the modern technology. Results for the tailwater recovery system show that if yields are reduced by a modern system, then costs are greatest on the poorer quality soils and for the higher valued crops. The other three technologies show that costs decrease as irrigation technologies are used on the poorer quality soils. In these three cases, costs are also reduced as higher valued crops are produced. It is of interest that the higher capital cost systems are the most economical under the assumed conditions. In fact, it appears that use of a drip system on poor quality soil to produce a high valued crop would actually increase profits contradicting the assumption of present efficient production practices.

The results in Table 3 are based on the values in Tables 1 and 2. To the extent that those numbers are correct, the annualized present values of costs can be used to determine which irrigation system to adopt (assuming drainage standards are met by each). The analysis suggests that modern technologies will have the smallest impact on costs in areas of relatively high output prices and low land quality. The individual producer would thus find it most beneficial to focus initial efforts on fields where these characteristics exist. Using the computerized spreadsheet approach, the analysis can be tailored to individual operations. The major problems in obtaining useful results will be accurately specifying the information requirements of Tables 1 and 2.

TABLE 1. SYSTEM INFORMATION

ITEM	tailwtr	shortrun	sprinklr	drip
System life	10.00	10.00	10.00	7.00
Salvage value at end of life	12.50	9.10	11.90	60.00
H2o needed by plant, acre in.	28.00	28.00	28.00	28.00
Irrigation Efficiency(65%=.65)	0.73	0.70	0.80	0.95
Lift in feet	0.00	0.00	0.00	0.00
P.S.I. of System			20.00	35.00

VARIABLE PRODUCTION COSTS	$/acre	$/acre	$/acre	$/acre
Fertilizer	19.00	19.00	24.00	24.00
Weed & Pest Mgmt.	25.00	25.00	25.00	19.00
Irrigation Prep.	50.00	50.00	70.00	35.00
Fixed Water Costs/acre	23.00	23.00	23.00	23.00
Ditch Water Cost/acre foot	13.65	13.65	13.65	13.65
Irr. System Main.	35.00	15.00	40.00	50.00
Office & Mgmt. Costs	24.00	45.00	68.00	57.00

CAPITAL COSTS				
Total system cost/acre	125.00	91.00	119.00	600.00
downpayment in percent	0.48	0.66	0.50	0.10
Interest rate from bank	0.10	0.10	0.10	0.10
loan term in years	3.00	3.00	3.00	5.00
Your tax bracket	0.28	0.28	0.28	0.28

TABLE 2. Assumed impacts on yields with differing soil quality

	Good	Moderate	Poor
Tailwater recovery	0	-0.02	-0.05
Shorter runs	0.03	0.07	0.12
Sprinkler	0.05	0.1	0.2
Drip	0.1	0.2	0.3

TABLE 3
ANNUALIZED NET PRESENT VALUE PER ACRE-COSTS LESS VALUE OF YIELD IMPACTS

	Soil Quality		
	Poor	Moderate	Good
Tailwater Recovery			
low value crop	317	301	290
medium value crop	344	312	290
high value crop	372	323	290
Shorter Runs			
low value crop	223	250	272
medium value crop	157	212	256
high value crop	92	174	239
Sprinkler			
low value crop	275	329	357
medium value crop	165	275	329
high value crop	56	220	302
Drip			
low value crop	244	294	344
medium value crop	94	194	294
high value crop	-56	94	244

IMPROVED FARM WATER MANAGEMENT: SURFACE IRRIGATION

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PERFORMANCE CHARACTERISTICS

The performance of a furrow irrigation system is described by the following characteristics:

1. Application efficiency-ratio of the amount of water stored in the root zone to the average amount of water applied. Losses from furrow systems affecting application efficiency are subsurface drainage and surface runoff. Subsurface drainage is applied water which infiltrates below the root zone, and occurs when the depth applied is greater than the soil moisture depletion. Surface runoff is applied water which runs off the lower end of the field, and occurs when the application rate exceeds the infiltration rate. These losses are characterized by:
   a. Deep percolation ratio - ratio of the amount of subsurface drainage over the average amount of applied water.
   b. Tailwater ratio - ratio of the amount of surface runoff over the average amount of applied water.
2. Uniformity of applied water - measure of how uniformly the water is applied throughout the field. Indexes of uniformity commonly used include the distribution uniformity and the coefficient of uniformity.

Losses in surface irrigation systems (subsurface drainage and surface runoff) are competitive, i.e. reducing one type of loss increases the other. Thus, decreasing the length of run to improve uniformity and reduce subsurface drainage will increase surface runoff. Runoff losses can be reduced with cutback irrigation (reducing the inflow rate after advance is complete). Surface runoff can also be recirculated or used on fields downslope.

The performance of a furrow irrigation system is described by the advance curve. This curve shows the elapsed time from the start of the irrigation required for water to arrive at a given distance along the length of run. Factors affecting the advance time include soil infiltration rate, length of run, furrow inflow rate, surface roughness, slope of the field, and furrow cross-sectional shape. Of these factors, the infiltration rate has the greatest influence.

Subsurface drainage occurs because of overirrigation (least-watered areas of the field receive more than the desired amount) and nonuniform water application. Because of nonuniform applications, some areas receive more water than others. Keys to drainage reduction are improving the uniformity of application and reducing the depth applied. The higher the uniformity, the higher the potential for drainage reduction, yet adequately irrigating the field.

Uniformity of a furrow irrigation system depends on the advance time and on the spatial variability of the soil infiltration rate. Because of the advance time, differences in time for infiltration exist between the upper and the lower ends of the field, with more water being infiltrated at the upper end than at the lower.

Differences in intake opportunity times can be reduced by decreasing the advance time as much as possible. Measures commonly recommended for decreasing the advance time include:

1. Reducing the length of run. The distance required for water to advance to the end of the field is decreased, thus reducing the time for complete advance.
2. Increasing the furrow inflow rate. The higher the furrow inflow rate, the faster the water advance since more water is available for flow in the furrow compared to that infiltrating into the soil.
3. Compacting the furrow. Furrow compaction reduces the intake rate, and thus less water per unit time infiltrates into the furrow. More water is available for flow in the furrow.
4. Improving the uniformity of the field slope.

While differences in infiltration time can be reduced, the maximum uniformity of a furrow irrigation system is limited by the spatial variability of the soil infiltration rate. A study of spatial variability of infiltration revealed a field-wide uniformity (DU) of the infiltration rate of about 80 percent. This may represent an upper limit since the field was described as having a relatively uniform soil texture.

One option for reducing subsurface drainage is surge irrigation, which applies the water in pulses instead of continuously. This intermittent application reduces the soil infiltration rate, and thus less water is needed for complete advance than for continuous flow systems. Some evidence suggests that surge irrigation also may improve the uniformity of the soil intake rate.

POTENTIAL FOR DRAINAGE REDUCTION

The potential for drainage reduction depends to some degree on the major source of subsurface drainage, i.e. overirrigation or nonuniformity. Ongoing research by University of California investigators is assessing the potential of the above measures for drainage reduction. Results thus far have shown that reducing the length of run from 1/2 mile to 1/4 mile might decrease the subsurface drainage by about 50 percent, provided nonuniformity is the primary source of drainage. However, this drainage reduction will occur only if the set time is reduced to compensate for the decreased advance time. Failure to reduce the set time may result in more subsurface drainage than for the longer length of run. Surface runoff will increase because of the smaller length of run.

While increasing the furrow inflow rate will increase the uniformity of opportunity times, this research has shown that if the set time is reduced to compensated for the smaller advance time, the volume of water infiltrated is about the same as that for a smaller inflow rate. These studies have shown that as the inflow rate increases, more water infiltrates into the soil per unit time, because of an increased intake rate due to a larger depth of flow in the furrow. Thus the potential for drainage reduction of increasing the furrow inflow rate appears to be minimal. However, this behavior provides some advantages in managing furrow systems, which will be discussed later.

