# ENGINEERING AND ECOLOGICAL EVALUATION OF ANTITRANSPIRANTS FOR INCREASING RUNOFF IN COLORADO WATERSHEDS

by

**Jay E. Anderson and Frank Kreith**

Colorado Water Resources Research Institute

**Completion Report No. 69**

Colorado State University

# ENGINEERING AND ECOLOGICAL EVALUATION OF ANTITRANSPIRANTS FOR INCREASING RUNOFF IN COLORADO WATERSHEDS

Completion Report

OWRT Project No. B-099-COLO

by

Jay E. Anderson and Frank Kreith

Department of Chemical Engineering

University of Colorado

submitted to

Office of Water Research and Technology

U. S. Department of the Interior
Washington, D. C. 20240

September, 1975

The work upon which this report is based was supported in part by funds provided by the United States Department of the Interior, Office of Water Research and Technology, as authorized by the Water Resources Research Act of 1964, and pursuant to Grant Agreement No.(s) 14-31-0001-4065.

COLORADO WATER RESOURCES RESEARCH INSTITUTE
Colorado State University
Fort Collins, Colorado

Norman A. Evans, Director

Table of Contents

# INTRODUCTION

The potential for water conservation and reallocation through reductions in transpiration is great because ninety-nine percent of the water absorbed from the soil by a plant is transpired into the atmosphere. In arid and semi-arid regions, actively growing plants with an adequate water supply (e.g. phreatophytes) will transpire a weight of water equal to their fresh leaf weight each hour. Phreatophytic vegetation in the Western United States covers about 16 million acres and transpires about 25 million acre feet of water each year. Salt cedar (Tamarix sp.) plants are estimated to cover over 1.3 million acres and to consume over 5 million acre feet of water per year (Robinson, 1965).

Transpiration reductions can be achieved in two general ways: (1) reduction of the transpiring surface by mechanical or chemical harvesting or eradication of the plants, and (2) reduction of the amount of water lost per unit leaf surface by treating the plants with chemical anti-transpirants.

Mechanical and chemical destruction of vegetation along irrigation canals and on watersheds has been widely used. However, permanent eradication of phreatophytis is seldom achieved, and these methods often also cause undesireable side effects, such as soil erosion, leaching of nutrients from the soil, increased silting of the waterway, loss of wild-life habitat, and decreased aesthetic value.

Chemical antitranspirants offer the potential for achieving significant water savings without seriously altering the ecosystem. Experiments conducted over the past decade and a half have demonstrated that antitranspirants

can appreciably reduce water consumption by plants (see e.g. Gale and Hagan, 1966; Davenport, et al. 1969; Poljakoff-Mayber and Gale, 1972; Davies and Kozlowski, 1974). However, the results have varied widely depending on the chemicals and amounts used, the plant species, and the environmental conditions.

Metabolic antitranspirants, which reduce stomatal aperture, have been found to reduce water consumption appreciable for periods of a week or more. But some of them have proved toxic to a variety of herbaceous and woody plants (Davenport, et al., 1971; Mishra and Pradham, 1972; Kreith, et al., 1975). However, recent studies indicate that naturally-occurring antitranspirant compounds such as abscisic acid and all-*trans*-farnesol may have promise as commercial metabolic antitranspirants without causing undesireable side effects (Ogunkanmi, et al., 1974; Wellburn, et al., 1974).

Film-forming antitranspirants, which reduce transpiration by coating the leaf with thin, water-impervious film, have been found to be less toxic and to have a longer period of effectiveness than metabolic antitranspirants (Davies and Kozlowski, 1974; Kreith, et al., 1975). Again, however, reported results vary aprreciably, depending upon (1) the plant species, (2) the antitranspirants and methods of application, and (3) the environmental conditions under which the plants were grown and the ambient environmental conditions at the time of antitranspirant application.

## PURPOSE AND SCOPE

The objective of this study was to evaluate the potential of using chemical antitranspirants on phreatophyte communities to increase watershed runoff and streamflow. More specifically, the research included (1)

laboratory evaluation of the effects of the most promising antitranspirants currently available on transpiration and photosynthesis of Tamarix sp. (2) phytotoxicity trials in the laboratory and in the field, and (3) field evaluation of one antitranspirant on Tamarix at the U.S. Bureau of Reclamation Evapotrnaspirometer Site at Bernardo, New Mexico.

In the summer of 1974 the original work plan was modified to include antitranspirant screening studies for the U.S. Bureau of Land Management (BLM). The BLM is interested in the potential of using antitrnaspirants along roadsides in the intermountain west to conserve soil moisture, which could, in turn, maintain the vegetation in a green state for longer periods and reduce fire hazard during the latter part of the growing season. The immediate objective of our studies for the BLM was to evaluate in the laboratory the effects of two antitranspirants on transpiration and photosynthesis of several species representative of roadside vegetation.

For convenience, the "Results and Discussion" section of this report is divided into "BLM Studies" and "Phreatophyte Studies".

## METHODS

### Plant Culture

The sources of plant materials for both the BLM and phreatophyte studies are shown in Table I. Stock cultures were maintained in a greenhouse at ambient temperatures ranging from 15° to 35°C. Photoperiod was extended to 16 hours during the winter months. Experimental plants were grown in a Warren/Sherer model CEL 36-10 controlled environment chamber programmed for a 16 hour photoperiod and a 25°C day/15°C night thermal regime. Plants in the growth chamber were watered daily,

alternating between Hoagland's solution and tap water.

Table I. Sources of Plant Material

| Species | Common Name | Source |
|---|---|---|
| *Achillea millifolium* L. | Yarrow | Vegetative clones collected at 5800' near Deer Lodge, Powell County, Montana |
| *Agropyron cristatum* (L.) Gaertn. | Crested wheatgrass | Seed collected from roadside, Interstate 80, Elk Mountain, Wyoming |
| *Elymus Canadensis* L. | Canada wild rye | Seeds collected from roadside, Deer Lodge, Montana |
| *Melilotus officinalis* (L.) Lam. | Yellow sweetclover | Seed purchased from Farmers Marketing Association, Denver Lot 14-305 |
| *Tamarix pentandra* Pall. | Salt cedar | Cuttings obtained from U.S. Bureau of Reclamation Site, Bernardo, New Mexico |

## Transpiration and Photosynthesis Measurements

Transpiration and net photosynthesis were measured with an open, gas exchange system similar to that described by Anderson and McNaughton (1973), but utilizing the plant cuvette described by Mooney, et al. (1971). Briefly, the plant top was sealed into the plexiglass cuvette through which air was circulated at a known flow rate. The net photosynthetic rate was determined by measuring the carbon dioxide concentrations of the air entering and leaving the cuvette with a Beckman 865 infrared gas analyzer. The infrared gas analyzer was calibrated daily against standard gases containing zero and 320 ppm carbon dioxide. The system was sensitive to carbon dioxide concentration changes of 1 - 2 parts per million.

The transpiration rate was determined by measuring the relative humidity of the air entering and leaving the chamber and calculating the amount of water added to the air stream. The relative humidity was determined with narrow range lithium chloride hydro-sensors (American Instrument Company, Silver Spring, Maryland) sensitive to relative humidity changes of 0.1 percent.

The accuracy of the transpiration measuring system was determined using a modification of the technique suggested by Tranquiliny and Caldwell (1972). The amount of water evaporating from an open plastic Petri dish base was measured gravimetrically and simultaneously with the gas exchange system. Paired results of ten trials at different cuvette temperatures and relative humidities agreed within 2%.

Cuvette temperature was maintained within 0.1°C by circulating an ethylene glycol solution through the cuvette heat exchanger from a constant temperature water bath. A fan within the cuvette provided for efficient heat exchange as well as excellent temperature control and prevented gradients in carbon dioxide or water vapor concentration. The cuvette temperature was measured with a thermistor and/or a copper-constantan thermocouple.

In the laboratory the plant was illuminated by one 500 watt quartz lamp (GE Q500 PAR56MFL) placed at a distance of 34 cm from the cuvette and one 150 watt tungston shaded spotlamp placed 15 cm from the side of the cuvette. Light in the cuvette (approximately 1/3 full sunlight) was near saturation for photosynthesis and above saturation for maximal stomatal opening for all species studies.

For the field studies, the cuvette was mounted on a heavy duty, TV tripot (Elevator Hi-Boy IV, Quick Set Inc., Northbrook, Illinois), which

can be adjusted to heights of up to 2.7 meters for use on shrub and tree branches. For measurements on salt cedar branches in the top of the canopy, each tripod leg was further extended with two one meter lengths 3.8 cm diameter plastic pipe telescoping on a wooden dowel. With this extension, the cuvette could be raised as high as 4.5 meters. The other components of the gas exchange system used in the field were housed in a small utility trailer. A nine meter umbilical cord containing water and air lines and thermocouple and thermistor wires coupled the cuvette to the measuring and recording components in the trailer. Cuvette illumination in the field was provided by full sunlight.

## Laboratory Antitranspirant Experiments

A plant was removed from the controlled environment chamber, sealed into the cuvette, and illuminated until transpiration and net photosynthesis reached steady state values. The plant was then removed from the cuvette and sprayed to run off with antitranspirant, using a Binks Model 15 paint spray gun. The plant was then returned to the growth chamber to allow the antitranspirant to dry, and then was returned to the cuvette periodically for transpiration and photosynthetic determinations. Control plants were treated identically, except that they were sprayed with distilled water. All laboratory experiments were conducted at 25°C air temperature and a relative humidity of from 35 to 42% inside the cuvette.

## Field Studies

Field studies were conducted at the United States Bureau of Reclamation Evapotranspirometer Installation at Bernardo, New Mexico, approximately 55 miles south of Albuquerque near the Rio Grande River.

At this site nine evapotranspirometer tansk, each 12 feet deep with a 1000 square foot surface, had been constructed in 1961-62. Each tank was lined with 1/16-inch butyl rubber and after construction, native soil was returned to each tank in as near the original profile as possible. Presently, four tanks are planted with Tamarix, two with Russian olive, two with salt grass, and one measures evaporation from bare ground. The surrounding area, which was originally cleared to facilitate construction of the tanks, was planted with Tamarix to eliminate any oasis effect. Evapotranspiration from each tank is determined by measuring the amount of water which must be added to maintain a constant water level. The water supply to each tank is regulated by a solenoid valve controlled by a suspended probe assembly and relay. As the water level falls below the lower probe, the relay is de-energized, completing the electrical circuit opening the solenoid valve. As the water table reaches the upper probe, the relay is energized and the valve closes. The amount of water added is measured by standard water meter to the nearest one-tenth.

Tamarix plants were planted on the tanks and surrounding area at a density of 1 plant per square foot, or 100 plants per evapotranspirometer, which was typical of the undisturbed Tamarix in the area. Our studies were confined to tanks 4, 5, and 6 which have similar Tamarix stands. Water consumption on the fourth Tamarix tank (Number 3) was too low to serve as a valid control.

Evapotranspirometer Number 6 served as a control for all studies. Number 4 was sprayed with 15 liters of 10% Mobileaf on 16 June 1975 and 17 liters of 15% Mobileaf on 24 June 1975. Tank number 5 was sprayed with 18.5 liters of 15% Mobileaf on 18 June 1975. The results of the second spraying of tank 4 were not available for inclusion in this report.

Antitranspirant was applied in the field with a KWH 66 Power Knapsack Mist Blower. In the first application on tank 4, the antitranspirant was applied primarily by spraying from the top of a 14-foot ladder which was moved around the periphery. In subsequent sprayings, individual plants were sprayed from top to bottom at close range with the operator standing on the ground, then the canopy was sprayed from the ladder top on the tank periphery.

Spray coverage was evaluated by two methods. Thirty-two paper tags, each with a microscope cover slip glued to it, were hung by strings at approximately 0.5, 1.5, 2.7, and 4 meters height on eight plants on each evapotranspirometer that was sprayed with antitranspirant. After spraying when the droplets had dried, the tags were collected for later evaluation of spray spattered density. Coverage was also evaluated on a random sample of twigs that were air freighted to the University of California, Davis, for scanning electron microscope cathode illuminescence studies. These studies are being completed by co-workers at the University of California, Davis, and are not available for inclusion in this report.

Field gas exchange studies were conducted on evapotranspirometers 5 and 6. The end of an intact branch 10 to 15 cm in length was sealed into the cuvette and steady state transpiration and net photosynthetic rates in full sunlight measured. Prior to spraying, steady state values were measured on 8 brnaches of plants on evapotranspirometer 5 and 7 branches on number 6, the latter serving as controls. During spraying, two of the eight branches on tank 5 were covered with plastic bags, to also serve as controls. When first measured, each branch was carefully tagged so that the same amount of plant material would be present when the branch was returned to the cuvette for periodic measurements after spraying. Green

leaf material was harvested after the last measurement had been taken on a branch, and also fresh and dry weight were determined so that rates could be compared on a unit plant material basis.

## Antitranspirants

The antitranspirants included in the study are shown in Table II. A literature review, and discussions with co-workers at the University of California, Davis, indicated that these were the most promising film type antitranspirants currently commercially available. They are also representative of the different types of chemicals used as film-forming antitranspirants.

Table II. Antitranspirants Included in the Study

| Antitranspirant | Type of Material | Concentrations Used | Manufacturer |
|---|---|---|---|
| Mobileaf* | Wax emulsion in water | 5-16.5% v/v, (stock solution diluted in water) | Mobil Chemical Company P.O. Box 26683 Richmond, VA 23261 |
| Wilt Pruf* | Beta pinene emulsion in water | 16.5% v/v, (1:5 dilution of stock solution in water) | Nursery Specialty Products 410 Greenwich Ave. Greenwich, CT 06830 |
| XEF-4-3561 | Siloxane emulsion in water | 5% siloxanes (1:9 dilution of stock solution in water) | Dow Corning Corporation Midland, MI 48640 |

*FDA approved for direct application to edible crops.

## Phytotoxicity Trials

On 27 May 1975, 5, 10, and 15% concentrations of Mobileaf were sprayed on Tamarix branches at the Bernardo evapotranspirometer site. Two branches received a heavy application (thorough drenching) and two received a light or application at each concentration. The branches selected were exposed

to full sunlight. Periodic observations revealed no apparent discoloration within a month after treatment. Studies conducted out of doors on growth chamber-reared Tamarix plants at Boulder, Colorado, during late May and early June similarly showed no apparent phytotoxicity at similar spray concentrations, but ambient temperatures at Boulder were cool and rains were frequent during the tests.

