



Transpiration coefficients for three Great Basin shrubs

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Transpiration by desert phreatophytes is poorly understood, and the few existing data are difficult to extrapolate spatially. This study developed transpiration coefficients (K_c) for *Atriplex lentiformis* ssp. *torreyi*, *Chrysothamnus nauseosus* and *Sarcobatus vermiculatus* to estimate transpiration using vegetation cover measurements. The K_c were developed from stomatal conductance, reference evapotranspiration (ET_r), and modeled leaf area index (LAI). Transpiration estimates using the K_c generally agree with values reported in the literature, but few examples of simultaneous leaf area and independent transpiration measurements exist to rigorously test this approach. A study has been initiated in the Owens Valley of California to make this necessary comparison.

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Introduction

Estimation of transpiration in arid lands is becoming increasingly important as management of these lands intensifies for agriculture, waste disposal, and water supply. In much of the Great Basin of the western U.S., shallow ground-water supports large areas of phreatophytic shrubs and grasses. Many early estimates of evapotranspiration (ET) of these species were derived from hydrologic studies to determine evaporative discharge from closed basins (Nichols, 1993). More recently, several researchers have applied porometer methods, sap flow methods, lysimeters, or micrometeorological methods to determine ET from phreatophytes in arid lands (Robinson, 1970; Romo & Haferkamp, 1989; Malek *et al.*, 1990; Stannard, 1993; Nichols, 1994; Sala *et al.*, 1996). Porometry is a well-established method still used occasionally to estimate transpiration (Conard *et al.*, 1997), but it requires careful experimental techniques and several assumptions to scale transpiration measured on a single leaf or branch to derive canopy or areal ET estimates. Stem heat balance methods are more straightforward than porometry, but both methods require similar assumptions regarding the canopy microclimate to derive transpiration estimates at scales larger than individual shrubs. Lysimeters and micrometeorological methods provide plot-scale estimates of ET which are difficult to extrapolate over large areas, especially if vegetation and water table conditions are variable. Additionally, the instruments are expensive and/or require considerable soil and vegetation disturbance that prevents routine use in remote areas.

It is common in irrigated agriculture to estimate ET using a dimensionless transpiration coefficient, K_c (Allen *et al.*, 1998). Few examples exist, however, of application of this concept to native vegetation ET (Wight *et al.*, 1986; Or & Groeneveld, 1994). The technique can be joined easily to measures of vegetation abundance and thus potentially could be applied to estimate transpiration over large areas (Hanks, 1985). Transpiration coefficients are also theoretically transferable geographically although care must be taken to insure the K_c is applicable in the new environment (Jagtop & Jones, 1989; Ritchie & Johnson, 1990; Annandale & Stockle, 1994).

In the early 1900s, the City of Los Angeles began to develop the extensive water resources of the Owens Valley as a potential water supply. The resulting water wars were historic and continued sporadically for decades (Reisner, 1986). In the 1980s, the U.S. Geological Survey, Inyo County, and Los Angeles conducted research on the effects of ground-water pumping on phreatophytic vegetation in the Owens Valley to assist settlement of a long-standing dispute between local residents and the City of Los Angeles (Sorenson *et al.*, 1991). That research produced a large database amenable for analysis to develop transpiration coefficients for the dominant phreatophytic shrub species. The objective of this study was to develop transpiration coefficients for *Atriplex lentiformis* (Torrey) S. Watson ssp. *torreyi* S. Watson (Nevada saltbush), *Chrysothamnus nauseosus* (Pallus) Britton (rabbitbrush), and *Sarcobatus vermiculatus* (Hook.) Torrey (greasewood) to permit estimation of transpiration using relatively simple measures of shrub cover.

Materials and methods

The Owens Valley is a long, narrow valley east of the Sierra Nevada in eastern California. Even though the valley lies in the rain shadow of the Sierra Nevada (mean annual precipitation at Bishop = 0.11 m), the valley floor supports large areas of phreatophytic shrubs and grasses due to a high water table sustained by runoff from the adjacent mountains. *Atriplex*, *Chrysothamnus*, and *Sarcobatus* dominate the shrub component of the phreatophytic communities and were the subject of this study.

Fifteen sites spanning the length of the valley were monitored from 1984 to 1988 to evaluate the effect of natural and induced water table fluctuations on leaf area and transpiration of the shrub species (Sorenson *et al.*, 1991). Only data from sites with shallow ground-water and adequate soil water conditions measured at adjacent piezometers and neutron gauge access tubes were selected for K_c preparation (Wright, 1981).