Compaction of nonwheel furrows, such as done by several growers using "torpedos", can reduce both the soil intake rate and opportunity time differences. A UC study where every other nonwheel furrow was compacted revealed that during the first seasonal irrigation, the advance times of the compacted nonwheel furrows were smaller than those of the noncompacted furrows, but not as small as the advance times of the wheel furrows. However, differences between compacted and noncompacted nonwheel furrows were no longer evident once cultivation ceased.

While the effect of surge irrigation on uniformity is uncertain, surge irrigation reduces the soil infiltration rate, and thus less water is needed for complete advance than under the conventional continuous inflow. UC studies of surge irrigation in the San Joaquin Valley has shown that about 30% to 40% less water is required for advance compared to continuous inflow. This reduction reflects the drainage reduction potential of this irrigation method.

THE CHALLENGE OF DRAINAGE REDUCTION

While these studies have shown the potential for substantial drainage reduction by upgrading existing furrow irrigation systems and/or by converting to surge irrigation, the challenge is to develop strategies for field-wide measures that are compatible with constraints involving labor management and field-wide operation. All of these measures require changes in the irrigation set times. Since odd set times are incompatible with labor constraints, furrow inflow rates must be selected for an advance time plus opportunity time at the lower end of the field that will satisfy the labor constraint. Fortunately, the previously-mentioned research has shown that changing inflow rates will not affected the subsurface drainage as long as set times are adjusted accordingly.

A key to selecting an appropriate advance time is a reliable estimate of the soil infiltration rate, for this soil property controls both the water advance and the intake opportunity time. However, the infiltration rate, which varies both spatially and temporally, is usually unknown for a given irrigation. Estimates obtained by conventional methods of measuring soil infiltration, which are time-consuming, may be very unreliable for many of the soils of California. Ongoing UC research, however, is field-verifying a computer model which estimates the cumulative infiltration equation given inputs of advance time at two locations, furrow inflow rate, and slope. It is hoped that this approach will overcome the limitations of the conventional methods.

In addition, several computer models are also being assessed for their ability to evaluate and predict the performance of furrow irrigation systems. If these models perform within acceptable limits, they may provide the needed tools for real-time management of furrow systems, and for evaluation and prediction of system performance.

These models, however, require data of the advance times at given locations. Spatial variability of soil infiltration, inflow, slope, surface roughness, and furrow shapes combine to create considerable variability in the advance times. Thus, an estimate of field-wide advance times based on a few samples may be in considerable error. One question, then, is the number and spacing of samples needed to obtain a reliable estimate. Such a sampling strategy must account for sources of variability, such as wheel versus nonwheel furrows, trend across a field, and random variability.

During a UC project, water advance in a level basin with furrows was measured in about 100 consecutive furrows, which was the basin population. Several different sampling strategies were investigated to compare their estimates of the mean and standard deviation with the population parameters. Results revealed little deviation from the population parameters with sample number and spacing. While statistically speaking, the confidence of the estimates decreases with decreasing sample number, physically speaking, this analysis shows that one might be confident that the deviation of the sample estimates from the population parameters is small, even for small sample sizes, provided certain conditions are met by the sampling strategy.

Conditions required for a sampling strategy are that both periodic behavior due to wheel/nonwheel furrows and trend across the region must be described. Thus, a strategy might consist of sampling in groups of consecutive furrows at equal intervals across an irrigation set. The number of furrows in a group will depend on the number of furrow cultivated per pass, since each pass will create wheel-and-nonwheel furrows. Thus, if eight furrows are cultivated per pass, a group might consist of eight consecutive furrows. Another option might be to monitor one wheel furrow and three nonwheel furrows for each eight-furrow group at three locations across a set.

SUMMARY

The studies reported herein show a drainage-reduction potential of at least 50% of the current volume of drainage water if nonuniformity is the primary source of drainage water by upgrading existing furrow systems and/or converting to surge irrigation. The challenge, however, is, can these strategies be implemented on a field-wide basis given constraints on labor management and field-wide operation.
The next step is to implement these strategies on field-wide systems and monitor the results.

PRESSURIZED IRRIGATION SYSTEMS: An Overview*

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INTRODUCTION - The Center for Irrigation Technology

The Center for Irrigation Technology (CIT) at California State University tests and evaluates irrigation equipment for a wide variety of clients. CIT is the only independent hydraulics laboratory in the United States specializing in irrigation. We work with manufacturers during the development of new products to evaluate performance and point the direction for further improvements. We work with designers, specifiers and dealers to provide technical and performance information beyond that provided by the manufacturers, and to verify published performance data. And we assist the end user by conducting product comparisons, and by verifying that the products delivered meet the specifications agreed to in the purchase contract. The Center also works with industry and professional groups to develop standardized methods of testing equipment and reporting results.

Other portions of the CIT program include: experimentation and demonstration of irrigation equipment and practices; economic, marketing and design studies of the potential benefits of newly developed products or techniques; and a variety of educational activities such as seminars, workshops, field days, publication of technical information, and the supervision of client sponsored student projects.

Unfortunately, the Center services are not without cost. The funds we receive from the State of California cover only about half of what is needed to support our program, so the remainder must come from other sources, primarily fees for testing, evaluation and analytical services. All of clients – irrigators, dealers, designers, manufacturers and others – are charged a fee to support services performed for them.

The results from our tests on irrigation equipment or other studies are available to anyone requesting the information. (We hope to have an index of our data on production irrigation products completed soon.) If you are interested in performance information on a specific item, give us the particulars (model, nozzle, pressure, etc.) and we'll send you the data, for a nominal charge to cover copying and handling, if we have it on file. For further information about CIT testing or other services, or data on file, please call David Zoldoske, CIT Hydraulics Laboratory Manager, at (209) 294-2066.

PRESSURIZED IRRIGATION SYSTEMS: An Overview

There are many types of pressurized irrigation systems. Even within sprinkler and micro-irrigation there are many subdivisions (aluminum solid set and center pivot sprinkler systems, drip and subsurface micro-irrigation systems to name just a few). Further, there are "hybrid" systems, combining the best attributes of other systems (bubbler-basin, micro-sprinkler and LEPA systems are some of the best known examples). Also, varying degrees of automation may be applied to each system. While space does not allow a complete discussion of all pressurized irrigation systems, the following reviews some common types, their capabilities and limitations, relevant labor and energy factors, and system economics.

SPRINKLER IRRIGATION

The basic components of any sprinkler systems are: a water source, a pump to pressurize the water, a pipe network to distribute the water, sprinklers to spray the water over the ground, and valves to control the flow of water. The sprinklers, when properly spaced, give a relatively uniform application of water over the irrigated area. Sprinkler systems are usually (there are some exceptions) designed to apply water at a lower rate than the soil infiltration rate, so that the amount of water infiltrated at any point depends upon the application rate and time of application, but not the soil infiltration rate.

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* Presented at the 1988 California Plant and Soil Conference of the California Chapter, American Society of Agronomy, "Agriculture: Changing Realities," Fresno, California, February 3-4, 1988.

Hand-Move or Portable Sprinkler System

These systems employ a lateral pipeline, usually aluminum, with sprinklers installed at regular intervals, such as 6, 9, or 12 meters, and special quick-coupling connections at each pipe joint. The sprinkler is installed on a pipe riser so that it may operate above the crop being grown (in orchards the sprinklers may operate under the tree canopy). The risers are connected to the lateral at the pipe coupling, and the length of pipe section corresponds to the sprinkler spacing. The sprinkler lateral is placed in one location and operated until the desired water application has been made. Then the lateral line is disassembled and moved to the next position. This type of sprinkler system has a low initial cost, but a high labor requirement. It can be used on most crops, though with some, such as corn, the laterals become difficult to move as the crop reaches maturity. On bare "sticky" soils, moving the lateral lines is very difficult, and an extra line (a "dry" line) is used.

