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1974 PROGRESS REPORT
[FINAL]

EFFECT OF SOIL WATER POTENTIAL ON SOIL MOISTURE
ABSORPTION, TRANSPIRATION RATE, PLANT WATER
POTENTIAL AND GROWTH FOR *ARTEMISIA TRIDENTATA*

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ABSTRACT

Plant water relations and soil moisture depletion and recharge were followed in a stand of *Artemisia tridentata* near Washtucna, Washington, during 1973 and 1974. Precipitation during the 1972-73 recharge season was 14.5 cm, 11 cm below normal. The 1973-74 precipitation was 35.7 cm, or 10 cm above normal. The two years were therefore ideal for comparing plant behavior on wet vs. dry years. Soil moisture was depleted to around -70 bars in 1973 and -60 bars in 1974 to depths of 2.5 m. Leaf water potentials were -10 bars in the spring and decreased to -50 to -60 bars in the summer of 1973. In 1974, summer leaf water potential was -30 bars. Osmotic potentials were around -20 bars in the spring of 1973 and throughout the spring and summer of 1974. In the summer of 1973 osmotic potentials dropped to -60 bars. Stomatal diffusive conductances of 0.5 cm/sec (resistance of 2 sec/cm) were common during the spring and summer of 1974 and the spring of 1973. Summer conductances in 1973 were 0.05 cm/sec (resistance of 10 sec/cm). A simple model is proposed which predicts evaporation and transpiration from daily precipitation and potential evapotranspiration. Model parameters include soil hydraulic properties and maximum transpiration rate as a function of available soil moisture. The agreement between model prediction and measured values is within the uncertainties imposed by the input data. The model predicts 9 cm of evaporation each year. In 1973 this was half of the total amount received. In 1974 it was only one-fourth of the total.

INTRODUCTION

This study was undertaken to relate plant water potential, stomatal diffusion resistance and evapotranspiration to soil water potential for *Artemisia tridentata*. Production data have not been taken, as originally planned, because it is a time-consuming operation, and intensive production sampling is underway at other Desert Biome sites. Water relations modeling is being pursued somewhat more intensively than was outlined in the original proposal, partly because of availability of improved measurement and analysis techniques. The use of a steady-state diffusion porometer, developed during the early part of this study, has provided diffusion resistance measurements which are much better than we originally thought possible. The two years selected for sampling gave an excellent picture of water relations because two extremes were represented. In 1973 precipitation was extremely low and plants were stressed throughout most of the year. In 1974 precipitation was well above normal, giving a year with unusually low water stress.

OBJECTIVES

The objectives of this study were to:

1. Determine transpiration, evaporation and growth for *A. tridentata* and relate these to soil and plant water potential and stage of plant development.
2. Determine the soil water potential at which absorption of water by roots of *A. tridentata* and associated grasses is reduced or ceases and how it changes with root depth in the soil.

For 1974, our specific objectives were to collect data on plant water potential, stomatal diffusion resistance, plant osmotic potential, evapotranspiration and soil water potential, and to provide an analysis of the data showing components of the water budget and relationships between plant water variables and soil moisture.

METHODS

All 1974 data were collected at a site near Washtucna, Washington, that was called site 1 in 1973. Site 1 is located in the SE ¼, SE ¼, NE ¼, SE ¼ Sec. 15, T. 15N, R36E WM in Adams County. The soil series is listed as Esquatzel silt loam. A small stand of *Artemisia tridentata* which is relatively undisturbed by grazing and farming and is in an area adjacent to the highway, a farm access road and a drainage was selected for study. An area approximately 20 x 20 m was fenced and a weather station installed, including an accumulating rain gauge, a maximum-minimum thermometer, an anemometer at 2-m height and a solar radiation integrator. Areas which were primarily grass, small sagebrush, large sagebrush and bare soil exist within the fenced area. Neutron access tubes were installed in each of these areas and in an adjacent sagebrush area across the access road west of the fenced area. Small sagebrush is up to 50 cm high, while the large sagebrush is about 200 cm.

SOIL DATA

Soil water content was measured using neutron scattering. Nine aluminum tubes were installed in site 1. Details on tube placement and measurement techniques can be found in our 1973 report (Campbell and Harris 1974). Water content was measured approximately every two weeks from January through December (more frequently in the summer, less frequently in the winter). The counts (30 sec) were converted to water content; the water contents are recorded in DSCODE A3UCJ02.