A second goal of this analysis was to prepare a K_c that could be used with either leaf area index (LAI) or vegetation cover measurements. Concurrent measurements of LAI and cover of green leaves and stems were collected at 33 transects (100 m long) visited once each summer from 1987 to 1995. Leaf area index was determined using the point quadrat method (Goodall, 1952; Groeneveld, 1997) and cover from the first pin contacts with green vegetation similar to the line-point method (Bonham, 1989).

K_c Derivation

The equation to determine daily ET from crop coefficients is:

$$ETa_i = K_c \times ETr_i \quad (\text{Eqn 1})$$

where i represents day of year, ETa_i is actual evapotranspiration (m day^{-1}), K_c is the transpiration coefficient (dimensionless), and ETr_i is reference evapotranspiration (m day^{-1}). Bare surface evaporation was not a subject of this study, and so was excluded from ETa_i . By simplifying and rearranging Eqn 1, K_c becomes the ratio of actual

transpiration (Ta_i) and ETr_i (Wright, 1981; Ritchie & Johnson, 1990; Hill, 1991) or:

$$Kc_i = \frac{Tlf_i \times LAI_i}{ETr_i} \quad (\text{Eqn 2})$$

where LAI_i is leaf area index ($\text{m}^2 \text{m}^{-2}$) and Tlf_i is transpiration per leaf area ($\text{m}^3 \text{H}_2\text{O} \text{m}^{-2} \text{leaf day}^{-1}$). Daily Kc values computed for all locations and years were pooled to prepare a general curve applicable to a broad set of conditions. Methods used to determine each component of the Kc are described in the following sections.

Tlf_i determination

Diurnal transpiration for the three species was determined from stomatal conductance measured approximately monthly using a Li-Cor 1600 null-balance porometer (Beardsell *et al.*, 1972). A polycarbonate chamber attachment was used to enclose small branch segments 4–6 cm in length for sampling. Measurements were collected on five to seven branches from each shrub at approximately 2-h intervals during the day. The branches were collected at the end of each day, and leaf area was determined using a stereological technique to correct stomatal conductance for actual leaf area sampled (Weibel, 1979). For *Chrysothamnus*, this correction included green stems. Ambient air temperature and relative humidity were measured with a sling psychrometer before and after each set of measurements.

Instantaneous Tlf was calculated according to:

$$Tlf = c_s(\rho_l - \rho_a) \quad (\text{Eqn 3})$$

where Tlf is transpiration per leaf area ($\text{m}^3 \text{m}^{-2} \text{s}^{-1}$), c_s is stomatal conductance (m s^{-1}), ρ_l is leaf water vapor density (g m^{-3}), and ρ_a is ambient air water vapor density (g m^{-3}) (McDermitt, 1990; Conard *et al.*, 1997). The values ρ_a and ρ_l were calculated from sling psychrometer relative humidity measurements. Vapor density in the leaf was assumed to be saturated.

Air and leaf temperature were assumed equal. Measured leaf and air temperature for *Atriplex* in the Owens Valley differed by $< 2^\circ\text{C}$ (Groeneveld, 1985), and Stannard (1993) reported that leaf and air temperature commonly differed by $< 1^\circ\text{C}$ for *Sarcobatus* and *Chrysothamnus* in the San Luis Valley, Colorado. Temperature differences this small would result in a relative conductance error of about 5% given the low humidity levels typically encountered during this study (McDermitt, 1990).

The assumption implicit in Eqn 3 of negligible boundary layer resistance relative to stomatal resistance probably applies here because coupling of the saturation deficit to ambient air is strong for small, well-ventilated leaves (Jarvis & McNaughton, 1986). Tlf sensitivity to boundary layer conductance at several wind speeds was evaluated using the method of Nichols (1992), which showed that Tlf results could be exaggerated about 10–15% if the assumption of negligible boundary layer resistance was invalid.

Second- or third-order polynomial functions were fitted using nonlinear regression to the means of the sampled branches from individual shrubs to permit integration to determine the daily flux. The curve fitting was not performed to provide inferences about physiological responses through the day. Datapoints at sunrise and sunset ($Tlf = 0$) were added to facilitate regression. This was justified by the observation that porometer measurements were below detection limits at these times. The curves were integrated between sunrise and sunset to yield diurnal flux, Tlf_i (mm day^{-1}).

