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A COMPARISON OF RATES OF WATER LOSS THROUGH TRANSPIRATION OF SEVERAL SOUTHERN NEW MEXICO PHREATOPHYTE SPECIES

Technical Completion Report

Project Nos. B-021 and B-027-NMEX

A COMPARISON OF RATES OF WATER LOSS THROUGH TRANSPIRATION OF SEVERAL SOUTHERN NEW MEXICO PHREATOPHYTE SPECIES

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ABSTRACT

This report describes the development and use of a method of estimating transpirational water use by riparian plant communities. The method involves the development and use of mathematical models to predict transpiration rates on a leaf area basis from environmental data. These models were used in conjunction with leaf area estimates for a study stand to evaluate transpirational water use. The results indicate that differences exist among species. Species which are found in less disturbed stands tend to be much more conservative in their transpirational water use.

Acknowledgments

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction

In the arid and semi-arid regions of the southwestern United States, large quantities of water are presumably utilized by riparian vegetation (Robinson, 1952). This high transpiration has been assumed because of the phreatophytic nature of the riparian vegetation. Phreatophytes are "plants that habitually grow where they can send their roots down to the water table, or the capillary fringe immediately overlying the water table, and are then able to obtain a perennial and secure supply of water" (Meinzer, 1927). Recently, many of the earlier reports of extremely high water utilization by riparian vegetation have been questioned (Campbell and Quimby, personal communication). The practice of clearing riparian vegetation to "salvage" water has also been questioned on both economic and environmental quality grounds (Campbell, 1970; Horton, 1972). These authors pointed out that the value of riparian communities for recreation, erosion control, and wildlife habitat may, in an objective analysis, outweigh any benefits that might be derived from their eradication. Decisions concerning management of riparian communities cannot be made without accurate estimates of transpirational water use by the phreatophytic vegetation.

This report describes the development and use of a method for estimating transpirational water use by riparian plant communities.

Many methods have been used for estimating transpiration rates of plant communities. The most widely used technique is the calculation of

evapotranspiration from the water balance equation:

$$0 = P - R - U - E + \Delta W \qquad (1)$$

where

P = precipitation or water input

R = run off

U = deep drainage

E = evapotranspiration

ΔW = change in water storage in the soil

The water table balance equation is commonly used in conjunction with lysimeters in which P can be monitored by rain gauges and irrigation control. R and U are eliminated, and ΔW is determined from weight changes or water table fluctuations (Slatyer, 1967). Lysimeters have been used effectively in many studies where the soil and vegetation structure could be adequately reproduced in lysimeters (Van Hycklama, 1970; Blaney and Hanson, 1965). However, the cost of lysimeter installations and the need to evaluate transpiration rates of many community types under different climatic conditions seems to limit the usefulness of this method as a management tool.

Evapotranspiration has also been evaluated by using the energy balance equation:

$$0 = R_n + H + (L \cdot E) + G + P \qquad (2)$$

where

R_n = net radiation

H = sensible heat transfer

L = latent heat of vaporization of water

E = evaporation rate

G = soil heat storage

P = photosynthetic energy storage

In use, P is usually ignored. G is either ignored or measured with soil heat flux plates. R_n is measured with a net radiometer. H and LE are then determined by evaluating the Bowen ratio for the surface using vertical measurement of temperature and water vapor above the canopy. This technique has been widely used in spatially homogeneous communities (see, for example, Begg et al., 1964). Difficulties in its application arise, however, when the community is spatially heterogeneous, since values of energy fluxes must be spatially averaged over the entire community. The heterogeneity of riparian communities makes its application difficult and expensive. The advection of warmer air from areas surrounding riparian communities also makes use of the energy balance technique difficult (Slatyer, 1967).

Transpiration can be evaluated directly by measuring vapor flux or indirectly by evaluating the relative humidity gradient above a plant community. This technique has not been widely used since it suffers from the same drawbacks as the energy balance method. In addition, the instrumentation required is more complex and expensive (Slatyer, 1967). Enclosure of the entire canopy of the community and measurement of air-stream humidities in and out of the enclosure have also been used (Decker, Gaylor, and Cole, 1962). This method is difficult to use since climate control within the enclosure requires complex and expensive equipment, and true simulation of the natural environment is never achieved.

The method utilized in this study for evaluating transpirational water loss from riparian stands is based on the following simple relationship:

$$E_t = \sum_{i=1}^{n} (E_i \cdot A_i) \qquad (3)$$

where

E_t = total transpiration of water loss from the community for any desired time interval

n = number of species in the stand

E_i = transpirational water loss per unit leaf area per unit time for the ith species

A_i = leaf area of the ith species in the stand

Utilization of the above equation requires estimation of the leaf area of each species in the stand and calculation of an average transpiration rate for each species. The remainder of this report will deal with the calculation of leaf surface areas within riparian stands and with developing an accurate estimation of transpiration rates on a leaf area basis for typical riparian species in southern New Mexico. A single study stand was selected. Species leaf surface areas were estimated for the stand. Mathematical models were developed to predict transpiration rates of each species on a leaf area basis from environmental data. Environmental and leaf area data from the stand were utilized in the models to estimate transpirational water loss from the stand.

The Study Site

The study stand was located on the west bank of the Rio Grande 1.5 miles north of La Mesilla, Dona Ana County, New Mexico. The entire belt of river vegetation in this area is considered post-climax (Clements, 1949). Alterations by man and modification of the dominants, due to invading species, have created a quasipermanent disclimax vegetation through-

out the river channel in southern New Mexico (Campbell and Dick-Peddie, 1964). The study stand is in one of the few local situations where the vegetation has been relatively undisturbed for some time. These undisturbed stands, although quite different from the climax vegetation, form a relatively stable community.

The study stand was four hectares (ha) in area. Sampling of the vegetation in the stand (by techniques described below) indicated six tree and shrub species* with the absolute and relative densities shown in Table 1.

Environmental Measurements

The environment of the study stand was monitored during the course of the study. All instruments were located in a small fenced enclosure in an open area in the center of the stand. Air temperature and relative humidity were monitored with a hygrothermograph (Belfort, model 5-594) located in a standard U.S. Weather Bureau instrument shelter. Total incoming sun and sky radiation was measured with a pyrheliograph (Belfort, model 5-3850). Wind speed was measured with a three cup anemometer (Science Associations, model 403A) and a spring wound event recorder (Science Associates, model 445 SW-10). The anemometer was located on a mast which elevated it above the canopy of the surrounding vegetation.

Estimation of Leaf Surface Area

To estimate leaf surface areas within the study stand it was necessary to ascertain the relationship between some parameter which could be measured

* *Nomenclature follows Correll and Johnston, 1970*

non-destructively in situ and the leaf surface area of individual species. It was felt that basal stem diameter might be a good predictor of leaf area on a stem. Further, basal stem diameters could be easily, accurately, and non-destructively sampled in the study stand. Therefore, an attempt was made to develop regression equations by which leaf area on a stem could be estimated from its basal diameter.

Stems of each of the six tree and shrub species were harvested and brought directly to the laboratory, during August 1970, near the end of the growing season. All plants had maximum leaf areas for the year at this time. Stems were selected to obtain a representative sample of the various stem sizes of each species. The basal diameter of each harvested stem was measured to the nearest millimeter and leaves were removed for area measurement. The total volume of all leaves on each sampled stem was measured by displacement of water in a graduated cylinder. The value for leaf volume on each sampled stem was converted to leaf area by multiplying by a predetermined ratio of leaf area to volume. The ratios were obtained by measuring the areas of known volumes of leaves. The area measurements were made by weighing cut-out tracings on paper of a known weight per unit area.

This technique worked well for all species except *Tamarix pentandra* Its morphology of slender branches covered by small, imbricate, scale-like leaves made the conversion from volume of leaves to leaf surface area more difficult, since tracing the leaves was not possible. All young *Tamarix* branches, i.e., those branches having leaves, have essentially the same diameter (1.5 mm). Therefore, each leaf-bearing branch can be considered a cylinder and its area calculated using a measurement of its length.

For each species, regression analysis was performed using basal stem diameter as the independent variable and leaf surface area (one side except

for *Tamarix* as the dependent variable. First, second, and third order polynomials were fitted to the data. The correlation and regression coefficients are given in Table 2. The Y intercept was assumed to be zero; consequently, no constant terms appear in the regression equations. If a higher order polynomial did not increase the r^2 value by more than 0.05, the lower order equation was selected for surface area predictions. The equations selected for prediction of leaf surface areas are indicated in the table.