Soil samples were collected periodically and water potentials were measured with a Wescor sample chamber psychrometer. These measurements, along with neutron meter water contents, were used to infer soil water content from water potential.

PLANT DATA

Plant water potential, osmotic potential and stomatal diffusion resistance were measured from January through

December. Leaf water potential was measured with a pressure chamber (P.M.S. Instrument Co., Corvallis, Oregon). Leaf osmotic potential was measured on cell sap which was expressed from leaves previously frozen with dry ice. The sap was absorbed on a filter paper disk and the measurement was made with a commercial sample chamber hygrometer (Wescor, Inc., Logan, Utah). Stomatal diffusion resistance was measured using a steady-state technique similar to that described by Beardsell et al. (1972).

The measurements were made by excising a 10- to 15-cm long branch tip and placing it in the porometer chamber. The diffusion resistance measurement was accomplished within 15 to 20 sec of excision. The branch was then placed in the pressure chamber and leaf water potential was measured. It was then stored in a closed Tygon tube on ice for transport to the laboratory. There, several leaves were removed and frozen with CO₂ ice, the sap was expressed and osmotic potential was measured with the hygrometer. What remained of the leaves was run through a commercial optical leaf area meter. The leaf area measurement was used to determine diffusion resistance. Generally, duplicate readings were made on a large (old) and a small (young) sagebrush every two weeks when the site was visited. These measurements are recorded in A3UCJ01. Notes on phenology were made and related to the numeric phenological code of Caldwell et al. (1973, 1974). The code is reproduced in Table 1 for convenient reference.

METEOROLOGICAL DATA

Biweekly measurements of precipitation, wind run, solar radiation, maximum and minimum temperature and soil temperature were made. Wet and dry bulb temperature were measured at the time the site was visited in order to calculate vapor pressure. Precipitation was measured with an accumulating rain gauge. Wind run was followed using a reed switch anemometer of the type described by Fritschen and Hinshaw (1972), operating into a battery-powered counter (circuit available from project leader on request). A silicon solar cell of the type described by Kerr et al. (1967) was used to measure solar radiation. The signal was integrated using a low-power, battery-operated circuit and electromechanical counter (circuit also available on request). Maximum and minimum temperatures were obtained from a standard max-min thermometer inside a ventilated shelter at a height of 2 m. Soil temperature was measured with thermocouples installed along with the soil psychrometers. Wet and dry bulb temperatures were measured with a standard sling psychrometer (A3UCJ03).

RESULTS AND DISCUSSION

METEOROLOGICAL DATA

The weekly or biweekly data collected at the site proved to be inadequate for necessary potential evapotranspiration (PET) estimates and for comparisons of the two years' data. They were therefore used as a basis for comparison with more extensive data available at other sites.

The rainfall record at Lind, Washington, was found to be very similar to the measurements we made at site 1, so these data were used for our analyses and comparisons. Monthly and annual totals are shown in Table 2 for 1973 and 1974. Soil-water recharge usually begins around September, so the annual totals are given to show water delivered to the system in a production year. The 1973 precipitation was below normal by about 10 cm and the 1974 precipitation was above normal by about this same amount. This difference had a marked effect on plant response, as we shall see.

To augment the solar radiation data collected at the site, ratios of measured to maximum possible solar radiation were computed and compared to National Weather Service

Table 1. Numeric phenological code of Caldwell et al. for *Artemisia tridentata*. Taken from Desert Biome Research Memorandum RM 73-13

| |
|---|
| 0 -- Winter dormancy |
| 1 -- Post-dormant quiescence |
| 2 -- Swelling leaf buds (mid-April to early May) |
| 3 -- Emergent large new leaves on vegetative branches (mid-May) |
| 4 -- Rapid new vegetative stem and leaf growth; reproductive shoots initiated (late May to mid-June) |
| 5 -- Reduced vegetative growth; reproductive shoot and bud growth; ephemeral leaves growing on reproductive shoots; (early July to mid-July) "spring" leaves shed |
| 6 -- Reproductive shoots full size; flower buds developing; little vegetative growth (mid-July to late August) |
| 7 -- Flower buds fully developed -- some beginning to burst; ephemeral leaves on reproductive shoots dying and being shed (September) |
| 8 -- Flowering (early October) |
| 9 -- Fruit developng (late October to early November) |
| 10 -- Shedding of fruit; predormancy quiescence (mid-November on) |

