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1975 PROGRESS REPORT

PLANT GROWTH AND WATER TRANSFER INTERACTIVE PROCESSES UNDER DESERT CONDITIONS

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ABSTRACT

Moisture transfer into and out of the root zone by abiotic processes is responsible for a significant portion of the observed soil moisture content variations adjacent to desert plants. In this study, the relative magnitudes of these processes were investigated. Data were collected on variations in moisture content and soil moisture potential within vegetated and nonvegetated desert study plots. Soil moisture extraction patterns were determined for the rooting habits of *Larrea tridentata* (creosotebush) and the results compared to the previous year's data. Throughfall measurements were collected for *Larrea tridentata*. Data were collected on plant leaf potentials for both the yearly and daily cycles, using pressure bomb techniques. Evapotranspiration rates were measured using the Bowen ratio technique and areal diffusion resistance values calculated from the potential and actual evapotranspiration rates. Temperature profiles were measured in the vertical and horizontal direction to estimate the direction of energy transfer from the creosotebush plants to the interspaces.

INTRODUCTION

This study is a continuation of an investigation reported by Evans and Sammis (1975). During most of the year transpiration losses from the creosotebush are controlled by the soil moisture content and not the evaporative demand of the air. The present investigation considers the relative magnitude of the physical processes controlling the response of desert plants and the resulting evapotranspiration rates.

An understanding of the daily and yearly interaction between soil water potential, plant water potential, plant diffusion resistance and the transpiration rate is needed to determine the response of creosotebush to changes in the limited available water from rainfall. Knowledge about these physical parameters is also needed to model the evapotranspiration component of the total desert ecosystem.

This report is supplemented by another research memorandum dealing with the reconstruction and new design of the monolith weighing lysimeter used in the study (Young et al. 1976, RM 76-34). The determination of the soil, plant and atmospheric parameters and their interactions controlling evapotranspiration are reported herein.

OBJECTIVES

The general objective of this study was to determine the evaporation rates from bare soil and transpiration rates from creosotebush and to delineate the parameters needed to model the evapotranspiration process. Specifically the objectives were:

1. To measure the evapotranspiration rate of creosotebush.
2. To separate the evapotranspiration rate into its components of evaporation from bare soil and transpiration from creosotebush.
3. To calculate the potential transpiration rate, the plant diffusion resistance of creosotebush and to reduce this potential rate to the actual evpotranspiration rate.

Due to reasons explained in the supplemental report (RM 76-34) measurement of the evapotranspiration rate of the creosotebush (the first objective) using the lysimeter was not accomplished during the time period when meteorological measurements were made to determine the evapotranspiration rates; instead we used the Bowen ratio method to measure the evapotranspiration rate.

METHODS

PLOT DESCRIPTION

This project was conducted at two field locations at the Silverbell Validation Site. Plot 1 was described by Qashu et al. (1973) and Evans and Sammis (1975); a plot diagram is presented in Figure 1. Plot 2, presented in Figure 2, is located next to the monolith weighing lysimeter and contains neutron access tubes for measuring soil moisture content (DSCODE A3UQH17), pelter psychrometers to measure the soil water potential and soil temperature (A3UQH13) and miniature rain gauges to measure interception and throughfall. Plot 2 also contains extensive meteorological equipment and a Hewlett Packard data acquisition system to record the data. Figure 3 gives a schematic diagram of the installation.

The climatic instruments installed at the field site and their locations (Fig. 3) are: an Eppley pyranometer facing down over the creosotebush to measure the reflected solar radiation (7); an Eppley facing up to measure incoming solar radiation (1); a Kipp Zonen solarimeter facing down over bare soil to measure reflected solar radiation (2); net radiometers over the plant (4) and bare soil (3); anometers located at 1.2-, 3.2- and 5-m heights above the soil surface (5); air temperatures measured at 30-cm intervals on two stationary masts using copper constantan thermocouples (6); Bowen ratio equipment to measure evapotranspiration rates (8); a hydrothermograph (9); and a standard rain gauge (10). Soil heat flux plates were also installed approximately 2 cm below the soil surface in a spiral around a creosotebush.

Measurements of leaf water potential were made using a pressure bomb technique described by Scholander et al. (1965). The assigned DSCODE is A3UQH15.

Rainfall data collected by other investigators at Silverbell are presented in the Appendix.

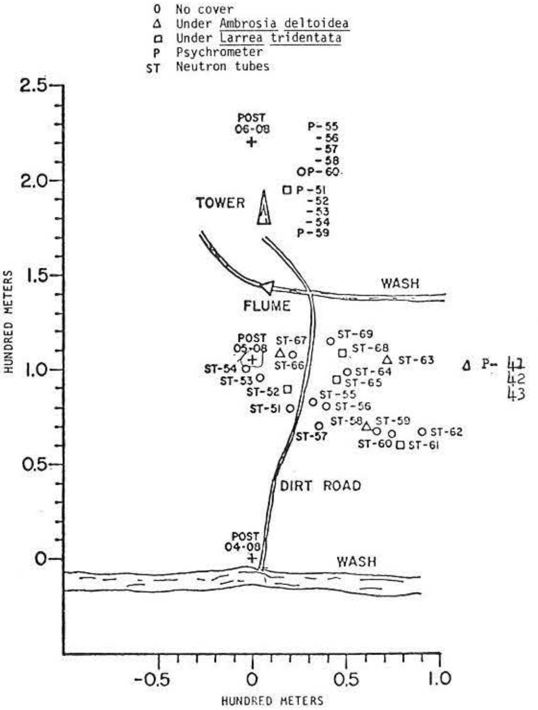

Figure 1. Diagram of Plot 1: approximate location of measurements taken near the center of the Silverbell Validation Site.

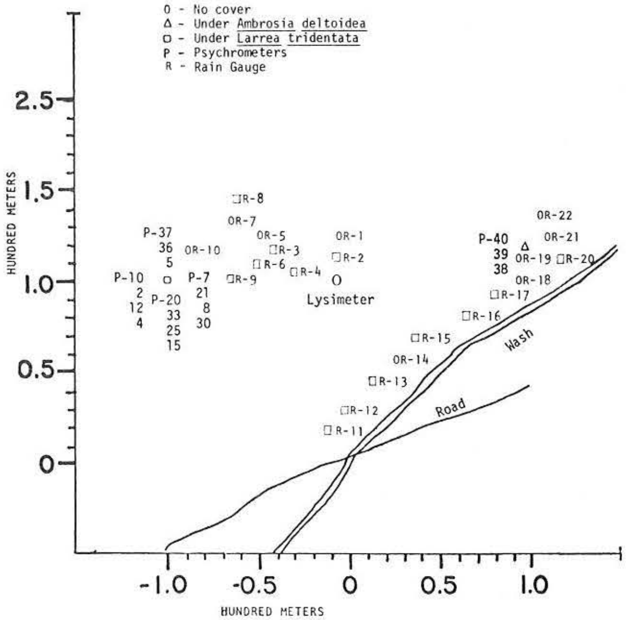

Figure 2. Diagram of Plot 2: approximate location of measurements taken in the northeast corner of the Silverbell Validation Site.

