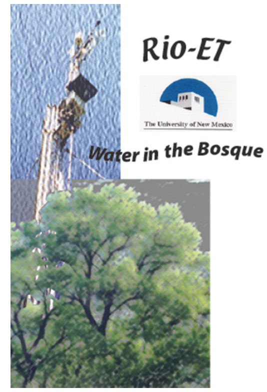
Evapotranspiration in the Middle Rio Grande Bosque



A Final Report submitted to the US Bureau of Reclamation's Endangered Species Workgroup, Science Subcommittee

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Executive Summary

With the assistance of the endangered species workgroup, the Rio-ET project at UNM was enabled to uninterruptedly collect evapotranspiration (ET) measurements from a variety of sites along the Middle Rio Grande (MRG) in New Mexico. Data on ET and related hydrologic and atmospheric conditions were collected from towers and shallow groundwater wells throughout the MRG. These vital measurements were made in saltcedar, cottonwood, and Russian olive ecosystems, beginning in 1999 and continuing through 2007.

Climatic conditions in the MRG basin and its headwaters in New Mexico and Colorado ranged from moderately wet to extreme drought. ET, or depletions from the water budget from evaporation and transpiration, was undiminished at the cottonwood sites during the drought period due to maintenance of groundwater levels at both sites–one in the outflow of the City of Albuquerque's wastewater recovery plant and the other surrounded by irrigation structures and drain channels. In the saltcedar thickets, ET was inconsistently depressed during the drought: lower ET was not observed in both locations and both years of extreme drought. Altogether, ET rates remained very high through the drought years, and plant water use returned to pre-drought levels within one year of release from drought.

ET Toolbox calibration coefficients (Kc) are provided for each site and in each month of the study. Kc was often very low in the winter, although a great deal of variability was observed. Kc at the southernmost saltcedar sites was always depressed in the spring driven by cold air drainage from the overlooking Magdelena mountains. Kc declined at the cottonwood site in the first year after completion of restoration ac-

tivities.

Of all the species in the MRG, Russian olive has the highest transpiration rates in a mixed stand. The trade-off between higher rates in cottonwoods and higher density of willows causes a balance in water use between these two members of the willow family. Small Russian olives and coyote willows were shown to supplement groundwater supplies with precipitation and soil water sources during the height of the drought in 2003.

Ecological restoration involving the removal on non-native species (Russian olive and saltcedar) from a native cottonwood forest was performed in Albuquerque's south valley. ET was 21%, or 26 cm, lesser in the year following the completion of restora-