## RESULTS AND DISCUSSION

### BLM Studies

XEF (5% solution) reduced transpiration and photosynthesis of Achillea Millefolium 40-60% within a few hours after spraying; however, both rates returned nearly to their original values within two days (Figure 1). Mobileaf (10% v/v solution) produced only a 10-30% reduction in transpiration and photosynthesis of A. millefolium, but at that concentration the Mobileaf did not appear to cover the surface well. A mixture (50:50 v/v) of 5% XEF and 10% Mobileaf produced about an 80% reduction of both transpiration and photosynthesis of A. millefolium, but also its effectiveness decayed within two days. Coverage of the finely dissected, pubescent Yarrow leaves appeared to be enhanced when using the mixture of antitranspirant compared to Mobileaf alone.

Because the XEF seemed to achieve larger initial reductions while Mobileaf appeared more persistent, we decided to conduct further experiments with both antitranspirants and a mixture of the two. The concentration of Mobileaf in subsequent experiments was increased to 16.5% (1:5 v/v dilution in distilled water), the concentration recommended by the manufacturer for treating tobacco transplants. The antitranspirant mixture in subsequent experiments was prepared by diluting stock Mobileaf 1:5 v/v in the 5% XEF solution.

Transpiration rates of Agropyron cristatum plants sprayed with 5% XEF were indistinguishable from controls after 24 hours (Figure 2). The pattern for photosynthesis was very similar. Because of the rapid decay of antitranspirant effectiveness of XEF on both Achillea millefolium and Agropyron cristatum, it seemed highly doubtful that this antitranspirant would be suitable for meeting the objectives of this project. Thus, no further trials with XEF on the herbaceous species were conducted.

Mobileaf (16.5%) reduced transpiration of A. cristatum plants 40-50% (Figure 3). The parallel slopes for the control and treated plants after 30 hours shows that most of the apparent decay of antitranspirant effectiveness is due to growth, i.e., the addition of new leaf surface. Note that control plants were adding biomass so rapidly that transpiration rates nearly doubled in four days. This rapid growth was typical of the four herbaceous plants studied, and emphasizes the necessity to correct antitranspirant data for the growth of controls in order to obtain an accurate picture of duration of effectiveness.

In Figure 4, the transpiration data are the same as those plotted in Figure 3, but the rates have been corrected for the growth of controls. The parallel reductions of transpiration and photosynthesis indicates that the antitranspirant film imposes a similar barrier to the diffusion of carbon dioxide and water vapor. It seems probable that the film is essentially impervious to both gases, and the magnitude of the reduction in rates is indicative of the extent of leaf surface coverage.

Initial reductions in transpiration and photosynthesis of A. cristatum treated with the Mobileaf/XEF mixture were greater than with Mobileaf alone (cf. Figures 4 and 5). However, effectiveness appeared to decay more rapidly with the Mobileaf/XEF mixture. Similar patterns were found

in experiments on Elymus canadensis plants (Figures 6 and 7); but there was no doubt that effectiveness of the antitranspirant mixture decayed more rapidly than that of Mobileaf alone. After nine days, rates of the Mobileaf/XEF treated plants were indistinguishable from controls, whereas rates of Mobileaf treated plants were only ca. 60% of controls (Figure 6).

We repeated the experiments on Achillea millefolium, comparing the effects of the Mobileaf/XEF mixture to 16.5% Mobileaf. The results were essentially identical to those for A. cristatum and E. canadensis. The mixture resulted in a larger initial decrease in rates but effectiveness decayed more rapidly than with Mobileaf only. The short-term enhancement of effectiveness appeared to be more than offset by the long-term reduction of effectiveness.

Twelve days after treatment, transpiration and photosynthesis of A. millefolium plants treated with 16.5% Mobileaf were still significantly lower than controls (Table III). Average transpiration rate of treated plants was 51% that of controls, while net photosynthesis of treated plants was 62% of the control rates.

Table III. Transpiration and net photosynthesis of Achillea millefolium plants 12 days ater spraying with 16.5 Mobileaf or distilled water (controls).

| Transpiration g $H_2O$/g dry weight leaf · hr | | Photosynthesis mg $CO_2$/g dry weight leaf · hr | |
|---|---|---|---|
| Mobileaf | Controls | | |
| 7.7 | 3.5 | 53.8 | 31.8 |
| 7.3 | 4.4 | 43.1 | 31.2 |
| 6.6 | 3.6 | 48.1 | 27.7 |
| $\bar{x}$ = 7.2 | 3.3 | $\bar{x}$ = 48.3 | 28.8 |
| | $\bar{x}$ = 3.7 | | $\bar{x}$ = 29.9 |

| | |
|---|---|
| $t = 9.4$ with 5 d.f. | $t = 6.5$ with 5 d.f. |
| $P < 0.001$ | $P < 0.01$ |

Mobileaf (16.5%) and Wilt Pruf (16.5%) resulted in similar initial reductions of transpiration of *Melilotus officinalis*, but long-term effectiveness was significantly better with Mobileaf (Figure 8).

Figure 8 points out two difficulties encountered in our antitranspirant research methods. First, there are practical limits on the amounts of plant materials that can be enclosed in the cuvette without causing mutual shading of leaves or restricted air circulation. Initially, one must have enough plant material in the cuvette for accruate rate measurements after antitranspirant treatment. Because of rapid growth, the *M. officinalis* plants had practically outgrown the capacity of the gas exchange system in two weeks. From Figure 8, one can infer that the average leaf biomass of control plants had tripled in the 14-day experiment.

Secondly, in longer experiments differences in the growth rates of individual plants become a problem. Note in Figure 8 that the standard error of both treated and control plant means becomes greater with time. This differential growth, especially of controls, makes it difficult to evaluate long-term effectiveness because antitranspirant effects may be obscured by the large sample variance. The solution to this problem, of course, is a larger sample; but one is again practically limited to measuring about eight plants per day with one gas-exchange system.

Although in Figure 8 transpiration appears to be reduced in treated vs. control plants on day 14, there was no significant differences in absolute rates of transpiration or photosynthesis (Table IV).

Table IV. Transpiration and photosynthesis of *Melilotus officinalis* plants 14 days after spraying with 16.5% Mobileaf, 16.5% Wilt Pruf, or distilled water (controls).

Transpiration
g $H_2O$/g dry weight leaf · hr

| Mobileaf | Wilt Pruf | Controls |
|---|---|---|
| 8.9 | 10.8 | 11.7 |
| 9.3 | 11.0 | 10.7 |
| 7.4 | 9.5 | 7.8 |
| 7.9 | 8.2 | 7.9 |
| $\bar{x}$ = 8.3 | $\bar{x}$ = 9.9 | $\bar{x}$ = 9.5 |

F = 1.2 with 9, 2 d.f.

P > 0.1 n.s.

Net Photosynthesis
mg $CO_2$/g dry weight leaf · hr

| Mobileaf | Wilt Pruf | Controls |
|---|---|---|
| 64.4 | 69.9 | 81.7 |
| 66.7 | 74.8 | 77.2 |
| 46.2 | 65.4 | 63.1 |
| 55.8 | 60.6 | 51.3 |
| $\bar{x}$ = 58.3 | $\bar{x}$ = 67.7 | $\bar{x}$ = 68.3 |

F = 1.2 with 9, 2 d.f.

P > 0.1 n.s.

## Conclusions and Recommendations: BLM Study

The results indicate that Mobileaf, Wilt Pruf, or similar antitranspirant formulations will effectively reduce transpiration of herbaceous species in the laboratory. Antitranspirant effectiveness, when corrected for growth of controls, appears to be satisfactory for 10-14 days after spraying. Obviously, because of rapid growth of new leaf area more frequent application would be necessary to achieve maximum water savings. This was found to be true for both dicotyledonous and monocotyledonous species.

The similarity of antitranspirant effects on all four species suggest that similar laboratory results could be expected with most herbaceous range or roadside species. It would be difficult, however, to achieve as thorough spray coverage in the field. Thus, the magnitude of transpiration reduction reported here probably indicates the maximum that can be achieved in the field.

An antitranspirant which would also function as a growth retardant, or a retardant/antitranspirant mixture, would be advantageous for meeting the BLM objectives. Several commercial growth retardants have been reported to have antitranspirant properties. We have obtained samples of two (Alar, a UNIROYAL product and Atrazine from CIBA-GEIGY Corporation) for laboratory trials singly and in combination with film-forming antitranspirants.

We would recommend the initiation of a small scale field study to attempt to quantify the magnitude of actual water savings along roadways by various antitranspirant treatments, including mowing. Using standard, inexpensive gravimetric soil moisture determination, it should be relatively easy to make quantiative estimates of the actual amount of

water saved. Comparing soil moisture on clipped and unclipped roadside stands should indicate the maximum potential for water savings and provide a good baseline to which values from areas treated with chemical antitranspirants could be compared. The relatively homogeneous extensive stands or reseeded vegetation along intermountain roadways provide a unique outdoor laboratory for such experiments.

## Phreatophyte Studies

Initial transpiration reductions in growth-chamber grown Tamarix plants treated with either XEF (5%) or Mobileaf (16.5%) were similar, but, as with the herbaceous species, XEF effectiveness was for more short-lived (Figure 9). Duration of antitranspirant effectiveness in Mobileaf-treated plants appeared to be better than that observed among the herbaceous species (compare Figures 3-8 with Figure 9). After six days, transpiration of the treated plants was still less than 55% of the original rates. Based on these results and discussions with co-workers at the University of California, Davis, Mobileaf was selected for use in the field studies at Bernardo, New Mexico.

Water consumption measured on Bernardo evapotranspirometers 4, 5, and 6 for the period with the exception of tanks 5 and 6 on 16 June, day to day variations among values for the three tanks tend to be parallel, indicating that the vegetation on the three tanks responded similarly to changing environmental conditions and that the measuring system recorded those responses. These data suggest that the integrity of the evapotranspirometers is good, but the water consumption data also raise some serious questions. Presumably, if all other factors were equal, the evapotranspirometers would respond identically to changing environmental

conditions. This obviously is not the case. For example, the decrease in water consumption on 17 June was due to afternoon cloudiness and high humidity on 16 June. But, the magnitude of the decrease on 17 June and following increase on 18 June was very different, especially comparing tanks 5 and 6. In addition, the percent of the total water consumed in 24 hours which was consumed during the night was usually higher on tank 6 than on 5 or 4 (Table V). There is no apparent reason for this difference, but it does indicate that there may be significant differences in the performance of the evapotranspirometers.

Table V. Comparison of "day" vs. "night" water consumption on evapotranspirometers 4, 5, and 6

Gallons of Water Consumed

| Evapotranspirometer | Date | "Day" 08:30-18:30 | "Night" 18:30-80:30 | % "Night" |
|---|---|---|---|---|
| | June 14-15 | 93 | 30 | 24 |
| | 15-16 | 96 | 44 | 32 |
| 4 | 16-17 | 79 | 31 | 25 |
| | 17-18 | 75 | 41 | 35 |
| | 18-19 | 87 | 57 | 39 |
| | June 14-15 | 128 | 53 | 29 |
| | 15-16 | 137 | 69 | 34 |
| 5 | 16-17 | 97 | 40 | 29 |
| | 17-18 | 104 | 44 | 30 |
| | 18-19 | 107 | 66 | 38 |
| | June 14-15 | 130 | 71 | 35 |
| | 15-16 | 116 | 77 | 40 |
| 6 | 16-17 | 109 | 60 | 36 |
| | 17-18 | 125 | 77 | 38 |
| | 18-19 | 129 | 100 | 44 |

The arrows in Figure 10 indicate the time of application of anti-transpirant. Tank 4 was sprayed with 10% Mobileaf between 9:00 and 10:00 AM on 16 June. The decrease in water consumption immediately

following spraying was probably due to afternoon cloudiness and high relative humidity. The data for the following days show a pattern very similar to that of the control tank (Number 6). No effect of the anti-transpirant application was apparent in the evapotranspirometer data.

Tank 5 was sprayed with 15% Mobileaf on 18 June. Again, no reduction in transpiration (water consumption) of the same order of magnitude expected from the laboratory results was found. The data suggest the possibility of some antitranspirant effect from 20-24 June. During the early part of the period, consumption on Tanks 5 and 6 were very similar. The large drop on Number 5 on the 17th was probably not due to spraying and it is not known. Whether the antitranspirant treatment was a factor in maintaining the lower rate of consumption on tank Number 5. If one assumes that the difference between the consumptions of Tanks 5 and 6 for for the period 20-24 June was entirely due to the antitranspirant, one could infer a maximum reduction in consumption of about a 30%. It seems doubtful that the difference was entirely due to the antitranspirant. The best interpretation is that the resulting water savings was probably something less than 30%.

Transpiration rates of individual branches after spraying, measured with the gas exchange system, are shown in Figure 11. None of the five sprayed branches showed a transpiration reduction of the same order of magnitude as was observed in the laboratory; initial reductions ranged from near zero to about 30 percent. Water consumption rates of sprayed branches were consistently lower than those of controls for six days after spraying, leaving little doubt that there was some antitranspirant effect. Absolute transpiration and photosynthetic rates on 24 June were significantly lower among treated than among control plants (Table VI).

Table VI. Comparison of transpiration and net photosynthetic rates of sprayed vs. control *Tamarix* branches 6 days after spraying at the Bernardo evapotranspirometer site.

| Transpiration ($g\ H_2O/g$ dry weight leaves · hr) | | Photosynthesis ($mg\ CO_2/g$ dry weight leaves · hr) | |
|---|---|---|---|
| Sprayed | Control | Sprayed | Control |
| 2.7 | 4.5 | 10.7 | 15.0 |
| 2.5 | 3.4 | 10.1 | 13.8 |
| 2.7 | 3.5 | 11.6 | 13.2 |
| 2.3 | 3.5 | 9.8 | 14.1 |
| 2.4 | $\bar{x}$ = 3.5 | 10.7 | $\bar{x}$ = 14.0 |
| $\bar{x}$ = 2.5 | | $\bar{x}$ = 10.6 | |
| t = 2.48 with 7 d.f. | | t = 7.17 with 7 d.f. | |
| P < 0.05 | | P < 0.001 | |

It should be noted that 2 of the control branches were on the sprayed tank (branches 5-6 and 5-11 in Figure 11). These were covered during spraying. The data for these branches is similar to the control branches in Tank 6.

