



## Seasonal estimates of actual evapo-transpiration from *Tamarix ramosissima* stands using three-dimensional eddy covariance

James R. Cleverly<sup>★\*</sup>, Clifford N. Dahm<sup>★</sup>, James R. Thibault<sup>★</sup>,  
David J. Gilroy<sup>★</sup> & Julie E. Allred Coonrod<sup>†</sup>

<sup>★</sup> *Department of Biology, University of New Mexico, Albuquerque, NM 87131-1091, U.S.A.*

<sup>†</sup> *Department of Civil Engineering, University of New Mexico, Albuquerque, NM 87131-1351, U.S.A.*

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This study addresses the pattern of evapo-transpiration (ET) throughout the growing season for *Tamarix ramosissima* between regularly flooded and unflooded sites. Spatial and temporal ET patterns along the Middle Rio Grande demonstrated considerable variability. ET at the unflooded site was 61% of ET at the flooded site, totaling 74 and 122 cm year<sup>-1</sup> at the unflooded and flooded sites, respectively. The seasonal coefficient of variability was 37% and 38% at the flooded and unflooded sites, respectively. Spatial variability was 39%. Determining ET patterns with respect to the spatial, ecological and temporal setting improves riparian zone ET depletion predictions.

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### Introduction

Riparian areas are prominent features within arid and semi-arid landscapes. They provide important economic, recreational and natural resources in disproportion to their limited spatial extent. Riparian water resources in the south-western U.S. are in great demand for use in agriculture, urban development and ecosystem services (Jackson *et al.*, 2001). Such conflicts of interests are especially acute during La Niña years, when water resources are commonly scarce (Molles & Dahm, 1990). Along the Middle Rio Grande, equitable assignment of water to competing groups and ecosystems has been hampered by the elusiveness of an accurate water budget. One of the main components lacking good quantification in the Middle Rio Grande water budget is evapo-transpiration (ET) from the riparian forest, or bosque as it is known in New Mexico.

\*Corresponding author. Fax: +1 505-277-5355. E-mail: [cleverly@sevilleta.unm.edu](mailto:cleverly@sevilleta.unm.edu)

Presently, ET estimates used in water budgets of the Middle Rio Grande bosque are based upon the modified Blaney–Criddle crop coefficient model (*cf.* Hansen & Gorbach, 1997):

$$u = \sum_{i=1}^{12} k \frac{\bar{T}_i}{\bar{p}_i} \quad (\text{Eqn 1})$$

where  $u$  is the consumptive water use,  $i$  the month of the year,  $k$  the empirical crop coefficient,  $\bar{T}$  the mean monthly temperature, and  $\bar{p}$  the mean monthly proportion of daylight hours (Jensen *et al.*, 1990). Semi-empirical methods like the Blaney–Criddle model perform well over uniform vegetation like crops, but spatial, inter-annual and even seasonal variability is often poorly represented in monthly temperature and crop coefficient estimates, assuming of course that temperature controls ET in such a simple manner. Further limitations on such models are related to the applicability of crop coefficient data sources. For example, Hansen & Gorbach (1997) applied a model to the Middle Rio Grande bosque for *Populus deltoides* subsp. *wisizenii* (S. Wats.) Eckenw. in which the crop coefficient was determined from a 3-year-old, well-watered *P. fremontii* S. Watson plantation. It is currently unknown whether crop coefficients developed from juveniles provide an accurate estimate of ET above mature stands that are exposed to seasonal cycles of flooding and drought. Such variability likely limits the accuracy and utility of crop coefficient-based ET estimates.

Determining sources of spatial and temporal variabilities in bosque ET will contribute to a more accurate quantification of actual ET. Many ecosystem characteristics vary in both time and space, thereby contributing to both spatial and temporal variability in ET. For example, the occurrence of flooding varies both spatially, peaking where the impact of anthropomorphic channelization and flow regulation is minimal, and temporally, peaking during spring snowmelt and immediately following strong monsoon precipitation in July and August. Likewise, leaf area index (LAI) is a measure of the evaporative surface area at a site that varies spatially with species composition and plant density and varies temporally with the phenology of the species occurring at a given site.

Historically, spring flooding along the Rio Grande was common in response to snow melt (Slack *et al.*, 1993). Recent diminishment of these floods has reduced decomposition (Molles *et al.*, 1995) and historic ecosystem function (Bayley, 1995; Molles *et al.*, 1998). Hydrologic modification, furthermore, directly impacts the physiology, growth and survivorship of native species and creates an opportunity for invasion by exotic species (Smith *et al.*, 1991; Auble *et al.*, 1994).

In the western U.S., the dominating presence of the exotic species *Tamarix ramosissima* Ledeb. (saltcedar) and *Elaeagnus angustifolia* L. (Russian olive) impacts the magnitude of ET in the water budget (Molles *et al.*, 1998). It has been sometimes presumed that *T. ramosissima* transpires more than co-occurring native species, although there is a paucity of direct comparisons between *T. ramosissima* and *P. deltoides*, especially at the stand-level. While some have begun to question the conventional wisdom that *T. ramosissima* is a spendthrift water consumer (Anderson, 1998), comparisons between *T. ramosissima* and other members of the Salicaceae (*P. fremontii* subsp. *fremontii*, *Salix gooddingii*, and *S. exigua*) demonstrate that *T. ramosissima* probably does transpire more than less stress-tolerant cottonwoods and willows (Busch & Smith, 1995; Cleverly *et al.*, 1997; Schaeffer *et al.*, 2000).

The objectives of this research in the Middle Rio Grande bosque are (1) to determine the spatial and temporal patterns of actual evapo-transpiration (AET) rates and (2) to characterize and explain spatial and temporal variabilities in *T. ramosissima* ET. We hypothesized that ET would vary more across a season than between locations along the river. We further predicted that *T. ramosissima* at a flooded site would exhibit a greater stand-level ET than at an unflooded site. A growing season estimate of ET

during 1999, along with the variability and error associated with the estimation of ET, has been developed from initial ET measurements at two sites along the Middle Rio Grande. These data for the growing season of 1999 are compared to previously published ET values originating from studies of varying duration at the leaf, canopy and stand-level for *T. ramosissima*.

### Methods and materials

The location for this research is the Middle Rio Grande in New Mexico, U.S.A. where dominant woody species are *T. ramosissima* and *P. deltoides*. *Tamarix ramosissima* is a weedy invasive species (Christensen, 1962; Robinson, 1965; Brock, 1994) that can form monospecific stands where it has successfully invaded. *Populus deltoides* is the dominant native woody species along the Middle Rio Grande where it forms an imposing canopy > 25 m tall in some locations.

