

Proceedings of the 1977 meetings of the Arizona Section of the American Water Resources Association and the Hydrology Section of the Arizona Academy of Science, held in Las Vegas, Nevada, April 15-16.

ESTIMATING PHREATOPHYTE TRANSPIRATION

by

Lloyd W. Gay and Theodore W. Sammis

ABSTRACT

Phreatophyte transpiration on the Colorado River floodplain in western Arizona was evaluated under hot, dry, midsummer weather conditions. The simple transpiration model used related transpiration to the vapor pressure deficit of the air and to the area and the diffusion resistance of the transpiring foliage. There were no independent transpiration measurements for verification of the results. On a relative basis, however, mesquite (*Prosopis* sp.) transpired more rapidly per unit of leaf area than did saltcedar (*Tamarix chinensis*, Lour.).

INTRODUCTION

Large quantities of water are used by riparian vegetation in the arid and semi-arid regions of the southwestern United States. Saltcedar (*Tamarix chinensis*, Lour.) and mesquite (*Prosopis* species) occur extensively along the watercourses in the southwest. The term phreatophyte was coined to describe plants of this type, which flourish where their roots can reach a plentiful supply of water. Phreatophytes extract water either directly from the water table, or indirectly from the saturated capillary fringe immediately overlying it.

It is evident that phreatophytes use large amounts of water, and it has been widely assumed that much of this consumptive use could be salvaged by the clearing of riparian vegetation. Evidence of substantial water salvage has not been convincing, however, and public opposition to phreatophyte clearance has been spirited and effective. As a consequence, there are few phreatophyte control programs now underway in the Southwest. Alternatives to clearing that have been suggested include management of riparian communities to favor phreatophyte species that use the least amount of water. It is becoming apparent, however, that the extent of water losses and the nature of the processes that control them are not yet well defined, despite a large amount of research that has been carried out (Horton, 1976)

This paper evaluates stomatal resistance as the key factor controlling the transfer of water between riparian vegetation and the atmosphere. A simple vapor transport model is applied to the problem of evaluating evapotranspiration rates from several species on the Colorado River flood plain in western Arizona.

BASIC MODEL

The basic diffusion resistance model relates the transpiration per unit area of individual leaves (E_L) to the vapor concentration gradient between the interior of the leaf and that in the free air, and to the diffusion resistance that exists between these two points. The basic model is

$$E_L = \frac{\rho C_p}{\gamma L} (e_s - e) / r_L \quad (1)$$

where ρ is air density (g/cm^3), C_p is the specific heat of air ($cal/g \text{ } ^\circ C$), γ is the psychrometric constant ($mb/^\circ C$), L is the latent heat of fusion (cal/g), $e_s - e$ is the vapor pressure deficit (VPD in mb) of the air with e_s being the saturation vapor pressure at air temperature and e being the actual vapor pressure, r_L is the leaf (essentially stomatal) resistance (s/cm) and E_L is the evaporation rate ($\mu g/cm^2 \cdot s$).

The authors are, respectively, Professor of Watershed Management, School of Renewable Natural Resources, University of Arizona, Tucson, and Assistant Professor, Department of Agricultural Engineering, New Mexico State University, Las Cruces. Approved for publication as Journal Paper No. 2738, Arizona Agricultural Experiment Station.

This model results from a number of simplifying assumptions. For example, diffusion resistance of the air can be neglected, as the rough canopy structure keeps it small with respect to the leaf diffusion resistance. Also, the model estimates the vapor concentration gradient between leaf and air by the vapor pressure deficit in the free air, assuming that the leaf elements are close to air temperature. Both assumptions are reasonable given the small sizes of leaves in saltcedar and mesquite.

The model can be extended to the problem of estimating evaporation (E) from a canopy if an appropriate canopy resistance (r_c) is substituted for the leaf resistance in Equation (1). Federer (1975) showed that the well-known Monteith-Penman model could be simplified into this form whenever the aerodynamic diffusion resistance approaches zero. This is very nearly true for forests and plant communities with rough, porous canopies, such as those of saltcedar and mesquite. The simple model of Equation (1) thus provides a way to estimate evapotranspiration from routine climatological measurements.