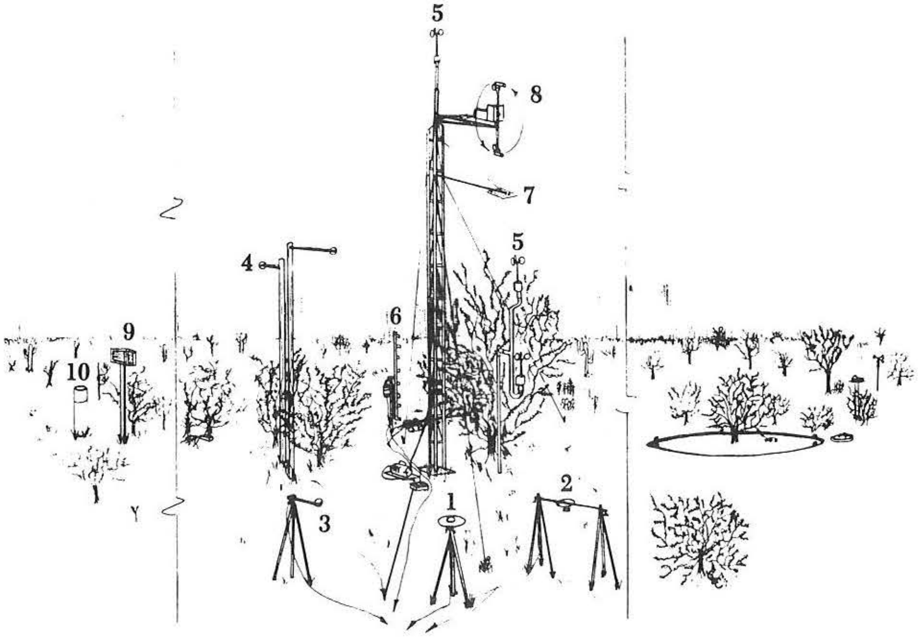

Figure 3. A schematic diagram of the climatic equipment located next to the lysimeter. (See page 24 of the text for explanation of numbers.)

RESULTS AND DISCUSSION

Soil Moisture

Accumulative soil moisture to 90 cm is presented in Table 1. At the 0.975 level of significance, as was determined in the 1974 study (Evans and Sammis 1975), there is no difference between the total soil moisture in the bare soil, which had been stripped of vegetation for a 10-m radius, vs. the moisture under the creosotebush and bursage plants. The rainfall in January and April tended to increase the spatial variability of the total soil moisture as did the summer rainfall in the 1974 study. The coefficient of variability increased from 10 to 20%. However, compared to the 1974 study, there was no significant increase in the total soil moisture spatial distribution under the creosotebush vs. the moisture under the bursage and in the open area. Because of the decrease in summer rainfall in 1975, compared to 1974, the available soil moisture in August (5.13 cm) was approximately 3 cm less. The plants were under greater moisture stress for a longer duration and their response, as measured by the plants' water potential (which will be discussed in a later section), was entirely different for the summer of 1975 as compared to the summer of 1974.

The extraction patterns of moisture for the vegetative and nonvegetative areas are presented in Table 2. The root activity of the creosotebush, as previously observed, is correlated to the moisture distribution. During the spring months the water appears to be extracted uniformly from the total 90-cm depths, during the summer months more is extracted from the 30- and 90-cm depths until the summer rainfall replenishes moisture to the 60-cm depth and then moisture is extracted mainly from that top 60 cm. The bursage plants draw most of their water from the top 60 cm but the extraction pattern is not as pronounced and distinctive as in the 1974 study.

Soil Moisture Potential

Psychrometer potential measurements for Plots 1 and 2 are presented in Tables 3 and 4. As observed in the previous study, the spatial variability in soil moisture potential is large due to the method of measurement and the differential throughfall input. The variability between Plots 1 and 2 also indicates that selected measurements of soil moisture potential can only be used to be representative of that soil type.

Throughfall Measurements

Miniature rain gauges were installed in the open and under the vegetative cover to evaluate throughfall; the data are presented in Table 5 with the additional number of rainfall events permitting a reevaluation of the results from the 1974 study. The coefficient of variation fluctuates for throughfall under the creosotebush and bursage plants in the same order of magnitude as it does for rainfall in the open. Some measurements, due to the drip phenomenon, show greater throughfall than rainfall, indicating that a large sample size is needed to measure a mean throughfall. An average 90% of the rainfall occurred as throughfall under the creosotebush compared to 65% in the 1974 study. However, the throughfall measurements ranged from 67 to greater than 100%.

The throughfall under the bursage averaged 68% and ranged from 26 to 100% compared to an average of 22% for the 1974 study. The difference between the two years was the size of the sample of rainfall events and the variation in the rainfall intensity.

Leaf Water Potential

Leaf water potential measurements were measured by the pressure bomb method. In order to maintain the water potential gradient from the soil to the plant leaf surface, the

Table 1. The amount of water and variability in bare soil, under the creosotebush (*Larrea tridentata*) and under the bursage (*Ambrosia deltoidea*), Plot 1

	No Cover				Larrea tridentata				Ambrosia deltoidea			
Date	$\overline{D}_T$* moisture	S**	Sample size	ΔD***	$\overline{D}_T$ moisture	S	Sample size	ΔD	$\overline{D}_T$ moisture to 90 cm	S	Sample size	ΔD
11-21-74	6.31	.86	10	--	6.56	2.15	3	--	6.37	.08	3	--
1-18-75	6.91	1.36	10	+.60	6.72	.85	3	+.15	6.73	.22	3	+.34
2-15-75	5.44	.58	10	-1.49	5.53	.22	3	-1.19	5.43	.32	3	-1.30
3-14-75	5.61	.52	10	+.17	5.54	.22	3	+.01	5.27	.48	3	- .15
4-5-75	8.36	1.70	10	+2.74	8.88	2.01	3	+3.34	7.07	.78	3	+1.80
5-14-75	6.83	.82	10	-1.53	7.55	.53	3	-1.33	7.08	.28	3	+ .01
7-9-75	5.71	.25	10	-1.12	5.63	.13	3	-1.92	5.73	.16	3	-1.35
8-14-75	5.13	.13	10	- .58	5.42	.39	3	- .21	5.00	.48	3	- .77
9-20-75	6.24	.44	10	+1.10	6.38	.57	3	+ .97	6.23	.33	3	+1.23
10-20-75	5.61	.41	10	- .69	5.26	.38	3	-1.12	5.56	.49	3	- .67
11- 7-75	--	--	--	--	8.91	.39		+3.65	9.55	.59		+3.99