It is encouraging that there was no large discrepancy between the evapotranspirometer results and the gas exchange results. Both suggest a transpiration reduction of somewhat less than 30%, and the gas exchange measurements indicate clearly that despite considerable "environmental noise" such a reduction can be detected in the field with an adequate sample size.

After several days of gas exchange measurements in the field it became obvious that the *Tamarix* plants were behaving quite differently than laboratory reared ones. Some appeared to have high transpiration and low photosynthesis rates, while in others the opposite was observed. This suggested a difference in stomatal resistance among plants. Water vapor diffusing from a leaf encounters two major resistances, a stomatal resistance ($r_s$) which is dependent upon stomatal pore size, and a

boundary layer resistance ($r_b$) which is dependent upon wind or turbulence at the leaf surface (here we will ignore cuticular resistance). Carbon dioxide diffusing into the leaf encounters $r_b$ and $r_s$ and a third resistance at the mesophyll ($r_m$) which is a resistance to trnasport from the mesophyll surface to the site of carboxylation at the chloroplast. Since the resistances are in series, an increase in $r_s$ (decrease in stomatal aperture) is expected to reduce transpiration proportionately more than photosynthesis. Thus, different ratios of photosynthesis to transpiration, which we shall refer to as water use efficiency, indicate different stomatal resistance.

Water use efficiency values for all the individual branch measurements made at Bernardo show a definite increase in the afternoon, indicating partial stomatal closure (Figure 12). Thus, it is apparent that the Tamarix plants, growing with a constant water supply, are closing their stomata and reducing transpiration during the afternoon of a typical June day. Such closure could be in response to one or a combination of three factors: (1) plant water stress, (2) high ambient temperatures, and (3) low relative humidity. During the field study, afternoon air temperatures were usually between 32 and 37°C, with relative humidity varying between 10 and 15%.

In an attempt to assess the magnitude of the afternoon depression of transpiration, steady-state measurements of transpiration and photosynthesis at 30°C were made on three Tamarix branches during the morning or early afternoon and were then repeated during the latter part of the same day. Afternoon transpiration reductions ranged from 17 to 43% (Table VII) and corresponding increases in water use efficiency were observed.

Table VII. Transpiration, photosynthesis, and water use efficiency of three Tamarix branches at different times of day, 23 June 1975, Bernardo, New Mexico

| Plant | Time | Net Photosynthesis ($mg\ CO_2/g$ dry wt · hr) | Transpiration ($g\ H_2O/g$ dry wt · hr) | Water Use Efficiency Net Photosynthesis Transpiration x $10^{-3}$ |
|---|---|---|---|---|
| 6-3 | 10:00AM | 15.4 | 3.8 | 0.41 |
| | 2:30PM | 14.0 | 3.2 | 0.44 |
| 6-4 | 11:35AM | 13.9 | 3.3 | 0.43 |
| | 3:15PM | 11.5 | 1.8 | 0.62 |
| 6-5 | 12:45PM | 11.2 | 2.6 | 0.44 |
| | 4:15PM | 11.0 | 1.7 | 0.65 |

Conclusions and Recommendations: Phreatophyte Studies

Laboratory transpiration reductions and antitranspirant persistance with Mobileaf on Tamarix appeared very satisfactory. Reuctions obtained in the field were not as large as in laboratory tests, but it was possible to show an antitranspirant effect with the gas exchange studies. Six days after antitranspirant application transpiration of sprayed branches averaged 70% of that of controls.

It is possible that the difference between laboratory and field effects is due to a lack of uniformity and thoroughness of spray coverage. It is very difficult to achieve as thorough of coverage in the field even with a hand-held sprayer. Under the high temperatures and low humidities encountered, some of the spray droplets may have evaporated before touching plant material. Coverage appeared to be enhanced by using a slower engine speed resulting in larger droplets during the final spraying. A study of application techniques to determine the best droplet size is needed. It it also possible that coverage would be enhanced it spraying could be completed at night or during the very early morning hours when evaporative

demand are lower.

More information on the physiological ecology of Tamarix is sorely needed. Studies should be initiated to determine the cause and mechanisms involved in the afternoon depression of the transpiration. If the mechanisms were understood, it might be possible to take advantage of the natural processes to reduce water consumption. Information on diurnal cycles in gas exchange rates is needed to facilitate the interpretation of data collected after antitranspirant application.

Field studies should be initiated to compare water consumption by various phreatophyte species. It was found in this study that salt cedars do not transpire at a potential rate all day. It should be ascertained if this is generally true of phreatophytes. At present, two evapotranspirometers at Bernardo are planted with Russian Olive. Water consumption on those tanks is double that of the Tamarix tanks. This suggests that it might be advantageous to have Tamarix present rather than another phreatophyte.

The field studies indicate that our knowledge of the physiology and ecology is insufficient for the interpretation of antitranspirant field trials. A better understanding of these should be of fundamental use in any future phreatophyte management program.

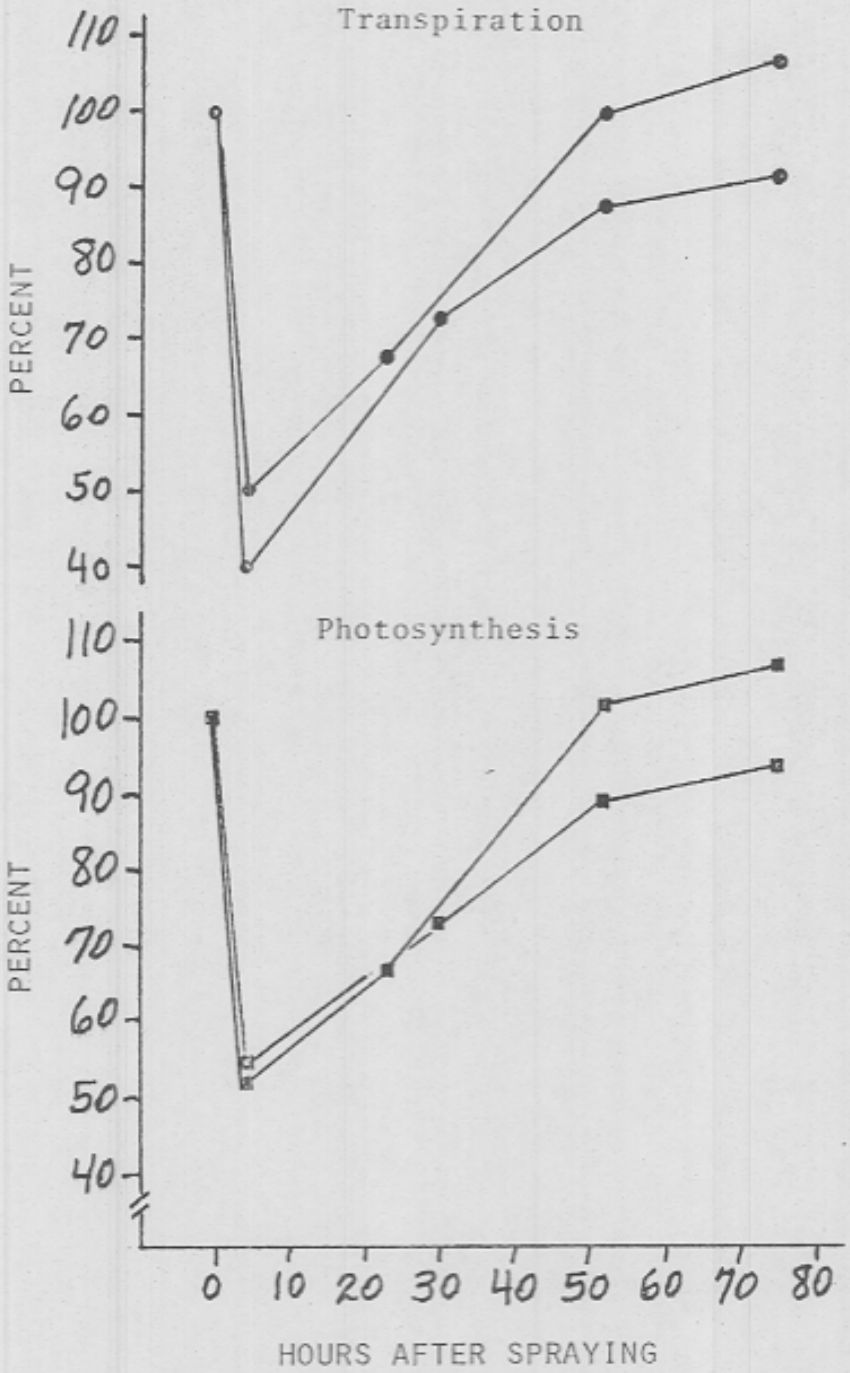



Figure 1. Transpiration and net photosynthesis of *Achillea millefolium* plants sprayed with a 5% solution of XEF-4-3561. Rates are expressed as percentages of the steady state rates just prior to spraying (time zero).

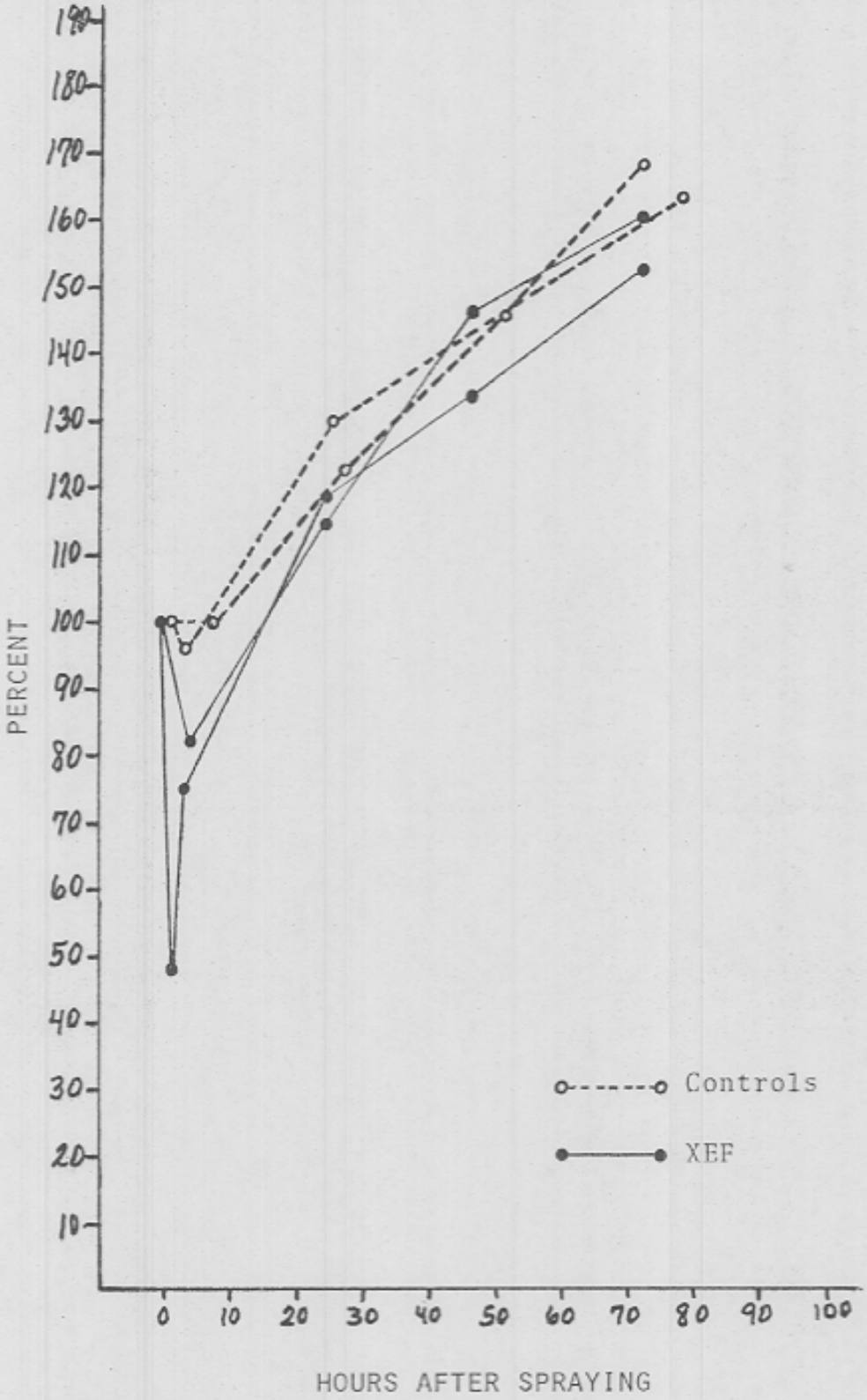



Figure 2. Transpiration of *Agropyron cristatum* plants sprayed with 5% XEF-4-3561, compared to control plants sprayed with distilled water. Rates are expressed as percentages of the rates just prior to spraying (time zero).