Growing season data were collected from two *T. ramosissima* stands along the Middle Rio Grande (Fig. 1). One of these sites is located on the Sevilleta National Wildlife Refuge (NWR) outside of San Acacia, NM and upstream of San Acacia diversion dam (34°16'N, 106°52'W, 1430 m elev.). The Sevilleta NWR site does not undergo annual flooding and supports a relatively low LAI ( $\approx 2.5$ ; Dahm *et al.*, 2002). The community contains a mixture of *T. ramosissima*, *Distichlis spicata* (L.) Greene, *Atriplex* L. spp, *Salix exigua* Nutt., and *Prosopis pubescens* Benth., but *T. ramosissima* and *D. spicata* dominate this site. The other site, located at the Bosque del Apache NWR (33°47'N, 106°53'W, 1375 m elev.), was flooded during the spring and summer of 1999, and a monospecific *T. ramosissima* stand supports a relatively high LAI ( $\approx 3.5$ ; Dahm *et al.*, 2002). At each site, a three-dimensional eddy covariance system (Campbell Scientific, Inc., Logan, UT) was mounted to a tower 2.5 m above the canopy. At both sites, the forested distance upwind in any direction was > 300 m, exceeding the fetch for these tower heights under even extremely stable conditions. The primary system consisted of a CSAT3 three-dimensional sonic anemometer and a KH20 krypton hygrometer.

The eddy covariance system was oriented toward the south to take advantage of the predominant wind direction along the relatively uniform riparian corridor, thereby reducing data loss due to winds from behind the tower and anemometer block. The three-dimensional sonic anemometer measures wind speed in three dimensions 10 times  $s^{-1}$ . Likewise, the Krypton hygrometer measures vapor pressure at a frequency of 10 Hz. The covariance between the vertical wind speed and vapor pressure are computed every 30 min, and the latent heat flux (LE;  $W m^{-2}$ ) is computed as

$$LE = \lambda_v \overline{w'e'} \quad (\text{Eqn 2})$$

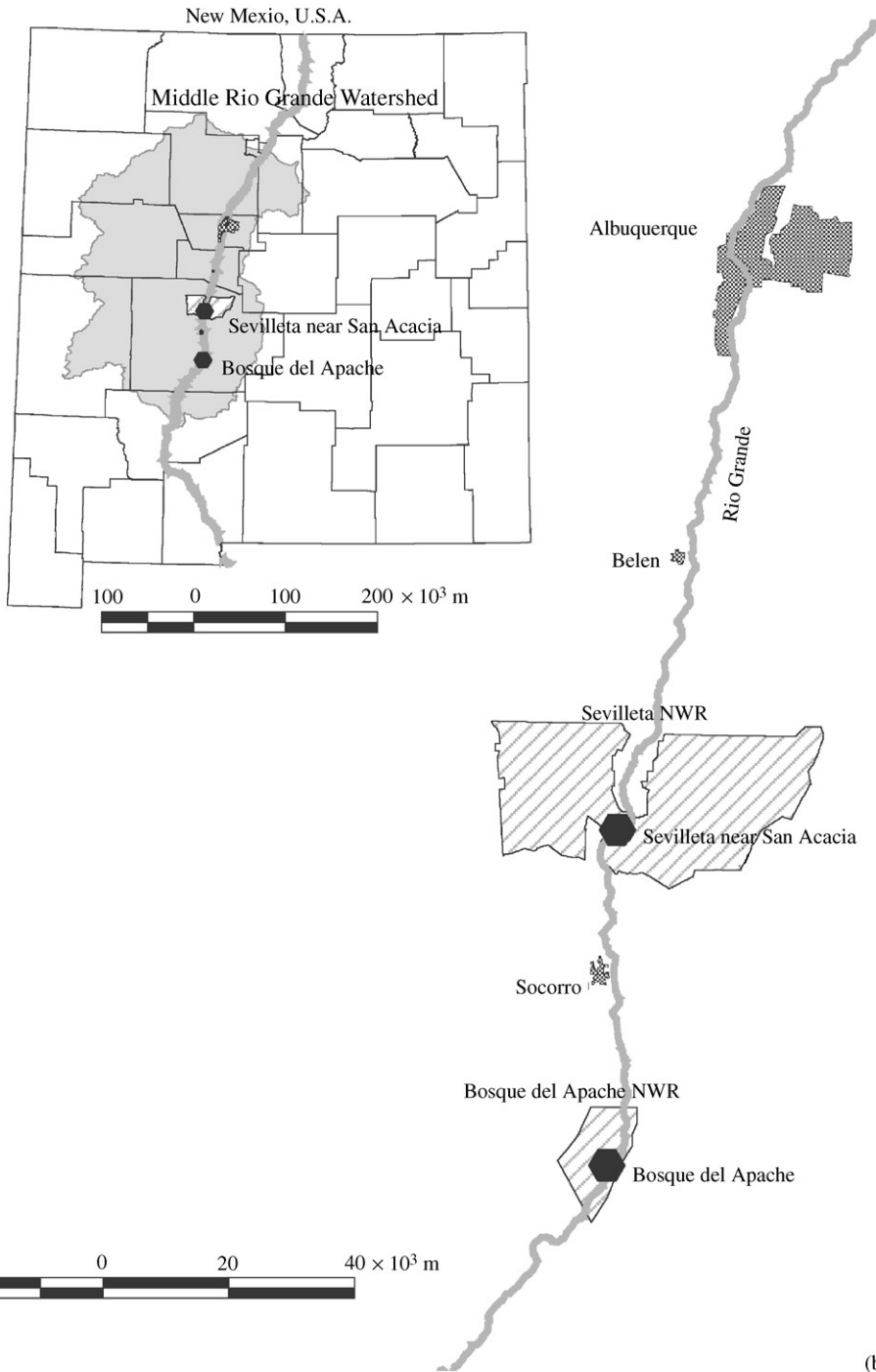
where  $\lambda_v$  (2441  $kJ kg^{-1}$ ) is the latent heat of vaporization for water and  $\overline{w'e'}$  is the 30-min covariance between the instantaneous deviation in vertical wind speed from the average vertical wind speed ( $w'$ ;  $\overline{w} = 0 m s^{-1}$ ) and the instantaneous deviation in water vapor pressure ( $e'$ ). Sensible heat flux ( $H$ ;  $W m^{-2}$ ) was computed as

$$H = \rho_a C_p \overline{w'T'} \quad (\text{Eqn 3})$$

where  $\rho_a$  ( $kg m^{-3}$ ) is the density of air,  $C_p$  is the specific heat of air ( $J g^{-1} \circ C^{-1}$ ) and  $T'$  is the instantaneous deviation in temperature. Temperature was measured throughout the growing season by the sonic anemometer (i.e. the virtual temperature) and part of the growing season by a very fragile FW05 fine wire thermocouple (0.0127 mm diameter type E chromel-constantan).