*$\overline{D}_T$ = mean total soil moisture, to 90 cm, in cm. $\overline{D}_T = \int_0^z \theta dz$ θ = moisture content $\frac{cm^3}{cm^3}$

**S = standard deviation.

***ΔD = change in total moisture content from the previous time period, in cm.

leaf potential in any plant decreases as the soil water potential decreases. The daily water potential of plants also responded to changes in the daily evaporative demand of the air. As the transpiration flux increases in the middle of the day, the water potential gradient increases. At night, the water potential gradient approaches zero and the plant water potential approaches the soil water potential. The yearly cycle of the water potential of the creosotebush is presented in Table 6, and the daily cycle is presented in Figure 4. Only in the months of April, November and December, when the total soil moisture content was relatively high, did the plant exhibit low stress conditions. During the day the plant water potential was greater than —50 bars. During the rest of the year the plant was under stress conditions, with the plant water potential reaching —65 bars in May. In the 1974 study the plant water potential during the day was above —50 after the summer rains in July.

The daily plant water potential responds to the evaporative demand of the air. The daily fluctuation in plant water potential is greater under conditions of high evaporative demand of the air and high moisture content in the soil.

CLIMATIC PARAMETERS

Climate, plant and soil parameters all control the evapotranspiration rate in the desert. One of the objectives of the research was to gain an understanding of the energy balance in the desert and to determine how the available energy is partitioned into sensible and latent heat. The energy balance in the desert can be expressed by the following equation:

$$\begin{aligned} R_n &= (Q + q)(1 - a_p) - l_n \\ &= H + LE + G + P + G_p \qquad (1) \end{aligned}$$

where

R_n = net radiation,
Q = direct beam solar radiation,
q = diffused solar radiation,
a_p = albedo of the surface,
l_n = net longwave radiation,
H = sensible heat flux to or from the air,
G = sensible heat flux to or from the soil and vegetation,
LE = latent heat of evaporation from the soil and plant,
P = energy used in the plant's physiological processes, and
G_p = plant heat storage.

The energy used in plant physiological processes and heat in the plant volume storage is small, about 5% of the net radiation, and is normally disregarded.

Table 2. Soil moisture extraction pattern for bare soil, the creosotebush (*Larrea tridentata*) and the bursage (*Ambrosia deltoidea*)

	No Cover				Larrea tridentata				Ambrosia deltoidea			
	% extraction at 3 depths (cm)				% extraction at 3 depths (cm)				% extraction at 3 depths (cm)			
Date	Δθ*	0-30	30-60	60-90	Δθ*	0-30	30-60	60-90	Δθ*	0-30	30-60	60-90
11-21-74												
1-18-75	+ .60	75	19	5	+ .15	173	80	-153	+ .34	-30	103	27
2-15-75	- 1.49	40	46	13	- 1.19	14	53	30	- 1.30	38	45	20
3-14-75	+ .17	-23	174	-50	.01	--	--	--	- .15	-86	60	126
4-5-75	+ 2.74	41	32	26	3.34	32	28	38	+ 1.80	35	38	25
5-14-75	- 1.53	40	33	26	- 1.33	42	22	35	+ .01	--	--	--
7-9-75	- 1.12	57	16	25	- 1.92	31	29	38	- 1.35	48	10	40
8-14-75	- .58	1.38	- 4	-34	- .21	290	23	-214	- .77	137	13	- 51
9-20-75	+ 1.10	91	15	- 6	+ .97	103	31	- 34	1.23	109	7	- 16
10-20-75	- .69	40	60	0	- 1.12	50	50	- 2	- .67	281	156	-337
11-10-75	--	--	--	--	+ 3.65	22	34	42	+ 3.99	27	35	36

*Δθ = change in total moisture content from the previous time period, in cm.

Table 3. Soil moisture negative potential (bars) at selected depths in Plot 1

	No Cover					Larrea tridentata					Ambrosia deltoidea		
Date	5 cm	10 cm	20 cm	40 cm	60 cm	5 cm	10 cm	20 cm	40 cm	60 cm	15 cm	30 cm	60 cm
1-3-75	.24	.29	2.90		22.67	5.54	<.20	<.20	<.20	<.20	<.20	2.62	<.20
2-22-75	<.20	42.16	6.84	10.09	15.71	8.84		4.91	21.48	2.28	11.12	5.77	20.77
3-23-75	<.20	42.19	8.12	8.61	15.44	11.60		6.17	31.11	2.29	8.65	6.33	19.17
4-5-75	<.20	50.07	11.96	25.50	8.56	13.34		3.89	21.41	<.20	12.97	18.11	38.34
4-22-75	4.67	5.15	20.36	20.19	<.20	10.13		31.50	19.98	<.20	29.16	19.98	35.46
11-7-75	21.9	17.0	16.6	20.2		16.4	15.7	10.3					

Table 4. Soil moisture negative potential (bars) at selected depths in Plot 2

	Larrea tridentata								Ambrosia deltoidea		
	15 cm		30 cm		60 cm		90 cm		15 cm	30 cm	60 cm
Date	$\overline{\psi}$*	S**	$\overline{\psi}$	S	$\overline{\psi}$	S	$\overline{\psi}$	S	$\overline{\psi}$	$\overline{\psi}$	$\overline{\psi}$
11-28-74	20.73	15.19	38.99	4.94	35.96	18.41	44.80	7.36			
1-3-75	1.08	1.04	0.46	0.46	10.18	0.15	0.31	0.18	<.20	<.20	<.20
2-1-75	1.98	2.51	13.02	4.38	2.50	4.60	2.04	3.19	<.20	50.00	39.51
2-8-75	13.34	11.54	4.85	4.22	12.67	2.99	7.79	1.57	<.20		16.61
2-22-75	<0.20	0.01	7.28	1.71	10.54	0.01	<0.20	0.01			
3-23-75	7.48	3.92	17.84	6.89	34.86	15.44	19.57	10.20	6.39		30.69
4-5-75	8.33	3.29	22.77	5.85	29.37	21.27	30.23	4.61	7.45	9.61	32.19
4-22-75	21.98	9.28	26.62	6.07	23.52	15.54	27.45	4.46	30.25	15.95	19.58
5-30-75	>50.00	0.01	>50.00	0.01	>50.00	0.01	>50.00	0.01	8.88	21.08	22.40
10-20-75	31.5	15.6	30.3	10.4	16.5	.71	19.5	2.12	33.7	50.0	45.0
11-7-75	24.0		22.5		24.5		17.9	3.6	20.2	28.1	20.2