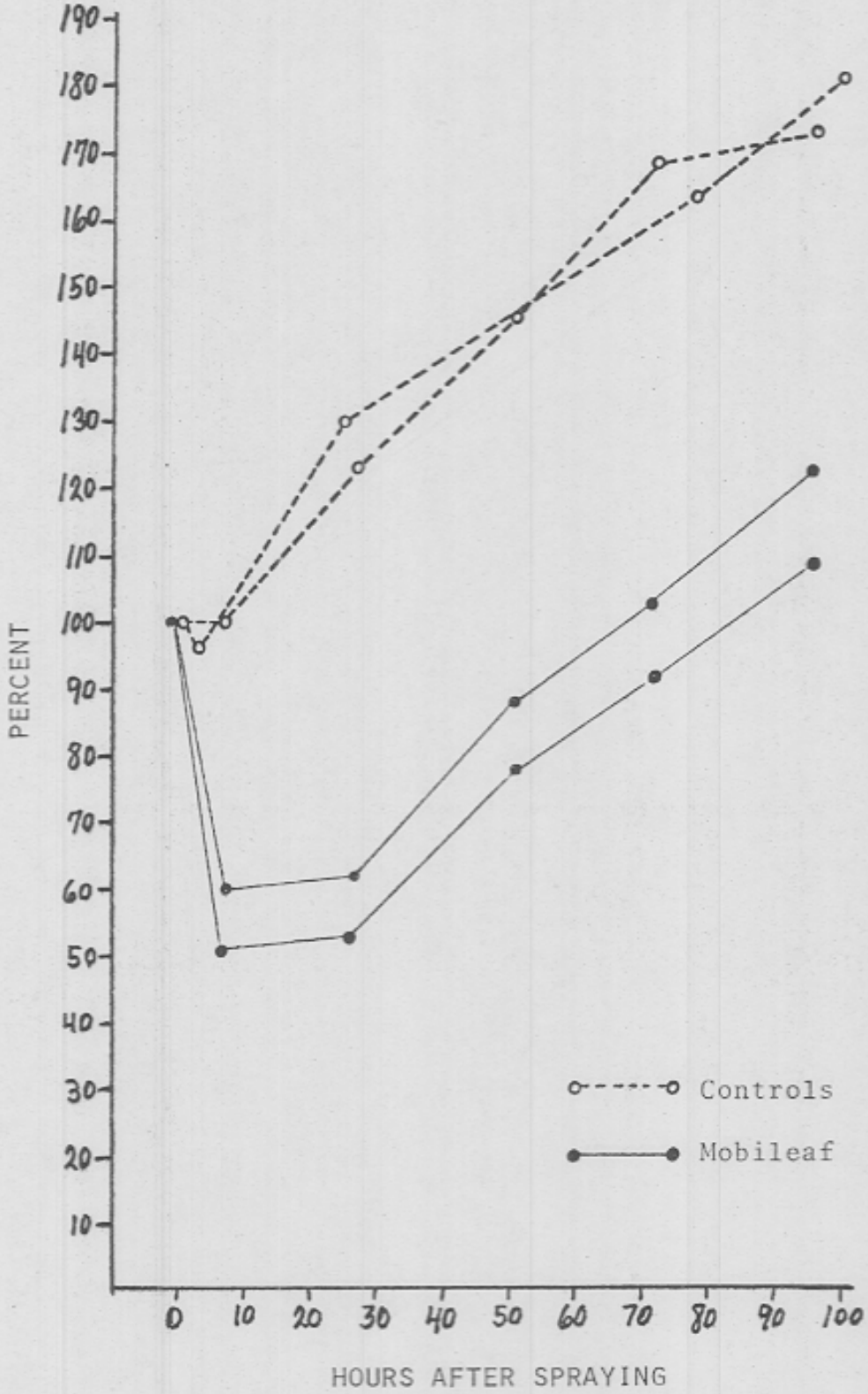



Figure 3. Transpiration of *Agropyron cristatum* plants sprayed with 16.5% Mobileaf, compared to control plants sprayed with distilled water. Rates are expressed as percentages of the rates just prior to spraying (time zero).

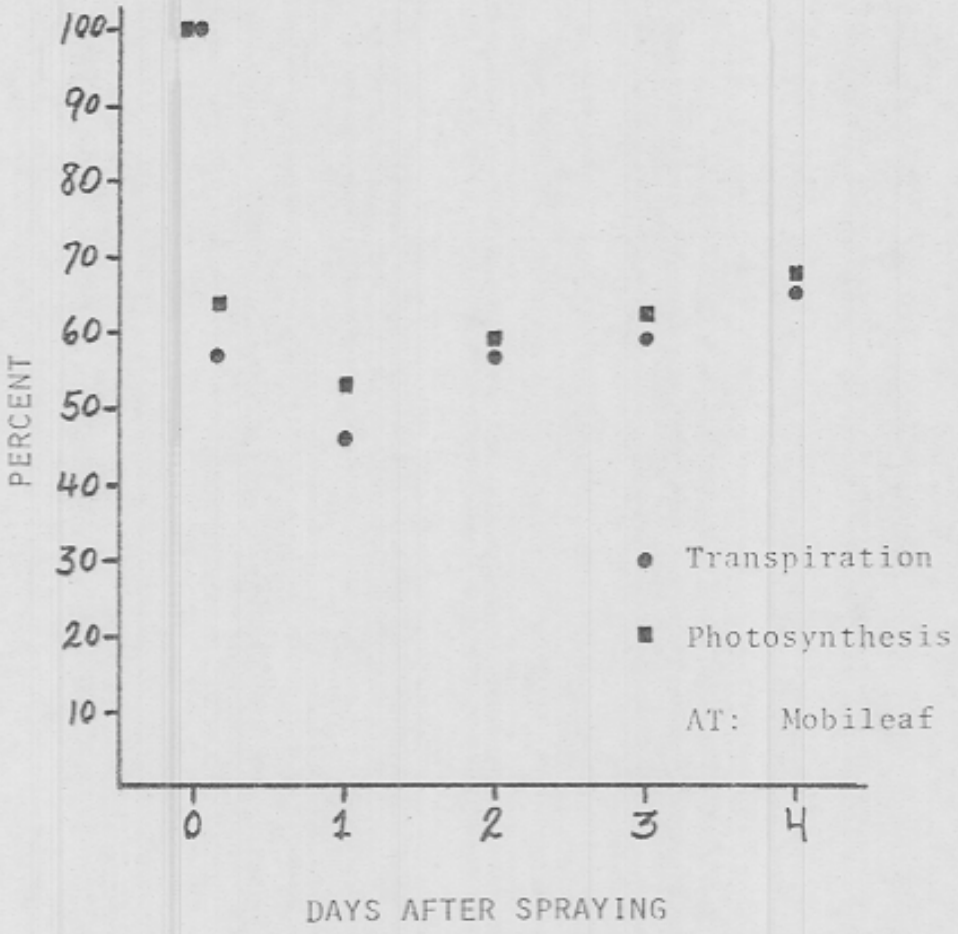



Figure 4. Transpiration and net photosynthesis of *Agropyron cristatum* plants sprayed with Mobileaf (1:5 v/v in distilled water). Rates are expressed as average percentages of the rates of control plants sprayed with distilled water. Each point is the average of two treated plants corrected for the average of two controls.

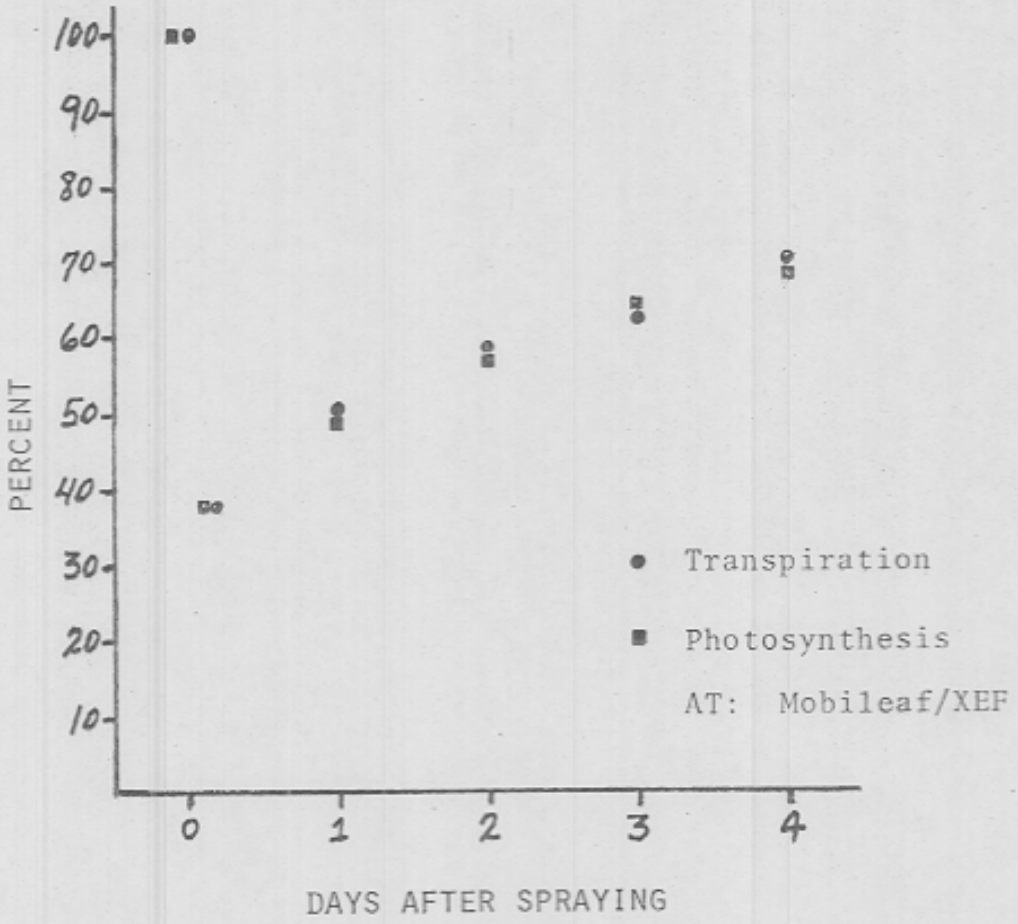



Figure 5. Transpiration and net photosynthesis of *Agropyron cristatum* plants sprayed with a mixture (1:5 v/v) of Mobileaf and 5% XEF-4-3561. Rates are expressed as average percentages of the rates of control plants sprayed with distilled water. Each point is the average of two treated plants corrected for the average of two controls.

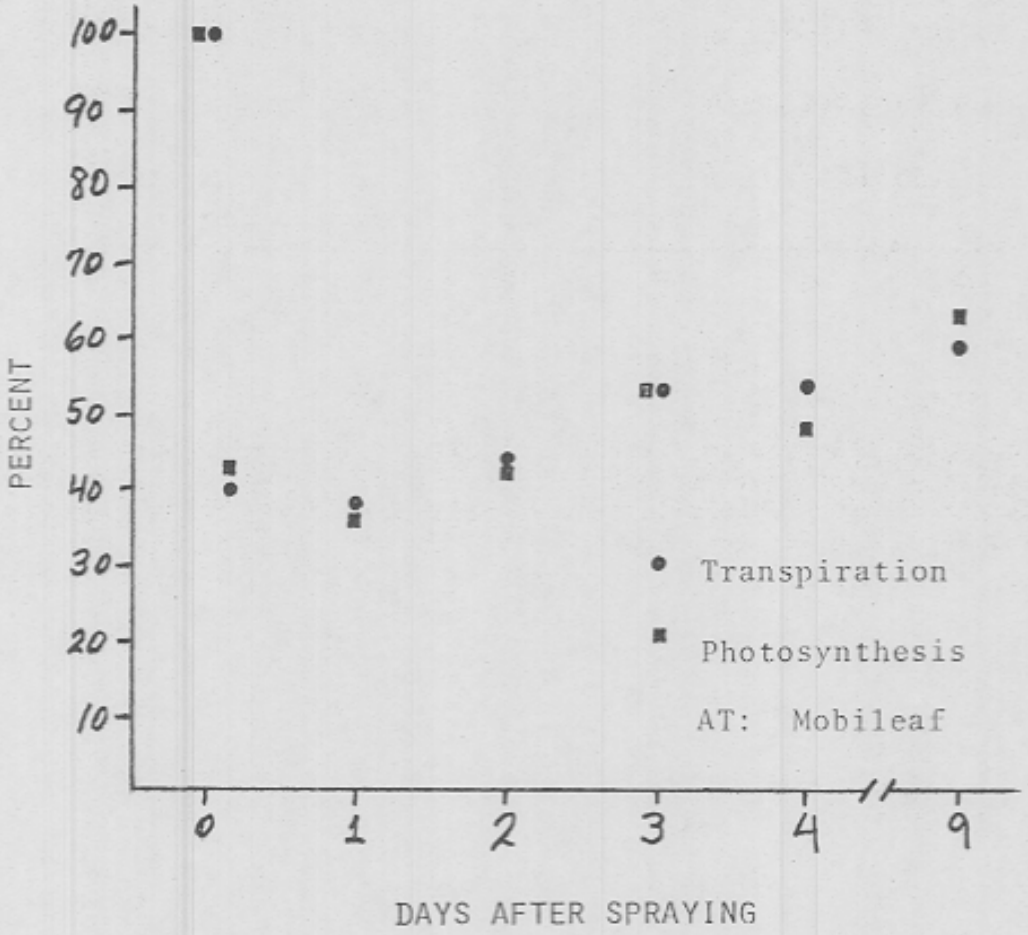



Figure 6. Transpiration and net photosynthesis of *Elymus canadensis* plants sprayed with Mobileaf (1:5 v/v in distilled water). Rates are expressed as average percentages of the rates of control plants sprayed with distilled water. Each point is the average of two treated plants corrected for the average of four controls.

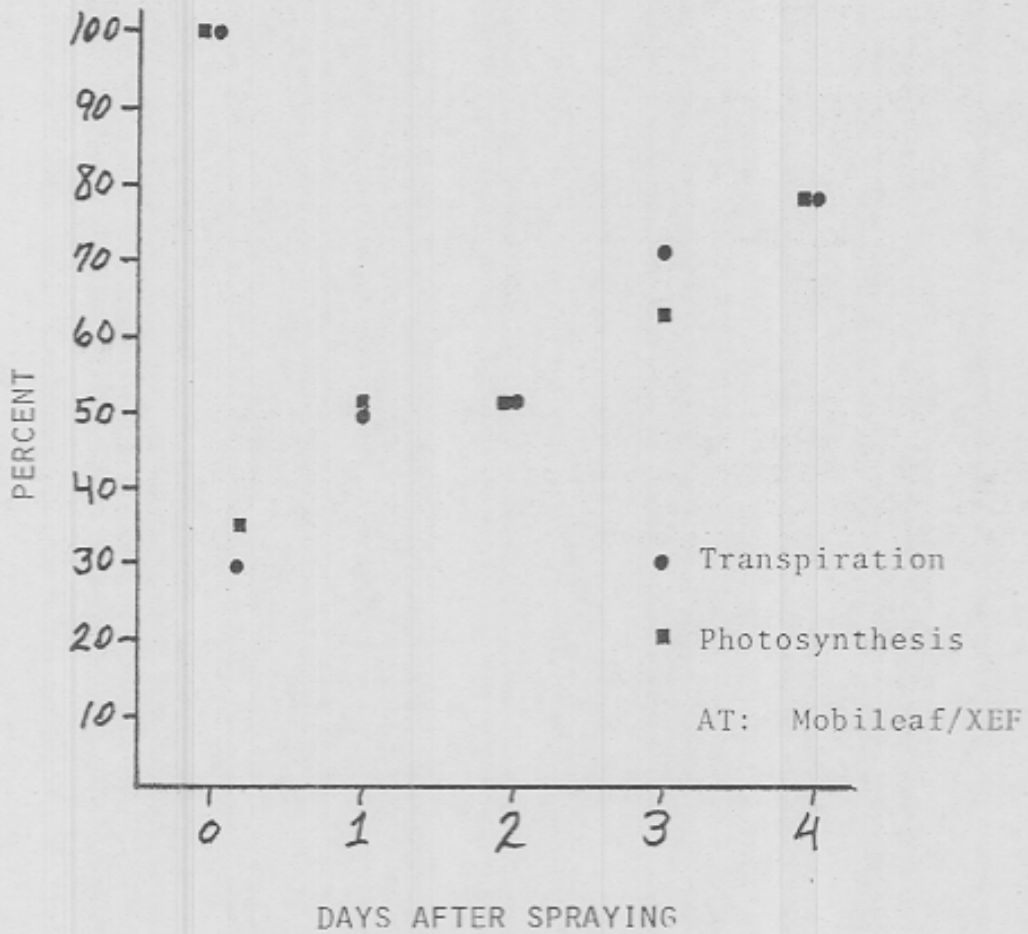



Figure 7. Transpiration and net photosynthesis of *Elymus canadensis* plants sprayed with a mixture (1:5 v/v) of Mobileaf and 5% XEF-4-3561. Rates are expressed as average percentages of the rates of control plants sprayed with distilled water. Each point is the average of two treated plants corrected for the average of four controls.