Side Roll System

This system is a variation on the hand-moved lateral sprinkler line. The lateral line is mounted on wheels, with the pipe forming the axle (special pipe and couplers are required for strength in this application). The wheel height must be selected so that the axle clears the crop as it is moved. A drive unit, most commonly an air-cooled gasoline-powered engine located near the center of the lateral, is used to move the system from one irrigation position to another by rolling the wheels.

Traveling Gun System

This system utilizes a high volume, high pressure sprinkler ("gun") mounted on a trailer, with water being supplied through a flexible hose or from an open ditch along which the trailer passes. The gun may be operated in a stationary position for the desired time, and then moved to the next location. However, the most common use is as a continuous move system, where the gun sprinkles as it moves. The trailer may be moved through the field by a winch and cable, or it may be pulled along as the hose is wound up on a reel at the edge of the field. The gun used is usually a part-circle sprinkler, operating through 80 to 90% of the circle for best uniformity, and allowing the trailer to move ahead on dry ground. These systems can be used on most crops, though due to the large droplets and high application rates produced, they are best suited to coarse soils having high intake rates and to crops providing good ground cover.

Center Pivot and Linear Move Systems

The center pivot system consists of a single sprinkler lateral supported by a series of towers. The towers are self-propelled so that the lateral rotates around a pivot point in the center of the irrigated area. The speed of rotation ranges from 12 hours to 120 hours. The longer the lateral, the faster the end of the lateral travels and the larger the area irrigated by the end section. Thus, the water application rate must increase with distance from the pivot, which may cause runoff on some soils. A variety of sprinkler products have been developed specifically for use on these machines to better match water requirements, water application rates and soil characteristics. Unless special equipment is added to the system, the center pivot irrigates a circle and leaves the corners of the field unirrigated. Center pivots are capable of irrigating most field crops, but have on occasion been used on tree and vine crops.

Linear move systems are similar to center pivot systems in construction, except that neither end of the lateral pipeline is fixed. The whole line moves down the field in a direction perpendicular to the lateral. Water delivery is by flexible hose or open ditch pickup. The system is designed to irrigate rectangular fields free of tall obstructions. Both center pivot and linear systems are capable of very high efficiency water application. They require high capital investments, but have low irrigation labor requirements.

LEPA Systems

Low Energy Precision Application (LEPA) systems are similar to linear move irrigations systems, but are different enough to deserve separate mention of their own. The lateral line is equipped with drop tubes and very low pressure orifice emission devices discharging water just above the ground surface into furrows. This distribution system is often combined with micro-basin land preparation for improved runoff control (and to retain rainfall which might fall during the season). As with the center pivot and linear systems, very high efficiency irrigation is possible.

Solid Set and Permanent Systems

Solid set systems are similar in concept to the hand-move lateral sprinkler system, except that enough laterals are used to cover the field. The laterals are moved into the field at the beginning of the season (after planting and perhaps the first cultivation), and are not removed until the end of the irrigation season (prior to harvest). The laterals are controlled by valves which direct the water into the laterals irrigating at any particular moment. The solid set system utilizes labor available at the beginning and ends of the irrigation season, but minimizes labor needs during the irrigation season. A permanent system is a solid set system where the main supply lines and the sprinkler laterals are buried and left in place permanently (this is usually done with PVC plastic pipe).

CAPABILITIES AND LIMITATIONS

Crops, Soils, and Topography

Nearly all crops can be irrigated with some type of sprinkler system, though the characteristics of the crop, especially the height, must be considered. Sprinklers are sometimes used to germinate seed and establish ground cover for crops like lettuce, alfalfa, and sod. The light frequent applications that are desirable for this purpose are easily achieved with some sprinkler systems. Most soils can be irrigated with the sprinkler method, although soils with an intake rate below 5 mm/hr may require special measures. Sprinklers are applicable to soils that are too shallow to permit surface shaping or too variable for efficient surface irrigation. Land leveling is not normally required.

Water Quantity and Quality

Leaching salts from the soil for reclamation can be done with sprinklers using much less water than is required by flooding methods (although a longer time is required to accomplish the reclamation). This can be particularly important in areas with a high water table. A disadvantage of sprinkler irrigation is that many crops (citrus, for example) are sensitive to foliar damage when sprinkled with saline waters.

Efficiencies

Attainable irrigation efficiencies for different sprinkler systems are:

Hand-Move or Portable	65-75%
Traveling Gun	60-70%
Center Pivot	75-90%
Linear Move	75-90%
Solid Set or Permanent	70-80%
LEPA	80-95%

LABOR AND ENERGY CONSIDERATIONS

Labor requirements vary depending on the degree of automation and mechanization of the equipment used. Hand-move systems require the least degree of skill, but the greatest amount of labor. At the other extreme, center pivot, linear move and LEPA systems require considerable skill in operation, but the overall amount of labor needed is low. Energy consumption relates to operating pressure requirements, which vary considerably among sprinkler systems. At the extremes, the LEPA systems may require only 1 bar pressure, while the travelling gun system requires 7 bars or more. Center pivot and linear move systems will use 2 to 5 bars, and solid set systems 2 to 4 bars.

ECONOMIC FACTORS

Capital costs for sprinkler systems depend on the type of system and size of the irrigated area. Typical investment costs (US $, 1985) are given below, assuming that water is available at ground level at the side of the field, and include mainline and pumping plant.

System Type	Field Type	Capital Cost
Hand-Move or Portable	65 ha	175 - 250 $/ha
Side Roll	65 ha	740-1000 $/ha
Travelling Gun	32 ha	865-1100 $/ha
Center Pivot	80-55 ha	620-1000 $/ha
Center Pivot + Corner System	60 ha	865-1100 $/ha
Linear Move (Ditch Fed)	130 ha	1000-1200 $/ha
Linear Move (Hose Fed)	130 ha	1500-1850 $/ha
Solid Set	65 ha	2500-3000 $/ha
Permanent	65 ha	2100-3000 $/ha

Energy costs are highly variable from place to place. The following energy requirements may be used to estimate costs by applying the locally appropriate unit energy cost. A pump efficiency of 75% has been assumed. The energy figures cited are in terms of kilowatt hours per hectare per millimeter (gross) of water applied.

System Type	Energy Use-KWH/h/mm
Hand-Move and Slide Roll	0.86-2.05
Traveling Gun	3.42-4.79
Center Pivot	0.86-2.23
Center Pivot + Corner System	0.96-2.33
Linear Move (Ditch Fed)	0.86-2.23
Linear Move (Hose Fed)	1.20-2.57
Solid Set & Permanent	0.86-2.05

Operating labor costs vary by system type and local costs for labor. The figures below are typical values for labor hours required per hectare per 100 mm (gross) of irrigation water applied.

System Type	Labor-hrs/ha/100mm
Hand-Move	1.65
Side Roll	1.17
Traveling Gun	0.68
Center Pivot	0.09
Linear Move	0.19
Solid Set	0.97
Permanent	0.09

Maintenance costs are difficult to predict, but the following figures may be used as an approximate guide. The annual maintenance cost is estimated by multiplying the initial capital cost of the system by the tabulated percentage factor.