*$\overline{\psi}$ = mean soil moisture potential
**S = standard deviation

Table 5. Throughfall as measured by miniature rain gauges

	Plot I												Plot II									
	No Cover				*Larrea tridentata*				*Ambrosia deltoidea*				No Cover				*Larrea tridentata*				*Ambrosia deltoidea*	
Date	$\overline{x}$ (cm)	s	CV	N*	$\overline{x}$ (cm)	s	CV	N	$\overline{x}$ (cm)	s	CV	N	$\overline{x}$ (cm)	s	CV	N	$\overline{x}$ (cm)	s	CV	N	ONLY 1 (cm)	S.D.**
2-17-75	0.34	0.11	32%	7	0.35	0.03	9%	4	0.43	0.10	23%	3	0.44	0.14	32%	8	0.39	0.09	23%	13	0.04	.38
3-10-75	2.61	0.24	9%	7	1.75	0.76	43%	4	1.26	0.72	57%	3	1.63	0.90	55%	8	2.16	1.10	51%	13	1.94	2.28
3-14-75	0.07	0.03	43%	7	0.10	0.02	20%	4	0.01	0.01	100%	3	0.11	0.22	20%	8	0.11	0.06	55%	13	0.04	.25
4-9-75	1.09	0.46	42%	7	1.08	0.15	14%	4	0.29	0.09	39%	3	1.17	0.18	15%	8	1.16	0.29	25%	13	1.05	1.52
7-7-75													0.62	0.07	11%	8	0.52	0.07	13%	13	0.59	
7-16-75	0.40	0.12	30%	7	0.34	0.05	15%	4	0.22	0.03	14%	3	0.38	0.14	37%	8	0.37	0.14	38%	13	0.32	.63
8-14-75	1.69	0.39	23%	7	2.07	0.21	10%	4	1.16	0.50	43%	3	2.21	0.52	24%	8	2.08	0.52	25%	13	1.27	.76
10-21-75													0.46	0.33	72%	8	0.32	0.14	44%	13	0.35	

*Sample size
**Standard 8" rain gauge
$\overline{x}$ = mean rainfall and throughfall
s = standard deviation
CV = coefficient of variation

Table 6. Plant leaf negative potential for *Larrea tridentata* and *Ambrosia deltoidea*

	Larrea tridentata						Ambrosia deltoidea					
	Morning			Afternoon			Morning			Afternoon		
Date	Time	Bars	S*	Time	Bars	S	Time	Bars	S	Time	Bars	S
11-1-75				1300	21.0	.9						
1-18-75				1100	57.0	1.8	1100	39.0	8.9			
2-1-75	0800	52.0	1.5	1200	53.0	2.7						
2-15-75							1100	63.0	12.8			
2-28-75	0800	62.0	4.9	1200	64.0	4.0						
4-5-75	0900	36.4	2.0	1400	35.0	2.2	0900	23.0	6.7	1400	30.0	4.2
4-22-75	1000	39.4	4.9	1100	39.4	2.7	1000	36.2	.7	1100	37.6	3.4
5-14-75	0100	56.0	1.0	1200	56.5	2.9						
5-29-75				1200	65.9	1.8						
5-30-75	0600	56.0	1.9	1200	53.6	.3						
7-8-75	1000	53.4	.9	1400	62.7	2.8						
7-9-75				1600	50.6	.4						
7-10-75	0800	54.0	1.2									
8-14-75	0800	57.0	1.0	1200	58.6	4.9						
9-20-75	0700	55.9	5.2	1500	59.3	1.2						
11-17-75	0900	48.7	5.7	1300	45.4	2.4						
12-28-75				1100	33.8	1.6						

*S = standard deviation on sample size of 3

Results of measurements of the radiation components of Equation 1 are presented in Figures 5-7 and Table 7. As Equation 1 states, the available net radiation is a function of the incoming shortwave radiation, the surface albedo and the net longwave radiation. The albedo, the ratio between the amount of solar radiation reflected from the plant and soil surface, is a function of the surface characteristics. Albedo data for the creosotebush varied from 30% in the early morning to 15-18% during the middle of the day and then increased toward evening as the solar zenith angle increased. The average albedo for the creosotebush is around 18-19%. During the same time period, albedo measurements over bare soil averaged 21-22%.

The net radiation that was not used to heat the air or evaporate water was used to heat the soil profile, the rate being described by the equation:

$$G = \lambda \; (\Delta T / \Delta z) \qquad (2)$$

where λ is thermal conductivity and $\Delta T / \Delta z$ is the vertical temperature gradient at the soil surface. The thermal conductivity is a function of the soil type and moisture content increasing with increase in moisture as water replaces air in the soil pore space. The soil heat flux (G) was measured directly by soil heat flux plates. These data are also presented in Figures 5-7.

On July 10, 1975, a large portion of the available net radiation was used as sensible heat into the soil. The large soil heat flux was due to an increase in the soil thermal conductivity caused by an increase in soil moisture from a rainfall event that had occurred three days previously.

Bowen Ratio

The available net radiation partitioned into sensible heat flux (H) and latent heat flux of evaporation (LE) can be expressed as the Bowen ratio (B) in Equation 3:

$$\begin{aligned} B &= H/LE = (k_h/k_v)\, y\, (\Delta T / \Delta e) \\ &= [(S/Y + 1)\, \Delta Tw / \Delta T - 1]^{-1} \qquad (3) \end{aligned}$$

where

y = the psychrometer constant,
T = the dry-bulb temperature,
e = the vapor pressure,
k_h & k_v = the eddy diffusivities of heat and water vapor,
S = the slope of the vapor pressure temperature curve ($\partial e_s / \partial Tw$), and
Tw = the wet-bulb temperature.