The vegetation of the study stand was sampled using belt transects two meters wide. The stand was divided into sections 30 m wide by the length of the stand. One transect was located at random within each section to avoid under-sampling any portion of the stand. The transects were run parallel to one another in an east-west direction (perpendicular to the river channel). All basal stem diameters were measured and the number of individuals within each belt transect were counted. Data from the belt transects were used to calculate plant densities (given above) and leaf surface area per hectare for each species (Table 3). Leaf surface area per hectare was calculated using the regression equations relating basal stem diameters to leaf surface area.

Estimations of Transpiration Rates

As pointed out above, evaluation of total transpirational water loss from a riparian stand using equation (3) requires a prediction of transpiration rate on a leaf area basis. This transpiration rate is a function of the environment of the stand and the species. Further, the environmental variables used for calculating transpiration rates should be ones for which

data is readily available or easily obtainable. This greatly adds to the usefulness of the method as a management tool for evaluating transpirational water loss. Therefore, mathematical expressions were developed for each of the six tree and shrub species to calculate transpiration rates as a function of irradiance, air temperature, relative humidity, and wind speed. This was done by developing a general mathematical model. Species specific coefficients for the model were determined by using simultaneous measurements of transpiration rates and the four environmental variables in a non-linear regression analysis.

The general model

Transpiration rate is equal to the water vapor concentration gradient from the evaporating surfaces within the leaves to the bulk air surrounding the leaves divided by the resistances to water vapor flux in the pathway:

$$E = \frac{\Delta\rho}{r_t} \qquad (4)$$

where

E = transpiration rate in mg $H_2O \cdot cm^{-2} \cdot min^{-1}$

$\Delta\rho$ = water vapor concentration gradient from evaporating surface to bulk air in mg $H_2O \cdot cm^{-3}$

r_t = total resistance to water vapor flux from evaporating surface to bulk air in $min \cdot cm^{-1}$

The water vapor concentration gradient is equal to the difference between the water vapor concentration at the evaporating surface of the leaf meso-

phyll cells and the water vapor concentration in the bulk air:

$$\Delta\rho = \rho_l - \rho_a \qquad (5)$$

where

ρ_l = concentration of water vapor at the evaporating surface in mg $H_2O \cdot cm^{-3}$

ρ_a = concentration of water vapor in the bulk air in mg $H_2O \cdot cm^{-3}$

If it is assumed that the water potential of the leaf mesophyll cells is at or near zero, the concentration of water vapor at the evaporating surface will be equal to the saturation water vapor concentration at the leaf temperature. This appears to be a valid assumption in the case of riparian plants which have their roots at or near the water table. The saturation vapor concentration is an exponential function of temperature. Using an exponential model, a regression analysis was performed using temperature as the independent variable and saturation vapor concentration as the dependent variable. The following relationship between the two was obtained:

$$\rho_s = 1.284 \cdot 10^{-3} + 1.76431 \cdot 10^{-7} \cdot T^{2.70452} \qquad (6)$$

where

ρ_s = saturation water vapor concentration in mg $H_2O \cdot cm^{-3}$

T = temperature in °F

The correlation coefficient (r^2) of the above equation is 0.99 which is significant at the 0.001 level of probability.

Since leaf temperatures were not measured and are not readily obtainable from climatic data, the assumption was made that leaf temperatures are

approximately equal to air temperature. This assumption probably does not introduce appreciable error in riparian stands where much of the energy is advected from adjacent warmer areas. Therefore,

$$T_l = T_a \tag{7}$$

where

T_l = leaf temperature in °F

T_a = air temperature in °F

and

$$\rho_l = \rho_s \tag{8}$$

Thus from equations 6, 7, and 8:

$$\rho_l = 1.284 \cdot 10^{-3} + 1.76431 \cdot 10^{-7} \cdot T_a^{2.70452} \tag{9}$$

The concentration of water vapor in the bulk air is equal to the saturation vapor concentration at the air temperature times the relative humidity of the bulk air divided by 100:

$$\rho_a = \rho_s \cdot \frac{RH}{100} \tag{10}$$

where

RH = relative humidity of the bulk air in percent

Combining equations 5, 6, 9, and 10 gives:

$$\Delta\rho = 1.284 \cdot 10^{-3} + 1.76431 \cdot 10^{-7} \cdot T_a^{2.70452} \left(1 - \frac{RH}{100}\right) \tag{11}$$

The total resistance to water vapor transport from the evaporating surfaces at the leaf mesophyll cell walls to the bulk air is the sum of the

three component resistances in series. These are the stomatal resistance, the boundary layer resistance, and the mesophyll resistance:

$$r_t = r_a + r_s + r_l \tag{12}$$

where

r_t = total resistance in min · cm^{-1}

r_a = boundary layer resistance in min · cm^{-1}

r_s = stomatal resistance in min · cm^{-1}

r_l = mesophyll resistance (a fixed resistance characteristic of the leaf anatomy) in min · cm^{-1}

Many researchers have shown that the boundary layer resistance is a power function of wind speed (see for example Gates, 1965):

$$r_a = k_1 \cdot U^{k_2} \tag{13}$$

where

r_a = boundary layer resistance in min · cm^{-1}

U = wind speed in miles · hr^{-1}

k_1 and k_2 species specific coefficients

Stomatal resistance is primarily a function of leaf water potential and irradiance. As pointed out above, the simplifying assumption that leaf water potential remains very near zero was made. Thus, it is also assumed that leaf water potential has little effect on stomatal resistance in these riparian species. Data in the literature is conflicting on the shape of the curve relating stomatal resistance to irradiance. Some data indicates that stomatal resistance is a hyperbolic function of irradiance (see, for example, Turner and Begg, 1972). Other research implies that stomatal resistance is an exponential function of irradiance (see, for example, Rijtema, 1965). In fact, the shape of these curves can be very similar and either

relationship could be used. For the present model it was assumed that the exponential function adequately describes the relationship:

$$r_s = k_1 \, e^{k_4 I} \tag{14}$$

where

e = base of natural logarithm

I = irradiance in ly · min^{-1}

k_3 and k_4 are species specific coefficients

Since the mesophyll resistance is species specific, it must be included as a variable coefficient in the general model:

$$r_1 = k_5 \tag{15}$$

where

k_5 = a species specific coefficient

Combining equations 12, 13, 14, and 15 gives:

$$r_t = k_1 \cdot U^{k_2} + (k_3 \cdot e^{k_4 I}) + k_5 \tag{16}$$

Further, combining equations 7, 11, and 16 gives the full model:

$$E = \frac{1.284 \cdot 10^{-3} + 1.76431 \cdot 10^{-7} \cdot T_a{}^{2.70452}(1 - \frac{RH}{100})}{k_1 \cdot U^{k_2} + (k_3 \, e^{k_4 I}) + k_5} \tag{17}$$

Determination of model coefficients

The species specific model coefficients were determined by using the general model explained above as a nonlinear regression model and determining the values for the coefficients which gave the best fit to measured values of transpiration rate. This was done using an algorithm for multiple nonlinear regression proposed by Marquardt (1970).

Values of the independent variables, irradiance, air temperature, relative humidity, and wind speed were taken from the environmental measuring instruments located on the study site.

Values for transpiration rate were measured for plants in situ on the study site using a short term enclosure technique described by Grieve and Went (1965). Transpiration rates of intact branches were measured every two hours from sunrise to sunset on each sample day. Measurements were made every other day throughout the growing season. Two of the six species were measured on each sample day so that all species were measured at least once weekly during the growing season. On each sample day three branches on each of three individuals of the two species being measured were utilized. Individuals and branches were selected to give a representative sample of branch heights and exposures for the species. All values for the transpiration rates used in the regression analysis were means of the nine sample branches. At the end of each sample day, branches measured were brought to the laboratory for leaf area determinations. These were done as described above.

Model coefficients determined by this method are presented in Table 4. Also given in the table are correlation coefficients (r^2) and F statistics. The models accounted for 68 to 93% of the variation in transpiration rates. The values indicate all models give a significant fit to the data at the 0.05 level of probability. T statistics indicate that all model coefficients are significantly different from zero at the 0.05 level of probability.

Use of the Models

The transpiration models and environmental data from the study site were used to calculate expected rates of transpiration for each of the six

species for the 1971 growing season. The predicted rates of transpiration per unit leaf area are given in Figures 1-6.

The predicted transpiration rates were combined with the leaf area estimates to give values for total transpirational water use by each species (Figs. 7-12).

Conclusions

It is apparent that the methods developed and outlined here do provide a means of estimating transpirational water loss from stands of riparian vegetation. The technique could be easily applied in any stand of interest. New leaf area estimation and transpiration model coefficients would have to be developed for each new species, however.

The method should be evaluated by comparison with other techniques. Although the method could be easily employed once appropriate equations are developed for each species, the effort saved cannot be justified until its accuracy has been completely evaluated.