System Type	Percentage Factor
Hand-Move	2
Side Roll	2.5
Traveling Gun	6
Center Pivot	5
Center Pivot + Corner System	6
Linear Move & LEPA	6
Solid Set	2
Permanent	1

MICRO-IRRIGATION

Micro-irrigation is the slow, frequent application of water to the soil though emitters placed along a water delivery line. The term micro-irrigation is general, and includes several more specific methods. Drip irrigation applies the water through small emitters to the soil surface, usually at or near the plant to be irrigated. Subsurface irrigation is the application of water below the soil surface. Emitter discharge rates for drip and subsurface irrigation are generally less than 12 liters per hour. Bubbler irrigation is the application of a small stream of water to the soil surface. The applicator discharge rate (up to 250 liters per hour) exceeds the soil's infiltration rate, so the water ponds on the soil surface. A small basin is used to control the distribution of water. Micro-spray irrigation applies water to the soil surface by a small spray or mist. Discharge rates are usually less than 120 liters per hour.

CAPABILITIES AND LIMITATIONS

Crops, Soil, and Topography

Micro-irrigation is best suited for tree, vine, and row crops. The main limitation is the cost of the system, which can be quite high for closely-spaced crops. Complete cover crops, such as grains or pasture cannot be economically irrigated with micro-irrigation systems. Micro-irrigation is suitable for most soils, with only the extremes causing any special concern. On very fine textured soils, micro-irrigation application rates may cause ponding, with potential runoff, erosion and aeration problems. On very coarse textured soils, lateral movement of water under the applicators will be limited, so more emission outlets per plant may be required to wet the desired root area. With proper design, using pressure compensating emitters and pressure regulators are required, micro-irrigation can be adapted to virtually any topography. In some areas, micro-irrigation is successfully practiced on such steep slopes that cultivation becomes the limiting factor.

Water Quantity and Quality

Micro-irrigation uses a slower rate of water application over a longer period of time than other irrigation methods. The most economical design would have water flowing into the farm area throughout most of the day, every day, during peak use periods. If water is not available on a continuous basis, on-farm water storage may be necessary. Micro-irrigation can be used successfully with waters of some salinity, although some special cautions are needed. Salts will tend to concentrate at the perimeter of the wetted soil volume. If too much time passes between irrigations, the movement of soil water may reverse itself, brining salts back into the root zone. Salts concentrating on the surface around the edge of the surface wetted area can be a hazard should a light rain occur. Such a rain can move the salts down into the root zone, without applying enough water to leach the salts through and below the root zone. When rain falls after a period of salt accumulation, irrigation should continue as normal until about 50 mm of rain have fallen to prevent salt damage. In arid regions where annual rainfall is insufficient (less than 300 to 400 mm) to leach the salts, artificial leaching may be necessary from time to time, requiring the use of a supplemental sprinkler or surface irrigation system.

Though a form of pressurized irrigation , micro-irrigation is a low pressure, low flow rate method. These conditions require small flow channel openings in the emission devices, which are prone to plugging. The sensitivity of emitters to plugging varies with design, but virtually all emitters will require some degree of water treatment in agricultural situations. Cyclonic separators and screen filters are used to remove inorganic particles from the irrigation water, and media filters are used to remove organic contaminants. Chemical treatment of the water may also be required to control biological activity in the water, to adjust pH, or to prevent chemical precipitation which could plug emitters. Proper design and care of the water treatment system is vital to the successful use of micro-irrigation.

Efficiencies

Properly designed and maintained micro-irrigation systems are capable of high efficiencies. Design efficiencies should be on the order of 90 to 95%. With reasonable care and maintenance, field efficiencies in the range of 80 to 90% may be expected. Where plugging is a problem, or emitter performance is highly variable, field efficiencies may be as low as 60%. A large field study in California found field measured micro-irrigation system efficiencies averaged 80%.

LABOR AND ENERGY CONSIDERATIONS

Due to their low flow characteristics, micro-irrigation systems usually have few subunits, and are designed for long irrigation times. The systems are easily operated manually, but can also be fully automated. Thus, the major labor requirement is for system maintenance and inspection. The amount of maintenance labor required is related to the sensitivity of the emitters to plugging and the quality of the irrigation water. In a vineyard situation, one irrigator can inspect and maintain about 20 hectares per day.

Micro-irrigation systems generally use less energy than other forms of pressurized irrigation systems. The emission devices usually operate at pressures ranging from 0.5 to 1.5 bars. Additional pressure is required to compensate for pressure losses through the control head (filters and control valves) and the pipe network. System pressures range from about 2 bars (small systems on flat terrain) to 4 bars (larger systems on undulating terrain).

ECONOMIC FACTORS

Micro-irrigation systems costs can vary greatly, depending on crop (plant, and therefore, emitter and hose spacings) and type of hose employed (permanent or "disposable" thin-walled tubing). Micro-irrigation costs will be the lowest for widely-spaced orchard crops, perhaps US$1200/ha. For closer-spaced vines, the costs increase to about US $2000/ha. For closely-spaced vegetable crops (tomatoes, etc.), micro-irrigation system costs can range from US $2500 to $3200/ha. Typical operation and maintenance costs (US $ per hectare per year), are given below as a percentage of the initial capital cost:

Expense	Percentage Factor
Labor	1.5
Power (depends on system efficiency)	3-7
Water(depends on system efficiency)	4-6
Maintenance	1
Taxes and Insurance	2

ACKNOWLEDGEMENT

This paper has drawn heavily upon a draft of the manual "Selection of Irrigation Methods for Agriculture" being prepared by the On-Farm Irrigation Committee of the Irrigation and Drainage Division of the American Society of Civil Engineers (ASCE). Most of the cost figures included here are taken directly from the draft manual. Interested readers are encouraged to contact the main ASCE office in New York to inquire about receiving a copy of this manual when it is completed. The members of the committee preparing the manual are:

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Skills Required to Implement Water Management Programs

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Introduction

"Water Management Programs" exist in many forms. This paper will deal with a water management program conducted by the Westside Resource Conservation District (WRCD) within the geographic boundaries of Westlands Water District in western Fresno County. Westlands Water District (WWD) conducts an identical program; the efforts have been coordinated so that the instructions, payment methods, grower selection, etc. are the same. The difference is that WWD does not receive outside funding, and it provides it own in-house technical review.

In both the 1986/87 and 1987/88 WWD and WRCD programs, farmers enrolled the maximum possible of approximately 22,000 acres/year in a 50/50 cost sharing Water Management Program. Farmers and the districts each pay $8/acre, for a total of $16/acre. The programs consist of a pre-season overview, detailed irrigation evaluations and irrigation scheduling on a field-by-field basis through the year, and a post-season review, . The field work is done by private irrigation consultants (called program advisors) who contract directly with the participating farmers.

The WWD and WRCD Water Management Programs are continually evolving and improving. They were developed after analyzing the objectives, successes, and failures of previous water management programs which have been conducted by Westlands Water District, the SCS, the USBR, Cal Poly, the OWC/DWR Mobile Labs, and others.

Starting a Water Management Program

A "Water Management Program" in the context of this presentation deals with a program funded by a government agency. When an agency decides to initiate a water management program, a number of a number of items must be addressed before any field work is done. These include:

a. What are the objectives?
b. What is the motivation for developing a program?
c. How much money is available?

d. For how many years will the money be available?

e. Is there a requirement to serve as many farmers as possible, or simply to provide management to a certain number of acres?

f. What accounting and report requirements does the funding agency have?

g. Does the administrating agency have sufficient technical and administrative staff to conduct the program?

h. How much time will administration take?

i. Will the program be conducted in-house, or will it be contracted out?

j. What are the farmer expectations?

k. What educational and informative requirements must be met before implementing the program?

l. Who will provide quality control?

m. What will the quality control consist of?

n. How will payments be made? Who will decide to make the payments? Who will receive the payments, and at what time and in what amounts?

o. What numbers will be measured and/or reported?

p. How will those numbers be collected? ie, what procedures should be used?

q. In what format should the numbers be reported?

r. How much preparation time is necessary before field implementation?

s. How will success or failure be measured, and what will be done if any element of the program fails?

t. Who will handle the secretarial, mailing, etc. tasks?

u. Will services be provided free, or will there be cost-sharing?

v. If more farmers sign up for the program than the funds can handle, how will the participating farmers be chosen?

w. What will be the responsibilities of each of the players?