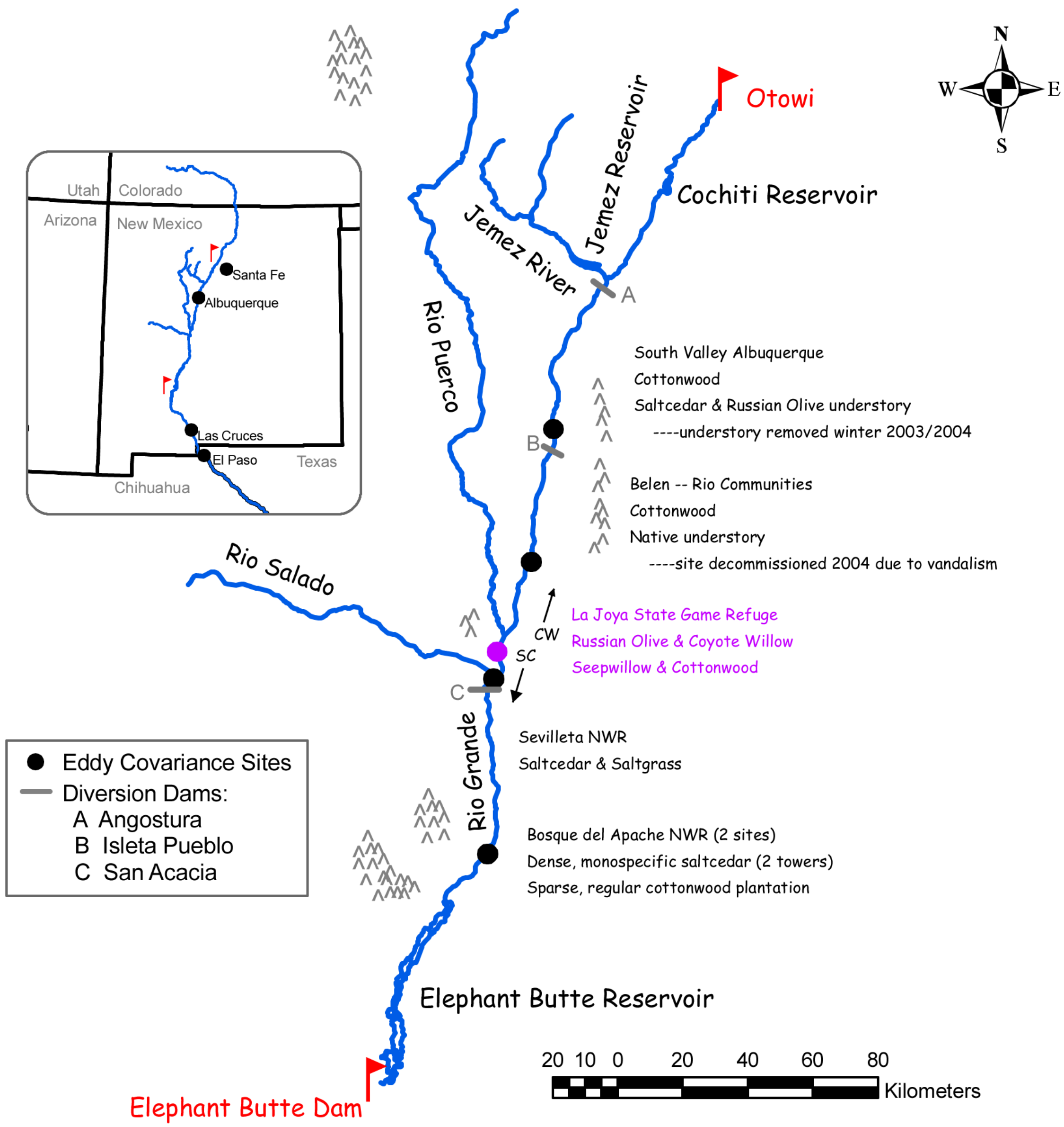

Figure 1. Map of field sites along the Middle Rio Grande.

tion activities than it would have been based upon comparison with reference sites. No further potential water savings were observed because vigorous regrowth of the removed vegetation was not kept in check. The restoration activities themselves, by opening the ground up to heretofore unobserved insolation, may have contributed to favorable conditions for regrowth of non-native species.

Introduction

The Rio-ET project at the University of New Mexico has been providing long-term bio-meteorological and eco-hydrological evaluation of riparian evapotranspiration (ET) depletions along the Middle Rio Grande (MRG) since 1999. At that time, defensible estimates of ET were rare and difficult to obtain. Often, incredible quantities of water loss were assigned to saltcedar (*Tamarix chinensis*). For example, water use by saltcedar has been popularly placed at 200 gallons per plant per day or more. Many locations are host to thousands of individual saltcedar plants per acre. There are 6,500 root crowns per acre at the Bosque del Apache NWR; at 200 gallons per plant per day, that works out to just over one meter of ET every day!

The UNM Rio-ET project obtained funding from the ESA workgroup in fiscal years 2003/2004 and 2004/2005 to maintain defensible ET measurements from MRG riparian forests (also called the Bosque). This project provides crucial information for testing the assumptions of the biological opinion and resultant tasks listed in the ESA workgroup's call for proposals. For example, the Biological Opinion regarding MRG endangered species opens with an in-depth discussion of hydrology and plant water use. These sections explicitly assume that removal of non-native riparian plants provides water savings. These savings are to be used to offset water costs of projects such as instream gradient structures and creation of overbank flooding. This project quantifies actual ET savings, if any, of a restoration project underway in Albuquerque's South Valley. The riparian ET project reported upon here will continue to make direct, state-of-the-art measurements to perform Task 1, "quantify and evaluate losses from evaporation and evapotranspiration." In addition, this project provides support and evaluation regarding interactions between creating favorable willow flycatcher habitat and changing water supply to maintain instream flows for the silvery minnow. Benefits from information gathered in this project include improved ability to predict ET depletions, thereby decreasing the probably of allowing the river to run dry. The objectives of this research were