Table 2. Precipitation (cm) and departure from normal for Lind, Washington. Precipitation at the study site was similar in pattern and amount

| | 1972-1973 | | 1973-1974 | |
|-----------|---------------|---------------|---------------|---------------|
| | Precipitation | Departure | Precipitation | Departure |
| September | 0.91 | - 0.53 | 1.91 | 0.46 |
| October | 0.18 | - 2.64 | 3.30 | 0.48 |
| November | 2.01 | - 0.84 | 8.51 | 5.66 |
| December | 4.57 | 1.32 | 7.67 | 4.42 |
| January | 2.54 | - 0.33 | 3.43 | 0.61 |
| February | 0.58 | - 1.88 | 2.01 | - 0.41 |
| March | 0.86 | - 1.19 | 2.90 | 1.17 |
| April | 0.58 | - 1.12 | 1.70 | - 0.13 |
| May | 1.52 | - 0.64 | 1.12 | - 1.45 |
| June | 0.58 | - 2.06 | 0.56 | - 1.85 |
| July | 0.13 | - 0.53 | 2.57 | 1.91 |
| August | <u>0.05</u> | <u>- 0.71</u> | <u>0.05</u> | <u>- 0.79</u> |
| Total | 14.53 | -11.15 | 35.71 | 10.08 |

records at Walla Walla and Spokane. The Walla Walla numbers were within a few percent of those we collected, so these were used to estimate solar radiation at the site.

Estimation of evaporation from the soil surface requires PET data. A simple PET equation which has reasonable theoretical justification is

$$PET = (0.9 - a)S_i$$

where S_i is the incoming short wave radiation and a is the albedo of the surface. At our site, surface albedo was assumed to be 0.3. Estimates of PET in 1973-74 were described, as a function of time, by the following line segments:

$$\begin{aligned} PET &= 0.46 - 5.64 \times 10^{-3}t & 0 \leq t \leq 78 \\ PET &= 0.02 & 78 \leq t \leq 126 \\ PET &= 0.02 + 3.3 \times 10^{-3}(t-126) & 126 \leq t \leq 226 \\ PET &= 0.35 + 8.0 \times 10^{-3}(t-226) & 226 \leq t \leq 286 \\ PET &= 0.83 - 3.56 \times 10^{-3}(t-286) & 286 \leq t \leq 376 \end{aligned}$$

where t is the time in days from September 1, 1973, and PET is in cm/day.

PLANT WATER DATA

During 1974 there were no consistent differences between measurements for large and small sagebrush. The four measurements for any particular time were therefore averaged. Osmotic potentials, leaf water potentials and diffusive conductances are plotted in Figure 1. The 1973 data are plotted on the same figure for reference. In 1973, potentials and conductances decreased to very low levels after about June 1. In 1974, stomatal conductance remained high throughout the year and osmotic potential remained almost constant at around -23 bars until the end of the season. Leaf water potentials were similar in the spring for both years, but reached only -30 bars or so in 1974. From about the first of April until mid-June 1974, turgor was positive. This corresponds to phenological states 1, 2, 3 and 4 (Table 3), the time of rapid vegetative growth. The data during late summer indicate negative turgor. Systematic errors in the measurement techniques may be responsible for this since negative turgor pressures in excess of a few bars are improbable. Turgor loss is followed, within a short time, by phenological stage 5, the shedding of spring leaves. During 1974 the osmotic potential increased from its winter value, then decreased slightly throughout the summer, dropping rapidly in the fall as dormancy approached. This was in marked contrast to 1973 when osmotic potentials dropped to -50 bars in midsummer. Experience with other species leads us to believe that the 1974 behavior is the usual behavior of sagebrush, and that osmotic potential is generally subject to strong homeostatic control. The unusually dry conditions of 1973 forced the plants out of their control mode.

Stomatal conductances remained high throughout 1974. Again, this is in contrast to 1973 when conductances fell to

very low values in June and did not recover for the remainder of the season. Again, experience with other species (Cline 1974) leads us to believe that the 1974 behavior is more typical. Under field conditions, long-term control of water loss is primarily by adjustments in leaf area, at least until leaf area is reduced to some minimum value required for survival. Stomatal control of water loss occurs only after adjustments in leaf area or during short-term stress periods. In 1973, the unusually severe stress resulted in low conductances during most of the summer.