As well as daily eddy covariance measurements above the canopy, temperature and relative humidity (RH) were monitored using an HMP45C temperature and RH

(a)



(b)

**Figure 1.** Locations of three-dimensional eddy covariance towers along the Rio Grande, New Mexico. (A) The Rio Grande in New Mexico, U.S.A., and the limits of the Middle Rio Grande watershed. The northern boundary of the Middle Rio Grande is located at Otowi Bridge, north of Cochiti Reservoir. The southern boundary is Elephant Butte Reservoir. (B) Tower locations along the Middle Rio Grande. The two *Tamarix ramosissima*-dominated sites are at the Sevilleta NWR and the Bosque del Apache NWR.

probe at the top of the canopy: 5.7 m at the *T. ramosissima* flooded site and 4.2 m at the *T. ramosissima* unflooded site. Net radiation ( $R_n$ ;  $\text{W m}^{-2}$ ) was measured well above the CSAT3 using vented and cross-calibrated Q7.1 net radiometers (Kustas *et al.*, 1998) and soil heat flux ( $G$ ;  $\text{W m}^{-2}$ ) was measured 8 cm below the soil surface using two HFT-3 soil heat flux plates at each site. All of the data were logged every 30 min using a CR23X. As with the eddy covariance system, all of the components were manufactured or re-marketed by Campbell Scientific, Inc. (Logan, UT). Sites were visited weekly to semiweekly to remove scale from sensors, check and replace desiccants, observe the state of the vegetation, and download data.

Closure of the energy balance was calculated as

$$R_n = LE + G + H + \text{closure} \quad (\text{Eqn 4})$$

Positive closure values are added to  $H$  and  $LE$  using the measured Bowen Ratio ( $\beta = H/LE$ ), thereby balancing the incoming and outgoing energy when  $R_n$  exceeds  $LE + G + H$ . This closure calibration has been adopted because total closure error tends to exceed errors in measuring net radiation (Twine *et al.*, 2000). ET ( $\text{mm day}^{-1}$ ) from each tower was computed every 30 min as

$$ET = \frac{LE}{\lambda_v \rho_w} \quad (\text{Eqn 5})$$

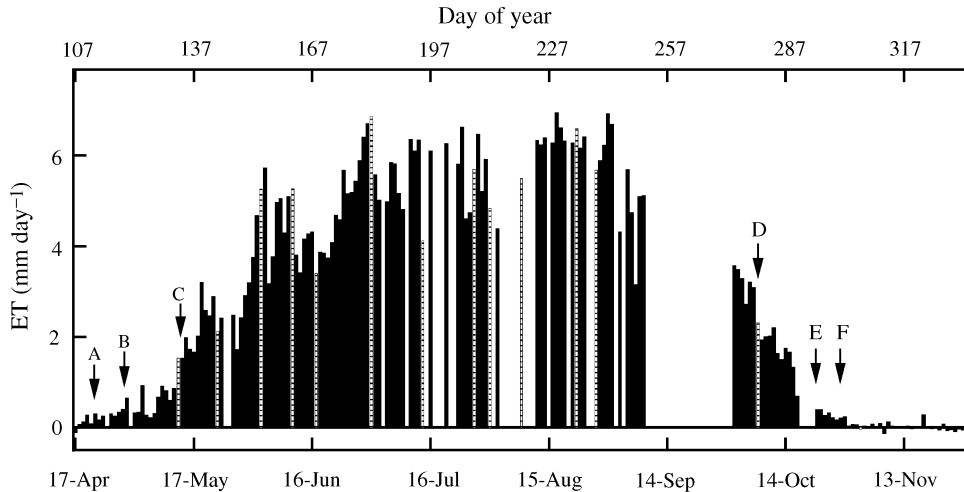
where  $\rho_w$  ( $997 \text{ kg m}^{-3}$  at  $25^\circ\text{C}$ ) is the density of water. On days in which all 30 min values were present, daily ET was computed as the sum of daytime (i.e. when  $R_n > 0$ ) 30 min ET values. On days when 1–4 of the 30 min values were missing, a general linear regression model between  $LE$  and  $R_n$  (Statistical Analysis Software, SAS Institute, Inc., Cary, NC) was used to estimate the missing data whenever the regression coefficient was significantly different from 0 (i.e.  $p > 0.05$ ). ET was not determined on days that did not match the above criteria. All daily means (e.g. mean daytime RH) and totals (e.g. daily total ET) were smoothed with a 5-day moving average to identify dynamic trends from random variability throughout the growing season. Comparisons of the ET and RH time series was performed using power spectral and coherence analyses (SAS, SAS Institute, Inc., Cary, NC) on the autocorrelation functions. Annual total ET was determined from the integration of the seasonal ET amounts (Fig. 2) after estimating the missing data using the regression between ET at the two sites (Fig. 5). When both sites were missing data on the same day, linear interpolation was used to fill missing days.

Seasonal and spatial variabilities were determined from the data between ET onset and cessation dates, inclusively. Seasonal ET variability was determined using the coefficient of variation (Statistical Analysis Software, SAS Institute, Inc., Cary, NC). Spatial ET variability between these sites was computed as  $1 - m$ , where  $m$  is the slope of the regression shown in Fig. 5; a 1:1 relationship (i.e.  $m = 1$ ) indicates, on average, 100% similarity between sites, and lack of a significant relationship (i.e.  $m = 0$ ), indicates 100% variability between sites.

Further ET data for *T. ramosissima* were compiled from the literature to obtain an *a priori* ET estimate in a variety of environmental conditions. Wherever possible, ET measurements in each paper were converted to common units for comparability between studies. The published ET values for *T. ramosissima* were distinguished by their levels (i.e. leaf, canopy or stand) and methodology (e.g. sap flux or Bowen Ratio).

## Results

The date of ET onset (i.e. the date when  $ET > 1.0 \text{ mm day}^{-1}$ ) occurred on 13 May at both the *T. ramosissima*-dominated unflooded (Fig. 2) and flooded (data not shown)



**Figure 2.** Daily ET at a *Tamarix ramosissima* dominated unflooded site. Filled bars represent measured ET values. Striped bars represent estimated ET using a general linear regression between  $R_n$  and LE, and missing bars represent days when ET could not be estimated. Approximate phenological events, based upon weekly or semiweekly observations, are indicated by the arrows, at which A = greening starts, B = canopy 50% greening, C = canopy fully green, D = senescence beginning, E = 50% senescent, and F = 100% senescent. Measured (■), partial GLM estimate ( $LE = xR_n + y$ , determined daily) (▨).