The method does allow comparisons of different species on both a leaf area and total stand basis. In this regard it is interesting to note that considerable species specific differences in transpiration rate do occur. It appears that the species which tend to increase following many of our current management manipulations (i.e., *Tamarix pentandra* and *Baccharis glutinosa*) have much greater transpiration rates per unit leaf area than do species which are components of the more stable undisturbed riparian stands (i.e., *Prosopis pubescens*, *Salix amygdaloides*, *Populus fremontii*, and *Lycium torreyi*).

Table 1. Absolute and relative densities of tree and shrub species in the study stand

Species	Density	
	Plants · ha^{-1}	Percent of total
Prosopis pubescens (screw bush)	58	2
Salix amygdaloides (willow)	28	1
Tamarix pentandra (salt cedar)	1,333	45
Baccharis glutinosa (seep willow)	18	21
Lycium torreyi (wolfberry)	1,513	51
Populus fremontii (cottonwood)	1	21

Table 2. Correlation data of leaf surface area vs. basal stem diameter

Species	Sample size	1st order $= B_1X$	2nd order $= B_1X + B_2X^2$	3rd order $= B_1X + B_2X^2 + B_3X^3$	"F" value[2]
Prosopis pubescens	10	$r^2 = 0.917$	$r^2 = 0.969$[1]	$r^2 = 0.977$	128*
		$B_1 = 24.1$	$B_1 = 27.1$	$B_1 = 281.7$	
			$B_2 = 13.4$	$B_3 = 0.940$	
Salix amydaloides	10	$r^2 = 0.741$	$r^2 = 0.972$[1]	$r^2 = 0.985$	175*
		$B_1 = 139.9$	$B_1 = 709.9$	$B_1 = 1057.7$	
			$B_2 = 39.0$	$B_2 = 32.3$	
				$B_3 = 0.629$	
Lycium torreyi	10	$r^2 = 0.900$	$r^2 = 0.970$[1]	$r^2 = 0.975$	131*
		$B_1 = 0.82$	$B_1 = 0.029$	$B_1 = 0.763$	
			$B_2 = 0.062$	$B_2 = 0.074$	
				$B_3 = 0.005$	
Tamarix pentandra	66	$r^2 = 0.675$	$r^2 = 0.866$	$r^2 = 0.906$[1]	203*
		$B_1 = 154.4$	$B_1 = 120.4$	$B_1 = 165.1$	
			$B_2 = 22.6$	$B_2 = 32.5$	
				$B_3 = 2.3$	
Baccharis glutinosa	30	$r^2 = 0.803$[1]	$r^2 = 0.831$	$r^2 = 0.831$	69*
		$B_1 = 18.9$	$B_1 = 8.71$	$B_1 = 11.8$	
			$B_2 = 1.03$	$B_2 = 0.359$	
				$B_3 = 0.032$	
Populus fremontii	22	$r^2 = 0.892$[1]	$r^2 = 0.892$	$r^2 = 0.897$	174*
		$B_1 = 252.3$	$B_1 = 250.3$	$B_1 = 512.2$	
			$B_2 = 0.045$	$B_2 = 13.2$	
				$B_3 = 0.015$	

(1) Equation selected for leaf area estimation

(2) F - value for the equation selected

* Significant at the 0.01 level of probability

Table 3. Estimated leaf surface areas for the study stand

Species	Leaf Surface Area	
	$m^2 \cdot ha^{-1}$	Percent of total
Prosopis pubescens	179	<1
Salix amydaloides	2,356	9
Tamarix pentandra	22,873	90
Baccharis glutinosa	3	<1
Lycium torreyi	4	<1
Populus fremontii	2	<1

Table 4. Species specific model coefficients and related statistics

Species	k_1	k_2	k_3	k_4	k_5	r^2	F	sig. level
Prosopis Pubescens	0.606	-8.02	0.066	-1.146	0.004	0.93	17.3	0.01
Lycium torreyi	0.204	-6.290	0.008	-0.847	0.002	0.79	4.4	0.05
Salix amydaloides	0.222	-4.428	0.016	-0.856	0.002	0.76	9.05	0.01
Baccharis glutinosa	0.009	-2.067	0.0008	-1.227	0.001	0.68	7.6	0.01
Populus fremontii	0.24	-4.078	0.015	-1.5	0.003	0.82	8.9	0.01
Tamarix pentandra	1.786	-6.682	0.090	-13.571	0.001	0.72	3.6	0.05

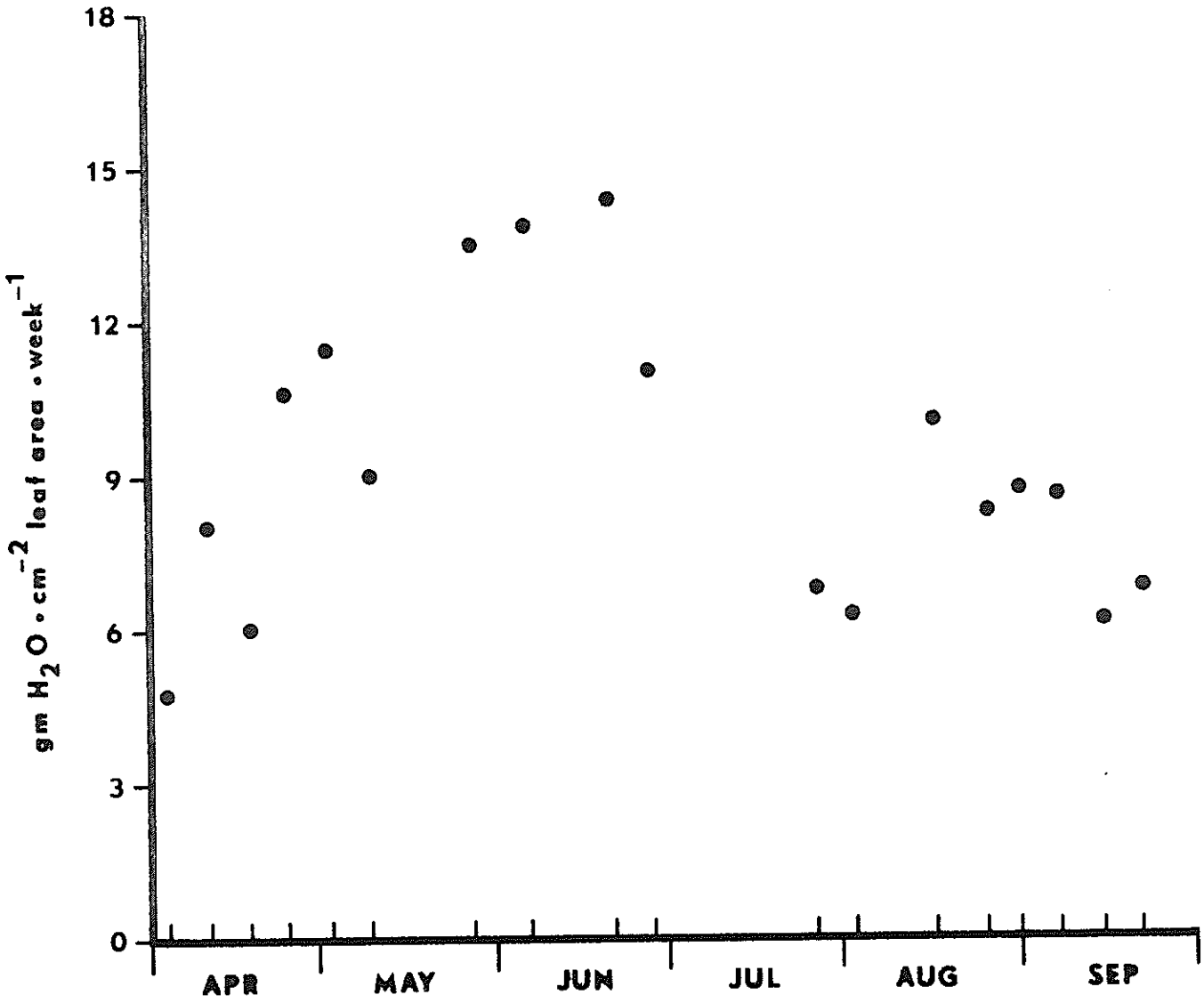

Figure 1. Seasonal variation in transpiration rate of *Populus fremontii* in the study stand during the 1971 growing season in gm H_2O $\cdot$ cm^{-2} leaf area $\cdot$ $week^{-1}$.