The first skill required, then, is to be able to accurately identify these and other questions. The ability to properly identify and answer these questions is absolutely crucial to the success of a water management program.

All of the questions listed above could be discussed, but only a few will be covered in this presentation. For more detailed information, a copy of the program description and sample report formats can be obtained through OWC/DWR.

Objectives

The objectives of the WRCD/WWD programs were to:

1. Evaluate existing irrigation systems.
2. Improve irrigation efficiency and distribution uniformity.
3. Reduce subsurface drainage contribution.
4. Maintain or increase crop yields.

Plant nutrition and soil fertility analysis, although very useful for crop production, are not a a part of the program. Only irrigation scheduling and evaluation services (offered together) are cost-shared.

On-Farm Measurements, Reports, etc.

The Water Conservation Program provides information to a farmer on a timely basis in order to implement appropriate changes in water management. A simplified list of tasks includes:

November interview.	In an interview with the farm manager and irrigation foreman, past management practices and water records are determined.
November field work	Determine water table heights, soil types, soil and water EC, irrigation system geometry, field boundaries, etc.
Report #1 (Dec 1)	Documentation of the November interview and field measurements. This report includes graphs of past irrigation performances, a schedule for next year's irrigation, and an executive summary.
Pre-pre-irrigation strategy meeting	A week before the pre-irrigation, the farmer reviews potential for modifications to that irrigation.
Pre-irrigation evaluation	A detailed evaluation of the field irrigation performance, including (for furrows) a hydraulic analysis of an individual furrow, examination of set time and soil differences, determination of deep percolation, beneficial use, and irrigation efficiency and distribution uniformity. Identification of ways to improve that irrigation. Measurement of water table heights before and after irrigation.
Report #2 (March 31)	Conclusions and data from the pre-irrigation evaluation
Irrigation Scheduling	Irrigation scheduling information based upon the crop type, climate, soil water holding capacities, etc. is provided throughout the growing season.
Water meter readings	Individual irrigations are observed and water meter readings are taken throughout the year to determine annual performance.
Prior reg. irrig. meeting	Prior to one of the first regular irrigations, another meeting is held with the farmer to review practices and suggest changes.
Regular irrig. evaluation	A detailed evaluation of the field irrigation performance is done for a regular irrigation during the summer.

Report #3 (July 31)	Results of the regular irrigation evaluation are presented, along with economic implications and recommendations.
Report #4 (Sept. 30)	Annual irrigation performance is presented in tables and graphs, along with supporting data. Recommendations are given.

Program Administration

The WRCD and the Office of Water Conservation, California Dept. of Water Resources (OWC/DWR) began a dialog which resulted in the decision to have a program. The WRCD, not having any permanent or full-time staff or significant bank account, or even an office space, must rely on outside technical and administrative assistance. A good cash flow is also essential.

The USDA/SCS has traditionally provided technical support for RCD's, and the Fresno office of the USDA/SCS has worked on all phases of the project. Due to the heavy committment of SCS personnel to other programs, it would have been difficult if not impossible for the USDA/SCS to be solely responsible for the timely implementation of this Water Management Project and to review reports.

James Tischer of The Tischer Group in Fresno, was selected by the WRCD to serve as program coordinator. His task was to arrange the contract and cash flow with DWR and to coordinate efforts by all the various entities which were to be involved. The skills required by a program coordinator are considerable due to the large dollar amount of the contracts and the wide variety of organizations and individuals which eventually interact.

At the same time, OWC/DWR contracted with Cal Poly for myself to serve as its quality control specialist in the program, and to work with the WRCD to develop a technically meaningful program. The role which I have played is fairly unusual for a university contract. In addition to helping in the development of the program, I was also part of a decisive team which insisted on high standard and and occasionally payment until problems were solved. As technical advisor, a necessary skill is to be decisive about the need to maintain reasonably high standards.

After a few discussions with the water management specialists at WWD, WWD decided (in 1986) to embark upon an identical but independent program, and to pool educational, advertisement, and some technical resources for a common goal. This interaction of WWD and the pooling of ideas was instrumental in developing a successful program.

One skill is absolutely necessary for all key players in a Water Management Program: timeliness. The program must be initiated well before the irrigations begin, payments must be made in time, reports must be checked on time, reports must be submitted to growers rapidly so that changes can be made immediately, instructions must be received on time, etc. If information is collected at the wrong time, if it is provided too late, or if the quality controllers are not aware of a problem as soon as it arises, the chances for failure and frustration are enormous.

<u>In-house or contract out?</u>

Water Management Programs can be conducted in-house. WWD, for example, has a Water Management staff. However, a program of this magnitude, with over 180 fields, would require a large increase in staff. Both WWD and the WRCD decided to hire private consultants to do the actual evaluation and scheduling work. Over the past few years, OWC/DWR has tried to channel much of its water conservation funding into joint public/private ventures such as this.

I believe there are many good reasons to involve private consultants. These include:

1. Private companies in the agricultural industry know how to "hustle". They are set up to make hard, fast decisions and to act quickly.
2. Private consultants command a whole range of knowledge which is often not held by government employees. The people they talk with, their economic constraints, and the activities they engage in provide a different set of experiences.
3. It may be easier to hold private companies accountable for work done than it is to hold a government agency accountable. Because of inter-office politics, unions, hiring policies, etc., it is more difficult to hire and fire people in a government agency.
4. Private companies are available with the expertise needed, and are able to mobilize quickly to meet the demands. **It should be pointed out that government agencies cannot expect top efforts from consulting companies to mobilize unless there is a reasonable promise of work for more than one year.

Government agencies can play a key role in improving the professionalism of private agricultural consultants by utilizing them more, by specifying performance criteria, and then by providing quality review of the work. By insisting that the agricultural consultants meet high standards of education and experience, the professionals can be recognized as such and be properly compensated.

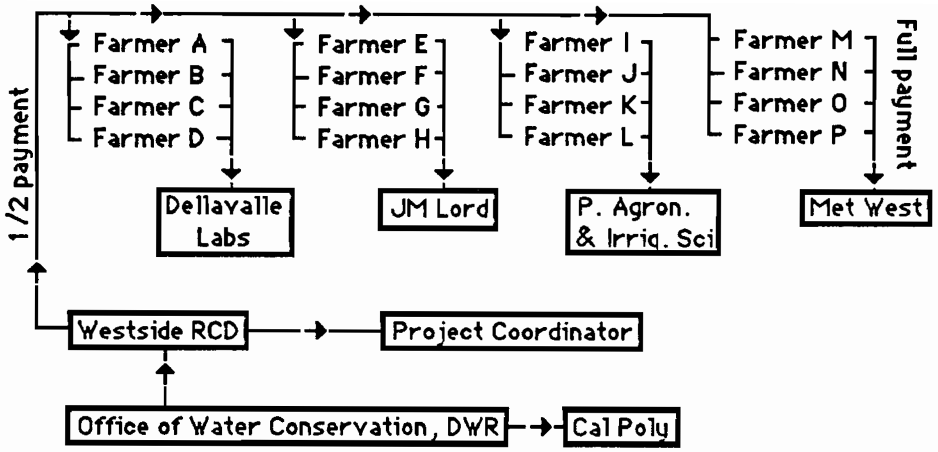

Figure 1. Payment flow in the 1987/87 WRCD Water Conservation and Drainage Reduction Program.