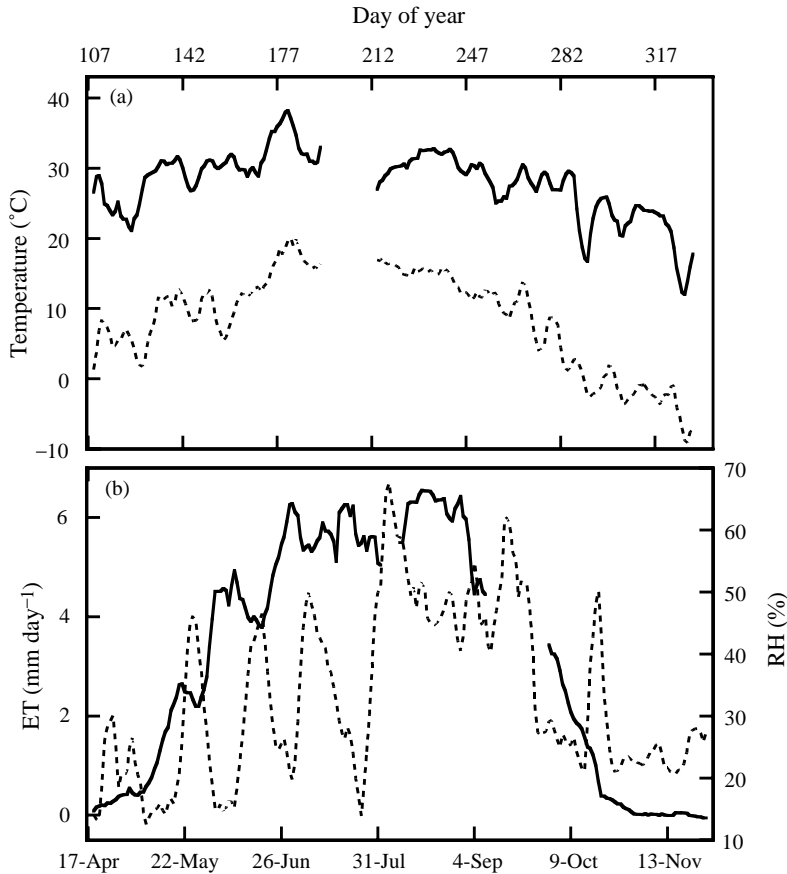
sites during 1999 along the Middle Rio Grande. Likewise, cessation of ET occurred simultaneously on 16 October 1999 at the *T. ramosissima* unflooded (Fig. 2) and flooded sites. These dates coincided with the start of springtime leaf development and the completion of autumnal senescence (Fig. 2). Between those dates, average daily ET rates were  $5.4 \pm 0.2$  and  $3.4 \pm 0.2$  mm day<sup>-1</sup> at the flooded and unflooded sites, respectively. The corresponding maximal ET rates at the flooded and unflooded sites were 9.8 and 6.9 mm day<sup>-1</sup>, respectively. The total ET from the *T. ramosissima* unflooded site during this 157-day growing period was 74 cm and was 122 cm at the *T. ramosissima* flooded site.

The coefficient of variation in seasonal ET was  $37 \pm 4\%$  (0.9–6.9 mm day<sup>-1</sup>; Figs 2 & 3) at the unflooded site and  $38 \pm 3\%$  (1.3–9.8 mm day<sup>-1</sup>; data not shown) at the flooded site. Daily maximum and minimum canopy temperatures also varied across the growing season (Fig. 3(A)) with an inconsistent relationship to variation in ET. During the growing season, but not before or after, daily average RH varied out of phase with growing season ET: ET increased when RH decreased and ET decreased when RH increased ( $f_{m_{ET}} = f_{m_{RH}} = 0.46$   $\mu\text{Hz}$  (25-day period),  $K = 0.02$ ; Fig. 3(B)). The same relationship was observed between ET and specific humidity ( $q$ ; g m<sup>-3</sup>; data not shown).

Mean daytime  $R_n$  also fluctuated in synchrony with LE (Fig. 4). Mean daytime LE and  $H$  were inversely related throughout the growing season, wherein  $H$  declined when LE increased. Mean daytime  $G$  was very minor throughout the year, and mean daytime closure varied between 0 and 150 W m<sup>-2</sup>. These closure values are equivalent to 1 and 0.60, respectively, using the Prueger *et al.* (1996) fraction of the energy balance due to closure calculation:

$$\text{frac}_{\text{closure}} = \frac{LE + H}{R_n + G} \quad (\text{Eqn 6})$$

Closure was highest during July and August, corresponding to the monsoon period in Central New Mexico.

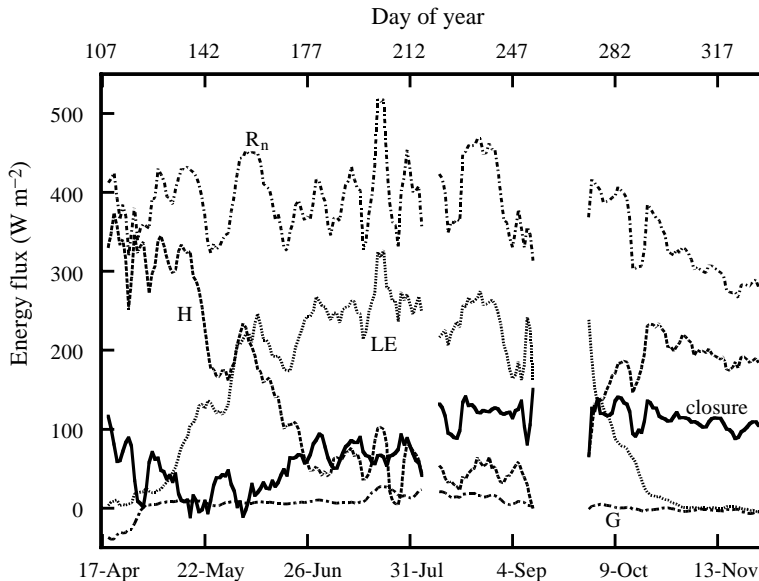


**Figure 3.** Daily maximal temperature ( $T_{\max}$ ; A; —), minimal temperature ( $T_{\min}$ ; A; ·····), evapo-transpiration (ET; B; —), and average relative humidity (RH; B; ·····) at the *Tamarix ramosissima* unflooded site. Temperature and RH were measured at the top of the canopy. Minimum and maximum temperatures were determined daily, as was total ET. Average RH was calculated from the daytime (i.e.  $R_n > 0$ ) values only. In both A and B, the values shown are 5-day running means.