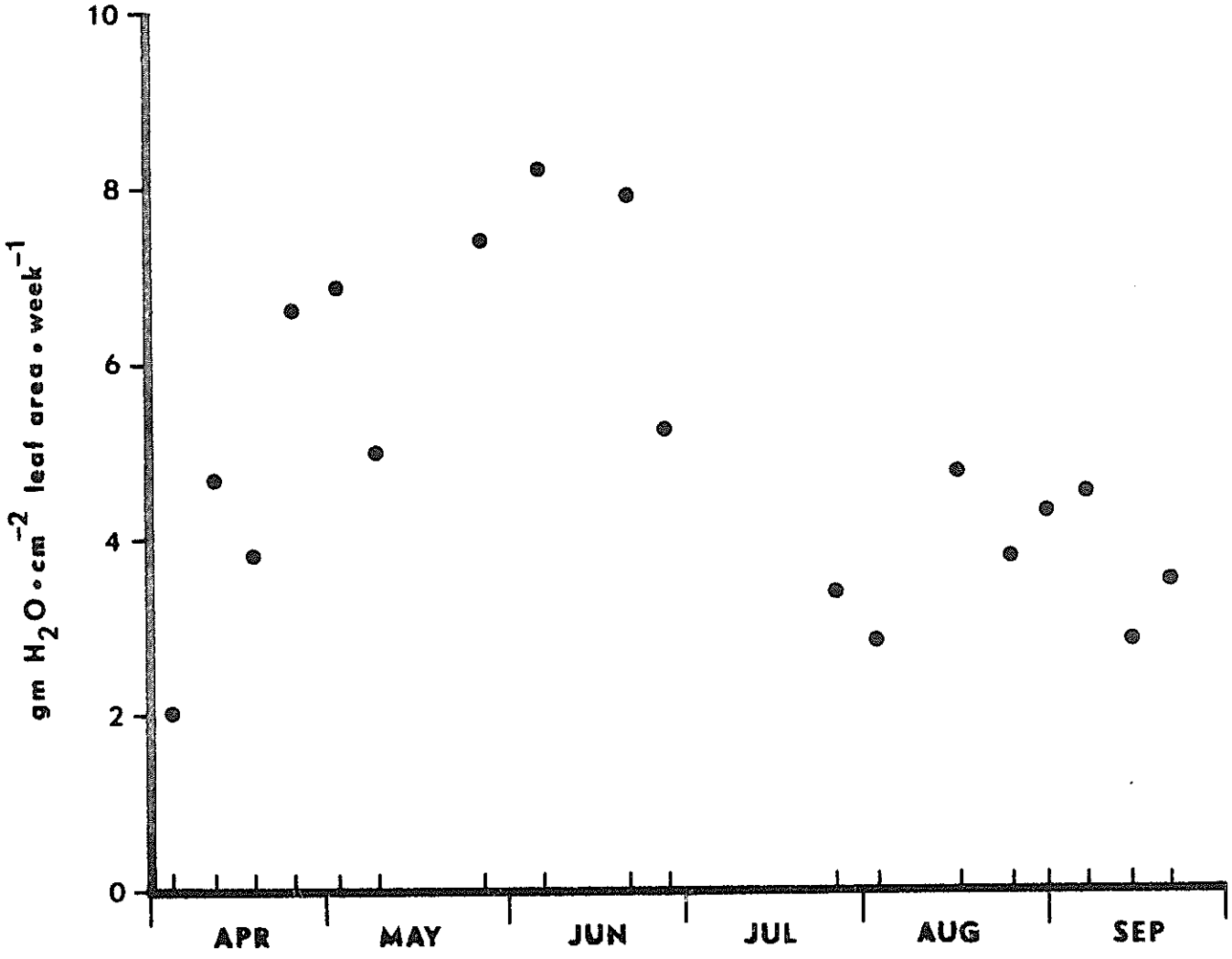

Figure 2. Seasonal variation in transpiration rate of *Prosopis pubescens* in the study stand during the 1971 growing season in gm H_2O $\cdot$ cm^{-2} leaf area $\cdot$ $week^{-1}$.

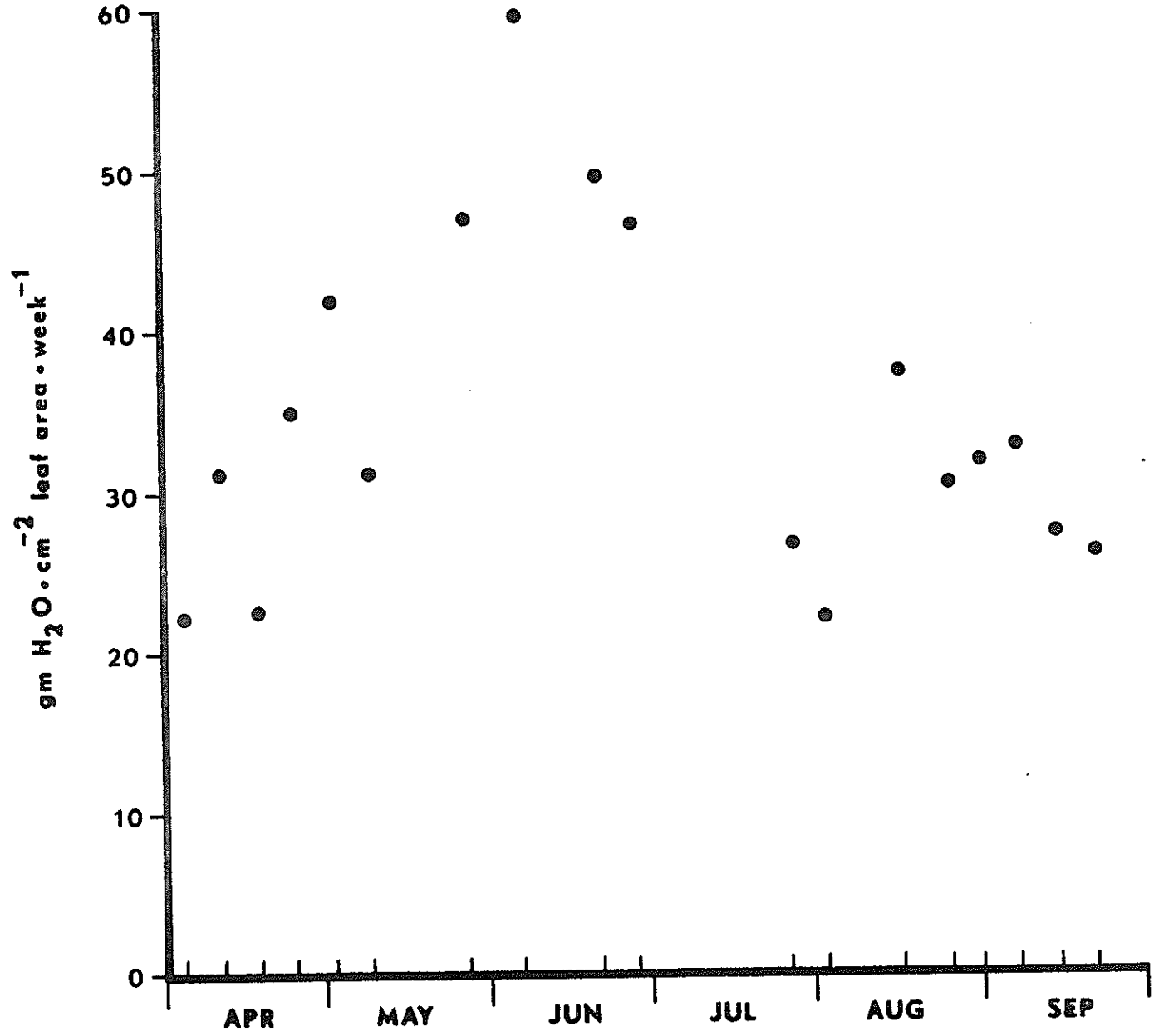

Figure 3. Seasonal variation in transpiration rate of *Baccharis glutinosa* in the study stand during the 1971 growing season in gm H_2O $\cdot$ cm^{-2} leaf area $\cdot$ $week^{-1}$.