- to evaluate the effectiveness of bosque restoration and the removal of non-native species by monitoring evapotranspiration depletions,
- to improve forecasts of MRG depletions due to riparian ET through coordinated efforts with the ET Toolbox,
- to identify vegetation factors, if any, controlling bosque ET rates, and
- to quantify the proportional contribution of individual vegetation species to ET in a mixed stand.

Background

The original research focus in 1999 was upon determining the roles of flooding and community composition on ET depletions. Interest in these questions was sparked by the success of the Albuquerque overbank project, in which the self-maintaining restoration of a native cottonwood-willow community has been achieved by removal of non-native species and bank modification promoting on-site flooding. Eddy covariance systems were mounted to four initial towers along the MRG (Fig. 1). These towers were located in one of each of the following forest types and flooding regimes:

- a cottonwood-dominated forest with a long (> 10 yrs) interflood interval (IFI) (Albuquerque's South Valley),
- a cottonwood-dominated forest with a short (< 3 yrs) IFI and mostly native understory species (Belen),
- a saltcedar-saltgrass woodland with a long IFI (Sevilleta NWR), and
- a monospecific thicket with a short IFI (Bosque del Apache NWR).

Later, an additional site was placed in a young Russian olive forest. This frequently flooded site at the La Joya State Game Refuge was within the braided channel in 2000 and has since become vegetated after the Rio Grande was restricted on a single channel.

The Biological Opinion (1999), sent from the US Fish and Wildlife service to the US Bureau of Reclamation, outlines the hydrological and biological requirements necessary for maintenance of endangered species populations along the MRG. One of the primary assumptions in this document is that clearing of non-native species will provide a water budget savings that can then be applied to depletions caused by instream restoration projects:

> "Given these considerations and the prevalence of non-native species vegetation in the bosque, Reclamation believes any net depletions created by a restoration project can be offset while simultaneously improving the ecological health of the bosque such as has been done at the Bosque del Apache National Wildlife refuge. This can be accomplished through a detailed vegetation management plan and a water budget analysis for any restoration project(s)."

Over the four year scope of this project, we have maintained ET data collection necessary for a detailed water budget analysis preceding and following restoration along the MRG. The site in Albuquerque's South Valley contained a thick understory of non-native species, especially saltcedar and Russian olive (*Elaeagnus angustifolia*), during the first three years of the study (2000 through 2002). Preceding the 2003 growing season, the non-native understory was removed from the nearest 30-m of the tower's measurement footprint. Before the following year, the rest of the forest had been restored. Then, in 2005, saltcedar and Russian olive was growing from stumps that had been previously treated with herbicide. In 2006, thirty to fifty percent of the remaining cottonwood canopy burned in a fire that was suppressed at the base of the tower.

ET can be limited (1) by fluctuations in and access to a shallow water table, (2) by physiological limitations in vegetation covering the surface, and (3) by unfavorable atmospheric conditions. By collecting groundwater, vegetation, and micrometeorological data from these sites over a series of years varying in climatic conditions, this project has identified conditions under which actual ET varies above and below the environmental potential for ET. This report will describe measured variability in riparian ET along the MRG over multi-annual records of continuous ET records, how actual ET measured from specific ecosystems compares with the expectations of the ET Toolbox, what vegetation factors controlling actual ET have been identified, the contributions of individual species to actual ET, and some hydrologic results of understory restoration.

Methodology

Three-dimensional sonic eddy covariance (3SEC) is the method by which turbulent fluxes of water vapor, energy, momentum, and trace gases are measured above a canopy. This is a novel method in evapotranspiration research, standing as the only method that can make direct measurements of surface water flux without inferring fluxes from related conditions or from the energy balance. This advantage gives the eddy covariance system a self-check for accuracy, an unheralded innovation in ET research (Drexler et al. 2004).