Throughout the growing season, ET at the *T. ramosissima* flooded site consistently exceeded ET at the unflooded site. Average growing season ET at the unflooded site was 61% of the ET at the flooded site (Fig. 5), and spatial variability was estimated at  $39 \pm 3\%$ . The shape of the ET trend was the same at both sites, varying in the same manner across the growing season. This relationship was strongest when  $ET < 5 \text{ mm day}^{-1}$ ; the residuals increased above  $5 \text{ mm day}^{-1}$  indicating a greater likelihood that ET at the Sevilleta NWR unflooded site was more or less than 61% of the ET at the Bosque del Apache NWR flooded site (Fig. 5). The  $y$ -intercept of this relationship ( $-0.02 \text{ mm day}^{-1}$ ; Fig. 5) was not significantly different from 0 ( $p = 0.85$ ).

## Discussion

Annual ET at the unflooded site ranged from 0 in winter to a maximum ( $6.9 \text{ mm day}^{-1}$ ) in summer (Fig. 2). In addition to LE,  $H$  and closure fluctuated throughout



**Figure 4.** Daily mean daytime ( $R_n > 0$ ) energy balance at the *T. ramosissima* unflooded site. Net radiation ( $R_n$ ; .....), ground heat flux ( $G$ ; - - - -), sensible heat flux ( $H$ ; - · - · - ·) and latent heat flux ( $LE$ ; - - - - -) were measured with the three-dimensional eddy covariance system. Closure (—) was computed as  $R_n - (G + H + LE)$ .

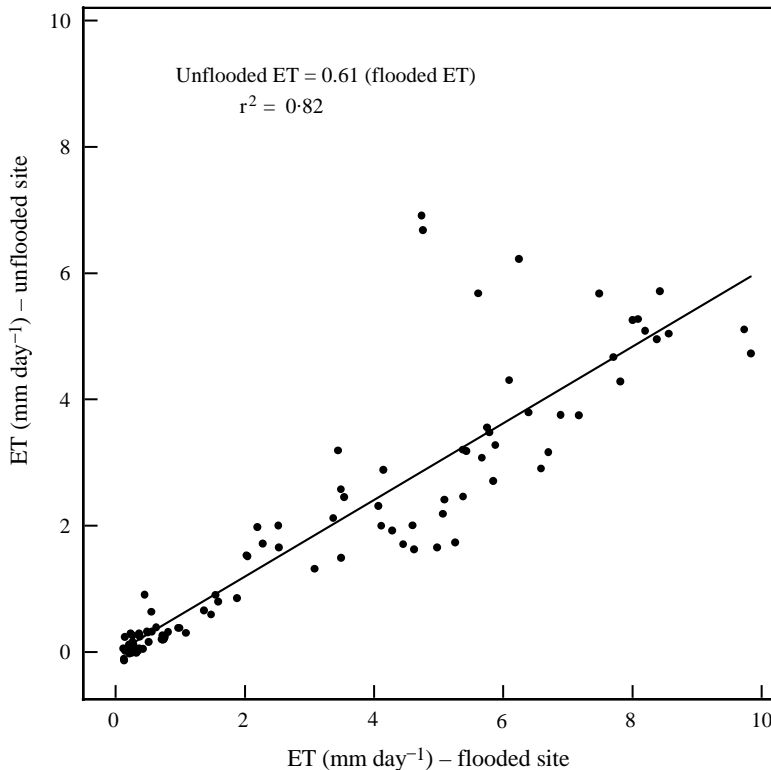
the year (Fig. 4), hence the measurement period can strongly influence ET estimates in *T. ramosissima* (Table 2). Short-term estimates of ET during different parts of the year complicate most of the comparisons that can be made in Table 1. Average growing season ET, along with the length of the season, are the most valuable data to report for facilitating ET comparisons between studies.

Previous studies have shown that ET in *T. ramosissima* is quite variable across numerous scales and conditions (see Table 1). ET was higher in some previous studies than in this study, ranging from 0 during the winter (Devitt *et al.*, 1998) or for severely stressed *T. ramosissima* (Devitt *et al.*, 1997a) to over  $20 \text{ mm day}^{-1}$  during the late summer (Sala *et al.*, 1996; Table 1). While few in number, studies performed over an entire growing season best illustrated the variability in ET as well as the consumptive water loss of which *T. ramosissima* is capable, and the published ET data from growing season studies were most easily compared to ET estimates in other studies (Table 2). Mean annual ET values tended to be lower in the full year study, averaging not only across the growing season but including the periods before and following plant water consumption (see Hansen & Gorbach (1997) in Table 1).

The seasonal coefficient of variation at the Sevilleta NWR unflooded site was 38% (Fig. 2). This level of variability, as well as the mean value, was medial to that in previous long-term studies (Table 1). Of the studies reported in Table 1 that were implemented over an entire season or longer (see Table 2), two reported a range in ET greater than that in Fig. 2 (Devitt *et al.*, 1997a, 1998) while the variability in the other two was considerably lower (Hansen & Gorbach, 1997; Xu *et al.*, 1998). Such large ranges in ET variability occur because ET in *T. ramosissima* is responsive to ambient environmental conditions (Fig. 3), and the very high ET values reported from the hot and dry Mojave Desert reflect a regional scale relationship between RH and ET in the south-western U.S.

The spatial variability in *T. ramosissima* ET from the unflooded to the flooded site was 39% along the Middle Rio Grande, very close to the 37% and 38% seasonal





**Figure 5.** Relationship between daily ET measured at *Tamarix ramosissima*-dominated flooded and unflooded sites. Line is least-squares regression ( $p < 0.0001$ ): Unflooded ET = 0.61 (flooded ET),  $r^2 = 0.82$ .

coefficients of variation. Flooding at Bosque del Apache NWR supports greater leaf area (Dahm *et al.*, 2002), allowing greater water loss to the atmosphere than at the unflooded Sevilleta NWR site (Fig. 5). Flooding typically influences the physiology of a stand of vegetation directly by regulating water relations of riparian plants (Smith *et al.*, 1991). Indirect influences of flooding on ET occur by the control of plant establishment (Van Auken & Bush, 1988; Molles *et al.*, 1998) and stand age structure (Scott *et al.*, 1997), dictating the type and amount of vegetation in the riparian corridor as well as nutrient availability through decomposition and related nutrient cycling (Molles *et al.*, 1995). While these mechanisms have been used to explain the decline of less stress-tolerant cottonwoods (*Populus* spp.) in the south-western U.S. (Busch & Smith, 1995), *T. ramosissima* stands are also more active under flooded conditions. Therefore, *T. ramosissima* is best described as a facultative stress-tolerant species (DiTomaso, 1998), able to dominate under both dry and wet conditions.