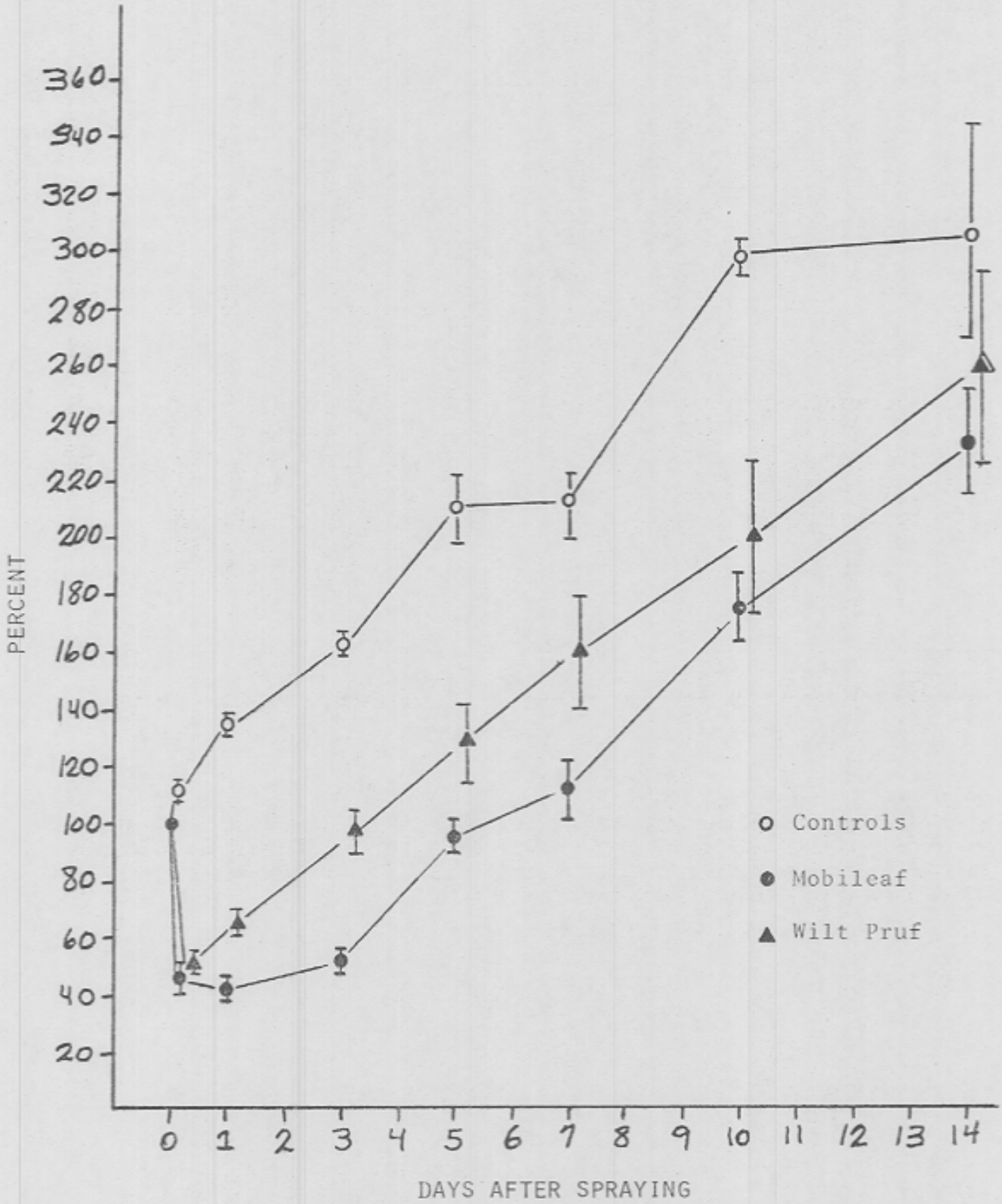



Figure 8. Transpiration of *Melilotus officinalis* plants sprayed with 16.5% Mobileaf, compared to control plants sprayed with distilled water. Rates are expressed as average percentages of the rates just prior to spraying (time zero). Each point is the mean of four plants; the vertical lines indicate standard errors.

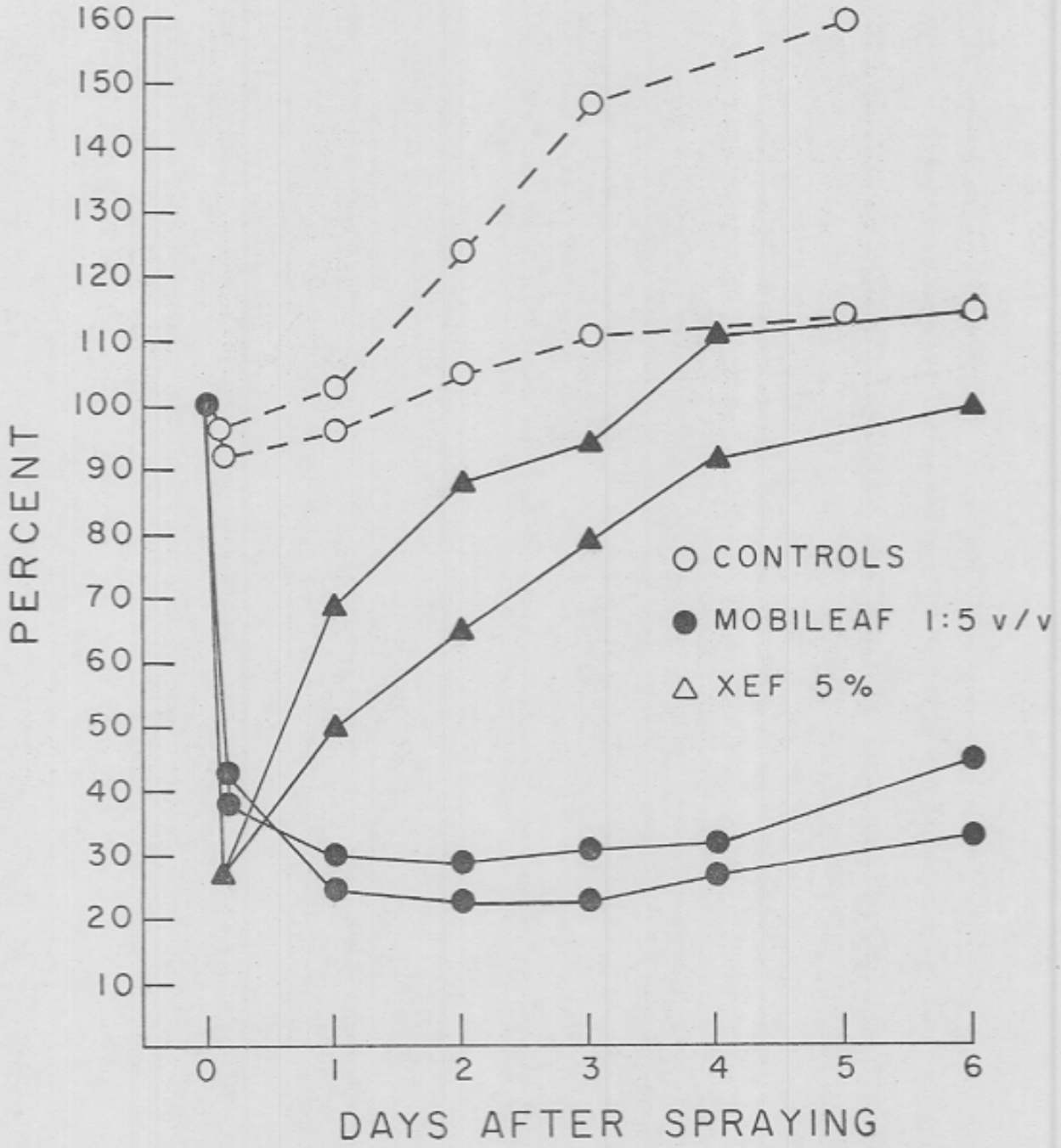



Figure 9. Transpiration of *Tamarix pentandra* plants sprayed with 16.5% Mobileaf or 5% XEF-4-3561. Rates are expressed as percentages of the steady state rates just prior to spraying (time zero).

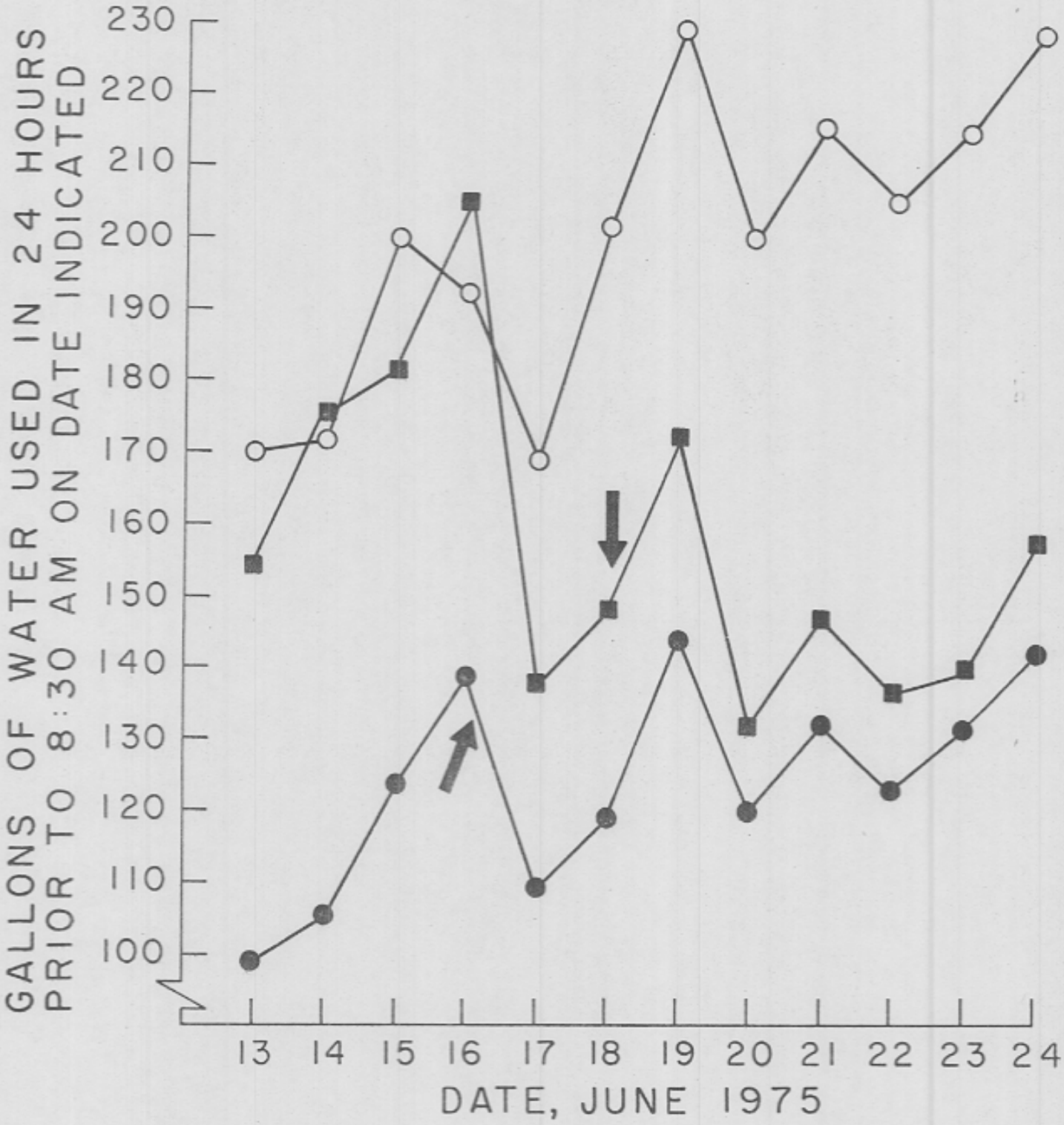



Figure 10. Water consumption on evapotranspirometers 4, 5, and 6 from 13 to 24 June 1975. Arrows indicate application of antitranspirant (see METHODS, Field Studies for Details).

Figure 11. Transpiration of individual branches sprayed with 15% Mobileaf compared to control branches. Rates are expressed as average percentages of the steady state rates measured on the day prior to spraying. Anti-transpirant was applied at time zero. Subsequent measurements were made at the same time of day as original measurements. Branches with "5" as the first numeral were from evapotranspirometer 5, those with "6" from evapotranspirometer 6.