The fundamental measurements in a 3SEC system are made using a 3-D sonic anemometer (CSAT3) and a fast-response humidity sensor, either a krypton hygrometer or an infrared gas analyzer. The CSAT3 measures wind speed in three dimensions as well as virtual temperature. The krypton hygrometer measures variations in humidity, and the infrared gas analyzer measures humidity and carbon dioxide concentration. Each of these sensors are mounted on towers above the canopy, where measurements are made 10 times per second (i.e., at 10 Hz). The covariance between vertical wind speed (w) and humidity (q), computed over a 30-minute period, is a statistical representation of the quantity of water that has transported away from or toward the canopy:

$$\mathrm{ET} = \frac{\mathrm{Cov}(wq)}{\rho} = \frac{\sum (w_i - \bar{w})(q_i - \bar{q})}{\rho \cdot n} = \frac{\sum w'q'}{\rho \cdot n} = \frac{\overline{w'q'}}{\rho}$$

where observations are denoted with a subscript-i, averages by an overbar, and the primes represent the turbulent portion of the transport:

$$q' = q_i - \bar{q}.$$

The energy balance is obtained for the surface layer above the canopy:

$$R_n = LE + H + G,$$

in which R_n is the net radiation, LE is the latent heat flux, H is the sensible heat flux, and G is the ground heat flux. R_n represents the difference between downwelling and upwelling radiation (both solar and thermal); positive values of R_n represent net radiation flux toward the canopy from above. By convention, all other fluxes are oriented such that positive values arise when the flux is oriented away from the canopy. Both LE and H are measured by the 3SEC system:

$$LE = \lambda \cdot \rho \cdot ET = \lambda \cdot \overline{w'q'},$$

and

$$H = C_p \rho \overline{w'T'},$$

where λ is the latent heat of vaporization of water, C_p is the specific heat of water, and ρ is the density of water in air, and T is the temperature. Because we measure virtual temperature rather than actual temperature, virtual heat flux is converted to actual heat flux (Swiatek, personal communication, Campbell Scientific, Inc., Logan, UT):

$$H = \left(\frac{\bar{T}}{\bar{T}_v}\right)\left(H_v - \frac{0.51 \cdot C_p \cdot \rho \cdot \Re \cdot LE \cdot \bar{T}^2}{P \cdot \lambda}\right),$$

where the subscript-v represents a virtual measurement and R is the universal gas constant. R_n was measured using a net radiometer at each site (REBS and Kipp & Zonen models). G was measured using ground heat flux plates (Campbell Scientific, Inc.) buried 8 cm below the surface. Storage of heat in the ground above the sensors was accounted by measurements of soil temperature change and soil water content.

Measurements from the towers also included temperature and relative humidity, precipitation, incoming solar radiation, and horizontal wind speed and direction (Campbell Scientific, Inc., Logan, UT). In addition to monitoring ambient conditions above the canopy, these instruments provide us the opportunity of calculating Penman potential ET at each site:

$$ET_0 = \frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma}\left(e_s - e_a\right)\left(15.36 \cdot \left(1.0 + \left(0.0062 \cdot \bar{u}\right)\right)\right),$$

where Δ is the slope of the saturated vapor pressure curve, γ is the psychrometric coefficient, $\bar{u}$ is the horizontal wind speed 2-m above the canopy surface, and the difference between saturation vapor pressure and atmospheric vapor pressure (e_s - e_a) is the vapor pressure deficit (VPD). This is the form of the equation used in the US Bureau of Reclamation's ET Toolbox (Sammis et al 1985).

ET_0 computed in the Penman model is calibrated throughout the MRG by applying a calibration coefficient, Kc, to the model prediction depending upon what type of vegetation is growing in a certain area. This calibration coefficient is computed as a ratio between ET_0 and actual ET (ET_a) measured by the 3SEC system:

$$ET_a = Kc \cdot ET_0.$$

Calibration coefficients are provided monthly for each system in operation.