Eddy covariance direct measurements of stand-level *T. ramosissima* ET are underrepresented in Table 1, especially in the four studies that reported ET over a full growing season (Table 2). The difficulties of upscaling physiological parameters, as with scaling up from lysimeters (Xu *et al.*, 1998), have been well discussed by Jarvis & McNaughton (1986). The primary difficulty in scaling from the leaf to the canopy level is the development of thicker boundary layers and consequentially larger boundary layer resistance at the larger scale. This difficulty is expressed when ET scaled up in Table 1 that were determined as a summation of the number of canopies at a site is compared to measurements made at the stand level. The other three full

**Table 1.** *Published data sources, measurement method, spatial scale, and ET measure for Tamarix ramosissima*

Study	Method	ET range
	<i>Leaf-level</i>	
Anderson, 1982	<i>In situ</i>	2.2–2.5 mmol m <sup>-2</sup> s <sup>-1</sup>
Busch & Smith, 1995	<i>In situ</i>	3–8 mmol m <sup>-2</sup> s <sup>-1</sup>
	<i>Canopy-level</i>	
Gay & Fritschen, 1979	Lysimeter	6.2–9.4 mm day <sup>-1</sup>
Sala <i>et al.</i> , 1996	Sap flux	0.3–0.6 kg (m <sup>2</sup> leaf area) <sup>-1</sup> h <sup>-1</sup>
Cleverly <i>et al.</i> , 1997	Sap flux	600–1000 kg (m <sup>2</sup> sapwood area) <sup>-1</sup> h <sup>-1</sup>
Devitt <i>et al.</i> , 1997a	Sap flux	0–2.1 kg (m <sup>2</sup> leaf area) <sup>-1</sup> h <sup>-1</sup>
Devitt <i>et al.</i> , 1997a	Sap flux	0–21 kg (m <sup>2</sup> leaf area) <sup>-1</sup> h <sup>-1</sup>
Devitt <i>et al.</i> , 1997b	Sap flux	200–2,000 kg (m <sup>2</sup> sapwood area) <sup>-1</sup> h <sup>-1</sup>
Glenn <i>et al.</i> , 1998	Lysimeter	12.9 ± 0.67 g (g fresh weight) <sup>-1</sup> day <sup>-1</sup>
Xu <i>et al.</i> , 1998	Lysimeter	3.1–3.8 mm day <sup>-1</sup>
	<i>Stand-level</i>	
Culler <i>et al.</i> , 1976	Near-IR	1.3–3.1 mm day <sup>-1</sup>
Gay & Fritschen, 1979	Bowen Ratio	7.2–9.5 mm day <sup>-1</sup>
Davenport <i>et al.</i> , 1982	Lysimeter*	2.2–15.8 mm day <sup>-1</sup>
Sala <i>et al.</i> , 1996	Sap flux*	5.4–20.2 mm day <sup>-1</sup>
Sala <i>et al.</i> , 1996	Penman–Monteith	3.1–8.2 mm day <sup>-1</sup>
Devitt <i>et al.</i> , 1997a	Penman–Monteith	3.5–8.0 mm day <sup>-1</sup>
Hansen & Gorbach, 1997	Blaney–Criddle	2.0–2.7 mm day <sup>-1</sup>
Devitt <i>et al.</i> , 1998	Bowen Ratio	0–12.5 mm day <sup>-1</sup>

Leaf-level data were collected using a leaf chamber on intact plants in the field (*in situ*).

\*Scaled up from the canopy level.

growing season studies in Tables 1 & 2 (Devitt *et al.*, 1997a; Hansen & Gorbach, 1997; Devitt *et al.*, 1998) were performed at the stand-level.

Semi-empirical ET models (modified Blaney–Criddle and Penman–Monteith) produce ET approximations that perform well under very specific conditions. Blaney–Criddle and Penman–Monteith work best for crops which have non-limiting water and nutrient resources and a uniform canopy, requiring near steady-state conditions in the one-dimensional vertical energy balance (Saugier & Katerji, 1991; Stannard, 1993; Steduto & Hsiao, 1998). Such is also the case using Bowen Ratio Energy Balance systems, in which departure from steady-state conditions or the influence of advective energy flux can strongly inhibit the validity of LE and *H* measurements because their ratio is unbounded when the eddy transfer coefficients for momentum and energy deviate from equality (Verma *et al.*, 1978; Motha *et al.*, 1979; Lang *et al.*, 1983). The most extreme cases occur when the solution of the Bowen Ratio indicates that LE > *R<sub>n</sub>* (Devitt *et al.*, 1998), clearly unlikely if *R<sub>n</sub>* is the measure of total energy input to the ecosystem.

Eddy covariance, on the other hand, directly measures all four of the vertical energy flux terms without assuming that they balance. In fact, the vertical energy fluxes do

**Table 2.** Measurement periods of ET estimates for *Tamarix ramosissima* in Table 1

Study	Period	Units
Culler <i>et al.</i> , 1976	Point estimates	ft month <sup>-1</sup>
Gay & Fritschen, 1979	14–18 June	mm day <sup>-1</sup>
Anderson, 1982	Point estimates during June	g dm <sup>-2</sup> h <sup>-1</sup>
Davenport <i>et al.</i> , 1982	June, July, August	mm day <sup>-1</sup>
Busch & Smith, 1995	Monthly point estimates	mmol m <sup>-2</sup> s <sup>-1</sup>
Sala <i>et al.</i> , 1996	7 July–18 October	mm day <sup>-1</sup>
Cleverly <i>et al.</i> , 1997	9 June & 23 August	kg (m <sup>2</sup> sapwood area) <sup>-1</sup> h <sup>-1</sup>
Devitt <i>et al.</i> , 1997a	Full season	mm day <sup>-1</sup>
Devitt <i>et al.</i> , 1997b	24 June & 5 August	kg (m <sup>2</sup> sapwood area) <sup>-1</sup> h <sup>-1</sup> in
Hansen & Gorbach, 1997	Full year	year <sup>-1</sup>
Devitt <i>et al.</i> , 1998	Full season	mm day <sup>-1</sup>
Glenn <i>et al.</i> , 1998	31 days	g (g shoot fresh weight) <sup>-1</sup> day <sup>-1</sup>
Xu <i>et al.</i> , 1998	Full season (183 days)	mm year <sup>-1</sup>

The original units are also shown illustrating where the measurement period affected scaling ET to mm day<sup>-1</sup>.

not balance during the monsoon season (Fig. 4) and in hot, dry aridlands. Monsoon events are associated with extreme turbulence and spectacular electrical activity. Such events increase the effects of advection, already strong along aridland rivers, by increasing convection across the landscape. Among eddy covariance systems, the three-dimensional sonic anemometer is currently favored because of its ability to rotate measurement axes (for flux deviations from vertical; Wesely, 1970), its long-term field deployability (relative to one-dimensional sonic or hot wire systems, which can only be used for short periods), and its ability to measure fluxes nearer the top of the canopy (relative to the great height required for propeller systems to overcome their rotational inertia).