FIELD MEASUREMENTS

Field measurements were carried out on the Colorado flood plain near Ehrenburg, Arizona during a warm, dry, clear weather period in June 1976. Incoming solar radiation was measured with an Eppley pyranometer. Air temperature and relative humidity were measured with a hydrothermograph in a weather shelter at 1.5 m height. Spot checks of air temperature and humidity were made with an aspirated psychrometer.

Leaf diffusion resistances were made on various saltcedar and mesquite samples from early morning to dusk, using a null-balance porometer after the design of Beardsell, Jarvis and Davison (1972). No distinction was made between the two species of mesquite present: honey mesquite (*P. juliflora* var. *glandulosa* Torr.) and screwbean mesquite (*P. pubescens* Benth.). The plant water potential (ψ_p) was measured with a pressure bomb (Scholander, et al., 1964) at the time of each leaf diffusion measurement.

The surface area of the sampled vegetation is needed for the resistance determinations. Dry weight was obtained for each sample, and converted to surface area by the factor of 200 cm²/g for saltcedar and 150 cm²/g for mesquite. These factors were developed from subsamples that were dried and then evaluated from projected area measurements made with an integrating densitometer.

RESULTS AND DISCUSSION

The basic measurements are summarized for saltcedar in Table 1 and for mesquite in Table 2. The porometer measurements were repeated on seven clumps of foliage on the same saltcedar plant at approximately two hour intervals from early morning until dark on June 17, 1976. The seven samples were collected at the end of the day and the surface areas measured for the evaluation of leaf resistance. Subsequent measurements of resistance on saltcedar and mesquite were obtained from individual samples on various plants. Leaf water potential measurements with the pressure bomb were made on adjacent clumps of foliage at the time of each resistance measurement.

Table 1. Mean values of salt cedar resistances, Colorado River floodplain, Ehrenburg, Arizona, 1976. Note that the number of samples (n) is given for the mean resistance value (r_p) and mean leaf water potential (ψ_p). Other data are vapor pressure deficit (VPD) and transpiration flux (E_p).

day	time (hr)	n	r_p (s/cm)	VPD (mb)	E_p ($\mu\text{g}/\text{cm}^2\text{-s}$)	ψ_p (bars)
6/17	0630	7	17.0	-12.6	0.54	-10.2
	0850	7	13.8	-27.8	1.46	-25.9
	1030	7	19.6	-42.0	1.56	-26.2
	1230	7	33.0	-51.4	1.13	-25.4
	1430	7	36.9	-57.4	1.13	-25.1
	1645	7	38.6	-59.0	1.11	-23.0
	1830	7	35.4	-52.9	1.08	-22.6
	2030	7	67.2	-35.4	0.38	-13.6
	2200	2	68.7	-25.8	0.27	-19.6
	6/20	0930	5	42.2	-32.8	0.56
1020		3	16.9	-41.0	1.76	-32.6
6/21	0730	2	4.3	-14.8	2.50	-22.3
	1030	6	12.2	-46.8	2.78	-31.0
6/22	0715	4	11.8	-21.3	1.31	-19.0
	0910	1	19.5	-33.0	1.23	-27.9

Table 2. Mesquite resistances, Colorado River floodplain, Ehrenburg, Arizona, 1976. Each resistance is derived from a single sample.

day	time (hr)	r_l (s/cm)	VPD (mb)	E_p $\mu\text{g}/\text{cm}^2\text{-s}$	ψ_l (bars)
6/21	0815	2.8	-22.4	5.91	-24.5
	0825	2.8	-24.5	6.24	-27.2
	0935	2.7	-41.8	11.24	-27.9
	0945	3.0	-39.2	9.58	-29.3
6/22	0735	3.5	-21.2	4.40	-27.2
	0745	6.8	-21.5	2.31	-23.1
	0800	13.8	-23.0	1.21	-21.8
	0815	7.0	-24.1	2.49	-24.0

LEAF RESISTANCE AND TRANSPIRATION.