Even though several precautions were taken to ensure accurate data, some diurnal Tlf_i data appeared faulty. Conventional statistical tests to identify outliers were insensitive to

aberrant data (Snedecor & Cochran, 1980; Dixon, 1986), so the method of Workman & Mark (1992) was adopted. It requires curve fitting with and without the suspect datum and calculating an F -statistic for each fit according to:

$$F = \frac{r^2(n-1)}{(1-r^2)} \quad (\text{Eqn 4})$$

where n is the number of data points and r is the correlation coefficient. If the decrease in F after removal of the suspect point is more than offset by the increase in overall fit, the datum is considered an outlier. To increase the rigor of the test, F was required to increase by more than 2X to declare a suspect point an outlier. Outliers were identified for diurnal Tlf_i from each sampled individual shrub and not the deviation from the pooled Tlf_i data. The fraction of the data removed by this procedure was small: *Atriplex*, 8%; *Chrysothamnus*, 6%; and *Sarcobatus*, 6%.

LAI_i determination

Leaf area index ($\text{m}^2 \text{m}^{-2}$) was determined using the point quadrat method (Goodall, 1952) at approximately monthly intervals during the summer. A grid was established over each shrub to determine pin locations and to define the shrub perimeter. Total pin contacts with transpiring vegetation were converted to leaf area using regression equations developed during a related experiment where leaf area of harvested shrubs was measured independently (Groeneveld, 1997). Leaf area index for *Chrysothamnus* included leaves and green stems.

The porometer and LAI measurements were conducted on individual shrubs with the interspaces cleared of vegetation. In this experimental design, multiplying LAI_i and Tlf_i yields water transpired from the canopy area, not for the land area supplying water to the shrub; thus, the resulting K_c (Eqn 2) would not be truly one-dimensional. Additionally, leaf area and porometer measurements rarely occurred on the same day. It was necessary, therefore to prepare a model of daily LAI to interpolate LAI between measurements, to match Tlf_i measurement dates, and to maintain one-dimensional measurements. Fortunately, the K_c only requires the shape of the LAI model that shows how the species add and lose leaves through the growing season. In the intended application, this K_c will be applied to sites with variable LAI, and the absolute magnitude of K_c will be scaled depending on leaf area measured at a particular site. Treating LAI separately in the K_c also allows utilization of LAI measurements collected specifically to account for variable leaf area spatially and between growing seasons (Wright, 1982).

Leaf area index data from individual specimens were fit to a Gaussian model by nonlinear regression. This model was chosen over similar models based on slightly higher r^2 in several test cases. The mean curve for each species was determined by calculating the means of the fitted parameters, and for convenience, the mean curve was normalized to a maximum value of 1.0. Uncertainty in the mean LAI curve was determined from the deviation of the scaled data points from the mean curve within several time periods. The standard deviation for the growing season period usually was 20–25% for each species (Fig. 1).

The relatively small datasets for each species and the similarity among parameters suggested that it may be advantageous to determine if a single mean LAI curve was appropriate for all species. Univariate analysis of variance (ANOVA) was used to detect differences between species parameter means. Parameter distribution, parameter variance stability, and correlation among parameters were examined to test assumptions necessary to perform ANOVA. For all analyses, the statistical significance criterion was $p \leq 0.05$.