Depth to groundwater was monitored using pressure transducers submerged in shallow wells that were screened throughout (EEI Technologies, Las Cruces, NM and Solinst, Inc., Georgetown, Ontario, Canada). Groundwater levels were monitored from three to five wells in a diamond pattern around the tower, including one well located in the center near the tower.

Granier-type sapflux probes were inserted into random individuals of various tree species at the La Joya site. This study encompassed Ms. Alea Trafton's Master's thesis (see attachment/enclosure). This method is used to measure the quantity of water that is translocated through the stem of a plant. Two wires are inserted into a stem — one wire is heated with a know electrical current, and the other wire measures the dissipation of that heat in the sap stream (Granier et al. 1990, Kjelgaard et al. 1997). In addition to sapflux measurements, Ms. Trafton collected stable isotope samples of water in groundwater, surface water, and vegetation tissues to identify the water source tapped by each species.

Bulk stomatal resistance was computed using an inverted version of the Penman-Montieth combination equation, named for the modification by Montieth to the original Penman equation defined above. The Penman-Montieth equation takes the form:

$$ET_{0_{PM}} = \frac{\Delta}{\Delta + \gamma^*} R_n + \frac{\gamma}{\Delta + \gamma^*} C_p \rho \left(\frac{e_s - e_a}{r_a} \right),$$

and

$$\gamma^* = \gamma \left[1 + {r_s}/{r_{av}} \right],$$

where r_{av} and r_c are the aerodynamic and bulk stomatal resistances, respectively. The aerodynamic resistance is determined from the bulk transfer coefficient for water (C_E) and $\bar{u}$:

$$r_{av} = \left(\bar{u} \cdot C_E \right)^{-1},$$

$$C_E = -\frac{\overline{w'q'}}{\bar{u}(1 - qD)},$$

and

$$qD = \mathrm{q_s} - \mathrm{q_a}.$$

The immediately preceding equations were taken from Brutsaert (1982) and Stull

(1988).

Continuous Evapotranspiration Monitoring

The climate varied along the MRG between moderately wet and extremely dry during the course of this study (Fig. 2). Extreme drought was persistent during 2002 and 2003, with little precipitation falling in any season. Reservoirs and lakes in New Mexico dried to a fraction of their capacity, and spill restrictions were imposed by the Rio Grande compact. However, ET was minimally affected along the MRG, undoubtedly due to relatively undiminished water availability and consistently shallow water tables in the cottonwood forests inhabiting the northern reaches (Fig. 3). Water table depth deepened in the southern reaches over the course of the drought (Fig. 3).

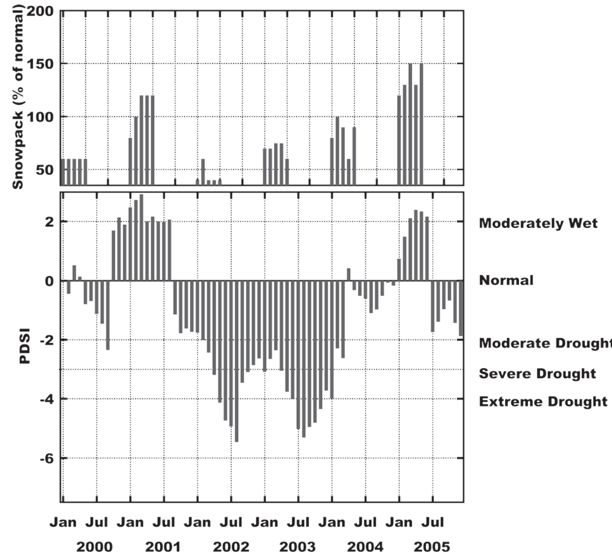

Figure 2. Snowpack estimated from USGS Snotel and Palmer Drought Severity Index. Data for each panel was obtained for the upper and middle basins in Colorado and New Mexico.