It is encouraging that rates of ET in *T. ramosissima* stands are correlated between sites (Fig. 5). An understanding of the physical environment that regulates stand-level ET provides a mechanism for comparing ET variability across studies. In this case, temperature of the *T. ramosissima* stand did not relate statistically to ET (Fig. 3(B)). However, temperature in combination with humidity was strongly ( $K=0.02$ ) related to ET following the average 25-day movements of large frontal systems that humidified the atmosphere and decreased the driving force for ET (Fig. 3(A)). Cross-site comparisons are possible when climate and meteorology are clearly described. However, riparian ecosystems in arid and semi-arid regions experience greater environmental variability, with associated variability in ET, than many other ecosystems, confounding direct comparisons to other ecosystem types.

In tallgrass prairie, for example, the seasonal pattern of ET was more responsive to local precipitation events and can be easily divided into characteristic phenological periods—early growth, peak growth, early senescence, and senescence (Kim & Verma, 1990). As with the tallgrass prairie, the onset and cessation times of ET from *T. ramosissima* along the Middle Rio Grande coincides well with leaf production and senescence, respectively (Fig. 2). However, the rest of *T. ramosissima*'s growing season does not form the characteristic growth peak that the tallgrass prairie does, fluctuating instead in a close relationship with the drying or wetting of the canopy (Fig. 3). This

response of ET to canopy RH can be explained in two ways: as a result of atmospheric transport or as a result of the physiology of the plants. The relative importance of physiology and atmosphere is influenced by both spatial scale and vegetation type (Jarvis & McNaughton, 1986).

Seasonal patterns of ET are of considerable importance when determining water budgets for large river systems. For example, a water budget recently has been compiled for the Middle Rio Grande (Fig. 6) and has become an important science-based tool in the Middle Rio Grande basin during recent La Niña-related drought. Equitable water resource allocation depends upon better knowledge of water supplies and depletions. Because water rights are an issue at the interface of science, politics and society (Jackson *et al.*, 2001), much of the information available relating to the water cycle along the Middle Rio Grande has not been published in a peer-reviewed forum.

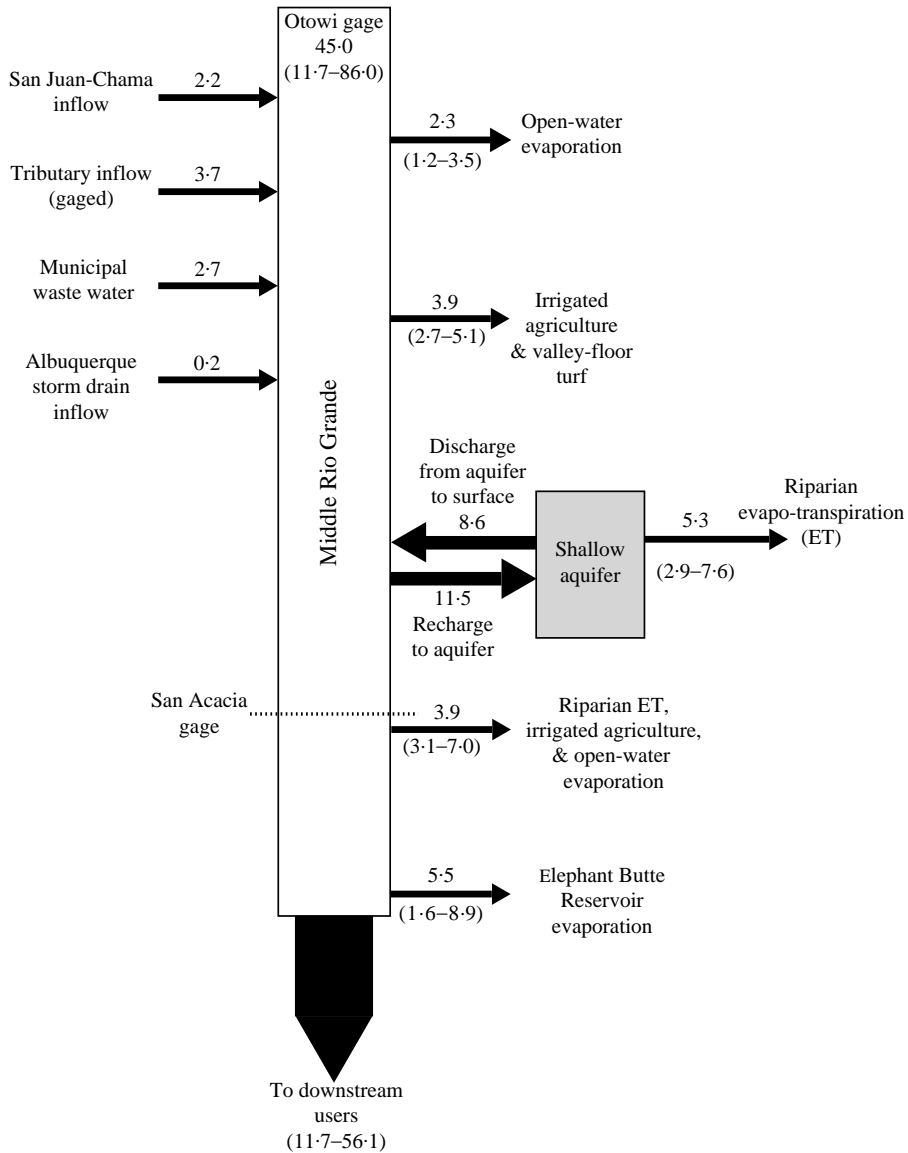
A study by Burkholder (1928) addressed evaporation rates in the Middle Rio Grande. Evaporation data were reported on a monthly basis, facilitating the use of these data in further describing water cycle dynamics throughout the year. The coefficient of variation between monthly evaporation rates was 62.8% in 1900 and 56.6% in 1903 (Burkholder, 1928). The coefficient of variation between 1900 and 1903 (Burkholder, 1928),  $17.7 \pm 4.4\%$ , is smaller than monthly variation, but it is nonetheless meaningful in its effect on estimating an annual water budget, especially from the surface of Elephant Butte Reservoir (Fig. 6). The magnitude of evaporation ( $1.2 \text{ mm day}^{-1}$  in December to  $10.7 \text{ mm day}^{-1}$  in June) is not different from *T. ramosissima* ET (Table 1), so the largest difference between ET and *E* is probably related to land-surface area of sunlit open water *vs.* riparian vegetation.