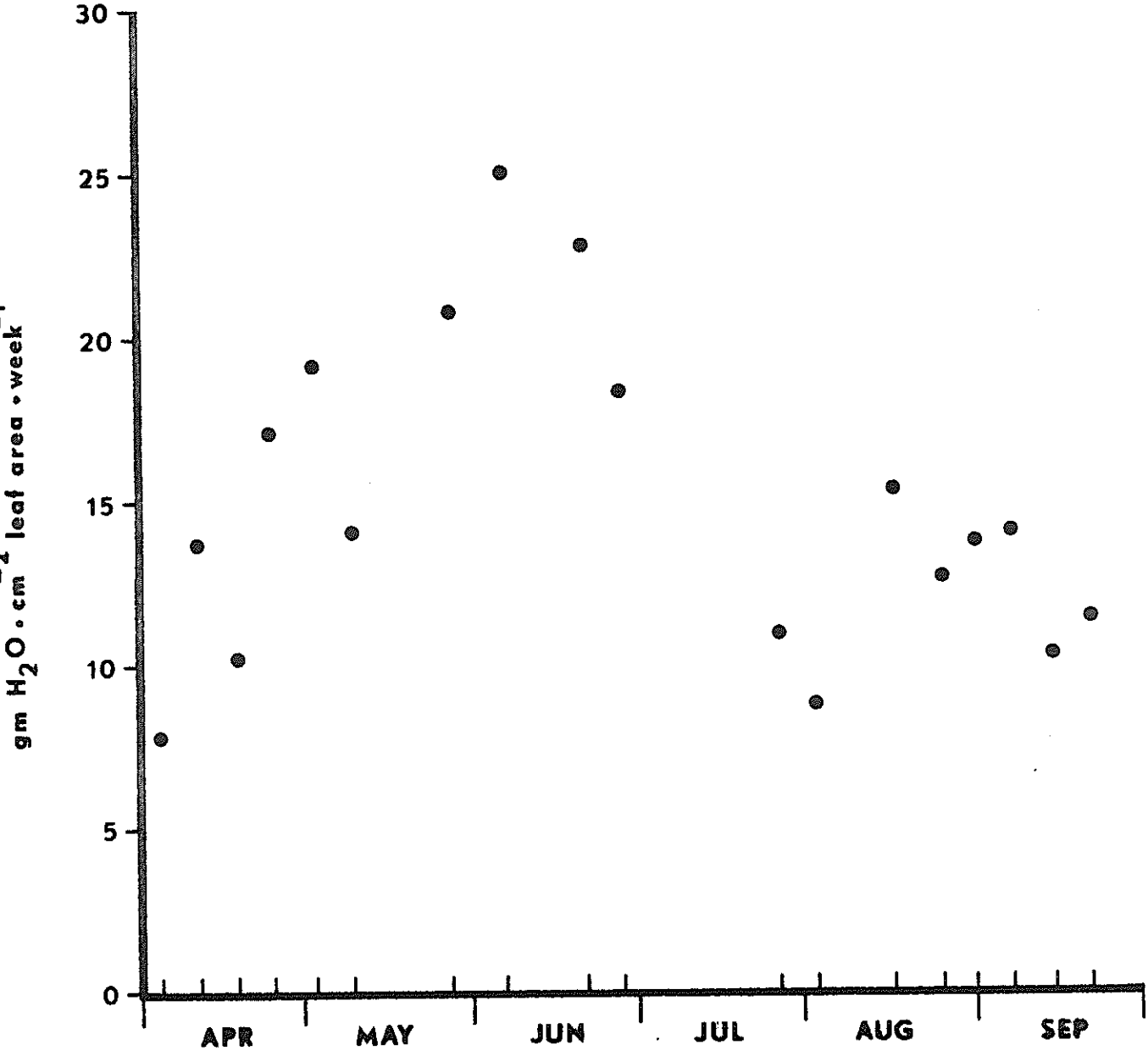

Figure 4. Seasonal variation in transpiration rate of *Lycium torreyi* in the study stand during the 1971 growing season in gm $H_2O \cdot cm^{-2}$ leaf area $\cdot$ $week^{-1}$.

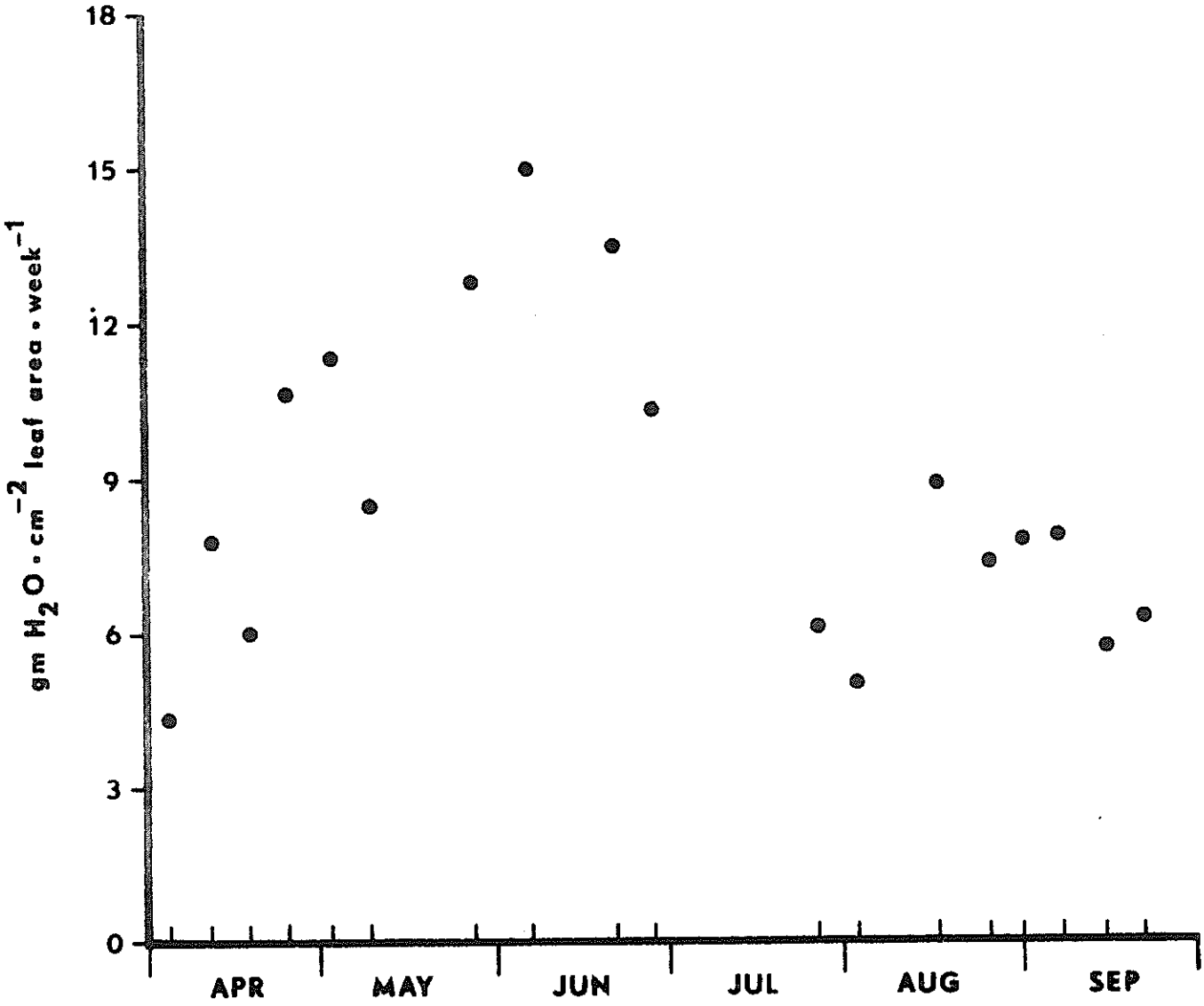

Figure 5. Seasonal variation in transpiration rate of *Salix amygdaloides* in the study stand during the 1971 growing season in gm H_2O $\cdot$ cm^{-2} leaf area $\cdot$ $week^{-1}$.