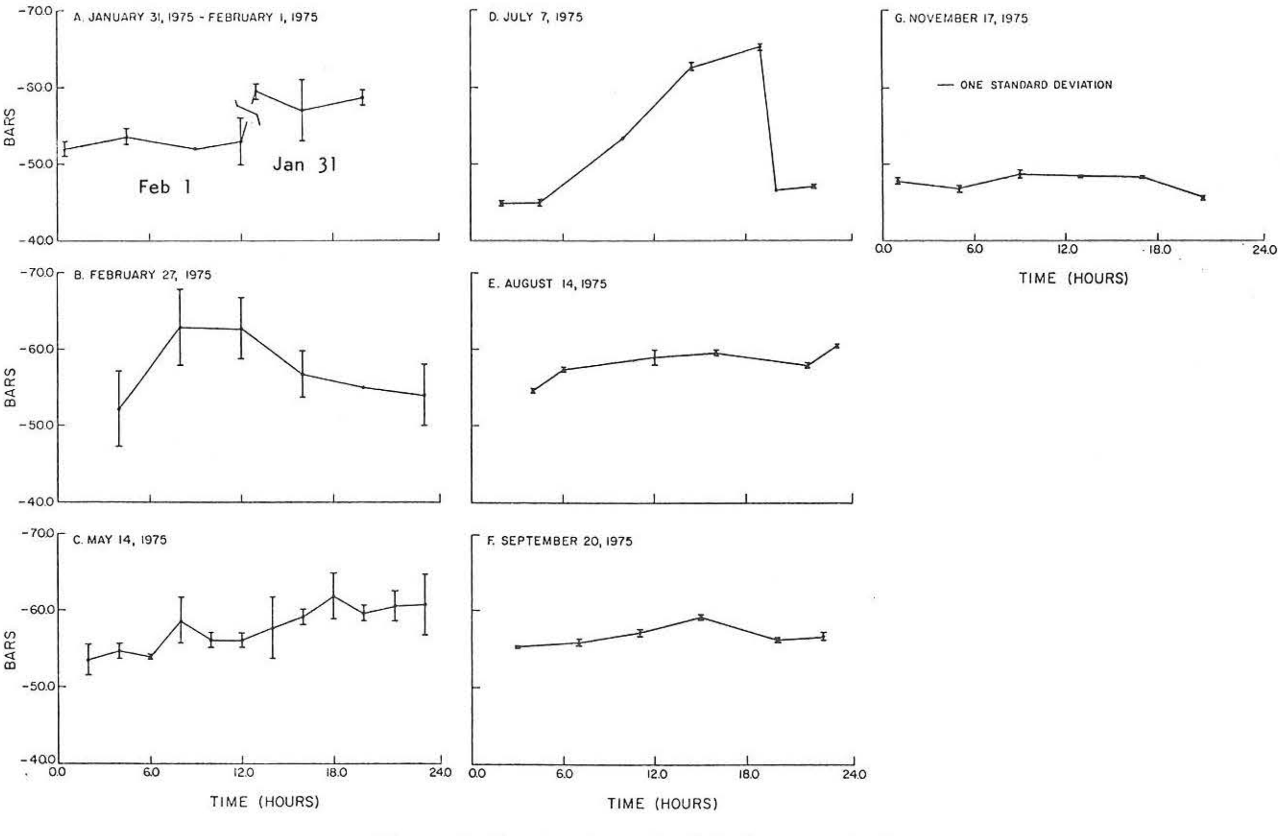

Figure 4. Plant water potential of creosotebush.

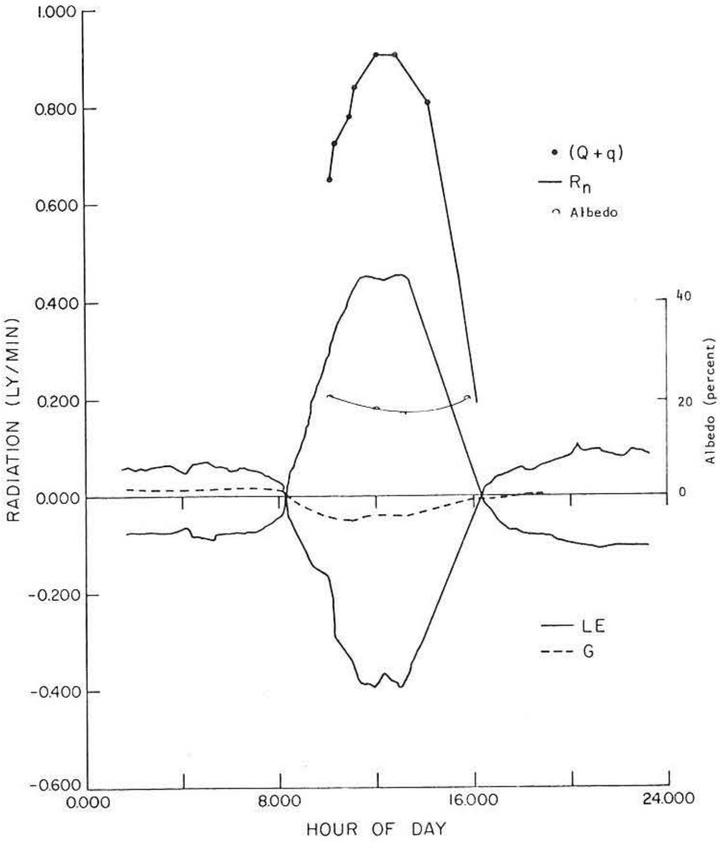

Figure 5. Energy balance on January 10, 1975.

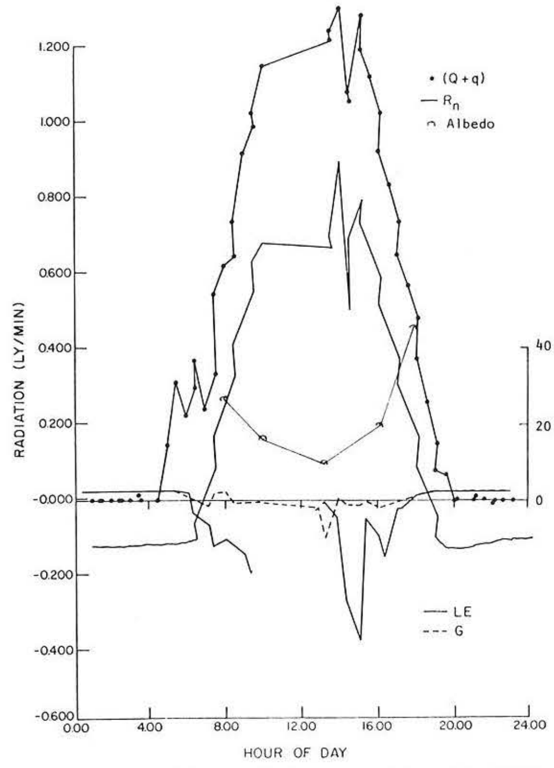

Figure 6. Energy balance on May 29, 1975.

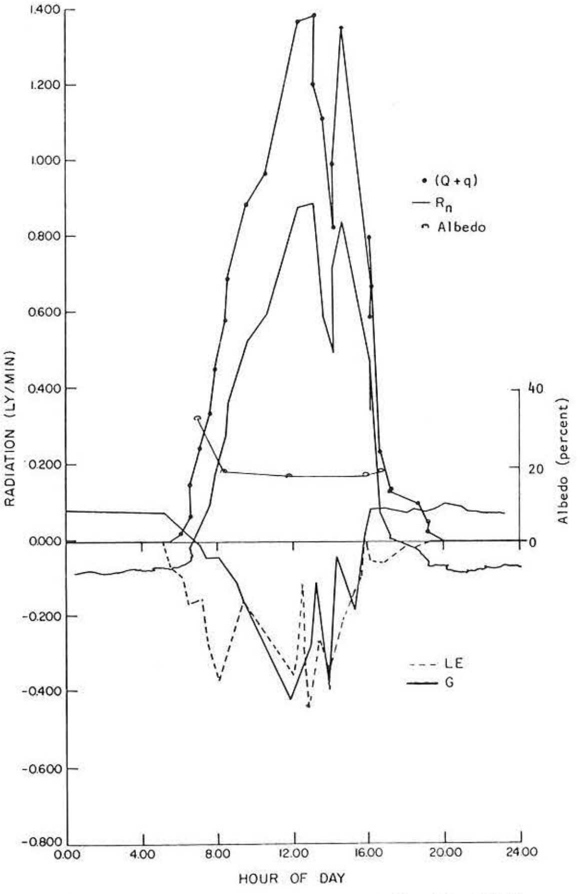

Figure 7. Energy balance on July 10, 1975.