The diurnal course of the saltcedar leaf resistance and solar radiation is plotted in Figure 1. The skies were cloudless throughout the day, although smoke from nearby field burning activities caused some unsteadiness in the radiation during the mid-morning hours.

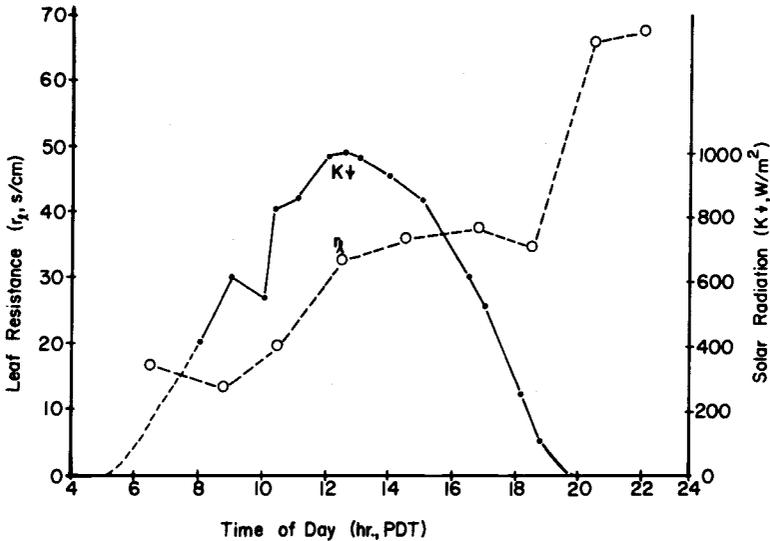


Figure 1. Solar radiation (K+) and leaf resistance (r_l) of saltcedar, Ehrenburg, Arizona, June 17, 1976.

The resistance measurements began soon after sunup. The initial readings (17 s/cm) indicated that the stomata were open. The values fell slightly, then increased to a plateau of about 35-40 s/cm from midday until sundown. The values climbed sharply to nearly 70 s/cm after dark. The Figure illustrates that the correlation between radiation and leaf resistance is weak. The stomata of many species will remain open once a relatively low level of visible light is exceeded, providing they are unaffected by other environmental factors. The leaf resistance, e.g., stomatal opening, is primarily controlled by physiological characteristics of the plant once the minimum light requirement is satisfied.

These characteristics are not yet defined for saltcedar although they are becoming known for other species. For example, the resistance of northern hardwood species (Federer and Gee, 1976) has been related directly to air temperature and to vapor pressure deficit. It is also indirectly related to moisture stress in the plant as the stomata close whenever the stress becomes too large.

Figure 2 illustrates the relationship between VPD and the leaf resistance throughout the day. The two curves are quite similar as long as the minimum light requirement is exceeded. The relationship is good until dusk; the resistance curve rises

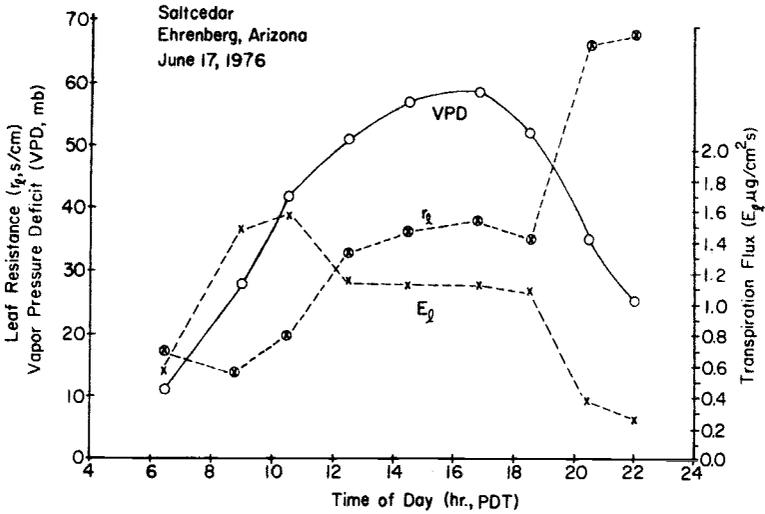


Figure 2. Vapor pressure deficit (VPD), leaf resistance (r_l) and transpiration rate (E_l). Saltcedar, Ehrenberg, Arizona, June 17, 1976.

sharply after dark while VPD continues to become smaller. Temperature is not plotted in the Figure. However, VPD is largely a function of air temperature; both reach a maximum in late afternoon.