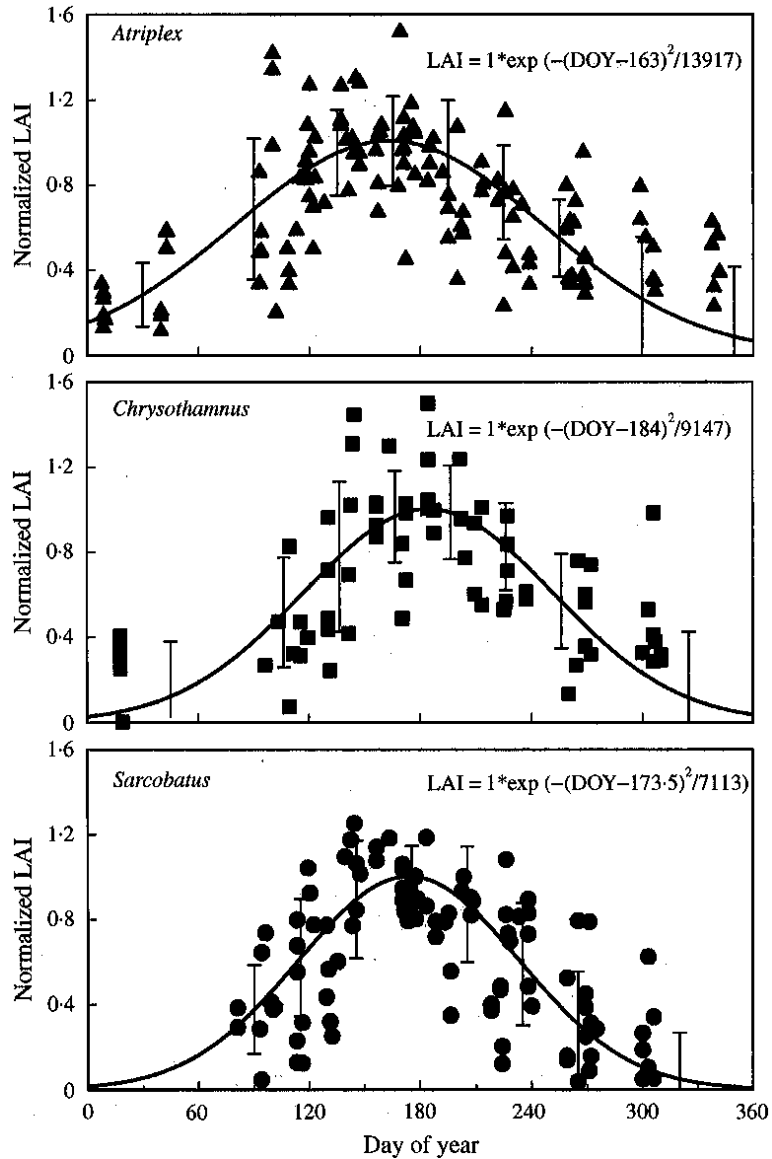


Figure 1. Mean LAI curves and S.D. about the mean curve for the three shrub species. For graphing purposes, the points shown have been normalized by dividing each datum by the maximum of its individual fitted curve. Each error bar is centered within the block of time it represents.

ET_r determination

ET_r estimates (grass reference crop) were obtained from the California Irrigation Management Information System (CIMIS). CIMIS maintains a monitoring station in the Owens Valley to provide daily *ET_r* and other climatic data to local irrigators. *ET_r* estimates are determined using a modified Penman equation (Pruitt & Doorenbos, 1977). In order to derive predictions of transpiration using Eqn 1, it is necessary to forecast likely *ET_r*; therefore, mean daily *ET_r* was derived by fitting a Fourier series model to *ET_r* measured during a 10-year period (Or & Groeneveld, 1994).

Results and discussion

Screened Tf_i data (outliers removed) are presented in Fig. 2. Despite the scatter, a clear seasonal trend is evident. The relative order of measured Tf was *Chrysothamnus* > *Sarcobatus* > *Atriplex*. Leaf area index curve fitting results are given in Table 1 and Fig. 1. The large CV for the c-parameter (peak width) was due partly to small model dependence when c is greater than about 7000. Both parameters were normally distributed and independent for all species. Mean and variance of parameter-c, were significantly correlated, however. Thus, the data were log-transformed to stabilize the variance before ANOVA was performed.