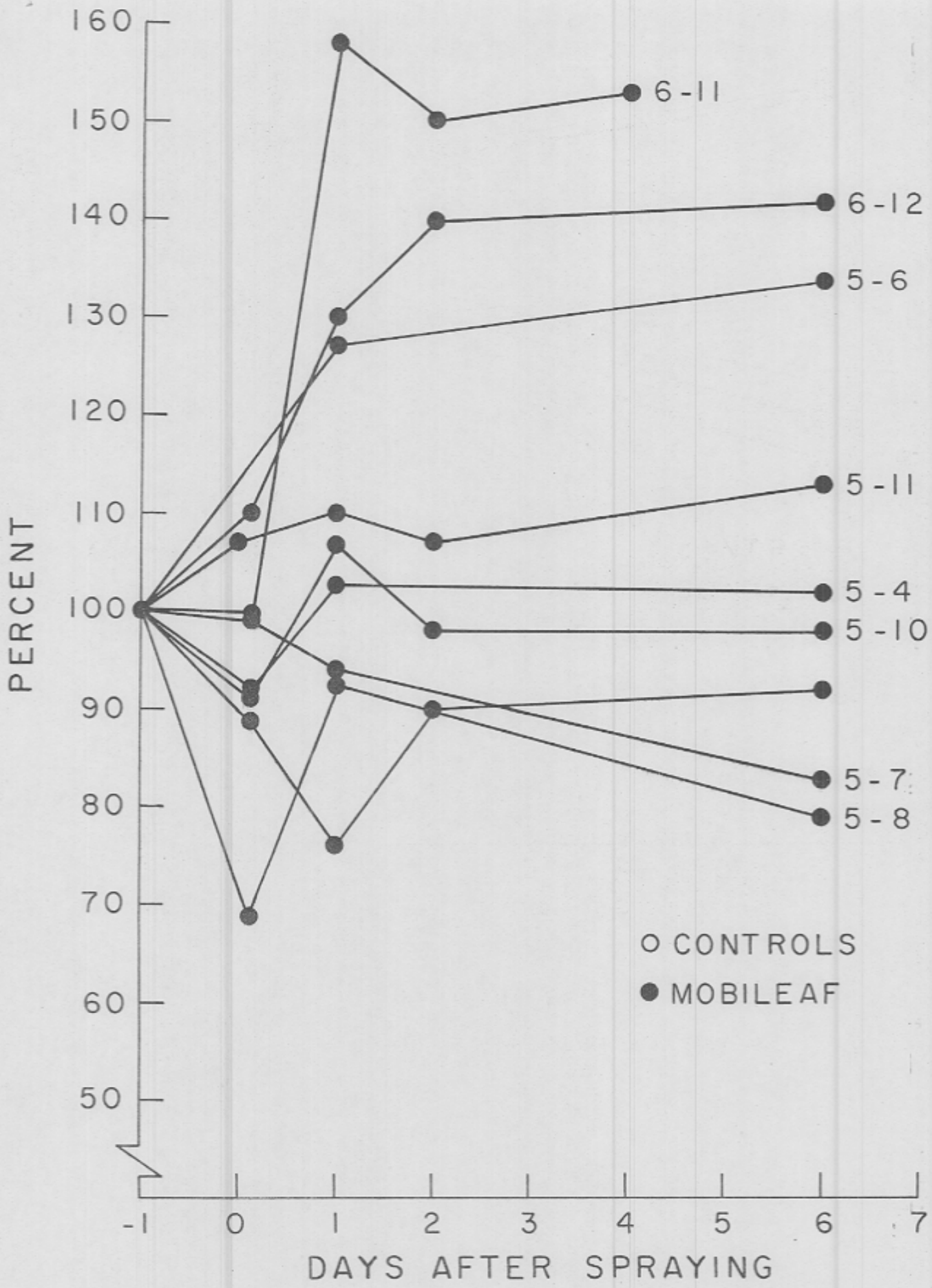
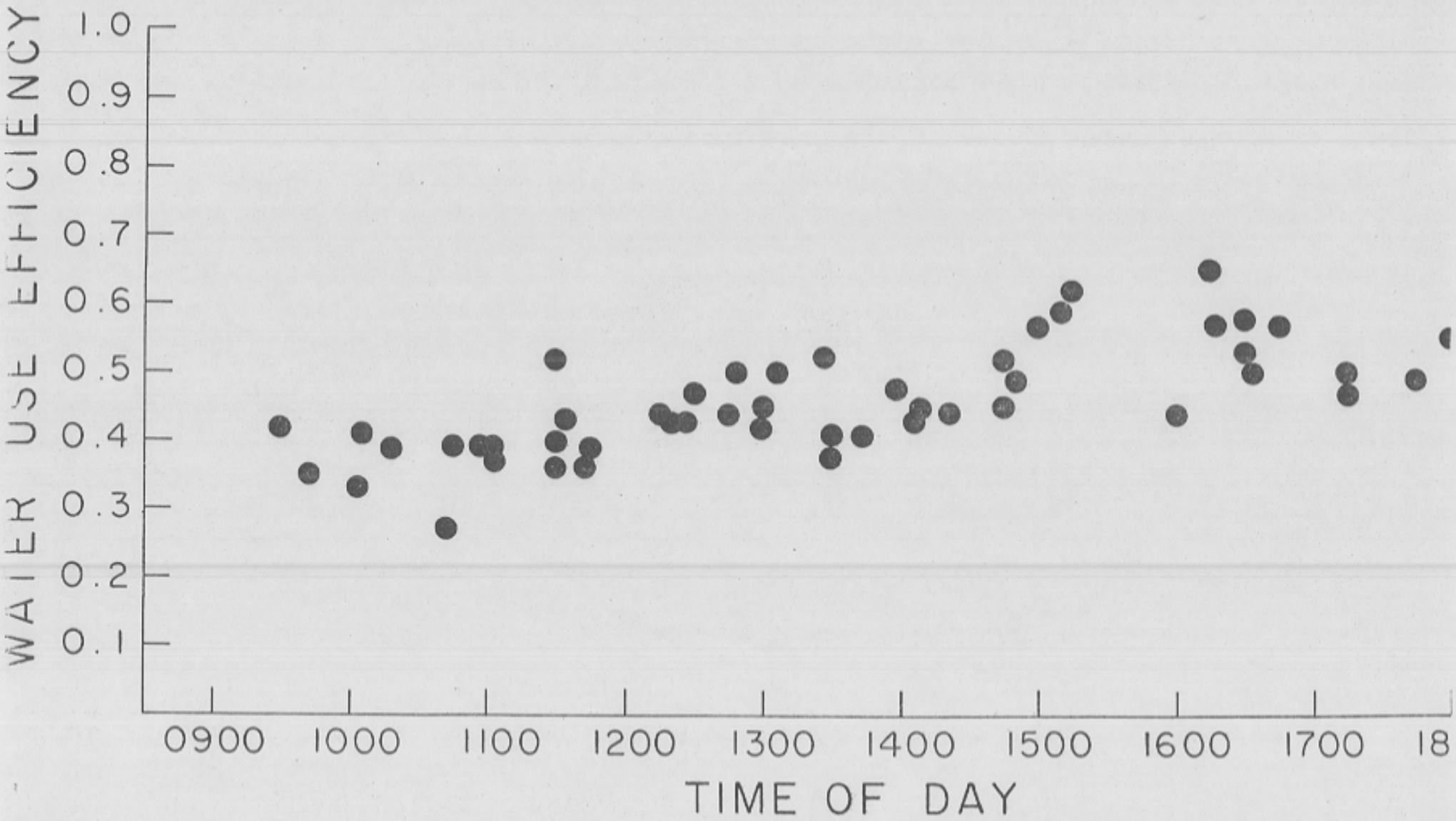

160
150
140
130
120
110
100
90
80
70
60
50
PERCENT
6-11
6-12
5-6
5-11
5-4
5-10
5-7
5-8
O CONTROLS
● MOBILEAF
-1
0
1
2
3
4
5
6
7
DAYS AFTER SPRAYING

Figure 12. Water use efficiency (ratio of photosynthesis to transpiration) as a function of time of day for measurements taken on *Tamarix* branches at Bernardo, New Mexico, June 13-24, 1975.

$$\text{Water Use Efficiency} = \frac{\text{mg } CO_2\text{/g dry wt. leaf-hr}}{\text{g } H_2)\text{/g dry wt. leaf-hr}} \times 10$$


WATER USE EFFICIENCY
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0900
1000
1100
1200
1300
1400
1500
1600
1700
18
TIME OF DAY

## REFERENCES


Anderson, J. E. and S. J. McNoughton. 1973. Effects of low soil temperature on transpiration, photosynthesis, leaf relative water content, and growth among elevationally diverse plant populations. Ecology 54(6):1220-1233.

Davenport, D. C., R. M. Hagan, and P. E. Martin. 1969. Antitranspirants... uses and effects on plant life. Calif. Agric. 23(5):14-16.

Davenport, D. C., M. A. Fisher, and R. M. Hagan. 1971. Retarded stomatal closure by phenylmercuric acetate. Physiol. Plant 24:330-336.

Davies, W. S. and T. T. Kozlowski. 1974. Short- and long-term effects of antitranspirants on water relations and photosynthesis of woody plants. J. Amer. Soc. Hart. Sci. 99(4):297-304.

Gale, J. and R. M. Hagan. 1966. Plant antitranspirants. Ann. Rev. of Plant Physiology, 17:269-282.

Kreith, F., A. Taori, and J. E. Anderson. 1975. Persistence of selected antitranspirants. Water Resour. Res. 11(2):281-286.

Mishra, D. and G. C. Pradham. 1972. Effect of transpiration reducing chemicals on growth, flowering and stomatal opening of tomato plants. Plant Physiol., 50:271-274.

Mooney, H. A., E. L. Dunn, A. T. Harrison, P. A. Morrow, B. Bartholomew, and R. L. Hays. 1971. A mobile laboratory for gas exchange measurements. Photosynthetica 5(2):128-132.

Ogunkanmi, A. B., A. R. Wellburn, and P. A. Mansfield. 1974. Detection and preliminary identification of endogenous antitranspirants in water-stressed Sorghum plants. Planta, 117:293-302.

Poljakoff-Mayber, A. and J. Gale. 1972. Physiological basis and practical problems of reducing transpiration. In Water Deficits and Plant Growth, T. T. Kozlowski, ed. Volume III, Chapter 9. Academic Press, NY.

Robinson, T. W. 1965. Introduction, spread, and area extent of salt cedar (Tamarix) in the Western States. U.S. Geol. Sur. Prof. Pap. 491-A. 12.

Wellburn, A. R., A. B. Ogunkanmi, R. Fenton, and P. A. Mansfield. 1974. All-trans-farnesol: a naturally occurring antitranspirant? Planta 120:255-263.

Tranquillini, W. and M. M. Caldwell. 1972. Integrated calibration of plant gas exchange systems. Ecology 53(6):974-976.

COLORADO WATER RESOURCES RESEARCH INSTITUTE

# LIST OF PUBLICATIONS AVAILABLE

## A. MANAGEMENT OF HYDROLOGIC EXTREMES

| | | Date | Price |
|---|---|---|---|
| CR 16 | Experimental Investigation of Small Watershed Floods | 6/68 | $ 2.00 |
| CR 18 | Experimental Investigation of Small Watershed Floods | 6/70 | 5.00 |
| CR 29 | Identification of Urban Watershed Units Using Remote Multispectral Sensing | 6/71 | 5.00 |
| CR 40 | Selection of Test Variable for Minimal Time Detection of Basin Response to Natural or Induced Changes | 12/72 | 3.00 |
| CR 42 | Theory and Experiments in the Prediction of Small Watershed Response | 12/72 | 5.00 |
| CR 43 | Experiments in Small Watershed Response | 12/72 | 5.00 |
| CR 56 | Evaluation and Implementation of Urban Drainage and Flood Control Projects | 6/74 | 8.00 |
| CR 65 | Urban Drainage and Flood Control Projects: Economic, Legal and Financial Aspects | 7/75 | 10.00 |
| CR 83 | Modelling the Dynamic Response of Floodplains to Urbanization in Eastern New England | 1/78 | 6.50 |
| CR 95 | Drought-Induced Problems and Responses of Small Towns and Rural Water Entities in Colorado: The 1976-1978 Drought | 6/80 | 4.00 |
| S-GS856 | Research Data Assembly for Small Watershed Floods, Part II | 1967 | .50 |
| IS 13 | Flood Plain Management of the Cache La Poudre River near Fort Collins | 8/74 | 2.75 |
| IS 17 | Cache La Poudre River near Fort Collins, Colorado - Flood Management Alternatives - Relocations and Levies | 8/74 | 5.00 |
| IS 22 | Implementation of the National Flood Insurance Program in Larimer County, Colorado | 9/76 | 4.00 |
| IS 24 | Factors Affecting Public Acceptance of Flood Insurance in Larimer and Weld Counties, Colorado | 9/77 | 3.00 |
| IS 27 | Proceedings, Colorado Drought Workshops | 11/77 | Free |
| IS 44 | The National Flood Insurance Program in the Larimer County, Colorado area | 8/80 | 3.00 |

## B. WATER SUPPLY AUGMENTATION AND CONSERVATION

| | | | |
|---|---|---|---|
| CR 3 | Snow Accumulation in Relation to Forest Canopy | 6/69 | 1.50 |
| CR 4 | Runoff from Forest and Agricultural Watersheds | 6/69 | 3.00 |
| CR 8 | Improving Efficiency in Agricultural Water Use | 6/69 | 1.00 |
| CR 9 | Controlled Accumulation of Blowing Snow | 6/69 | 2.50 |
| CR 15 | Hydraulic Operating Characteristics of Low Gradient Border Checks in the Management of Irrigation Water | 6/68 | 3.00 |
| CR 16 | Experimental Investigation of Small Watershed Floods | 6/68 | 2.00 |
| CR 18 | Experimental Investigation of Small Watershed Floods | 6/70 | 5.00 |
| CR 19 | Hydraulics of Low Gradient Border Irrigation Systems | 6/70 | 3.00 |
| CR 20 | Improving Efficiency in Agricultural Water Use | 7/70 | 3.00 |
| CR 23 | A Systematic Treatment of the Problem of Infiltration | 6/71 | 3.00 |
| CR 24 | Studies of the Atmospheric Water Balance | 8/71 | 5.00 |
| CR 25 | Evaporation of Water as Related to Wind Barriers | 6/71 | 5.00 |
| CR 30 | Geohydraulics at the Unconformity between Bedrock and Alluvial Aquifers | 6/72 | 5.00 |
| CR 35 | An Application of Multi-Variate Analysis in Hydrology | 8/72 | 5.00 |
| CR 40 | Selection of Test Variable for Minimal Time Detection of Basin REsponse to Natural or Induced Changes | 12/72 | 3.00 |
| CR 41 | Groundwater Recharge as Affected by Surface Vegetation and Management | 12/72 | 5.00 |
| CR 42 | Theory and Experiments in the Prediction of Small Watershed Response | 12/72 | 5.00 |
| CR 43 | Experiments in Small Watershed Response | 12/72 | 5.00 |
| CR 49 | Improvements in Moving Sprinkler Irrigation Systems for Conservation of Water | 6/73 | 7.50 |
| CR 50 | Systematic Treatment of Infiltration with Applications | 6/73 | 5.00 |