The resistance changes tend to equalize or reduce the transpiration rate as VPD increases through the late afternoon period. The transpiration predicted by the simple vapor loss model in Equation (1) is directly related to VPD. If the leaf resistance were to remain constant, then doubling VPD would double E_l . If VPD increased sixfold, as found on this measurement day, the corresponding sixfold increase in transpiration would be excessively large. It is expected that some increase in resistance must occur to keep transpiration rates moderate.

The transpiration rates predicted by Equation (1) are also plotted in Figure 2. It is evident that the increased resistance more than compensates for the increased VPD, and the transpiration rate thus falls after the early morning hours. This suggests that the plant is exercising some physiological control on the stomata to counteract the evaporation demand of this warm dry atmosphere.

LEAF WATER POTENTIAL AND TRANSPIRATION

The loss of water through the stomata increases the water potential of the leaves. Pressure bomb estimates of the leaf water potential are now thought to be reasonably close to the actual values (Talbot, et al., 1975). The pressure bomb measurements are easy to make, and may eventually provide a basis for evaluating transpiration.

The interaction between water potential and transpiration can be examined with the simple model of Elfving, et al. (1972) that links the liquid flow through the soil-plant continuum to the vapor flow between the leaf and the atmosphere. The flow equation is

$$E_l = \frac{\psi_l - \psi_s}{r_p + r_s} = \frac{\psi_l - \psi_a}{r_l + r_a} \quad (2)$$

where $\psi_l - \psi_s$ is the difference in potential for liquid flow in the plant and in the soil, r_p and r_s are the soil and plant resistances to liquid flow, $\psi_l - \psi_a$ is the potential for vapor flow from the leaf to the atmosphere and r_l and r_a are the leaf and atmosphere resistance to vapor flow. The resistances are expressed in units appropriate to liquid or to vapor flow.

The vapor flow term can be simplified in accord with Equation (1) and the leaf potential becomes

$$\begin{aligned} \psi_l &= \psi_s + \frac{\rho C_p (e_s - e)}{\gamma L} (r_p + r_s) \\ &= \psi_s + kE \end{aligned} \quad (3)$$

where k is a constant associated with the resistances for liquid flow through the soil and plant. If the soil and plant resistances remain constant through the day, Elfving's model predicts that the leaf water potential is linearly related to the transpiration rate.

The plot of ψ_l versus E_l for saltcedar and for mesquite in Figure 3 suggests that the simple linear model may indeed define this relationship adequately. The saltcedar

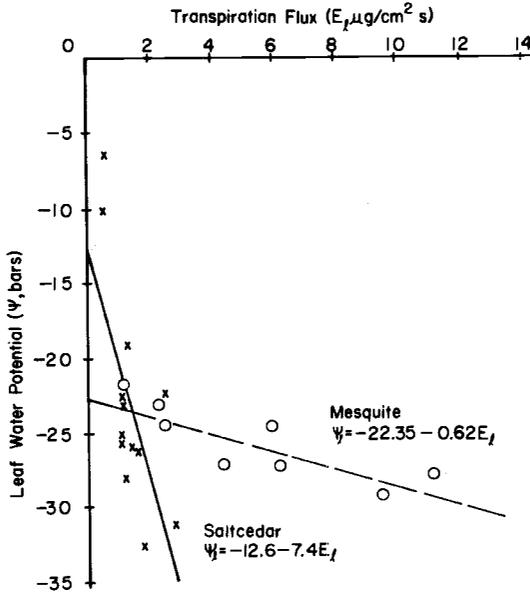


Figure 3. Leaf water potential (ψ_l) and transpiration flux (E_l) in saltcedar and mesquite, Ehrenburg, Arizona, June 17-22, 1976.

relationship is

$$\psi_l = -12.6 - 7.4E_l \quad (4)$$

based upon all the observations in Table 1 except for the two after sundown (2030 and 2200 hours, June 17). The visual impression of goodness of fit is not borne out by statistical evidence, however, as the r^2 value for this relationship is only 0.42. Some additional studies must be made to see if the variability could be reduced to an acceptable level. The expression also predicts that the soil potential would be -12.6 bars when the transpiration rate goes to zero. Predawn measurements of leaf water potential will be needed to test the intercept in further experiments.