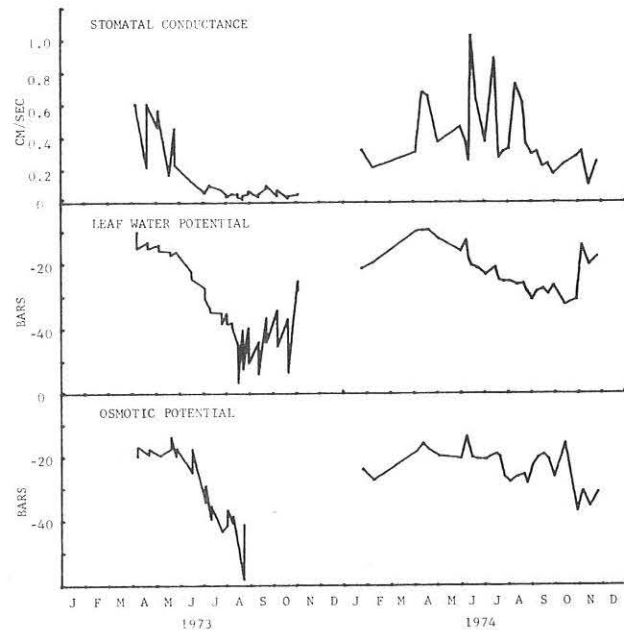


Figure 1. Stomatal conductance, leaf water potential and osmotic potential of *Artemisia tridentata* during 1973 and 1974.

Table 3. Phenology of *Artemisia tridentata* during 1973 and 1974. Date shown is the first date on which the indicated characteristics were observed

| Phenological Code Number | First Date of Occurrence | |
|-----------------------------|--------------------------|--------------|
| | 1973 | 1974 |
| 1 | | April 13 |
| 2 | April 2 | April 20 |
| 3 | May 4 | May 31 |
| 4 | May 19 | June 21 |
| 5 | July 2* | July 2 |
| 6 | July 16 | August 30 |
| 7 | August 28 | September 20 |
| 8 | October 5 | October 11 |
| 9 | October 26 | October 26 |
| 10 | | November 22 |

*This date appears to be in error. The early 1973 code numbers were reconstructed from field notes on phenology rather than direct observation.

Diurnal patterns of plant water variables were followed on four occasions. These are shown as Figure 2. Diffusive conductances were low in the afternoon and evening, and increased to their highest values a few hours after sunup. Nighttime water potentials recovered to -10 bars early in the season and -20 bars by the end of the season. Daytime water potentials were about as those shown in Figure 1. Osmotic potentials show some diurnal fluctuation, especially early in the season. The fluctuations are probably primarily due to cell volume changes with turgor. Both maximum and minimum conductances tend to decrease as the season progresses.

SOIL WATER

The water-use pattern (neutron tube 6) for 1973 is shown in Figure 3 and for 1974 in Figure 4. The 1973 recharge was much lower than normal, as has been mentioned, and essentially all stored moisture was used by the end of May. It is significant that the water content at 2.5 m remained essentially constant in 1974, even though precipitation was

140% of normal. A substantial change occurred in the 2.3-m water content during the season, so roots must have extended to that depth.

By the end of the season each year, water contents to 2 m were reduced to about 0.03 cm³/cm³. Neutron data and psychrometer measurements on samples established the following water potential-water content relationship:

$$\Psi = 3.67 \times 10^{-3} \theta^{-2.8}$$

where Ψ is in bars and θ in cm³/cm³. Use of this relationship indicates that water potentials to 2 m were around -70 bars in 1973, and at least -60 bars in 1974. This is a little puzzling since leaf water potentials were never measured to be this low and evaporative loss directly from the soil is limited in its influence to the top few decimeters of soil. The soil was stratified with layers of coarser material between layers of fines, so the moisture retention curve is not exact for all layers, but we measured water potentials of