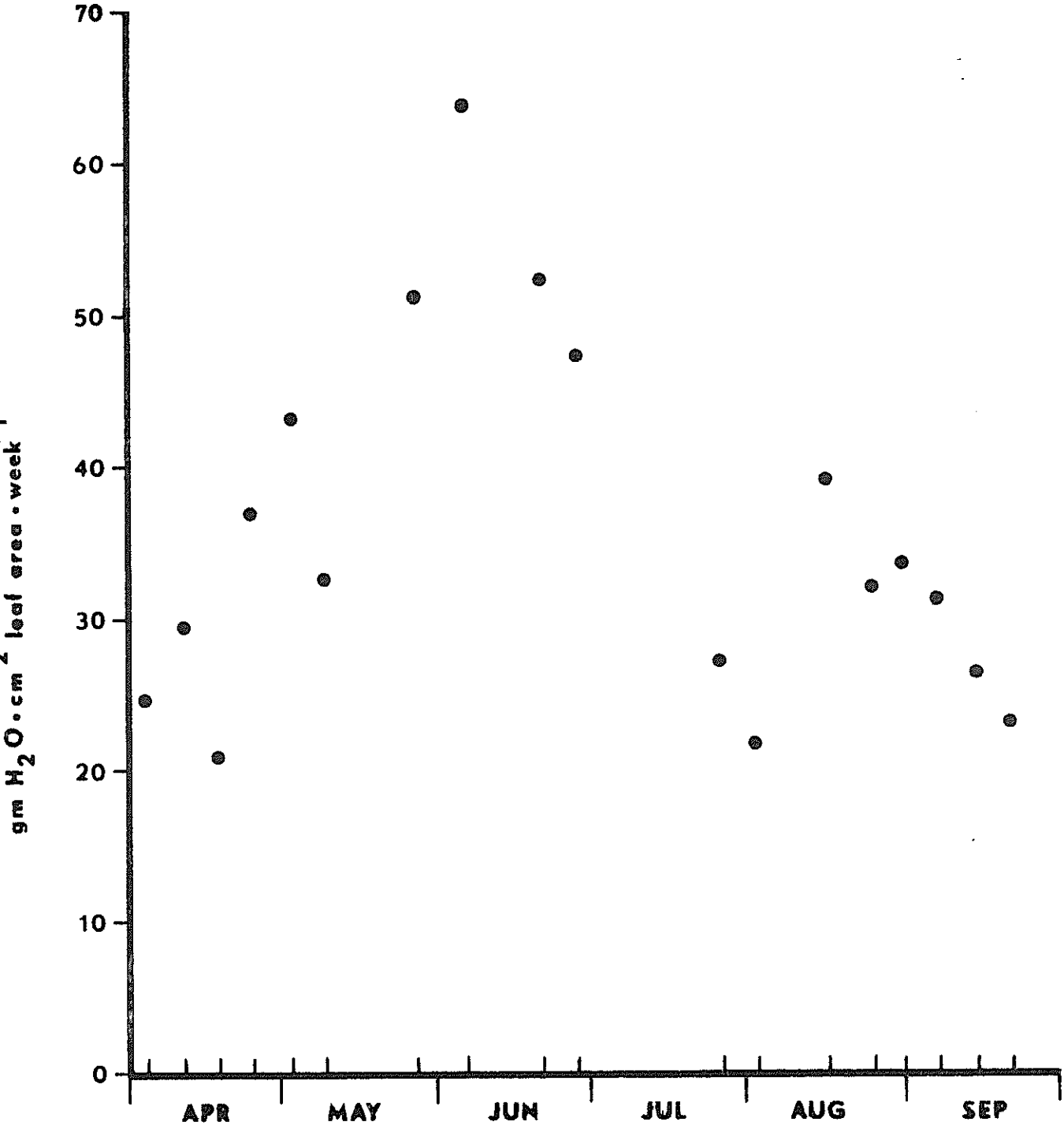

Figure 6. Seasonal variation in transpiration rate of *Tamarix pentandra* in the study stand during the 1971 growing season in gm $H_2O \cdot cm^{-2}$ leaf area $\cdot$ $week^{-1}$.

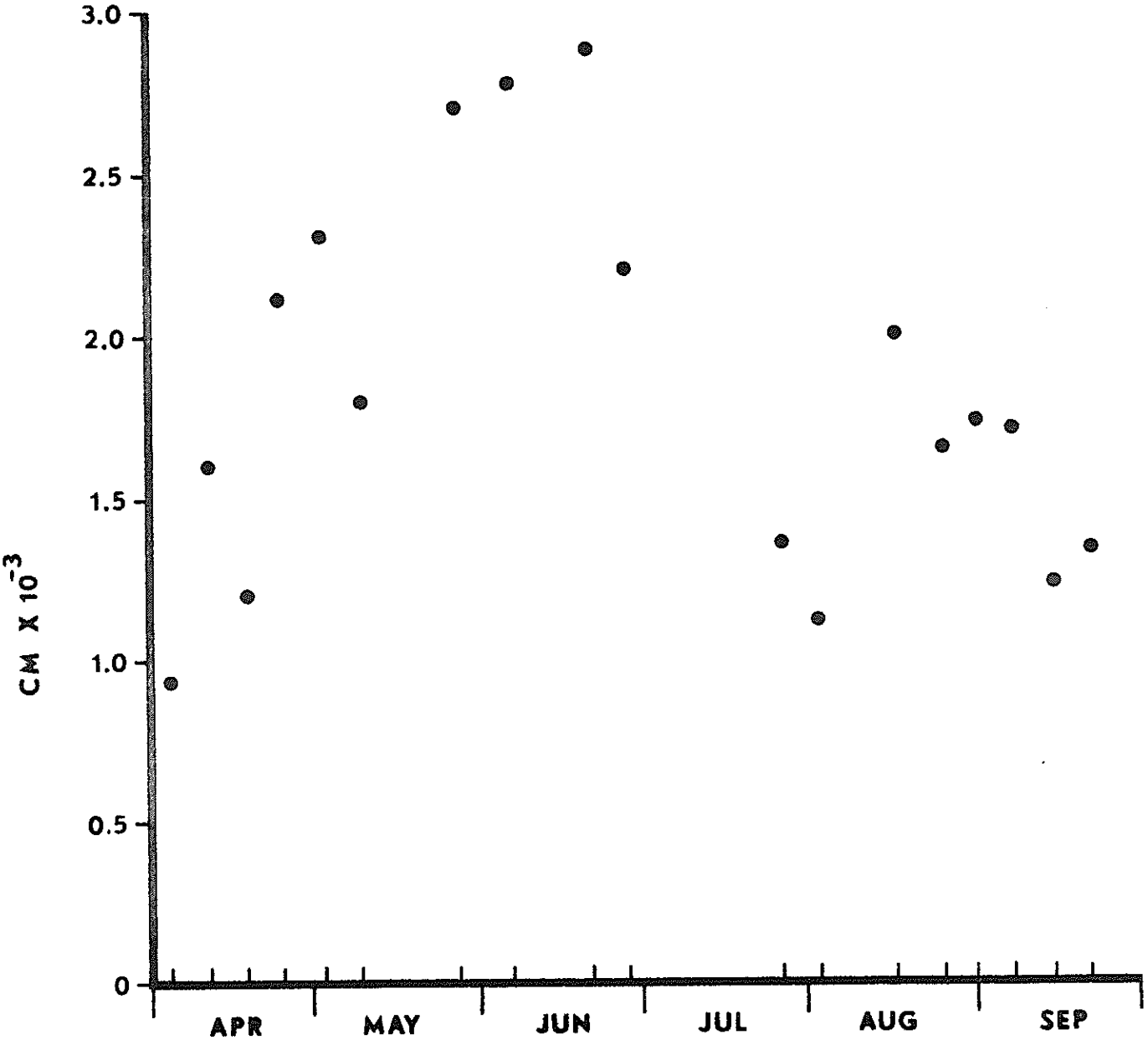

Figure 7. Total weekly water loss by *Populus fremontii* in the study stand during the 1971 growing season in cm of water.