Quality control

In order to obtain a quality product, the following steps must be accomplished:

1. The task must be clearly defined before-hand.
2. The exact report format must be specified.
3. The exact methodology for computations and data collection must be specified.
4. The review process must be defined.
5. The review process must indeed take place, and be substantial.
6. A means must be available for private consultants to correct errors, and to terminate a contract if errors continue.
7. Meetings and training programs must be established to make certain the consultants understand why and how things must be done.

Some (not all) private consultants will not initially delivery quality work, even if they are capable of doing so. This was obvious when some of the first reports were submitted in the 1986 program. I believe that this initial lack of internal quality control on the part of some private consultants has been partly responsible for the lower wage standard for professional agricultural services. Experience has indicated that if some companies do not provide a quality product, yet are not "called on the carpet", eventually the work quality of the other consultants also begins to decline.

I believe that it can be unequivocally stated that without a strong quality control program of immediate, thorough, continuing, and documented reviews, a Water Management Program has almost no chance of success. Glowing reports and irrigation efficiency numbers may be published at the end of an unmonitored program, but they are probably meaningless.

Why are reports needed?

Program advisors and their staff members are key elements in the success of the WWD and WRCD programs. They, not WWD and WRCD, are responsible for assessing irrigation performance, making recommendations, and communicating this knowledge in a clear, concise, and understandable manner.

It has been argued by program advisors that reports are just "paper" and farmers are not interested in them. The WWD and WRCD programs required complete reports in very specific formats, with calculation procedures closely defined. When participating farmers were interviewed by SCS and WWD staff, James Tischer and myself, they responded that the paperwork was "about right".

Some say that the "experience" of the program advisor and the ability to "communicate" with the grower is much more important than reports. Therefore, one argument goes, reports are primarily a waste of time.

These comments bring to mind a statement which has been made by a farm manager in the WWD. That manager was discussing his frustration with irrigation "experts" which had visited his ranch and made recommendations. He said that each expert seemed to come to a different conclusion as to what should be done to solve the ranch's problems.

I believe that there are several reasons the recommendations were so varied:

1. The manager, although very experienced in irrigation, may not know how to make the proper selection of a true expert consultant, or may not know how to specify exactly what service he wants.
2. With a mix of good and bad consultants, the advice was bound to vary.
3. In the past, methods of irrigation evaluation have not been standardized. Even if consultants had good educations and experience, they could come up with entirely different numbers for irrigation efficiency, deep percolation, etc.

The variation in quality of recommendations was very evident when the first reports arrived during the first year of the program. Even though care had been taken to specify procedures and reporting format, numerous problems existed. These included:

1. Whole pages were missing in reports.
2. Numbers did not match up or make sense.
3. Some consultants had many excuses for not being able to accomplish certain tasks; other consultants accomplished the same tasks under the same constraints and did an excellent job.

4. Some recommendations were just plain incorrect.

The reports gave the program administrators immediate feedback as to how competent and complete the various program advisors were. It enabled the appropriate modifications to be made so that the program would go ahead on a positive basis.

In summary, I would conclude that if the proper recommendation cannot be made and substantiated on paper, the correct advice will certainly not be given to the farmer. It was our belief that friendly bad advice was worse than no advice at all. Reports provided the check needed on the progress of the program.

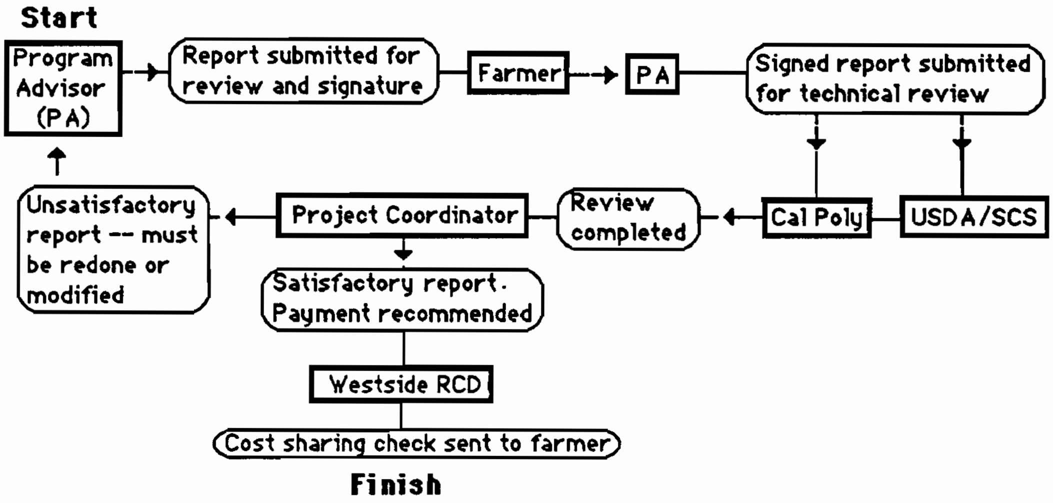

Figure 2. Lines of communication and quality control for each report.

Program Advisor Qualifications

There are a good number of competent irrigation consultants in the Fresno area. Our job as program administrators is to:

1. Determine which ones have the necessary qualifications.
2. Clearly define their obligations so that they can make an economic decision as to the value of participating in the program and how they will schedule work.
3. Monitor their work to assist them in providing a top quality product to the farmers.

Prior to acceptance as an approved "program advisor", consultants now must present their qualifications in writing and appear individually to answer capability questions posed by a panel made up of WWD, James Tischer, the SCS, and myself. Not all applicants are accepted. The next paragraphs discuss some of those qualifications and why they are important.

Team Makeup. A "program advisor" is a company made up of a team of individuals. This team must include (1) an agronomist or soil/water scientist, and (2) an engineer specializing in irrigation. The team must be part of a formal business relationship. The requirement of having an engineer on the team was met with a large resistance by some original program advisors, but is considered essential by the administrators. Agronomists and soil scientists in general do not have the background in irrigation system modification and number manipulation that engineers have. The requirements have also been tightened up to specify the management experience and specific educational requirements.

Broad requirements such as "a degree in agriculture or a related subject" simply cause headaches. The fact is that individuals do go to universities and rigorously study subjects such as irrigation and agronomy. Therefore, the logical people to choose for irrigation and agronomy consultants are those people. When high educational standards are not required, it is equivalent to saying that dedication to studying a speciality has no reward and that anyone can do the same job.

Agronomist or soil/water scientist. This individual(s) must have an B.S. degree with a major in agronomy, soils, water science, or a closely related field and two years field experience in (1) on-farm water management; (2) irrigation scheduling by water budget method; (3) irrigation evaluations of furrow, sprinkler, and drip irrigation systems; and (4) managing a perched saline groundwater table.

Engineer specializing in irrigation. This individual(s) must have a B.S. degree with a major in agricultural, civil, or irrigation engineering and have an Engineering in Training (EIT) certificate, plus two years field experience in (1) the design and evaluation of furrow, sprinkle, and drip irrigation systems; (2) irrigtion scheduling by water budget method; and (3) managing a perched saline groundwater table.

Supplemental training. All program managers or team members having direct contact with growers or being responsible for reviewing and submitting reports must have attended the short course entitled "Irrigation Evaluation" presented by the Agricultural Engineering Department of Cal Poly, San Luis Obispo. This 3 day short course, offered twice a year, provides review , a standard vocabulary, and a standardized procedure for conducting evaluations.

This standardization is extremely important. If two different companies give reports of "irrigation efficiency" in the same program, it is essential that the numbers were arrived at using the same techniques and calculation methods.

Ability and willingness to understand and follow program guidelines. Program advisors must understand that programs have certain administrative and quality control requirements. These programs, out of necessity, must have consistency in reporting format and procedure. Production agricultural consultants are accustomed to operating independently without review, and quality control procedures and reports can be viewed by some as burdensome. Program administrators do not have the money and time available to argue such points. On the other hand, the quality control should be reasonable, and the program administrators must incorporate constructive recommendations into the program at an appropriate time.