Table 7. Energy balance and diffusion resistance of the creosotebush

Date	Potential Evaporation (mm/day)	ly/day	Bowen Ratio Computed Evapotranspiration (mm/day)	ly/day	Soil Moisture Balance Evapotranspiration (mm/day)*	Net Radiation (ly/day)	Heat Flux (ly/day)	Average Areal Diffusion Resistance (sec/cm)	Aero-dynamic Resistance (sec/cm)	Daily Average Plant Albedo (%)	Soil Albedo (%)
1-10-75	1.9	113	1.9	114	.53***	137	13	0.000	.12	18	--
5-29-75	5.4	321	1.8	106	.5	340	11	6 range= .4-132	.56	19	22
7-10-75	3.6	212	2.4	141	.8 1.3**	316	74	1.2 range= .48-2.7	.18	18	21

*Long-term average values.
**.5 cm of rainfall on July 7; evaporation from the top 2 cm on July 8-9
***Represents average evapotranspiration from late January through early February.

Combining Equations 1 and 3, the evapotranspiration rate in the desert can be expressed as

$$LE = (R_n - G)/(1 + B) \qquad (4)$$

Sargeant and Tanner (1967) described a simple reversing psychrometric apparatus for measurement of the Bowen ratio. A modification of their design was built by Ben Asher (1972) and the use of this equipment resulted in the determination of LE, presented in Figures 5-7 and Table 7. The Bowen ratio method of determining LE requires very sensitive measurements of the dry- and wet-bulb temperature gradients. The theory behind this method also assumes that the eddy diffusivity coefficients for heat and water vapor are the same, and that a homogeneous cover exists. Both conditions are not met in the desert. Under low evaporation rates and nonhomogeneous cover, the temperature gradients become extremely small and any measurement error magnifies the error in calculating the Bowen ratio and LE. Because of instrument error, or the low evapotranspiration rate that occurred in May, the equipment was unable to determine a reasonable Bowen ratio during the time period between 9:00 a.m. to 1:00 p.m. on May 29. For determination of the daily evapotranspiration, an average was taken over that time period. During the rest of the reported hours and days the Bowen ratio appeared reasonable, but fluctuated more than would be expected. Error analyses of the evaportranspiration measurements by the energy balance/Bowen ratio method were computed based on a method by Fuchs and Tanner (1970). The calculations show that in January, when the actual evapotranspiration approached the potential evapotranspiration and the Bowen ratio was less than 1, the maximum error ($\partial E/E$) was 200% with an average error of only 8%. The large maximum error is attributed to the small temperature gradients that occurred during parts of the day. Under these conditions the error in the resolution of the digital voltmeter to read the temperature gradients becomes significant. In May, when most of the energy was going into sensible heat and the Bowen ratio was large (maximum 15), the maximum error was 400% with an average error of 50%. The large maximum error is again caused by the low wet-bulb temperature gradients. In July, after the rainfall event, the Bowen ratio decreased and the wet- and dry-bulb gradients increased, causing a maximum of 54% error with an average 20% error.

Table 8. Plant diffusion resistance for different vegetation types (after Monteith 1965)

Vegetation	Site	Plant Diffusion Resistance (sec-cm^{-1})	
Grass			
Timothy and meadow fescue	Rothamsted	0.5	
Rough pasture with some clover	Cambridge	0.5	
Lawn	Kew	4.1	
Rye-grass	Davis, California	0.5 1.1	
Natural prairie	O'Neill, Nebraska	2.1 7.0 15.0	
Alfalfa-brome mixture	Hancock, Nebraska	0.4	
Beans	Rothamsted	0.5 1.1 2.3	
Rice			
Paddy field	--	0.5 0.9	
Pine forest	Munich	0.9	
Glasshouse crops			
Beans	Griffith, Australia	0.3	
Cotton	Griffith, Australia	0.3	
Saltbush	Griffith, Australia	0.8	
Desert hackberry plant	Arizona	4.0	100

This is the first time, as reported in the literature, that the Bowen ratio has been used to determine the low evapotranspiration rates occurring in a natural desert under nonhomogeneous conditions. The results indicate that it is imperative to compare the results to a weighing lysimeter to determine if the measurement of hourly fluctuations in evapotranspiration is real or measurement error, and to determine if the daily evapotranspiration rate determined from energy balance is truly representative of the evapotranspiration from the desert ecosystem. Also, the reported evapotranspiration is an area average, dependent on the density of the cover. It is too soon to make an accurate estimate of the evapotranspiration of an individual plant based on the Bowen ratio measurements. A rough estimate can be made by assuming that all the evapotranspiration comes from the creosotebush and grass cover and none from the bare soil. Under this condition the actual evapotranspiration from the creosotebush and grasses would be obtained by dividing the areal evapotranspiration by the percentage of projected cover. This ranged from 100% in January, when the grasses were present, to an estimated 35% using photographic techniques during the middle of summer.

POTENTIAL EVAPOTRANSPIRATION

The rate of potential evaporation is controlled by the meteorological variables and the radiative and aerodynamic properties of the surface. Van Bavel (1966) used a combination equation for calculating potential evaporation using Penman's approach and the equation:

$$E_0 = [S/L\,(R_n - G) + \gamma B_v d_a]/(S + \gamma) \qquad (5)$$

where

E_0 = potential evaporation rate,
G = soil heat flux,
S = slope of the vapor pressure-temperature curve,
R_n = net radiation,
γ = psychrometric constant,
B_v = turbulent transfer coefficient,
d_a = $(e_a' - e_a)$, and
e_a, e_a' = actual and saturation vapor in air.

The turbulent transfer coefficient, B_v, is the coefficient of vapor transfer from the plant surface to the bulk air above and is defined by

$$B_v = (\varepsilon\,\rho\,k^2/P)\,[u_a/\ln\,(z_a/z_o)^2] \qquad (6)$$

where

u_a = wind speed,
z_a = elevation above crop,
z_o = roughness length,
k = the Von Kormon constant,
ε = water:air molecular weight ratio,
ρ = density of water, and
P = barometric pressure.

Evaporation from the plant surface to the air can also be expressed as in Monteith (1965):

$$E = (\varepsilon\,\rho/P)\,[(e_s - e_a)/R_a] \qquad (7)$$

where

e_s = the water vapor pressure at the leaf,
e_a = the water vapor pressure of the air,
R_a = the diffusion resistance from the evaporation surface to bulk air.