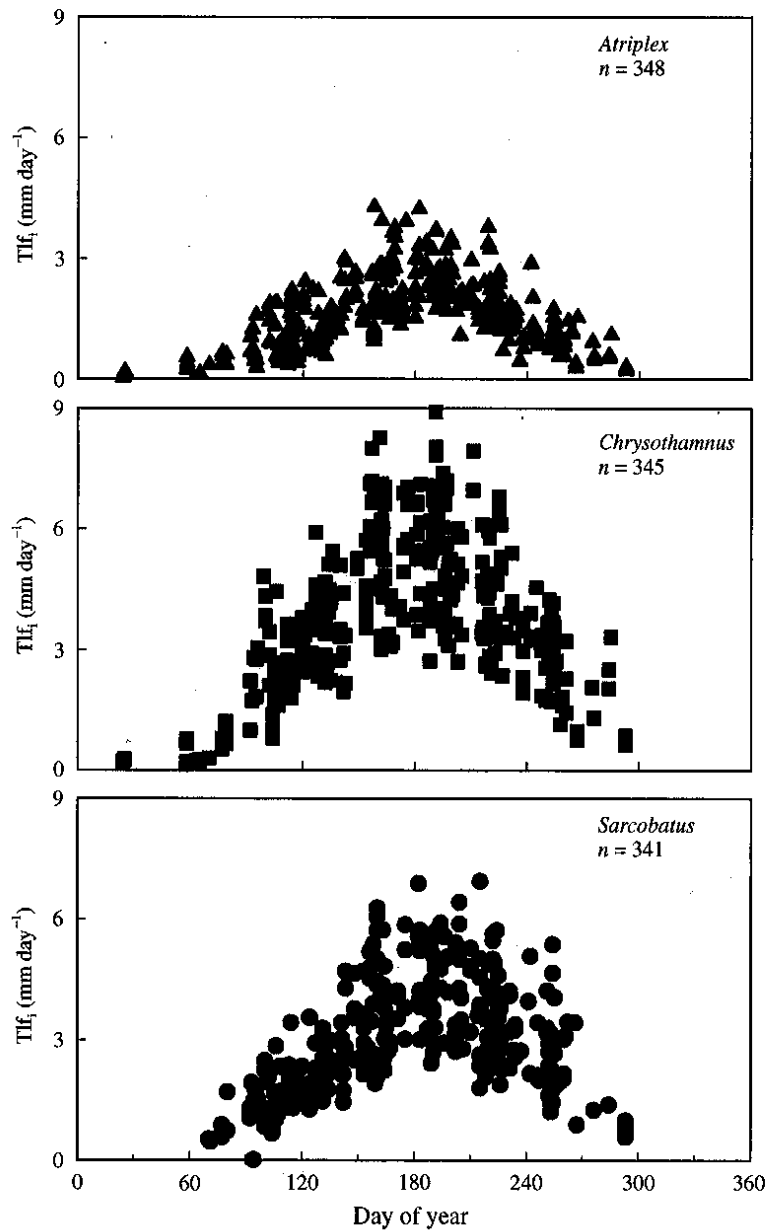


Figure 2. Screened Tf_i data for the three shrub species (n = number of data points).

Table 1. Leaf area index mean curve fitting parameters

Species	Parameter	<i>n</i>	Mean	S.D.	C.V.
<i>Atriplex</i>	b (peak DOY)	18	163.2	30.7	0.19
	c (width)		13916.5	6701.7	0.48
	ln(c)		9.37	0.71	0.08
<i>Chrysothamnus</i>	b (peak DOY)	10	184.0	14.5	0.08
	c (width)		9147.1	4942.2	0.54
	ln(c)		8.97	0.60	0.07
<i>Sarcobatus</i>	b (peak DOY)	18	173.5	17.2	0.10
	c (width)		7113.0	1983.3	0.28
	ln(c)		8.77	0.48	0.05

Univariate ANOVA results for each parameter with species as the main effect were statistically significant. To investigate further, a multiple pairwise comparison of means was performed. The Tukey HSD test with automatic compensation for unequal replication (Wilkinson, 1990) was conducted for each parameter. Only the c-parameter for *Atriplex* and *Chrysothamnus* differed. Based on these results, it is reasonable to group LAI curves for *Chrysothamnus* and *Sarcobatus*, and possibly *Atriplex*.

The relationship between cover and LAI for the three species is shown in Fig. 3. The two indices were highly correlated, and as expected, the intercept was not significant ($p > 0.05$). These results allow conversion of cover measurements using the line-point method into LAI for use in the Kc.

The Kc_i data and fitted curves are presented in Fig. 4. Generally, correlation coefficients of the fitted curves were acceptable. Because mean parameters were used to calculate LAI_j , the Kc correlation coefficient does not account for parameter uncertainty in the LAI curves. Using ETr data from a single station did not result in an obvious disparity in Kc between sites in the northern and southern portions of the valley.

The primary goal of the study was to develop a method to estimate transpiration using simple vegetation measurements. To estimate transpiration using the Kc requires a measure of maximum LAI or cover, Kc_j , and mean ETr_i (Eqn 5).

$$Ta = \sum_{j=1}^n \sum_{i=85}^{289} Kc_{ij} \times \overline{ETr}_i \times LAI_{jmax} \quad (\text{Eqn 5})$$

where ETr_i is mean reference ET for day i (Or & Groeneveld, 1994), n is number of species, and LAI_{jmax} is mid-summer LAI for species j . In Eqn 5, Ta is a linear function of maximum LAI or cover for the growing season (approximately at the summer solstice). Without additional data coupling stomatal conductance to canopy ET for these species, the scaling in Eqn 5 necessarily ignores the effect of canopy microclimate on stomatal conductance as LAI increases. The linear scaling method presented here should be applied cautiously at sites with high cover to avoid violating assumptions of negligible boundary layer and canopy resistance to water flux.