Seven years of daily ET measurements were collected from the cottonwood-dominated site in Albuquerque's South Valley and from two saltcedar sites at Bosque

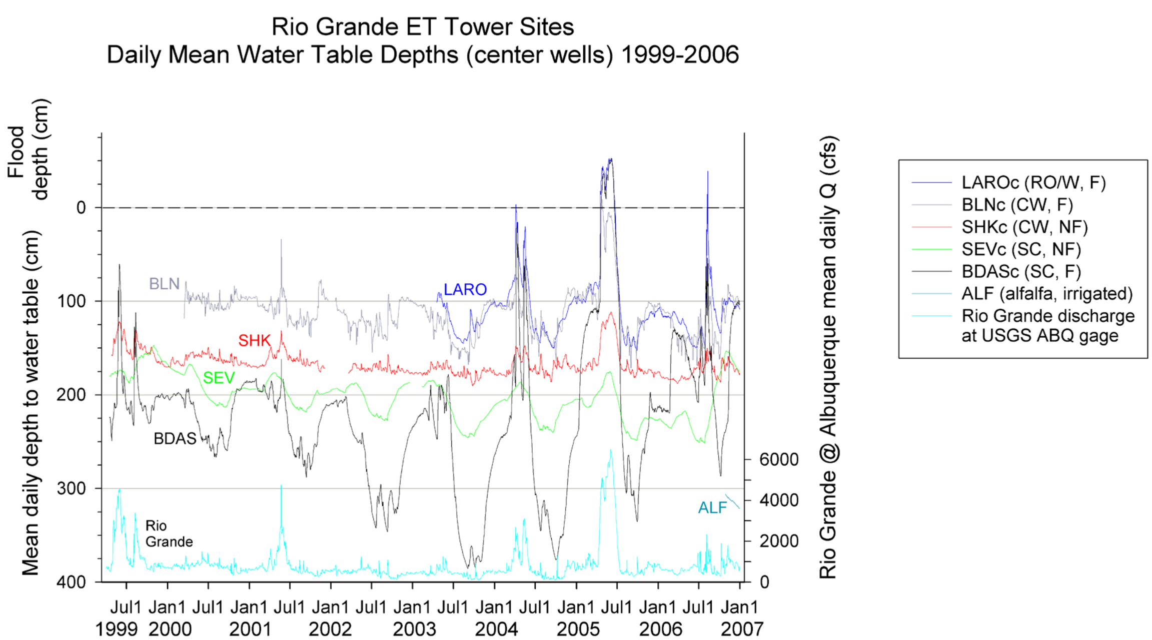

Figure 3. Record of daily depth to groundwater at each of the tower-equipped sites in the study.

del Apache and Sevilleta NWR's (Figs. 4a through 4f). Due to inevitable system failures and discarded observations following corrections and QA/QC procedures, polynomial regression lines were fit to the seasonal ET curve. Annual ET was determined from the summation of daily regression model values during the growing season and average winter ET rates ($ET_{winter} \approx 0.8$ mm/day).

At the two saltcedar sites, ET rates were depressed in 2002 (Fig. 4). However, annual ET at the Bosque del Apache monospecific saltcedar site increased in 2003, the same year that depth to groundwater fell below 3.5 m (Fig. 3). Cleverly et al. (2006) has been included with this report (see enclosures/attachments). We demonstrated in this paper that enhanced ET in 2003 was a result of saltcedar's ability to exploit soil moisture left behind by the rapidly declining water table. ET at the two saltcedar sites returned to pre-drought levels within a year of returning wet conditions. ET at the cottonwood site in Albuquerque's south valley did not decline significantly during the drought (Fig. 4).