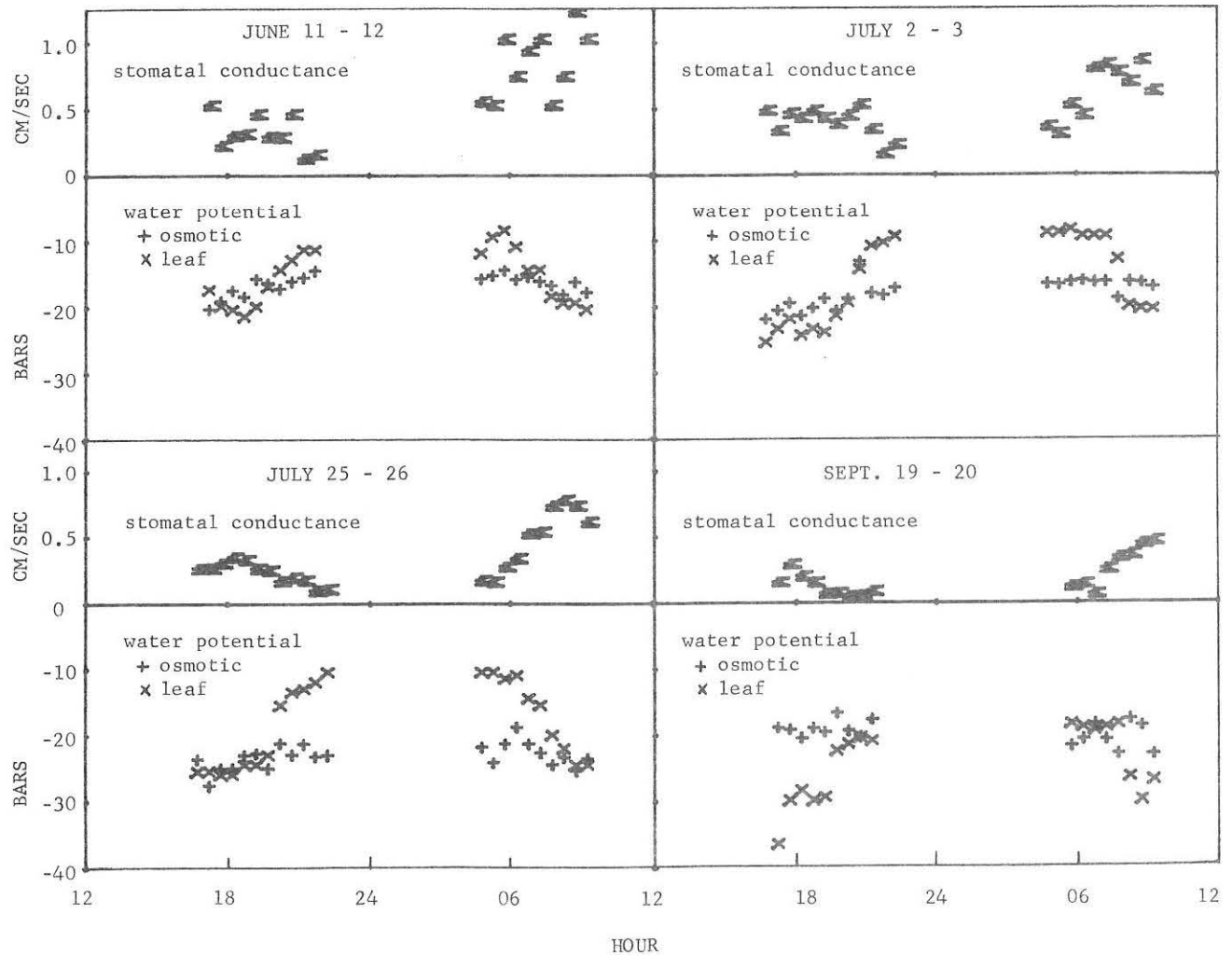


Figure 2. Diurnal patterns of stomatal conductance, leaf water potential and osmotic potential for *Artemisia tridentata* during 1974.

-60 bars with the psychrometers in August 1974. Again, similar observations of other species at other sites lead us to believe that this observation is not the result of experimental errors, but we have no explanation for it at present.

The overnight observations on September 20 (Fig. 2) show nighttime recovery to -20 bars. Water potentials throughout the profile were lower than this except possibly at 2.5 m. Comparisons at earlier times seem to indicate that overnight recovery is about to the highest water potential in the root zone once soil water potentials are below about -10 bars. Daytime leaf potentials (Fig. 1) began to decrease around May 1 when the maximum profile water content was between -1 and -2 bars, but water potential in the upper 50 cm (the zone of maximum root concentration) was below -10 bars. Daytime turgor pressures near zero were common after mid-June when the maximum profile water potential was around -10 bars and water potentials in the upper 50 cm were below -60 bars. The 30-cm neutron reading is inaccurate at these low water contents because the scattering volume became too large to be contained by a 30-cm soil depth. The 30-cm reading should probably be about the same as the 60-cm reading.

Onset of phenological stage 5 marks the end of rapid dry matter production and photosynthesis. In 1974 this occurred around the first of July (Fig. 1). Water potentials in the top 2 m of the profile were at or below -30 bars by July 12.