Equation 7 can be evaluated only if e_s is assumed to be at the saturated vapor pressure of the leaf temperature. Because the evaporating surface of the leaf is an internal location, there is an apparent resistance by the plants, which has to be added to the air diffusion resistance, resulting in Equation 8:

$$E_T = (\varepsilon\,\rho/P)\,[(e_{int} - e_a)/(R_a + R_c)] \qquad (8)$$

ACTUAL EVAPOTRANSPIRATION

Rijtema (1965), using the same approach as Penman, derived an equation for evaporation that incorporated the plant diffusion resistance (R_c):

$$E_T = [S/L\,(R_n - G) + B_v d_a] \,/[S + y\,(1 + R_c/R_a)] \qquad (9)$$

where the symbols are defined as before. The plant's diffusion resistance (R_c) will increase as the moisture potential decreases. Depending on the plant physiology, the plant's diffusion resistance may or may not be zero when the plant is under no water stress. The plant's diffusion resistance will also increase as the light intensity decreases below certain levels. Rijtema (1965) determined that, for grass, the level below which R_c started increasing was 0.4 $\text{cal}\cdot\text{cm}^{-2}\cdot\text{min}^{-1}$, and can be considered not a controlling factor in the desert environment. Knowing the actual evapotranspiration from estimates by the Bowen ratio, the areal diffusion resistance R_c can be solved from Equation 9. Determination of this parameter is presented in Table 7. Because the diffusion resistance determination is based on the accuracy of determining the actual evapotranspiration from the Bowen ratio and the potential evapotranspiration from the meteorological parameter, there is a large scatter around the daily mean value. Figure 8 presents a plot of the areal diffusion resistance based on half-hour averages. In May, the diffusion resistance varied from .4 to 132 sec/cm with a mean of 6 sec/cm, and in July, from .48 to 2.7 with a mean of 1.2. In January the actual and potential were the same so the areal diffusion resistance was zero. Table 8 presents the plant diffusion resistance for different vegetation types. The scatter in the half-hour determination of the diffusion resistance compared to the mean value for different crops determined by other investigators indicates that only daily values of evapotranspiration determined from Equation 9 would have any meaning. The areal diffusion resistance decreased in July because of the increase in evapotranspiration resulting from the limited rainfall on July 7. Subsequent investigation will include following the decrease in evapotranspiration and increase in diffusion resistance following a rainfall event. All information points to the fact that under limited soil moisture the evapotranspiration rate will drop rapidly after a rainfall event and this will have to be considered in any modeling of the evapotranspiration in the desert.

TEMPERATURE PROFILES

Temperature profiles were measured in the vertical direction in the center of an open space surrounded by creosotebush plants and from the center of the open to under the canopy of a creosotebush plant. The measured temperature profiles for selected dates are presented in Figures 9 and 10. The purpose of the profiles was to gain some understanding of the temperature and thus the energy regime in a nonhomogeneous canopy. The roughness length or the height above the ground that the wind speed becomes zero was estimated to be 20 cm from wind profiles; consequently, there is forced convection above 20 cm. In May the wind speed averaged .4 m/sec and in July it averaged 1.8 m/sec at 2.2 m above the ground. The result is that, in May, the interspace develops temperature profiles below the canopy level of 170 cm that depend on the energy balance on the side of the canopy. In July, the air was mixed sufficiently to result in a neutral temperature gradient profile. The vertical temperature profiles, when the wind speed is low enough to make the measurements detectable, indicate that the vegetation acts as a heat source for the air in the interspaces. This hypothesis is substantiated by the horizontal temperature measurements, again indicating that the canopy is a heat source. The variation in the sensible heat transfer from the surface to the air may affect the horizontal temperature measurements so that future horizontal measurements will be made at .5-m intervals from the soil surface to the canopy to verify that convective heat is not transferred from the interspace to the canopy, but from the creosotebush plants to the interspace.

In conclusion, it can be stated that the energy balance around the creosotebush plant is a complicated problem which needs more study.

Measurement of the energy balance above the canopy with the irregular spacing and low densities results in a large amount of scatter around the average values of measured evapotranspiration. Additional work has to be centered on the operation of the weighing lysimeter as it is the only instrument with sufficient sensitivity to accurately measure the small changes in evapotranspiration that occur from and around a creosotebush plant.

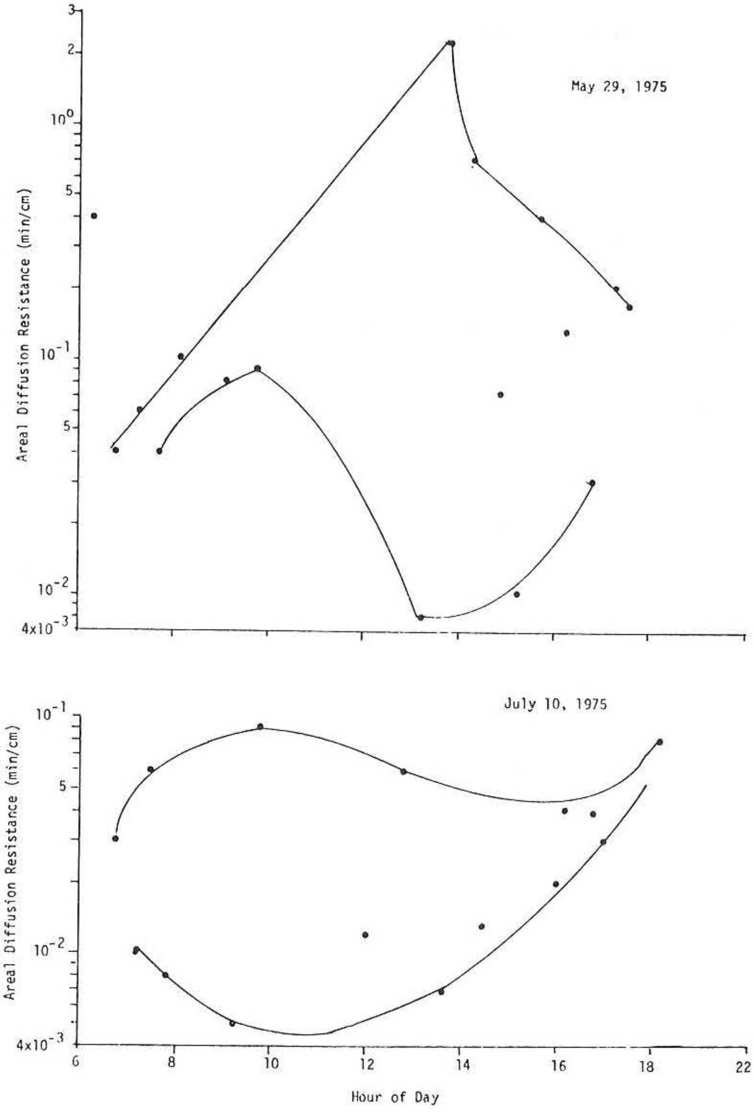

Figure 8. Areal diffusion resistance for creosotebush plants at Silverbell.