| | | Date | Price |
|---|---|---|---|
| CR 51 | An Experimental Study of Soil Water Flow Systems Involving Hystersis | 8/73 | $ 7.00 |
| CR 52 | Consolidation of Irrigation Systems: Phase 1 - Engineering, Legal and Sociological Constraints and/or Facilitators | 6/73 | 25.00 |
| CR 53 | Systematic Design of Legal Regulations for Optimal Surface-Groundwater Usage | 8/73 | 7.00 |
| CR 57 | Snow-Air Interactions and Management of Mountain Watershed Snowpack | 6/74 | 3.00 |
| CR 63 | Analysis of Colorado Precipitation | 6/75 | 2.00 |
| CR 64 | Computer Estimates of Natural Recharge from Soil Moisture Data - High Plains of Colorado | 1/76 | 4.00 |
| CR 68 | Systematic Design of Legal Regulations for Optimal Surface-Groundwater Usage, Phase 2 | 9/75 | 12.00 |
| CR 69 | Engineering and Ecological Evaluation of Antitranspirants for Increasing Runoff in Colorado Watersheds | 9/75 | 2.50 |
| CR 75 | Physical and Economic Effects on the Local Agricultural Economy of Water Transfer to Cities | 10/76 | 3.00 |
| CR 76 | Determination of Snow Depth and Water EQuivalent by Remote Sensing | 6/76 | 2.00 |
| CR 80 | Achieving Urban Water Conservation, A Handbook | 9/77 | 6.00 |
| CR 81 | Achieving Urban Water Conservation, Testing Community Acceptance | 9/77 | 5.00 |
| CR 82 | Development of a Subsurface Hydrologic Model and Use for Integrated Management of Surface and Subsurface Water Resources | 12/77 | 3.00 |
| CR 87 | Development of a Stream-Aquifer Model Suited for Management | 8/78 | 3.00 |
| CR 89 | Synthesis and Calibration of a River Basin Water Management Model | 10/78 | 3.00 |
| CR 90 | Models for System Water Planning with Special Reference to Water Reuse | 6/78 | 5.00 |
| CR 92 | Hydraulic Conductivity of Mountain Soils | 10/78 | 3.00 |
| CR 94 | Consolidation of Irrigation Systems: Phase II, Engineering, Economic, Legal and Sociological Requirements | 5/80 | 8.00 |
| CR 97 | Water REquirements for Urban Lawns in Colorado | 8/80 | 3.00 |
| CR 99 | Applications of Remote Sensing in Hydrology | 9/80 | 3.00 |
| CR 100 | A Watershed Information System | 9/80 | 4.00 |
| CR 105 | Municipal Water Use in Northern Colorado: Development of Efficiency-of-Use Criterion | 9/80 | 4.00 |
| CR 106 | Urban Lawn Irrigation and Management Practices for Water Saving with Minimum Effect on Lawn Quality | 9/80 | 6.00 |
| IS 16 | Annotated Bibliography on Trickle Irrigation | 6/75 | Free |
| IS 26 | Water Use and Management in an Arid Region (Fort Collins, Colorado and Vicinity) | 9/77 | 5.00 |
| IS 31 | The Denver Basin: Its Bedrock Aquifers | 1/79 | Free |
| IS 32 | Snowpack Augmentation by Cloud Seeding in Colorado and Utah | 8/79 | 4.00 |
| IS 33 | The Impacts of Improving Efficiency of Irrigation Systems on Water Availability | 1/79 | Free |
| IS 35 | Federal Water Storage Projects: Pluses and Minuses | 6/79 | Free |
| IS 36 | Cutting City Water Demand | 5/79 | Free |
| IS 37 | Water for the South Platte Basin | 3/79 | Free |
| IS 39 | Administration of the Small Watershed Program, 1955-1978 - An Analysis | 8/79 | 3.00 |
| TR 8 | Models Designed to Efficiently Allocate Irrigation Water Use Based on Crop Response to Soil Moisture Stress | 5/77 | 4.00 |
| TR 13 | Impact of Irrigation Efficiency Improvements on Water Availability in the South Platte River Basin | 1/79 | 5.00 |
| TR 15 | Weekly Crop Consumptive Use and Precipitation in the Lower South Platte River Basin | 2/79 | Free |
| TR 16 | Water Management Model for Front Range River Basins | 4/79 | 5.00 |
| TR 18 | An Interactive River Basin Water Management Model: Synthesis and Application | 8/79 | 4.00 |
| TR 28 | An Assessment of Water Use and Policies in Northern Colorado Cities | 3/81 | 5.00 |
| S-TB128 | Evaluating Water Distributions of Sprinkler Irrigations Systems | 1976 | .85 |
| S-TB 76 | Introduction of Supplemental Irrigation Water | 1965 | .50 |

## C. IDENTIFICATION AND CONTROL OF ENTERING POLLUTANTS

| | | Date | Price |
|---|---|---|---|
| CR 14 | Hydrogeology and Water Quality Studies in the Cache La Poudre River Basin, Colorado | 6/69 | $ 5.00 |
| CR 21 | Waterfowl-Water Temperature Relations in Winter | 6/70 | 5.00 |
| CR 26 | Water Temperature as a Quality Factor in the Use of Streams and Reservoirs | 12/71 | 3.00 |
| CR 31 | Sedimentation and Contaminant Criteria for Watershed Planning and Management | 6/72 | 5.00 |
| CR 54 | Geologic Factors in the Evaluation of Water Pollution Potential at Mountain Dwelling Sites | 12/73 | 10.00 |
| CR 59 | A System for Geologic Evaluation of Pollution at Mountain Dwelling Sites | 1/75 | 3.50 |
| CR 60 | Research Needs as Related to the Development of Sediment Standards in Rivers | 3/75 | 3.00 |
| CR 67 | Toxic Heavy Metals in Groundwater of a Portion of the Front Range Mineral Belt | 6/75 | 3.00 |
| CR 71 | Salt Transport in Soil Profiles with Application to Irrigation Return Flow - The Dissolution and Transport of Gypsum in Soils | 1/76 | 5.00 |
| CR 72 | Toxic Heavy Metals in Groundwater of a Portion of the Front Range Mineral Belt | 6/76 | 4.00 |
| CR 79 | Evaluation of the Storage of Diffuse Sources of Salinity in the Upper Colorado River Basin | 9/77 | 4.00 |
| CR 84 | Pollutional Characteristics of Urban Stormwater Funoff | 9/78 | 7.00 |
| CR 104 | Detection of Water Quality Changes Through Optimal Tests and Reliability of Tests | 9/80 | 4.00 |

## D. EFFECTS OF POLLUTANTS

| | | | |
|---|---|---|---|
| CR 26 | Water Temperature as a Quality Factor in the Use of Streams and Reservoirs | 12/71 | 3.00 |
| CR 67 | Toxic Heavy Metals in Groundwater of a Portion of the Front Range Mineral Belt | 6/75 | 3.00 |
| CR 72 | Toxic Heavy Metals in Groundwater of a Portion of the Front Range Mineral Belt | 6/76 | 4.00 |
| CR 73 | Production of Mutant Plants Conducive to Salt Tolerance | 7/76 | 4.00 |
| CR 96 | The Production of Agriculturally Useful Mutant Plants with Characteristics Conducive to Salt Tolerance and Efficient Water Utilization | 10/79 | 3.00 |
| CR 98 | The Effect of Algal Inhibitors on Higher Plant Tissues | 7/80 | 2.50 |
| IS 25 | Surveillance Data Plains Segment of the Cache La Poudre River, Colorado 1970-1977 | 1/78 | 5.00 |
| S-GS870 | Chemical Quality of Ground Water in the Prospect Valley Area, Colorado | 1968 | .25 |

## E. TREATMENT AND DISPOSAL OF WASTES

| | | | |
|---|---|---|---|
| CR 1 | Bacterial Response to the Soil Environment | 6/69 | 3.50 |
| CR 2 | Computer Simulation of Waste Transport in Groundwater Aquifers | 6/69 | 2.00 |
| CR 23 | A Systematic Treatment of the Problem of Infiltration | 6/71 | 3.00 |
| CR 28 | Combined Cooling and Bio-Treatment of Beet Sugar Factory Condenser Water Effluent | 6/71 | 5.00 |
| CR 32 | Bacterial Movement Through Fractured Bedrock | 7/72 | 5.00 |
| CR 33 | The Mechanism of Waste Treatment at Low Temperature, Part A: Microbiology | 8/72 | 5.00 |
| CR 34 | The Mechanism of Waste Treatment at Low Temperature, Part B: Sanitary Engineering | 8/72 | 5.00 |
| CR 50 | Systematic Treatment of Infiltration with Applications | 6/73 | 5.00 |
| CR 66 | Individual Home Wastewater Characterization and Treatment | 7/75 | 8.00 |
| CR 77 | Evaporation of Wastewater from Mountain Cabins | 3/77 | 8.00 |
| IS 4 | Proceedings Workshop on Home Sewage Disposal in Colorado | 6/72 | Free |
| IS 9 | Proceedings of the Symposium on Land Treatment and Secondary Effluent | 11/73 | 3.00 |
| IS 10 | Proceedings of a Workshop on Revegatation of High-Altitude Disturbed Lands | 7/74 | 3.00 |
| IS 12 | Recreation Benefits of Water Quality: Rocky Mountain National Park, South Platte River Basin, Colorado | 5/78 | 4.00 |
| IS 20 | Proceedings, Second Workshop on Home Sewage Disposal in Colorado | 9/75 | 3.00 |
| IS 29 | Third Workshop on Home Sewage Disposal in Colorado - Community Systems Management | 7/78 | 4.00 |

| | | Date | Price |
|---|---|---|---|
| TR 17 | Land Treatment of Municipal Sewage Effluent at Hayden, Colorado | 10/77 | $ 3.00 |

## F. ECONOMIC EFFECTS

| | | | |
|---|---|---|---|
| CR 10 | Economics and Administration of Water Resources | 6/69 | 2.00 |
| CR 12 | Economics and Administration of Water Resources | 6/69 | 3.00 |
| CR 13 | Economics of Groundwater Development in the High Plains of Colorado | 6/69 | 1.50 |
| CR 44 | Economic, Political, and Legal Aspects of Colorado Water Law | 2/73 | 5.00 |
| CR 46 | Evaluation or Urban Water Management Policies in the Denver Metropolitan Area | 6/73 | 7.50 |
| CR 58 | Primary Data on Economic Activity and Water Use in Prototype Oil Shale Development Areas of Colorado: An Initial Inquiry | 6/74 | 2.00 |
| CR 61 | Economic and Institutional Analysis of Colorado Water Quality Management | 6/74 | 2.00 |
| CR 65 | Urban Drainage and Flood Control Projects: Economic, Legal and Financial Aspects | 7/75 | 10.00 |
| CR 70 | An Economic Analysis of Water Use in Colorado's Economy | 12/75 | 5.00 |
| CR 75 | Physical and Economic Effects on the Local Agricultural Economy of Water Transfer to Cities | 10/76 | 3.00 |
| CR 91 | Economic Benefits from Instream Flow in a Colorado Mountain Stream | 6/79 | 5.00 |
| CR 101 | An Empirical Application of a Model for Estimating the Recreation Value of Instream Flow | 10/80 | 3.00 |
| CR 102 | Measuring Benefits and the Economic Value of Water in Recreation on High Country Reservoirs | 9/80 | 3.00 |
| SR 3 | Irrigation Development Potential in Colorado | | 4.00 |
| IS 2 | Economics of Water Quality--Salinity Pollution - Abridged Bibliography | 6/71 | 11.00 |
| IS 35 | Federal Water Storage Projects: Pluses and Minuses | 6/79 | Free |
| TR 14 | Economic Value of Benefits from Recreation at High Mountain Reservoirs | 12/78 | 3.00 |
| TR 19 | An Economic Evaluation of the General Management for Yosemite National Park | 3/80 | 4.00 |
| TR 21 | The Economy of Albany, Carbon, and Sweetwater Counties,Wyoming-Description & Analysis | 1/81 | 3.00 |
| TR 22 | An Input-Output Study of the Upper Colorado Main Stem Region of Western Colorado | 1/81 | 4.00 |
| TR 23 | The Economy of Moffat, Routt, & Rio Blanco Counties,Colorado-Description and Analysis | 1/81 | 4.00 |
| TR 24 | The Survey-Based Input-Output Model as a Resource Planning Tool | 1/81 | 3.00 |
| TR 25 | The Economy of Northwestern Colorado - Description and Analysis | 1/81 | 4.00 |
| TR 26 | An Input-Output Analysis of Sportsman Expenditures in Colorado | 1/81 | 4.00 |
| TR 27 | An Input-Output Study of the Kremmling Region of Western Colorado | 3/81 | 3.00 |
| S-GS953 | Economic Analysis of Water Use in Boulder, Larimer and Weld Counties, with Projections to 1980 | 1976 | 1.00 |
| S-543S | Pump Irrigation on the Colorado High Plains | 1970 | .65 |
| S-545S | Secondary Economic Effects of Irrigation on the Colorado High Plains | 1971 | .80 |

## G. ECOSYSTEM EFFECTS

| | | Date | Price |
|---|---|---|---|
| CR 5 | Soil Movement in an Alpine Area | 6/69 | 1.00 |
| CR 21 | Waterfowl-Water Temperature Relations in Winter | 6/70 | 5.00 |
| CR 55 | Water Law in Relation to Environmental Quality | 3/74 | 30.00 |
| CR 69 | Engineering and Ecological Evaluation of Antitranspirants for Increasing Runoff in Colorado Watersheds | 9/75 | 2.50 |
| CR 93 | Application of Geomorphic Principles to Environmental Management | 2/80 | 3.00 |
| SR 2 | Environment and Colorado - A Handbook | 1973 | 4.00 |
| SR 4 | Piceance Basin Inventory | 12/71 | 10.00 |
| IS 7 | Wildlife and the Environment, Proceedings of Governor's Conference, March 1973 | 3/73 | 3.00 |
| IS 10 | Proceedings of a Workshop on Revegetation of High-Altitude Distrubed Lands | 7/74 | 3.00 |
| IS 11 | Surface Rehabilitation of Land Distrubances Resulting from Oil Shale Development | 6/74 | Free |
| IS 14 | Bibliography Pertinent to Disturbance and Rehabilitation of Alpine and Subalpine Lands in Southern Rocky Mountains | 2/75 | 3.00 |
| IS 21 | Proceedings: High Altitude Revegetation Workshop No. 2 | 8/76 | 4.00 |
| IS 25 | Surveillance Data - Plains Segment of the Cache La Poudre River, Colorado 1970-77 | 1/78 | 5.00 |
| IS 28 | Proceedings of a Workshop on Revegetation of High-Altitude Distrubed Lands, No. 3 | 6/68 | 4.00 |
| IS 40 | Proceedings of the Workshop on Instream Flow Habitat Criteria and Modeling | 12/79 | 5.00 |
| IS 42 | Proceedings: High-Altitude Revegetation Workshop No. 4 | 6/80 | 4.00 |
| TR 1 | Surface Rehabilitation of Land Distrubances Resulting from Oil Shale Development | 6/74 | 10.00 |
| TR 4 | Vegetative Stabilization of Spent Oil Shales | 12/74 | 3.00 |
| TR 5 | Revegetation of Distrubed Surface Soils in Various Vegetation Ecosystems of the Piceance Basin | 12/74 | 4.25 |