To summarize, it appears that rapid growth occurs when water potentials in the upper 50 cm or so of the profile are

above -1 to -2 bars, that growth continues at slower rates until potentials throughout the root zone reach -30 bars, and that the plant can continue to maintain itself and draw some water from the profile at water potentials of -60 to -70 bars.

WATER BUDGET MODELS

The close relationship between production and transpiration (Hanks 1974) makes it almost mandatory that any production model has an accurate submodel to predict the volume of water available for transpiration. Generally one can obtain data on PET and precipitation. Soil hydraulic and retention properties can also be assessed. From this input data, one would like to predict how much water evaporates from the soil, how much is stored and how much is transpired.

Evaporative loss can be estimated using the Ritchie (1972) model, but with a modified equation for the second stage of drying to account for the finite depth of wetting (Papendick and Campbell 1974). Evaporation is limited either by potential evaporation or by the soil water supply rate. The model we used computed potential evaporation and the maximum rate of evaporation from a soil with a dry surface. Actual evaporation was taken as the smaller of the two. Our procedure for calculating second-stage drying was similar to that described by Gardner (1974). Potential evaporation was taken as

$$PE = (1-c) PET$$

where c is the fraction of the surface covered by vegetation.

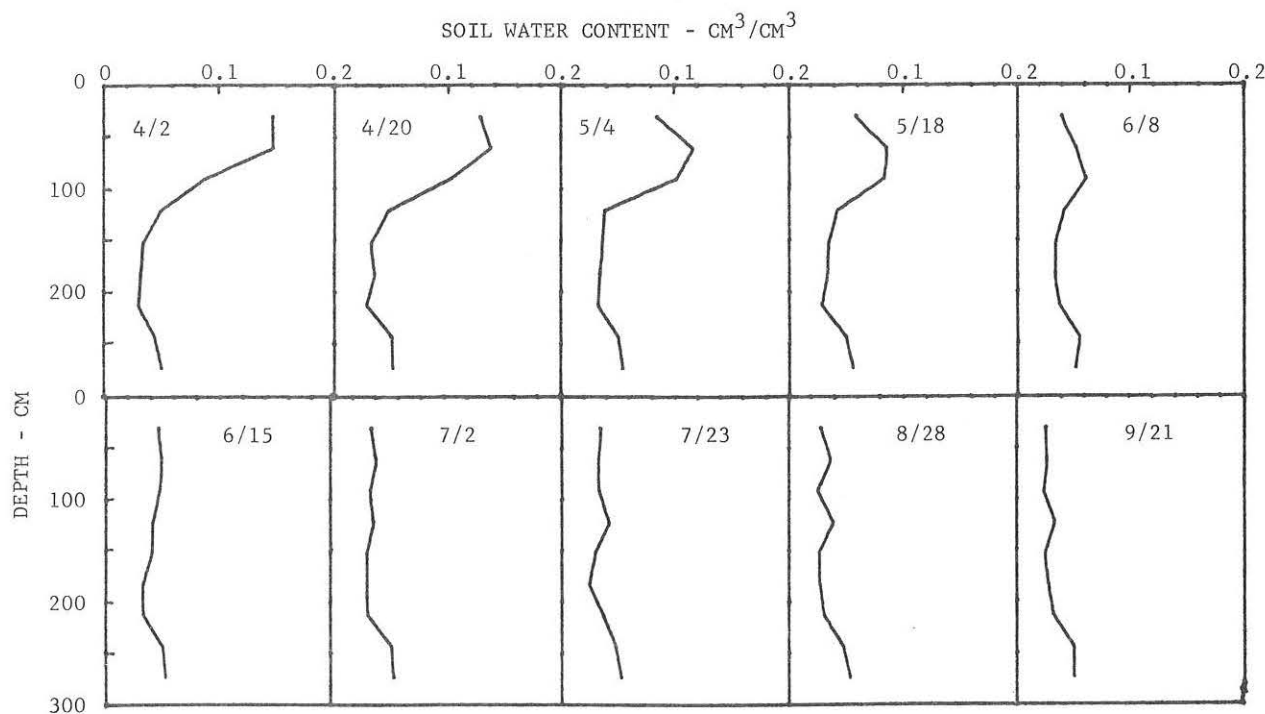


Figure 3. Soil moisture depletion patterns for 1973.