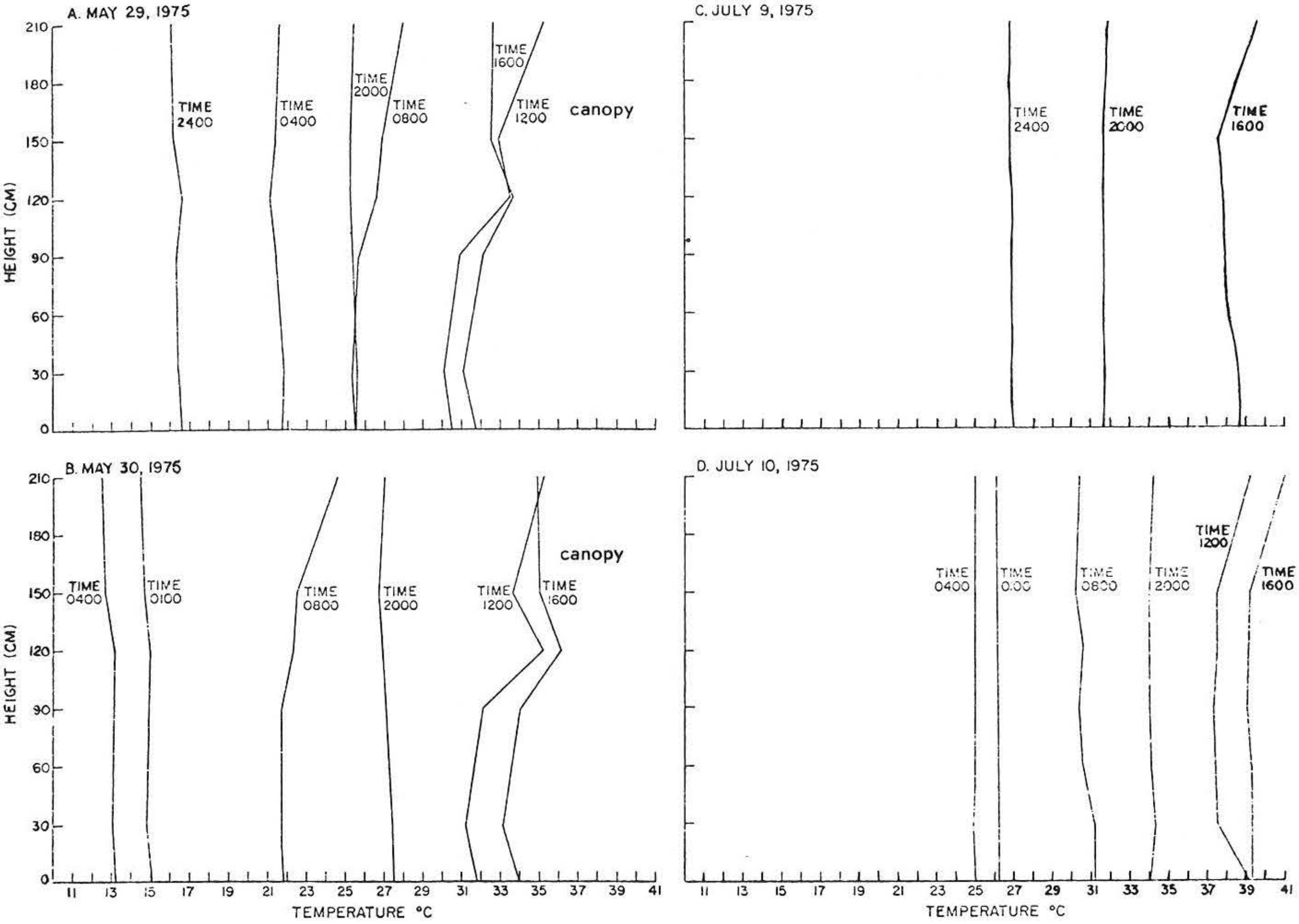

Figure 9. Air temperature in an interspace between creosotebush plants.

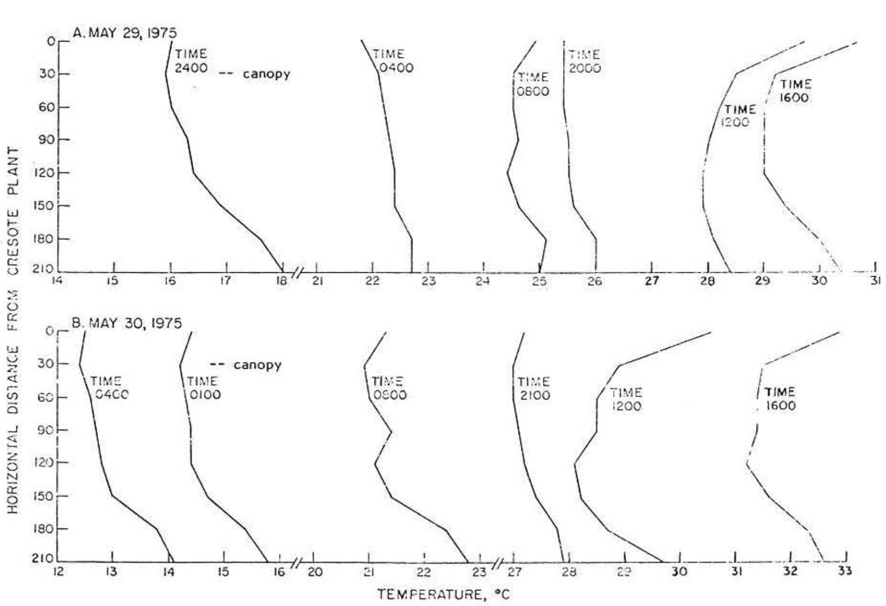

Figure 10. Air temperature from the interspace to a creosotebush plant at 5 cm above the ground.

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APPENDIX

(The rainfall data collected at Silverbell by John Thames as part of the Silverbell validation data set follow.)

RAINFALL DATA, SILVERBELL; DECEMBER 30, 1974, TO NOVEMBER 18, 1975

Date	Amount (mm)
Jan 1	3.81
Jan 9	1.27
Feb 17	3.81
Mar 10	22.86
Mar 14	2.54
Mar 26	12.70
Apr 7	11.43
Apr 8	1.27
Apr 9	2.54
Jul 7	5.08
Jul 16	6.35
Jul 26	3.81
Aug 10	7.62
Aug 13	7.62
Aug 19	T (1.02)
Aug 26	2.54
Sep 5	11.43
Oct 21	7.62
Total to date:	115.32