Preparation of the Kc and mean ETr models required several steps that introduce uncertainty in the final Ta estimates. Analytically propagating the uncertainty through all steps is difficult and cumbersome, and it may not be appropriate given its magnitude (Mandel, 1964). For this study, assessment of uncertainty in Ta determined from Eqn 5 was performed using the bootstrap method of Monte Carlo (MC) simulation (Press *et al.*, 1992). This method is particularly suited to small datasets because the

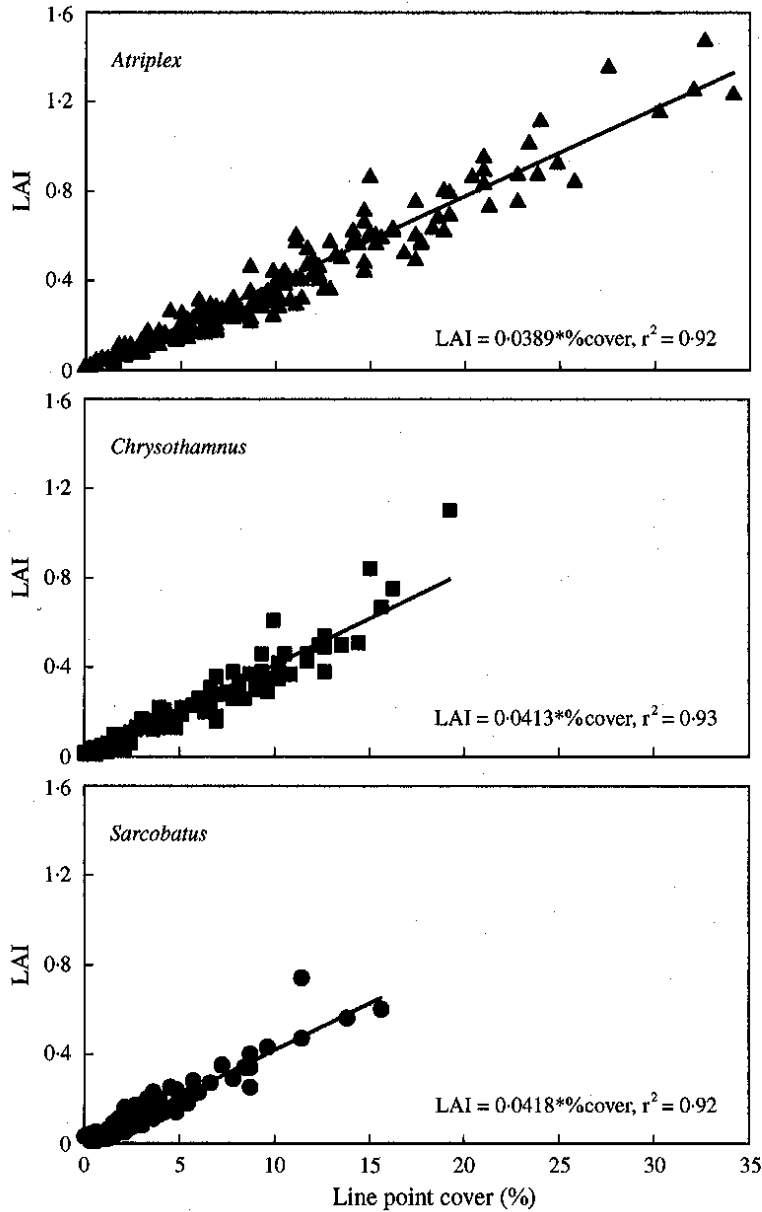


Figure 3. LAI vs. percent cover data and linear regression results for the three shrub species.

raw data or residuals are treated as a discrete population distribution from which samples are drawn with replacement. The bootstrap method, therefore, makes no assumptions about the distribution of the sampled population. Multiple simulations (> 2500) of independent daily Ta for each species were generated and then summed to obtain growing season Ta . For each simulation, samples drawn from the population of residuals about the fitted models were added to Kc_i and mean ETp_i . It was evident that the magnitude of the residuals varies as a function of Kc and mean ETr (Fig. 4). To accommodate heteroscedasticity of the residuals, samples were drawn from discrete time frames (3 or 4) selected to enclose segments with a visually similar spread of data points about the model. LAI_{max} was considered free from error, but MC simulations