Estimates of annual ET in the Middle Rio Grande water budget are poorly parameterized. Above San Acacia (see Fig. 1), riparian ET is estimated to average  $167 \times 10^6 \text{ m}^3 \text{ year}^{-1}$  (19% of the total Middle Rio Grande Depletions), ranging from  $93$  to  $241 \times 10^6 \text{ m}^3 \text{ year}^{-1}$  over a 26-year record (Fig. 6). Below San Acacia, however, further uncertainty is built into the water budget by combining riparian ET, irrigated agriculture and open-water evaporation into a single term, estimated at  $123 \times 10^6 \text{ m}^3 \text{ year}^{-1}$  (14% of depletions) and ranging from  $99$  to  $222 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ . These numbers were generated by solving the Blaney–Criddle equation estimates of ET for each vegetation and crop type (Hansen & Gorbach, 1997) and multiplying that quantity by the 1989 estimate of areal coverage for each vegetation type (Crawford *et al.*, 1993).

This application of a Blaney–Criddle equation using a crop coefficient for *T. ramosissima* developed at Bosque del Apache overestimates ET in areas like the unflooded site in this study because application of a single empirically based equation does not account for spatial variability in ET along the Middle Rio Grande (Fig. 5). While recent budgets of water resources in central New Mexico are beginning to consider this type of variability, uncertainty is generally given as a single term that is not explicitly defined. Three types of variability and error can be illustrated from this study: spatial, seasonal, and annual. Recognizing mechanistic ways in which these uncertainties relate to physical and biological phenomena will contribute substantially to a better accounting of water depletions from ET in the Middle Rio Grande.

ET varies spatially along the riparian corridor due to both intraspecific (Fig. 5) and interspecific variabilities. Intraspecific variability occurs both within a reach, from the river's edge to the desert's edge (Devitt *et al.*, 1997a), or between reaches that have different ecosystem structure (Fig. 5). This intraspecific variability is very important in determining a water budget because the structure of the riparian forest changes with age (Schaeffer *et al.*, 2000). It is unknown how the Middle Rio Grande water budget accounts for these phenological differences on the 26-year average ET estimate.

Another major complication lies in long-term changes in the community composition of a riparian forest. Obtaining accurate species composition information



**Figure 6.** A partial water budget for the Middle Rio Grande. The budget presented here was modified from a budget prepared by the Action Committee of the Middle Rio Grande Water Assembly in October 1999. Exchanges with the deep aquifer have been omitted for clarity. All values are in units of  $\text{m}^3 \text{s}^{-1}$ . Values are average (rounded). Natural variability is large for most, but not all variabilities are available. Data were included from 1972 through 1997.

along an entire river is expensive and laborious. The community classifications along the Middle Rio Grande used by the Biological Management Plan for the Middle Rio Grande (Crawford *et al.*, 1993) were obtained from the National Wetlands Inventory (1989) from two survey dates: 1935 and 1989. Over that time, there have been drastic changes from *P. deltoides*-dominated forests to *T. ramosissima*- and *E. angustifolia*-dominated forests. Similar transformations have occurred throughout the western U.S. For example, Rood *et al.* (1995) reported in Montana a 68% decline in *P. deltoides*

abundance along lower St Mary River and a 52% increase in *P. deltoides* abundance along the lower Belly River. Other reaches and rivers in Montana were reported to change in *P. deltoides* density intermediate to these values (Rood *et al.*, 1995). Snyder & Miller (1992) reported a 17.5% decline in cottonwood abundance along the upper Colorado River and a 9.3% increase in cottonwood abundance along the upper Rio Grande over the same 37-year interval. The current water budget accounts for interspecific differences in ET, as well as the areal coverage of each species, but both those parameters are held static. While a new classification is under way using remote sensing, annual variability in community composition remains unknown.

Applying these three-dimensional eddy covariance ET estimates to canopy characteristics and remote sensing techniques is the next step toward upscaling ET estimates along the entire Middle Rio Grande. Methods of upscaling will require a better understanding of thickness and dynamics of the boundary layer over different vegetation types (Cooper *et al.*, 2000), extent of the footprint under various atmospheric conditions, and the role of advected energy exchange with neighboring ecosystem types. LAI also provides an easily calibrated and simple method to predict ET rates away from towered sites. This study, as the first study to compare full growing season ET estimates at multiple sites along the same river, illustrates the necessity of multiple ground truth points for the application of multi-spectral information to estimate ET. Further ground truth points in other forest types, along with watershed-wide precipitation and stream discharge characteristics, will considerably improve estimates of ET in the Middle Rio Grande water budget. Such modeling efforts are beginning along the Rio Grande, and the preliminary results promise to improve estimates of consumptive water loss along a riparian corridor.

### Summary

Rates of ET from *T. ramosissima* stands vary in complex patterns through various spatial and temporal scales. Such temporal variability in plant function makes full season estimates of ET crucial for characterizing actual consumptive water loss under natural conditions. Combined with the necessity of collecting full growing season data, three-dimensional eddy covariance demonstrated its efficacy for long-term ET determination as well as closure of the energy balance, both of which greatly limits both Bowen Ratio and semi-empirical model estimates (e.g. Penman–Monteith approximations and modified Blaney–Criddle). Spatial variability in flooding regime, consumptive water loss, and vegetation density render simultaneous seasonal measurements of ET necessary for applying these data in regional water budgets. Parameterizing the riparian terms in the water budget with data from one site (e.g. 122 cm year<sup>-1</sup> at Bosque del Apache NWR) can provide a very different estimate of water loss than using data from another individual site (e.g. 74 cm year<sup>-1</sup> at Sevilleta NWR). Incorporated into spatial ET variability for *T. ramosissima* is spatial variability in other riparian species (e.g. *P. deltoides*) along the Middle Rio Grande. Three-dimensional eddy covariance data from *T. ramosissima* and *P. deltoides* communities, measured across a full growing season at multiple sites, will greatly assist in the success or failure of planning regional water resources, characterizing and explaining plant invasions, and restoring riparian gallery forests.

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