The mesquite measurements yield the relationship

$$\psi_l = -22.35 - 0.62E_l$$

with a more reassuring r^2 value of 0.72.

The two species demonstrate quite different behavior. The mesquite indicates that the soil potential is -22.35 bars, which is substantially more negative (greater stress) than that of the saltcedar. This may represent either differences in the water uptake mechanisms of the two species, or the location of the active roots with respect to the water table. The resistance to liquid water movement between the soil and the plant and within the plant is given by the slope of ψ_s versus E_g ; the steeper the slope, the greater the resistance to flow. The saltcedar shows much greater resistance than the mesquite. The mesquite is transpiring much more rapidly per unit area than the saltcedar. Most of the readings were two to three times greater, and the maximum rate was nearly five times greater.

Our lack of knowledge of the actual state of moisture available to the roots limits our interpretation of these results. The Ehrenburg region is the driest in Arizona; it has an annual rainfall of only 9 cm. The depth of the water table was not measured directly at the field site. However, 31 observations of water table depth by the U.S. Geological Survey in this region on June 16 averaged 3.1 m. This is not an unreasonable depth for the roots of riparian vegetation to reach, so one would expect that the extensive vegetation on the flood plain is tapping the water table of the Colorado River. The soil potentials predicted by the model (-12.6 and -22.35 bars) are much too low for vegetation with ready access to ground water. If the water table underwent rapid fluctuations associated with varying discharge from the Colorado River dam system, then it is possible that few active roots were tapping the capillary fringe. We do not have enough information to do more than speculate of the validity of these low soil potentials.

TRANSPIRATION FROM RIPARIAN STANDS

The diffusion resistance model may possibly provide simple estimates of transpiration from plant communities. Cunningham *et al.* (1973) used this method to estimate mean weekly transpiration from a riparian community over an entire growing season. No independent estimates were available for comparison, however, and his transpiration rates appeared high. The energy budget or Bowen ratio method is applicable to extensive, uniform stands. Gay, *et al.* (1976) have reported the results on one of the few such studies to be carried out over saltcedar; their measurements extended over only a single day. The two methods need to be compared to determine the closeness of agreement.

The results obtained here can be extended from a unit leaf area basis to an entire stand by multiplying with the leaf area index (LAI). There are very few LAI estimates for stands of riparian vegetation. We sampled a 3.25 m^2 plot through the canopy of two different saltcedar stands of approximately 5 m height. The over-dried foliage was converted to area by the previously determined factor of $200 \text{ cm}^2/\text{g}$. The LAI of the first plot was 8.1 and the second was 7.45. The vegetation at this experimental site was discontinuous, however, and additional sampling would have to be undertaken before an average stand LAI could be estimated. The measurements of Cunningham *et al.* (1973) gave a total LAI of only 2.5 for their saltcedar stand.

The maximum transpiration loss for the saltcedar was $2.78 \mu\text{g}/\text{cm}^2\text{-s}$, which is equivalent to the evaporation of 0.1mm an hour per unit leaf area. The evaporation rate from a dense stand (LAI = 8) would be 0.8mm per hour. The higher rates for mesquite (say $10 \mu\text{g}/\text{cm}^2\text{ s}$) yield a loss of 0.36mm per hour from a unit leaf area. LAI of a mesquite stand is substantially less than that of saltcedar, however. A plausible (though arbitrary) estimate of mesquite LAI = 3 would yield maximum hourly loss rates of about 1mm per hour from a mesquite stand.