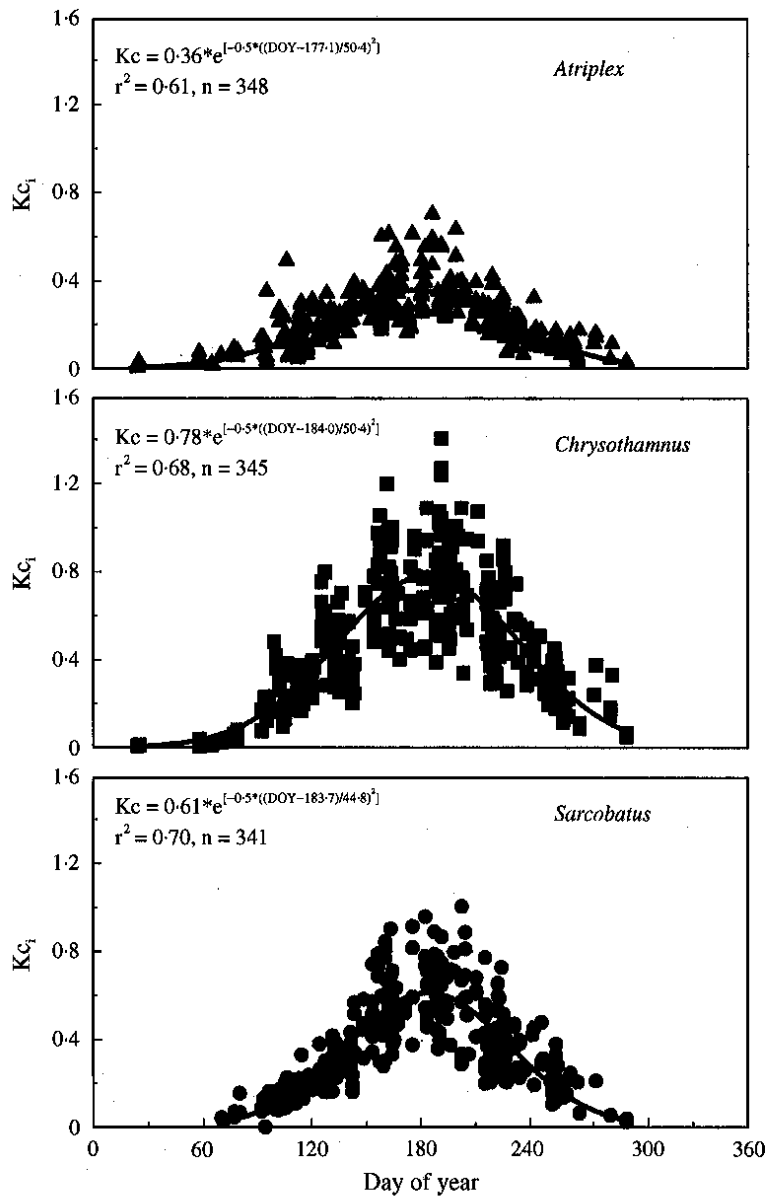


Figure 4. K_{c_i} and fitted curves for the three shrub species.

were carried out for several values to investigate the dependence of T_a uncertainty on LAI_{max} .

The uncertainty in growing season T_a was acceptable for our application (Fig. 5), and even though daily variation about the K_c and mean ET_r models can be important, the seasonal total is not sensitive. This evaluation, however, primarily accounts for variability between shrubs, sites, and years. It does not explicitly include uncertainty from the LAI model, the LAI_{max} or cover measurement, or from the calculation of diurnal T_f . Also, the K_c and mean ET_r model coefficients are assumed without error. As such, the error bars presented in Fig. 5 underestimate actual uncertainty, but these results account for several large and important sources. The size of the 90% confidence interval about the growing season T_a (mm) increased linearly with increasing LAI_{max} (Fig. 5).