## H. PUBLIC WELFARE (SOCIAL GOALS) EFFECTS

| | | | |
|---|---|---|---|
| CR 37 | Searching the Social Science Literature on Water: A Guide to Selected Information Storage and Retrieval Systems - Preliminary Version | 9/72 | 5.00 |
| CR 38 | Water Quality Management Decision in Colorado | 6/72 | 5.00 |
| CR 39 | Institutions for Urban-Metropolitan Water Management Essays in Social Theory | 11/72 | 5.00 |
| CR 62 | Feasibility and Potential of Enhancing Water Recreation Opportunities on High Country Reservoirs | 6/75 | 4.00 |
| CR 75 | Physical and Economic Effects on the Local Agricultural Economy of Water Transfer to Cities | 10/76 | 3.00 |
| CR 78 | Selecting and Planning High Country Reservoirs for Recreation Within a Multi-purpose Management Framework | 7/77 | 6.00 |
| CR 81 | Achieving Urban Water Conservation: Testing Community Acceptance | 9/77 | 5.00 |
| CR 91 | Economic Benefits from Instream Flow in a Colorado Mountain Stream | 6/79 | 5.00 |
| CR 95 | Drought-Induced Problems and Responses of Small Towns and Rural Water Entities in Colorado: The 1976-1978 Drought | 6/80 | 4.00 |
| CR 103 | Empirical Application of a Model for Estimating the Recreation Value of Water in Reservoirs Compared to Instream Flow | 12/80 | 3.00 |
| CR 106 | Urban Lawn Irrigation and Management Practices for Water Saving with Minimum Effect on Lawn Quality | 5/81 | 6.00 |

| | | Date | Price |
|---|---|---|---|
| IS 15 | Proceedings of the Symposium on Water Policies on U.S. Irrigated Agriculture: Are Increased Acreages Needed to Meet Domestic or World Needs? | 3/75 | 4.00 |
| IS 18 | Minimum Stream Flows and Lake Levels in Colorado | 8/75 | 8.00 |
| IS 35 | Federal Water Storage Projects: Pluses and Minuses | 6/79 | Free |
| IS 38 | Public Participation Practices of the U.S. Army Corps of Engineers | 7/79 | 3.00 |
| TR 3 | Implementation of the Federal Water Project Recreation Act in Colorado | 6/74 | Free |
| TR 11 | Federal Water Recreation in Colorado: Comprehensive View and Analysis | 1978 | 4.00 |
| TR 12 | Recreation Benefits of Water Quality: Rocky Mountain National Park, South Platte River Basin, Colorado | 5/78 | 4.00 |

## I. INSTITUTIONAL PROBLEMS

| | | | |
|---|---|---|---|
| CR 11 | Organizational Adaptation to Change in Public Objectives for Water Management of Cache La Poudre River System | 6/69 | 3.00 |
| CR 12 | Economics and Administration of Water Resources | 6/69 | 3.00 |
| CR 17 | An Exploration of Components Affecting and Limiting Policymaking Options in Local Water Agencies | 11/68 | 5.00 |
| CR 36 | Urban-Metropolitan Institutions for Water Planning Development and Management | 9/72 | 5.00 |
| CR 39 | Institutions for Urban-Metropolitan Water Management Essays in Social Theory | 11/72 | 5.00 |
| CR 44 | Economic, Political and Legal Aspects of Colorado Water Law | 2/73 | 5.00 |
| CR 48 | Institutional Requirements for Optimal Water Quality Management in Arid Urban Areas | 6/73 | 3.00 |
| CR 52 | Consolidation of Irrigation Systems: Phase 1 - Engineering, Legal and Sociological Constraints and/or Facilitators | 6/73 | 25.00 |
| CR 55 | Water Law in Relation to Environmental Quality | 3/74 | 30.00 |
| CR 65 | Urban Drainage and Flood Control Projects: Economic, Legal and Financial Aspects | 7/75 | 10.00 |
| CR 68 | Systematic Design of Legal Regulations for Optimal Surface-Groundwater Usage, Phase 2 | 9/75 | 12.00 |
| CR 88 | Institutional Arrangements for Effective Water Management in Colorado | 11/78 | 4.00 |
| CR 94 | Consolidation of Irrigation Systems: Phase II - Engineering, Economic, Legal and Sociological Requirements | 5/80 | 8.00 |
| CR 95 | Drought-Induced Problems and Responses of Small Towns and Rural Water Entities in Colorado: The 1976-1978 Drought | 6/80 | 4.00 |
| CR 105 | Municipal Water Use in Northern Colorado: Development of Efficiency of Use Criterion | 9/80 | 4.00 |
| CR 106 | Urban Lawn Irrigation and Management Practices for Water Saving with Minimum Effect on Lawn Quality | 5/81 | 6.00 |
| IS 6 | Water Law and Its Relationship to Environmental Quality: Bibliography of Source Material | 1/73 | 7.00 |
| IS 12 | Water Quality Control and Administration Laws and Regulations | 1974 | 15.00 |
| IS 22 | Implementation of the National Flood Insurance Program in Larimer County, Colorado | 9/76 | 4.00 |
| IS 24 | Factors Affecting Public Acceptance of Flood Insurance in Larimer and Weld Counties, Colorado | 9/77 | 3.00 |
| IS 34 | San Luis Valley Water Problems: A Legal Perspective | 1/79 | 4.00 |
| IS 39 | Administration of the Small Watershed Program, 1955-1978 - An Analysis | 8/79 | 3.00 |
| TR 28 | An Assessment of Water Use and Policies in Northern Colorado Cities | 3/81 | 5.00 |

| | | Date | Price |
|---|---|---|---|
| X-740A | Ground Water Management District Director's Handbook | 1970 | .25 |
| SR 5 | A Guide to Colorado Water Law | 9/78 | 2.50 |

## J. PLANNING AND ANALYSIS METHODOLOGY

| | | | |
|---|---|---|---|
| CR 11 | Organizational Adaptation to Change in Public Objectives for Water Management of Cache La Poudre River System | 6/69 | 3.00 |
| CR 13 | Economics of Groundwater Development in the High Plains of Colorado | 6/69 | 1.50 |
| CR 17 | An Exploration of Components Affecting and Limiting Policymaking Options in Local Water Agencies | 11/68 | 5.00 |
| CR 22 | An Exploration of Components Affecting and Limiting Policymaking Options in Local Water Agencies | 6/70 | 3.00 |
| CR 27 | Local Water Agencies, Communication Patterns, and the Planning Process | 9/71 | 5.00 |
| CR 37 | Searching the Social Science Literature on Water: A Guide to Selected Information Storage and Retrieval Systems - Preliminary Version | 9/72 | 5.00 |
| CR 38 | Water Quality Management Decisions in Colorado | 6/72 | 5.00 |
| CR 45 | Mathematical Modeling of Water Management Strategies in Urbanizing River Basins | 6/73 | 7.50 |
| CR 46 | Evaluation of Urban Water Management Policies in the Denver Metropolitan Area | 6/73 | 7.50 |
| CR 47 | Coordination of Agricultural and Urban Water Quality Management in the Utah Lake Drainage Area | 6/73 | 7.50 |
| CR 56 | Evaluation and Implementation of Urban Drainage and Flood Control Projects | 6/74 | 8.00 |
| CR 61 | Economic and Institutional Analysis of Colorado Water Quality Management | 3/75 | 5.00 |
| CR 62 | Feasibility and Potential of Enhancing Water Recreation Opportunities on High Country Reservoirs | 6/75 | 4.00 |
| CR 70 | An Economic Analysis of Water Use in Colorado's Economy | 12/75 | 5.00 |
| CR 74 | The Relevance of Technological Change in Long Term Water Resources Planning | 10/76 | 3.50 |
| CR 75 | Physical and Economic Effects on the Local Agricultural Economy of Water Transfer to Cities | 10/76 | 3.00 |
| CR 78 | Selecting and Planning High Country Reservoirs for Recreation Within a Multi-purpose Management Framework | 7/77 | 6.00 |
| CR 82 | Development of a Subsurface Hydrologic Model and Use for Integrated Management of Surface and Subsurface Water Resources | 12/77 | 3.00 |
| CR 85 | Development of a Drainage and Flood Control Management Program for Urbanizing Communities - Part I | 9/78 | 2.00 |
| CR 86 | Development of a Drainage and Flood Control Management Program for Urbanizing Communities - Part II | 9/78 | 7.00 |
| CR 87 | Development of a Stream-Aquifer Model Suited for Management | 9/78 | 3.00 |
| CR 89 | Synthesis and Calibration of a River Basin Water Management Model | 10/78 | 3.00 |
| CR 90 | Models for System Water Planning with Special Reference to Water Reuse | 6/78 | 5.00 |
| CR 91 | Economic Benefits from Instream Flow in a Colorado Mountain Stream | 6/79 | 5.00 |
| CR 93 | Application of Geomorphic Principles to Environmental Management | 2/80 | 3.00 |
| CR 101 | An Empirical Application of a Model for Estimating the Recreation Value of Instream Flow | 10/80 | 3.00 |
| CR 102 | Measuring Benefits and the Economic Value of Water in Recreation on High Country Reservoirs | 9/80 | 3.00 |
| CR 103 | Empirical Application of a Model for Estimating the Recreation Value of Water in Reservoirs Compared to Instream Flow | 12/80 | 3.00 |
| CR 105 | Municipal Water Use in Northern Colorado: Development of Efficiency-of-Use Criterion | 9/80 | 4.00 |
| CR 106 | Urban Lawn Irrigation and Management Practices for Water Saving with Minimum Effect on Lawn Quality | 5/81 | 6.00 |
| SR 1 | Design of Water and Wastewater Systems for Rapid Growth Areas (Boom Towns - Mountain Resorts) | 7/76 | 4.00 |
| SR 3 | Irrigation Development Potential in Colorado | 5/77 | 4.00 |

| | | Date | Price |
|---|---|---|---|
| IS 19 | The Environmental Quality Objective of Principles and Standards for Planning | 8/75 | 7.00 |
| IS 38 | Public Participation Practices of the U.S. Army Corps of Engineers | 7/79 | 3.00 |
| IS 40 | Proceedings of the Workshop on Instream Flow Habitat Criteria and Modeling | 12/79 | 5.00 |
| IS 43 | An Evaluation of the Cache La Poudre Wild and Scenic River Draft Environmental Impact Statement and Study Report | 8/80 | 5.00 |
| TR 6 | Colorado Environmental Data Systems (abridged) | 10/72 | 5.00 |
| TR 7 | Manual for Training in the Application of Principles and Standards (Water Resources Council) | 12/74 | 10.00 |
| TR 8 | Models Designed to Efficiently Allocate Irrigation Water Use Based on Crop Response to Soil Moisture Stress | 5/77 | 4.00 |
| TR 9 | The 1972 Federal Water Pollution Control Act's Area-Wide Planning Provision: Has Executive Implementation Met Congressional Intent? | 11/77 | 5.00 |
| TR 10 | Efficiency of Wastewater Disposal in Mountain Areas | 1/78 | 5.00 |
| TR 18 | An Interactive River Basin Water Management Model: Synthesis and Application | 3/80 | 4.00 |
| TR 20 | Development of Methodologies for Determining Optimal Water Storage Strategies | 9/80 | 2.00 |
| TR 26 | An Input-Output Analysis of Sportsman Expenditures in Colorado | 1/81 | 4.00 |
| S-TB127 | A Simulation Model for Analyzing Timber-Water Joint Production in the Colorado Rockies | 1975 | 1.25 |

## K. WATER CONVEYANCE AND CONTROL WORKS

| | | | |
|---|---|---|---|
| CR 6 | Stabilization of Alluvial Channels | 6/69 | 3.00 |
| CR 7 | Stability of Slopes with Seepage | 6/69 | 3.00 |
| SR 1 | Design of Water and Wastewater Systems for Rapid Growth Areas (Boom Towns - Mountain Resorts) | 6/76 | 4.00 |
| S-496S | Farm Irrigation Structures | 1966 | .50 |
| S-TB76 | Parshall Measuring Flumes of Small Sizes | 1957 | .25 |
| X-426A | Parshall Flumes of Large Size | 1961 | .50 |
| S-TB120 | Selection and Installation of Cutthroat Flumes for Measuring Irrigation and Drainage Water | 1976 | 1.25 |
| S-TB126 | A Shunt-Line Metering System for Irrigation Wells | 1977 | .75 |
| S-522S | Weed Seed and Trash Screens for Irrigation Water | 1966 | .35 |

## L. OTHER

| | | Date | Price |
|---|---|---|---|
| IS 1 | Inventory of Environmental Resources Research in Progress - Colorado State University | 1/71 | Free |
| IS 3 | Inventory of Environmental Resources Research in Progress - Colorado State University | 7/72 | Free |
| IS 5 | Directory of Environmental Research Faculty - Colorado State University | 12/72 | Free |
| IS 8 | Inventory of Current Water Resources Research at Colorado State University | 7/73 | Free |
| IS 23 | Inventory of Colorado's Front Range Mountain Reservoirs | 5/77 | 5.00 |
| IS 30 | The Larimer-Weld Council of Governments 208 Water Quality Plan: An Assessment and Suggestions for Future Directions | 8/78 | 2.00 |
| TR 2 | Estimated Average Annual Water Balance for Piceance and Yellow Creek Watersheds | 8/74 | Free |
| S-504S | Colorado's Ground Water Problems | 1967 | .35 |
| S-512S | Ground Water in the Bijou Valley | 1961 | .25 |
| S-GS757 | Public Water Supplies of Colorado 1959-1960 | 1961 | 1.25 |