Ability to write a report. In a report the numbers must coincide, reports must be complete, and summaries must be made. When reports cannot meet these requirements, it is either because the report was considered to be unimportant or because the consultant is incapable of preparing a proper report. Both situations can be encountered.

Management expertise. A successful program advisor company must carefully schedule its work and personnel to accomplish the task on time.

Internal quality control. Consultants should initiate internal quality control procedures on work. This is much less expensive than having to resubmit a report one or more times before acceptance.

Communication skills with farmers. The best recommendations in the world will not be implemented unless theprogram advisor can convince the farm manager and perhaps the owner and irrigator, also.

Summary

A successful Water Management Program requires skills by a wide range of people. Consultants, technical advisors, and funding agencies must cooperate to develop a meaningful program which will provide some benefit to the ultimate customer, the farmer.

BIOTECHNOLOGY IN THE RHIZOSPHERE:

SOME APPLICATION AND LIMITATIONS

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Crop improvement through selection and culturing of plants with desirable traits has been on-going for centuries. More recently, attempts by plant breeders have sought new sources of genetic variation for use in improving cultivated varieties beyond the boundaries of a single species to crosses among species and even to intergeneric crosses. Many hybrids have been produced in this way despite the many intervening natural barriers. Even when hybrids are produced by this "traditional" exchanging of genetic material among parents by the sexual process of cross-fertilization, the products are not necessarily ready for or useful in agriculture. A major problem remains of separating out the gene responsible for a desirable trait from others, possibly deleterious, to which it may be linked - a time-consuming and laborious process. Repeated back-crossing of subsequent generations to the appropriate parent is the technique of choice here, but success is by no means guaranteed.

The newer techniques of gene transfer by non-sexual methods expand the opportunities for improving crop varieties, in principle, beyond introducing genetic variablility from closely related sources to any source of DNA, even that synthesized chemically. With the exception of protoplast fusion, these methods should also bypass any incompatibility between parents and remove the need for back-crossing associated with the imprecise multi-gene transfers which occur with plant breeding techniques (1,2). In principle, it is also possible to target the tissue in which the gene is to be expressed and both the timing and level of its expression. In practice, major problems remain with using these techniques on agriculturally important crops. The most advanced technique of Agrobacterium-mediated gene transfer (3) has been limited to the Solonaceae (tomato and potato) until recently, when cultured soybean cells were transformed, but not regenerated into complete plants. The situation is even less encouraging with the important monocots (wheat, rice and corn), where not even gene transfer has been demonstrated by this way. Stable maize cell lines have, however, been transformed by direct transfer of DNA into protoplasts and complete rice plants have been regenerated from protoplasts.

As yet, these non-sexual genetic transfer techniques have not produced a crop variety in use commercially nor, in fact, have many useful traits been non-sexually transferred. But it must be emphasized that the application of these molecular biology techniques to agricultually important crop plants and microorganisms is still in its infancy. The major goals in agricultural biotechnology are yield and quality improvement and resistance to stress, disease and pests, effectively identical to those of any plant breeding program. Biotechnology is then a complement to conventional breeding techniques, both will be necessary for the successful commercialization of any newly engineered variety.

Roles of Microorganisms in Crop Production Systems

Because of the more extensive research background, these microbes may well be more easily manipulated and used to appropriate agricultural effect than the plant. In addition to being used as a source of vectors for insertion of foreign DNA into plants, a spectrum of roles for microorganisms exists, either adverse or beneficial. The impact of each on crops is very difficult to assess because only those causing obvious and extreme damage or loss or positive benefit are usually quantified.

Along with the direct application of biotechnological methods to plant improvement, a companion approach involves soil microorganisms. Plants are exposed to enormous numbers of microorganisms, many of which will have an impact on the plant's production and performance by either direct or indirect interactions. These interactions may affect any or all of the goals set in crop improvement programs. Thus, the understanding of the molecular bases of such interactions and the chemical and biological processes involved, followed by the appropriate biotechnological manipulations, could well have as significant an impact in agriculture as direct manipulation of the plant itself.

Overcoming Adverse Interactions of Microbes with Plants

Immunity to Plant Pathogens

Infection by either pathogenic microorganisms or insect pests results in at least a yield reduction if not total crop loss. Biotechnology could impact here through both developing the existing biological control methods and producing new techniques. A major effort over the years has been to breed resistant plants, but in cases where the usable genetic pool lacks a recognized source of such resistance, this approach is not feasible. The molecular biology approach is not limited to any particular gene pool. In principle, any disease- or pest-repelling gene(s) from any source could be introduced and used as long as its product is non-toxic to the targeted consumers. For example, those genes for the toxins produced by the microbe, Bacillus thuringiensis, could be transferred either to a plant directly or to a root-colonizing bacterium, which could then protect the plant's roots specifically. Further, "inoculation" with an avirulent strain of a pathogenic organism has protected some crops from infection by the virulent form of the pathogen (4). Once genes important for virulence are recognized in more pathogens, they too may be "disarmed" by molecular genetic techniques and used for "inoculation". Pathogens might be modified so that they carry "killer" elements, which are transferred to and destroy unmodified forms of the same pathogen in the soil (5).

These approaches to controlling pathogens and pests suffer from two major limitations. Both are common shortcomings. The first is that, with very few exceptions, e.g., Agrobacterium, insufficient genetic and biochemical information is available for intelligent manipulation of the organisms involved. The second limitation concerns providing sufficient disarmed microbes to control the pathogen initially and then to compete with it and become established in the soil. This holds even though they should be in competition for the same environmental niches.

Amelioration of Local Environmental Effects

Adverse interactions of microbes with plant come about in various ways not necessarily involving direct association or infection. Microorganisms can compete with plants for nutrients, produce toxic materials and induce damage through, for example, ice nucleation. The last example is highly topical and one where deletion of DNA rather than supplementation by an additional gene results in the required effect. Here, the gene responsible for a bacterial protein is deleted from a leaf-surface-populating Pseudomonas species such that it can no longer initiate ice crystal formation, which would otherwise result in frost damage to the plant. The limitation here again is the central problem to all biological control methods, that of introducing and establishing sufficient numbers to compete effectively with the native population.

The problems of microbial competition with plants for nutrients and their production of toxic materials may be highlighted by consideration of the problem of plant residues remaining in the field after harvest. Should they be incorporated into the soil or removed, by burning for example? Some studies suggest that the microorganisms decomposing these residues may take up and deplete the soil's fixed nitrogen reserves. These microbes may also compete for fixed nitrogen when the succeeding crop is sown. In addition, stubble decomposition can produce organic acids, such as acetic acid, which are detrimental to seed germination (6). A positive biotechnological approach to this problem is to find naturally occurring organisms (or combinations) which produce a <u>net gain</u> in the fixed nitrogen balance. Then, the biochemical and genetic bases for the processes involved would be elucidated and finally, genetic manipulation of the cognizant microbes is attempted to increase the positive balance or efficiency of the system. In practice, combinations of microorganisms do exist, both in the laboratory (7) and, more importantly, in continuous commercial wheat cropping systems (8), which fix significant amounts of nitrogen from the decomposition of straw. The amounts of nitrogen fixed are extensive enough such that these wheat systems are largely independent of added fertilizer nitrogen. For utilization generally in agriculture appropriate microbial combinations for the various prevailing environments would have to be identified and established. Crop residue use in this way could reduce fertilizer nitrogen input and so prevent run off problems as well as conserve natural resources.