These estimates are rather close to the maximum hourly transpiration rate of 1mm that was measured for saltcedar by Gay *et al.* (1976). Midday values of this magnitude are associated with total daily losses of 8 to 10mm for clear weather conditions. This is in line with estimates of saltcedar and mesquite transpiration made elsewhere. Overall, the loss rates based upon these diffusion measurements appear a little low for a saltcedar stand, but quite reasonable for the mesquite.

CONCLUSIONS

A simple diffusion model gave reasonable estimates of transpiration although no direct comparisons were made with other methods. The leaf diffusion measurements required for the model are relatively easily obtained with a porometer. The leaf area index is needed to extend the transpiration estimates from a unit area to a stand basis, and considerable sampling may be necessary to obtain this value.

The transpiration rates ranged from 0.5 to $2.78 \mu\text{g}/\text{cm}^2\text{-s}$ per unit of leaf area in saltcedar and from 1.2 to $11.2 \mu\text{g}/\text{cm}^2\text{-s}$ in mesquite. If the water loss rates were projected to a stand basis, the larger leaf area index of saltcedar (as high as 8.1) would tend to compensate for the lower rate per unit of leaf area. The mesquite leaf area index was not measured, but it is probably less than 3.0. Thus the water loss from a stand may be much closer than that indicated by the unit area water loss rates.

The diffusion resistance model can be applied to plant communities of irregular dimensions, or to clumps, while other methods, such as the Bowen ratio or energy budget, need large, uniform areas of vegetation for application. A definitive comparison between methods is now needed.

The diffusion resistance model also provides an insight into the response of the plant to soil-water potential and to vapor pressure deficits. A simple linear model did not appear to adequately link soil potential, leaf potential and transpiration rates. The soil potential predicted by the model was much lower than expected for plants with ready access to the ground water table. Further work is needed to determine whether phreatophytes normally have access to ground water throughout the growing season, or whether the discrepancy is associated with either measurement errors or failure of the model to adequately represent the process.

REFERENCES CITED

- Beardsell, M. F., P. G. Jarvis, and B. Davidson. 1972. A null-balance diffusion porometer suitable for use with leaves of many shapes. *J. Appl. Ecol.* 9:677-690.
- Cunningham, G. L., J. G. Fraser, R. E. Grieve, and H. G. Wolfe. 1973. A comparison of rates of water loss through transpiration of several southern New Mexico phreatophyte species. WRR Report No. 25. New Mexico Water Resources Research Institute, Las Cruces, NM.
- Elfving, D. C., M. R. Kaufman, and A. E. Hall. 1972. Interpreting leaf water potential measurements with a model of the soil-plant-atmosphere continuum. *Physiol. Plant.* 27:161-168.
- Federer, C. A. 1975. Evapotranspiration. *Reviews Geophysics and Space Physics* 13:442-445, 487-494.
- Federer, C. A. and G. W. Gee. 1976. Diffusion resistance and xylem potential in stressed and unstressed northern hardwood trees. *Ecology* 57:975-984.
- Gay, L. W., T. W. Sammis and J. Ben-Asher. 1976. An energy budget analysis of evapotranspiration from saltcedar. *Proceedings: Hydrology and Water Resources in Arizona and the Southwest.* 6:181-187.
- Horton, J. L. 1976. Management of moist-site vegetation for water: past history, present status, and future needs. Contract Report. U.S. Forest Service Region 5, San Francisco, California. February 1, 1976. 41 pp.
- Scholander, P. F., H. T. Hammel, E. D. Bradstreet, and E. A. Hemmingen. 1964. Sap pressure in vascular plants. *Science* 148:339-345.
- Talbot, A. J. B., M. T. Tyree and J. Dainty. 1975. Some notes concerning the measurement of water potentials of leaf tissue with specific references to Tsuga canadensis and Picea abies. *Can. Jour. Botany* 53:784-788.

ACKNOWLEDGEMENTS

The work upon which this publication is based was supported in part by funds provided by the United States Department of the Interior (Project C-6030) as authorized under the Water Resources Research Act of 1964, as amended, and in part by the Arizona Agricultural Experiment Station, Hatch Project 04.