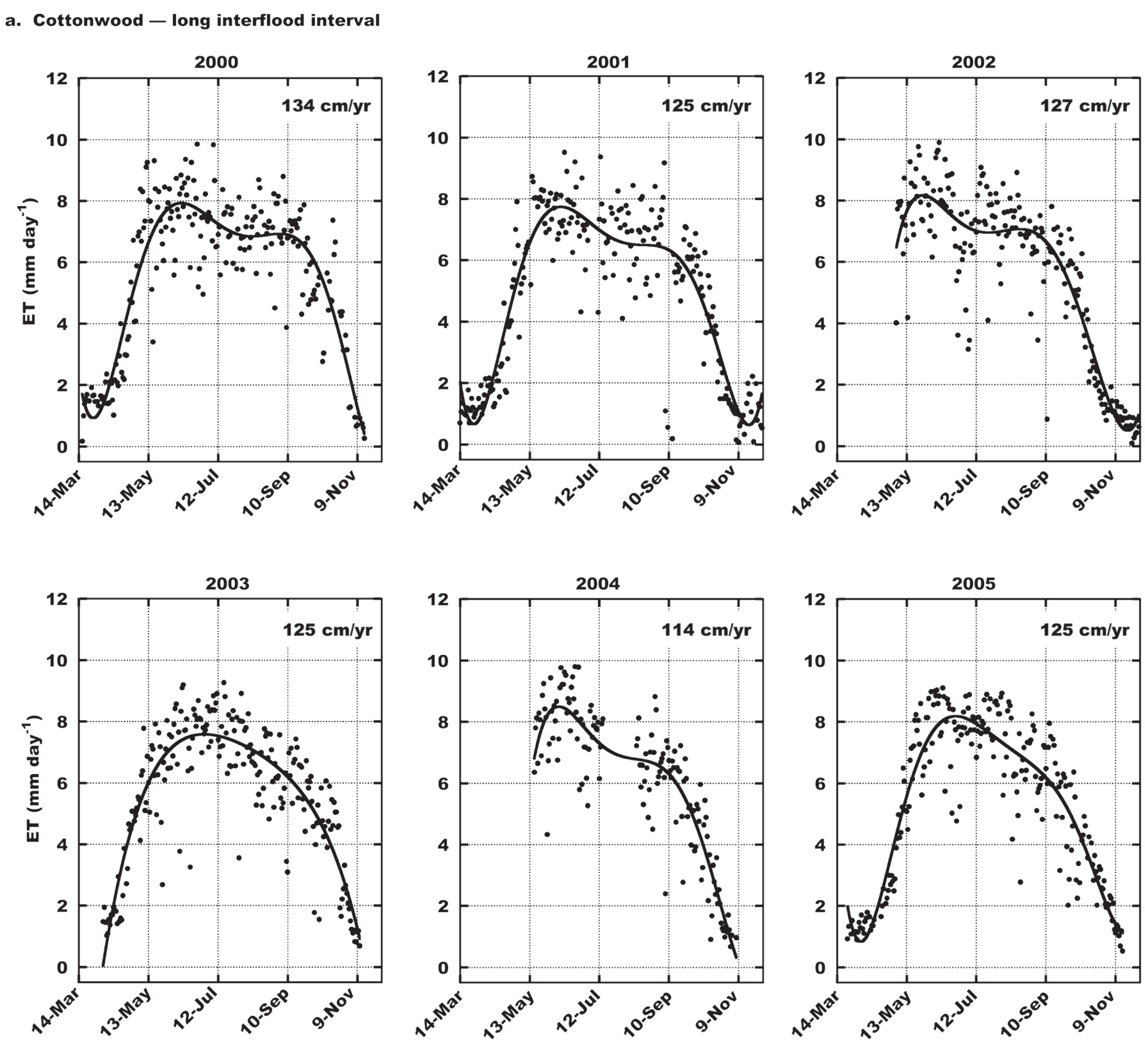

Figure 4a. Record of daily ET observations at Albuquerque's South Valley. Regression line is the best-fit n^{th}-degree polynomial.