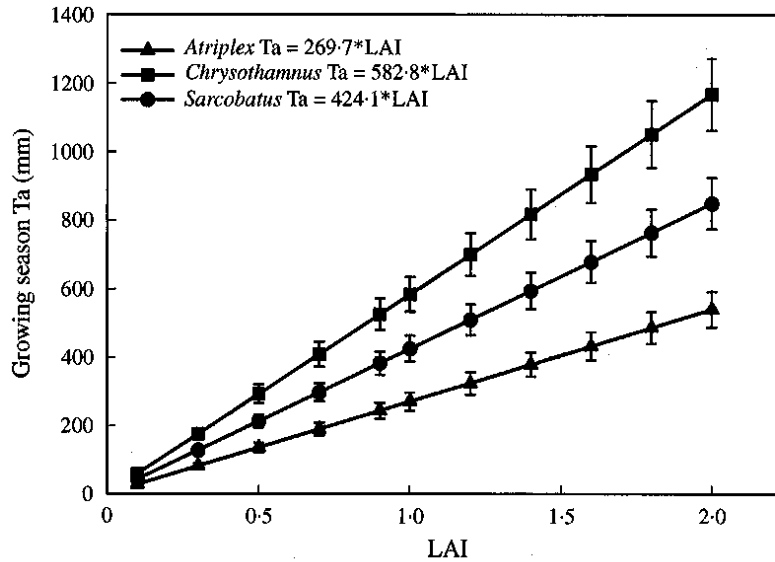


Figure 5. Growing season transpiration by species for several values of LAI. Error bars represent 90% of the Monte Carlo simulation results.

As noted earlier, scaling from measurements on small leaf samples to larger scales presents several difficulties, and these results should be applied cautiously until substantiated by independent measures of ET. Unfortunately, no published study on these species has collected concurrent LAI or cover data and independent ET measures to test the accuracy of this Kc method. Steinwand *et al.* (1996) estimated transpiration from frequent LAI and porometer sampling (Table 2) at sites located within homogeneous stands of *Atriplex* in the Owens Valley. Measured values of Tlf_i were similar to the data used to prepare the Kc, and measured growing season Ta (calculated according to $\sum Tlf_i * LAI_i$) agreed well with Ta estimates from the Kc model (Eqn 5). The comparison is not conclusive because questions raised by scaling up porometer measurements remain, but since Tlf_i was similar to measurements reported here, the good agreement suggests the mean ETr and LAI curves were adequate to forecast Ta of *Atriplex*. In the Owens Valley, we routinely use Eqn 5 to estimate transpiration for the growing season. Estimates typically range between 290–820 mm, which compares well with the range of values measured by Duell (1990) at sites with similar species, cover, and water table depths (230–770 mm) in the Owens Valley. The Kc model results also compare well with transpiration estimates from a near playa environment in Utah with similar species

Table 2. Comparison of *Atriplex* growing season transpiration (Ta) measured in the Owens Valley (Steinwand *et al.*, 1996) and Kc-estimated transpiration using the maximum measured LAI and Eqn 5

Site/Year	Ta, measured	Ta, Kc estimate
	(mm)	(mm)
IC1, 1996	322	351
IC1, 1997	287	284
SS4, 1996	427	493
SS4, 1997	412	367

(640 mm) (Malek *et al.*, 1990). We have recently initiated a study to collect concurrent vegetation and micrometeorological data to test the transpiration coefficients further.

Conclusions

Transpiration coefficients for three common phreatophytic shrub species in the Owens Valley of California were developed that potentially offer efficient estimation of transpiration from desert phreatophyte shrubs. An extensive database of stomatal conductance and LAI collected over several years at sites located many kilometers apart were pooled to develop generalized coefficients. To reduce site-specificity, these coefficients ignore soil evaporation and incorporate leaf area as a separate variable. The method requires only simple measurements of vegetation cover, and thus, transpiration estimates can be derived quickly and inexpensively. Also, for areas dominated by these species, the method can account for spatial and temporal variability of cover and composition allowing development of areal transpiration estimates as opposed to point estimates commonly derived with more sophisticated methods. That capability could assist the development of ground-water models in areas where spatial estimates of ET are required, but actual measurements are scarce. Generally, transpiration estimates based on the coefficients developed here occur within the range of values determined for similar plant communities, but collection of independent measures of ET are needed to corroborate estimates based on Kc. Because the Kc was developed with data from well-watered plants, transpiration estimates represent an upper limit and do not consider that these species will limit leaf area and stomatal conductance when stressed. Monte Carlo simulation of uncertainty in the growing season *Ta* estimates suggest that the effect of data variability between shrubs, sites, and years was acceptable for our applications.

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