We estimated c to be about 0.3. The evaporation rate after the soil surface has dried is given by Papendick and Campbell (1974):

$$E = (\pi^2 W D_0 e^{aW/L}) / 4L^2$$

where W is the total profile water content, L is the depth of wetting, D_0 is the air dry diffusivity of the soil and a is an empirical constant. The depth of wetting was found by dividing the amount of precipitation received by the field capacity water content. For our simulation, we used $D_0 = 0.2 \text{ cm}^2/\text{day}$, $a = 29$, and field capacity water content, $\theta_{fc} = 0.16 \text{ cm}^3/\text{cm}^3$ (Fig. 4). The model is extremely sensitive to changes in θ_{fc} , but is insensitive to changes in D_0 and a .

To simulate plant water use, we assumed that transpiration was zero until April 10. After that time transpiration was assumed to be equal to PET or to a soil-plant determined rate, whichever was smaller. The maximum rate of moisture withdrawal from a soil profile was assumed to be a function of available soil moisture. The profile was assumed to hold 40 cm ($250 \text{ cm} \times 0.16 \text{ cm}^3/\text{cm}^3$) of water at field capacity and 7.5 cm at zero available moisture. Once transpiration was limited by available soil moisture, available moisture was described adequately as a function of time in 1973 and 1974 by the following expression:

$$A = me^{-bt} \quad (1)$$

where m and b are empirical constants. Transpiration rate is just a constant multiplied by the derivative of equation (1). Taking the derivative of equation (1) and substituting equation (1) into it we obtain transpiration rate as a

function of available moisture:

$$T = kbA$$

For our experiment, $k = 32.5 \text{ cm}$ and $b = 0.026 \text{ day}^{-1}$, so $T = 0.85 A \text{ cm/day}$. Springtime PET is generally around 0.3 to 0.4 cm/day, so more than half the available moisture (assuming a full profile) must be used before the soil-plant system begins to limit water loss.

The 1973 simulation is shown in Figure 5 and the 1974 simulation in Figure 6. The agreement between simulation and observation appears good. The major discrepancies are the result of the gross approximations used to estimate PET and precipitation. The 1974 precipitation data were adjusted on three occasions where our biweekly measurements showed substantially more rain than was received at Lind during the same time period. No such adjustment of the 1973 data was possible because we did not have data at the site. Slight adjustments in PET and precipitation were found to substantially improve the agreement between simulation and measurement, but the model was found to be insensitive to adjustments in other parameters.

During 1973 (Fig. 5) the total precipitation was about 16.4 cm. Evaporation was estimated to be 8.6 cm, or about 50%. In 1974 (Fig. 6) precipitation was 38 cm, of which we estimated 9 cm or 25% was lost to evaporation. If the simulation is correct, it indicates that evaporation remains relatively constant and is somewhat independent of large fluctuations in precipitation. Thus we might expect doubling the precipitation to more than double transpiration and therefore production.