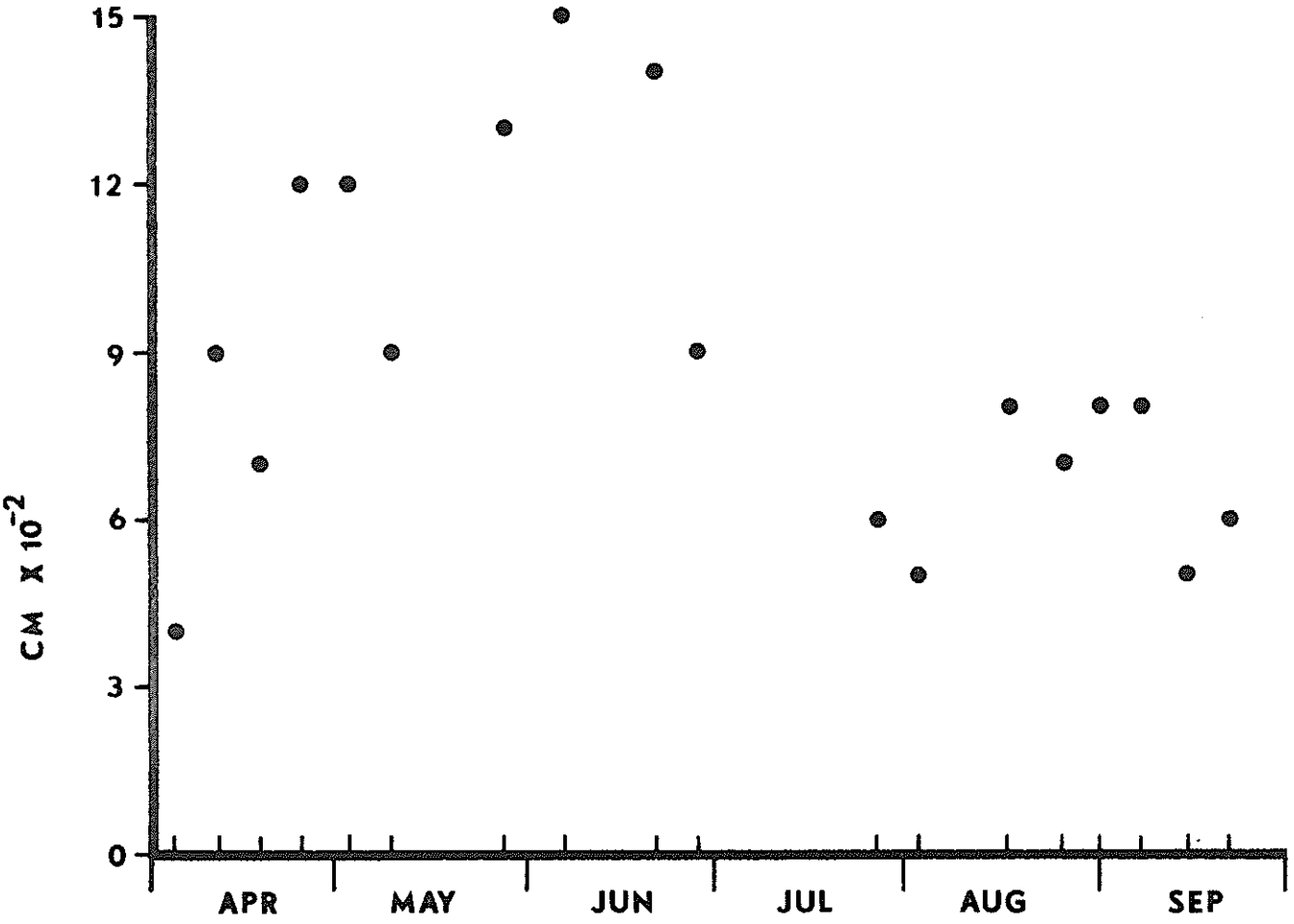

Figure 8. Total weekly water loss by *Prosopis pubescens* in the study stand during the 1971 growing season in cm of water.

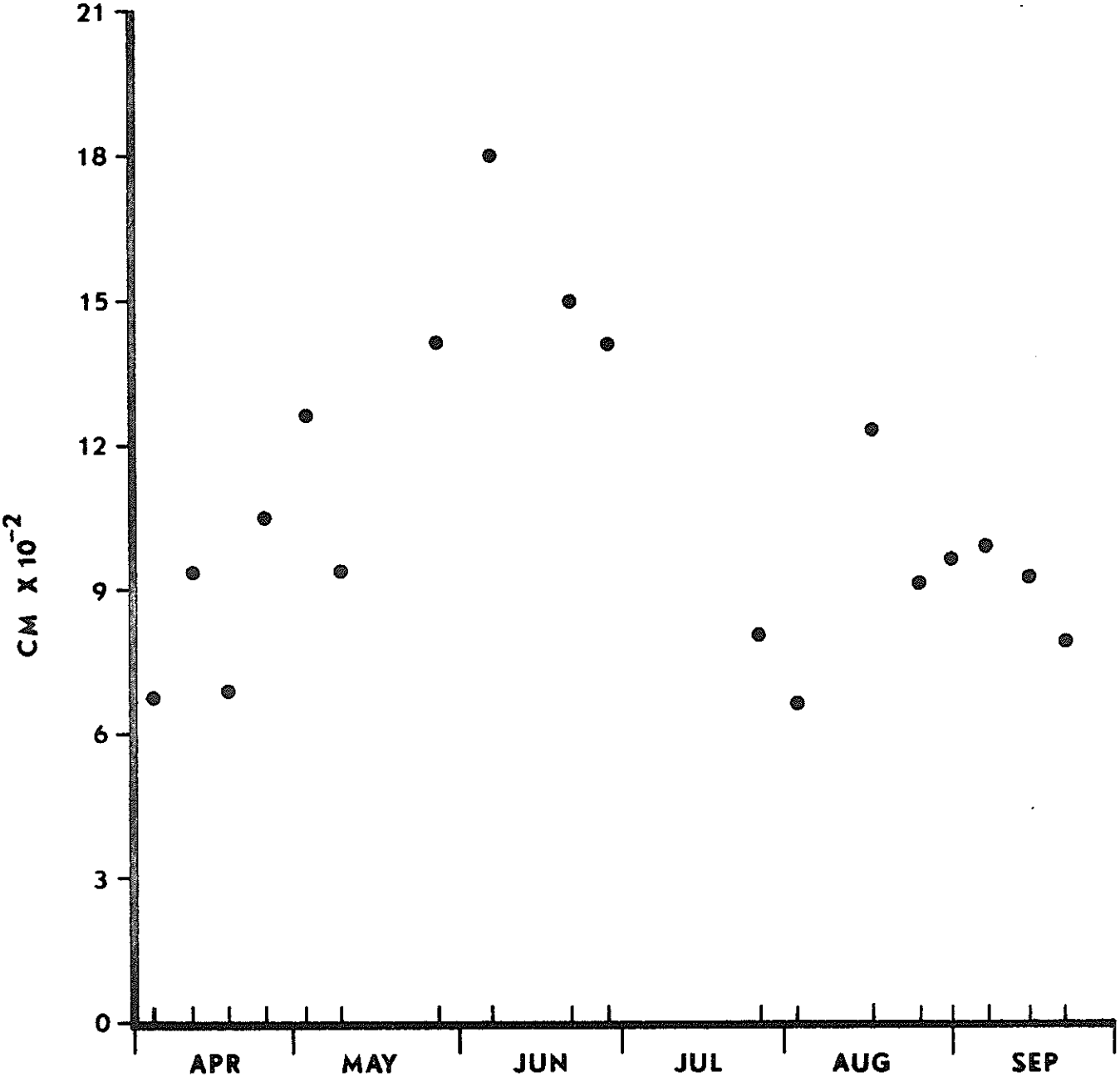

Figure 9. Total weekly water loss by *Baccharis glutinosa* in the study stand during the 1971 growing season in cm of water.

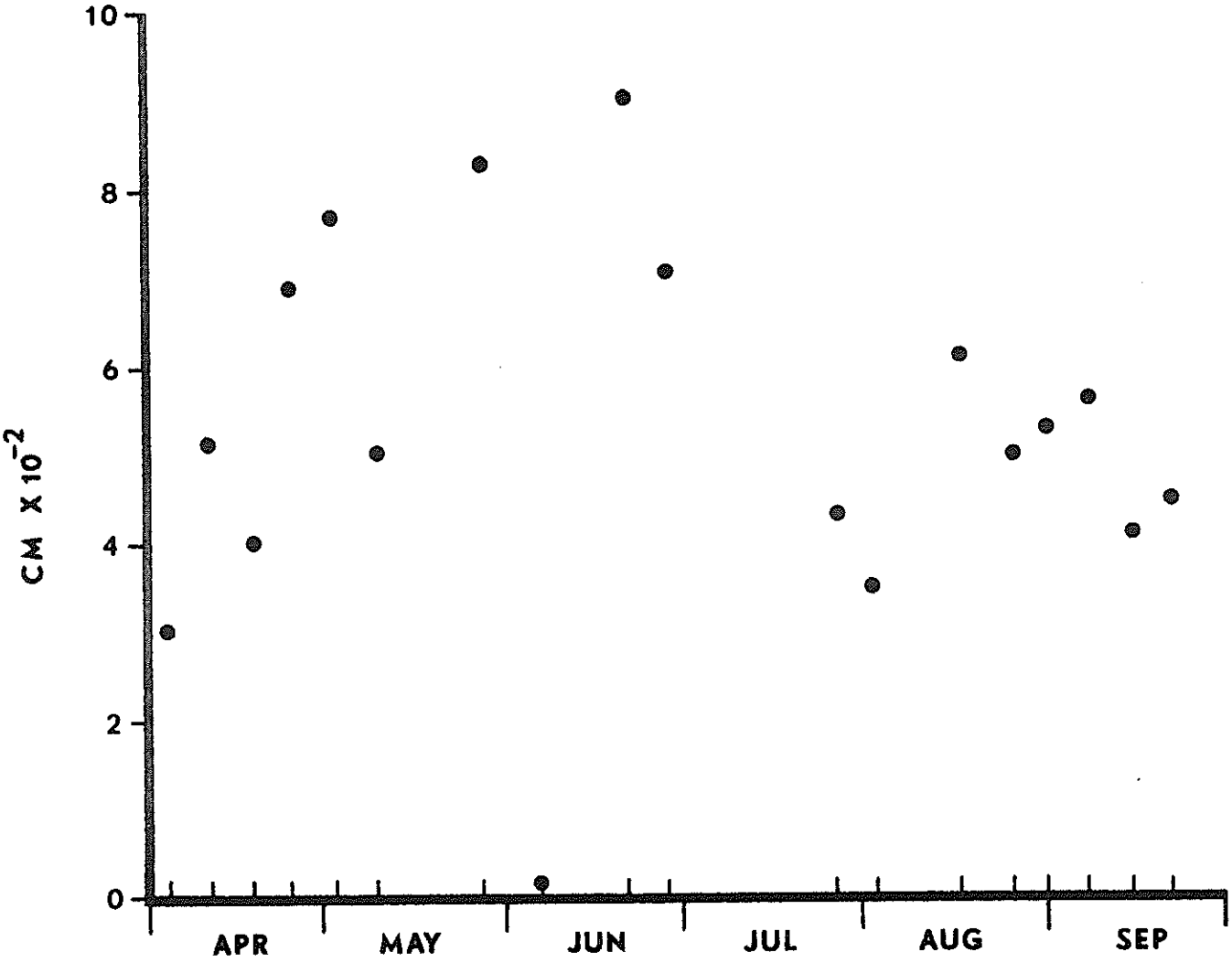

Figure 10. Total weekly water loss by *Lycium torreyi* in the study stand during the 1971 growing season in cm of water.