Enhancing Beneficial Microbe-Plant Interactions

Just how much increase in yield, for example, might accrue with, say, newly engineered, disease-resistant crops? Might they not be limited by the availability of nutrients? In this respect, it appears particularly important to understand how microorganisms facilitate nutrient delivery or uptake from the soil by plant roots and the effect of microbial metabolites as plant growth promoting substances.

Nitrogen-fixing Associations

Biological nitrogen fixation is a vital process in nature because fixed nitrogen is usually limiting for crop growth. This conversion of the normally inert atmospheric dinitrogen molecule to ammonia occurs only in prokaryotic microorganisms, which may do so either in a free-living state or in associations with plants, shrubs and trees (9). Only the very formalized symbiotic associations between various species of <u>Rhizobium</u> and legumes have any real agricultural value currently. These impact associations can fix up to 600 lb. N per acre annually, a considerable excess over that required by, say, a wheat crop, with essentially all of the biologically fixed N available to the crop. The potential for agricultural impact here is obvious and significant, if the process could be extended to crops generally.

Biological nitrogen fixation, however, has its problems. One is the energy cost involved. Whether this cost impacts growth and consequently yield is still under debate. It seems clear, however, that fixation by the enzyme *in vitro* comes close to the thermodynamic minimum and might reach it if the energetically wasteful evolution of hydrogen gas could be eliminated. In addition, the assimilation of nitrate from the soil may not be more cost-effective (15). A second problem is the enzyme's sensitivity to atmospheric oxygen. Protection is afforded in the leguminous symbiosis by bathing the bacteria in the nodule with leghemoglobin. This oxygen-binding protein provides oxygen at less than an enzyme-destroying level, but sufficient for bacterial metabolic purposes.

Opportunities obviously exist for manipulating this process either in systems currently constituted or in developing new nitrogen-fixing systems. It is clear that, if the energy efficiency of nitrogen fixation could be improved, the saved energy could be diverted to other plant processes and, if energy limited, yield increases should accrue. How this might be done is not at all clear. A similar situation exists with regard to oxygen sensitivity. Only recently are we beginning to explore the molecular architecture of nitrogenase (11) in attempts to determine appropriate targets. It is likely to take considerable ingenuity to circumvent the hydrogen evolution and oxygen-sensitivity problems, which some suggest might be inextricably intertwined with the reduction of dinitrogen.

Problems also exist at the organism level; although the fast-growing *Rhizobium* species are relatively easy to manipulate genetically, the slow-growing *Bradyrhizobium* species, e.g., that infecting soybean, are less firmly under control. In addition, the major obstacle here as in all attempts to manipulate bacterial populations in crop-soil systems is just how to establish *Rhizobium* strains in the soil and how colonization and eventual nodulation of plant roots occurs. These problems must be overcome if new desirable strains are to impact agriculture. One approach is to collect competitive strains for engineering; another would be to endow plants directly with the ability to fix nitrogen. Here with plants, just as with microbes, the two major enzyme-level factors, energy supply and oxygen protection, must be overcome. One thought is to insert and express the genes in the chloroplast, where excess energy resides and where oxygen-sensitive proteins already operate (12). Such manipulations, however, are not possible at our present stage of understanding and technique development.

A third option is offered by the symbioses between the nitrogen-fixing Frankia and woody dicots, where the same actinomycete nodulates a wide range of unrelated plants. Thus, a genetic analysis of how Frankia and its hosts interact should aid in increasing the spectrum of plants benefitting from symbiosis. Unfortunately, Frankia isolates have only fairly recently been grown in pure culture and even more recently, subjected to genetic analysis. However, sophisticated genetic techniques have been developed for related genera and should greatly assist in Frankia analysis in the future.

Symbiotic systems have been emphasized here for two main reasons. First, they have evolved in a regulated way with nutrient being delivered in the amounts and at the times required by the plant, which apparently has controls through the number and size of the nodules that develop. Thus, new symbioses or nitrogen-fixing plants must have or be endowed with similar regulatory features. Second, the nature of symbiosis is such that it should allow the involved microorganisms to be carriers of foreign genes. These may be expressed either by the microbe or the plant.

Endomyccorhizal Associations

The most important of these fungi, the vesicular-arbuscular mycorrhizal (VAM) fungi, form symbioses with almost all major types of crop plants. They are involved in a variety of functions, including nutrient (mainly phosphate) and micronutrient uptake, ameliorating drought stress and conferring resistance to pathogens, which benefit their hosts. The fungi may be thought of as extensions of the root system to mobilize otherwise unobtainable or immobile nutrients in the soil. Unfortunately, it is not possible yet to culture these fungi ex planta and this formidable obstacle must be overcome if the full potential of biotechnological applications is to be realized (13). As with Frankia, their broad host range offers the advantage of using a single engineered strain to colonize a wide range of plants and be a transporter of foreign genes into hosts. Possibilities exist for introducing either nitrogen-fixation or other beneficial genes, e.g., for substances toxic to pathogens, into the fungus or incorporating nitrogen-fixing bacteria within the hyphae.

The gene products may not even need to be transported into the host. But problems exist with these approaches: (i) what molecules (size and type) can be exchanged between fungus and host?; (ii) can engineered strains be re-introduced and compete effectively?; and (iii) are controls available to ensure that only the targeted crop receives the genes (or products) being transferred?

All these presuppose the presence of effective transformation systems for VAM fungi. There are none, although some may develop from those currently available for filamentous fungi like Aspergillus and Neurospora. In addition, these fungi are multi-nucleate and it is unlikely all the nuclei will be transformed by introduced DNA. How rapidly these systems develop will depend in large part on success in culturing VAM fungi.

Bacterially-derived Growth Promotors and Protective Agents

Although free-living nitrogen-fixers, like Azotobacter and Azospirillum, some of which associate strongly with the external surfaces of roots, are of very limited value in agriculture based on their small annual rates of fixation (<100 lbs per acre), they are known to produce plant growth promoting substances, notably auxin (14). Many other rhizosphere microorganisms also do so. Presumably, all crops are exposed to such substances excreted by these rhizosphere microorganisms. As these populations vary, so their likely effect on the root systems must vary. Whether advantage can be taken of this situation by manipulating the population as a whole or by enhancing growth promotor production from sub-populations is unknown. Similar potential exists for manipulating rhizosphere populations to effect protection from root pathogens.

Conclusions

The recently introduced techniques of molecular biology have served to focus attention on gene transfers in general. But gene transfer is not new in agriculture. Such transfer between species and even genera have occurred in breeding programs for many years. Biotechnology has its basis in past studies of bacterial genetics and biochemistry and, in this context, is really just an extension of these techniques to crop plants. It constitutes a powerful tool to aid in the continued improvement of crops. It is difficult to predict or foresee all the opportunities and problems that will arise from current research efforts, particularly where neither the detailed biochemistry nor the genetic complexity of the desirable trait is understood.

As with the introduction of any new technique, some general questions arise. With such a broad spectrum of agriculturally important microbes and plants available for, and requiring improvement, how will priorities be determined? Should those crops already subjected to prior intensive breeding be first or those which have resisted or not received such attention? Temperate or tropical? Well studied or recalcitrant? Priorities and opportunities will change over time.

Concern over the release of microbes or plants with newly inserted genes into agricultural systems must also be addressed. It is difficult to imagine realistically any problem that could not be handled by existing testing and quarantine requirements. However, it might be very difficult to eliminate a microbe distributed into agricultural soils. The incorporation of, say, lethal agents into such microbes, which are then triggered by low temperatures, has been suggested as a control. In this way, these populations would be eliminated during the winter season.

It seems obvious that enhancement of the various beneficial effects and diminution of the adverse effects of microorganisms associated with the rhizosphere is likely to result in increased plant growth. Whether they will be of agricultural benefit, however, depends on how cost effective each and every change is to the farmer.

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