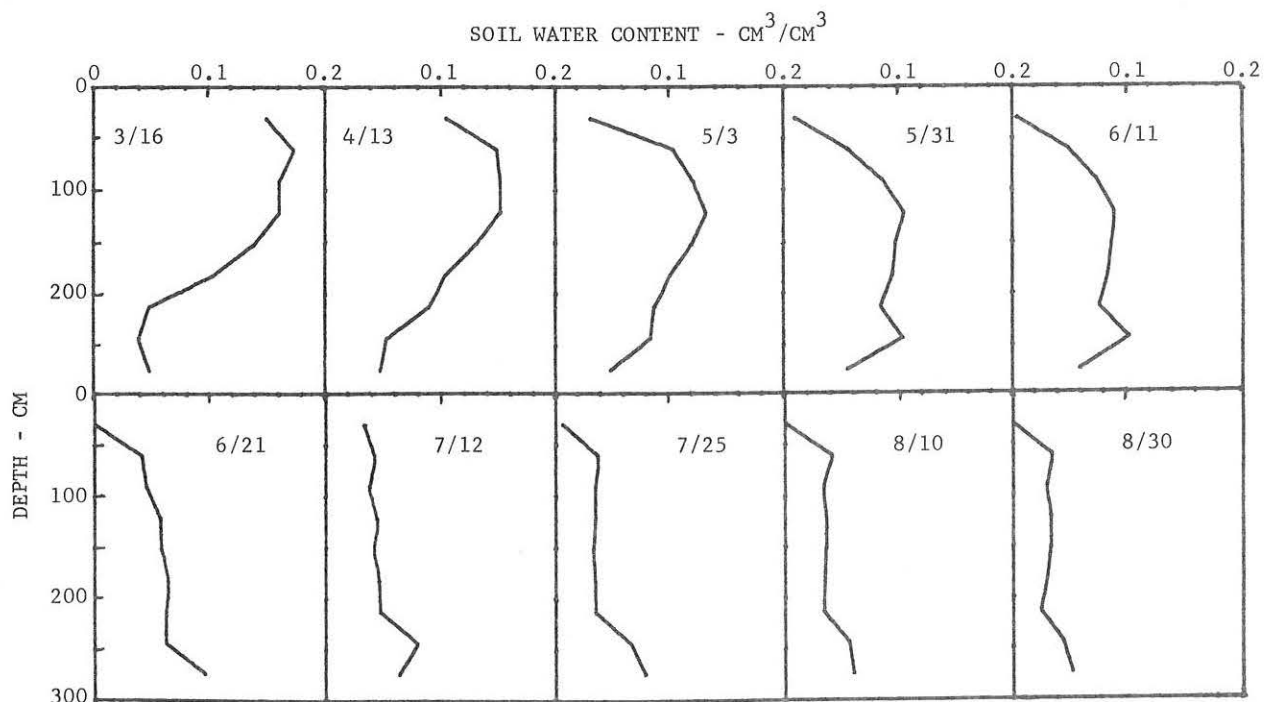


Figure 4. Soil moisture depletion patterns for 1974.

These observations can be tied in with a recent Desert Biome effort; determining the effect on production of doubling or halving the annual precipitation. In fact, the 1973 precipitation was about half of normal and the 1974 was almost 1.5 x normal. In 1974 the soil was filled to near 100% of field capacity so additional stored moisture would probably not have changed transpiration or production significantly. The excess moisture would have gone to deep drainage or evaporation. Some additional summer moisture would have been useful to the plant. Recharge of the upper 50 cm of soil in late April or early May would probably have increased the period of rapid growth.

Decreasing precipitation would decrease water available for transpiration in two ways. The input would be less, but

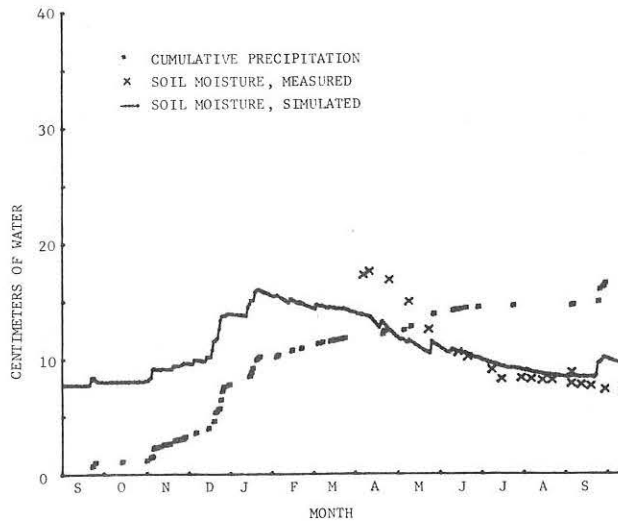


Figure 5. Cumulative rainfall and simulated and measured profile water content in 1972-73.

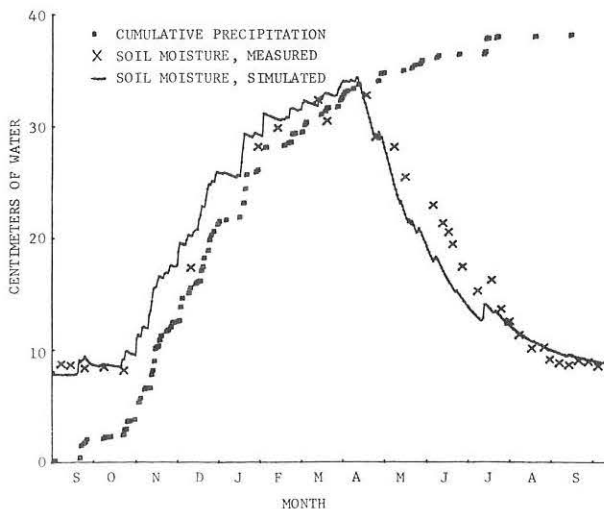


Figure 6. Cumulative rainfall and simulated and measured profile water content in 1973-74.

smaller rains would result in a larger fraction of the moisture being lost to evaporation. The result would be a faster rate of decrease in production than in precipitation.

ACKNOWLEDGMENTS

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