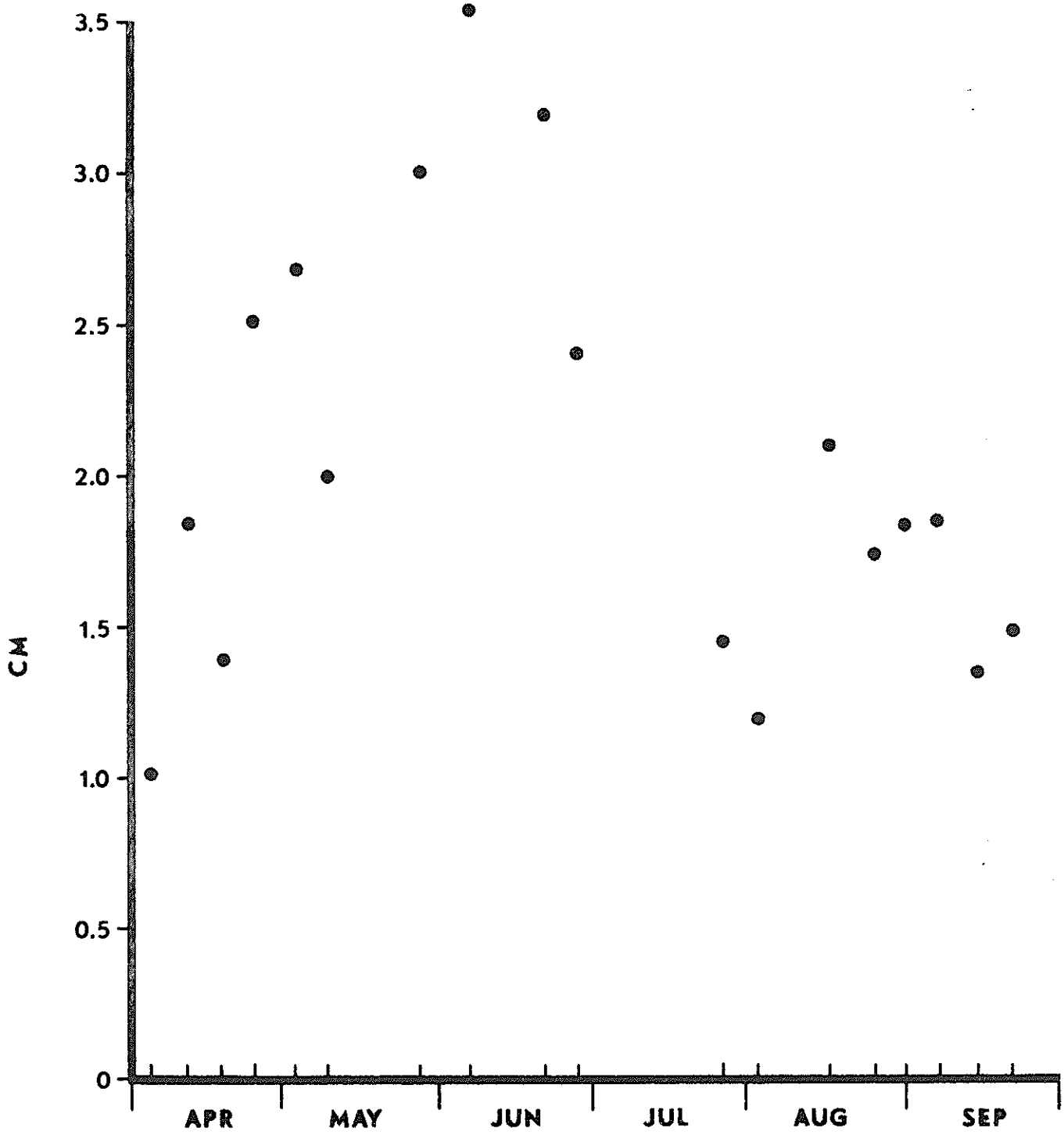

Figure 11. Total weekly water loss by *Salix amygdaloides* in the study stand during the 1971 growing season in cm of water.

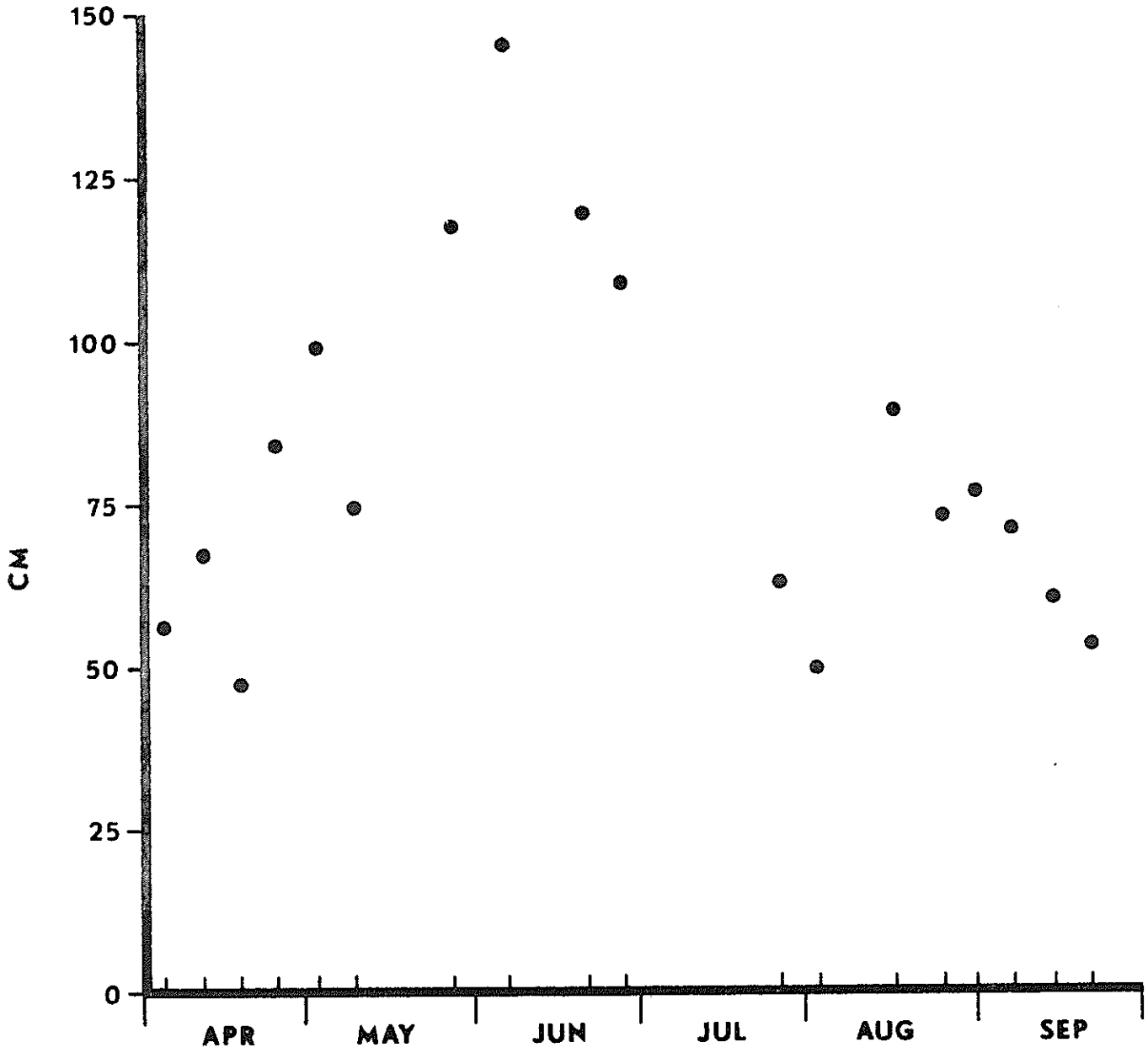

Figure 12. Total weekly water loss by *Tamarix pentandra* in the study stand during the 1971 growing season in cm of water.

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