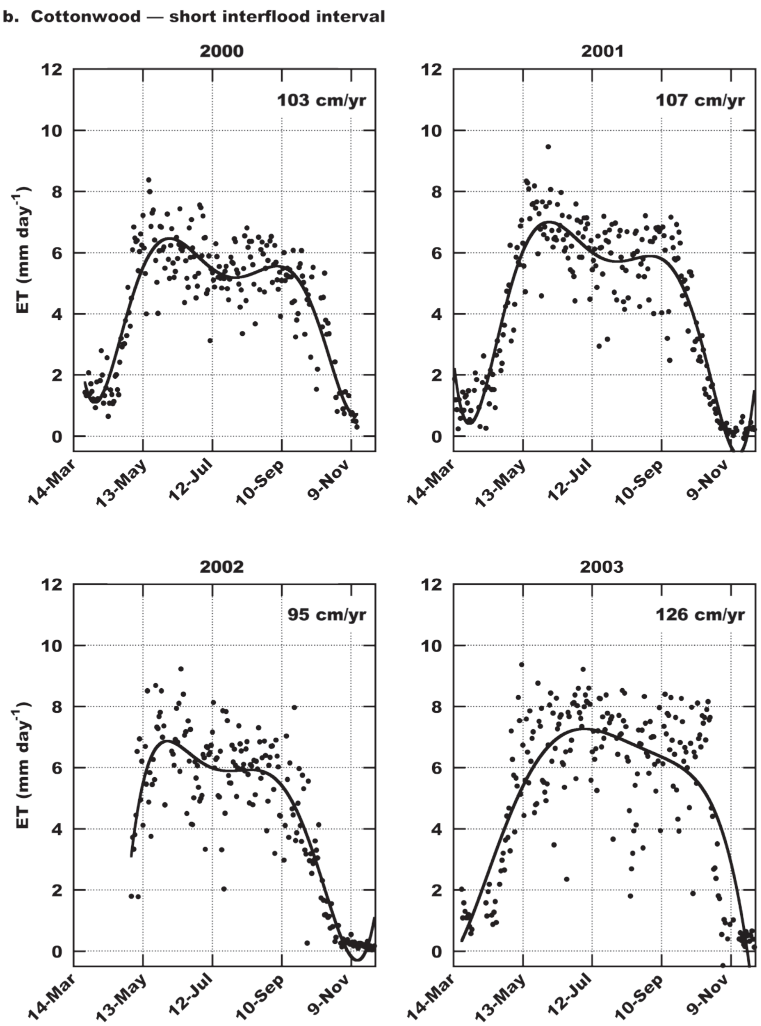

Figure 4b. Record of daily ET observations near Belen and Rio Communities. Regression line is the best-fit n^{th}-degree polynomial.

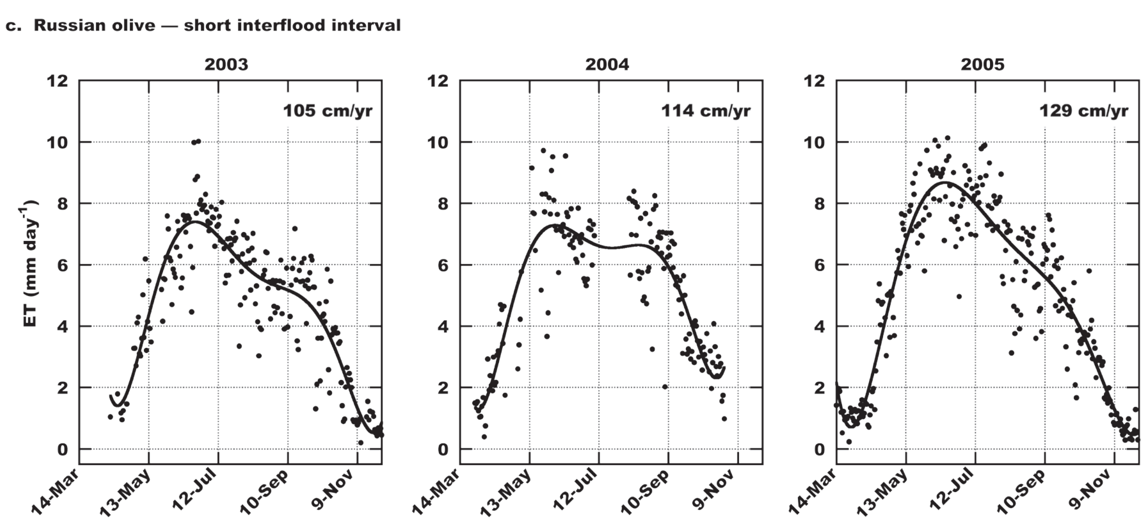

Figure 4c. Record of daily ET observations at La Joya State Game Refuge. Regression line is the best-fit n^{th}-degree polynomial.

d. Saltcedar — long interflood interval

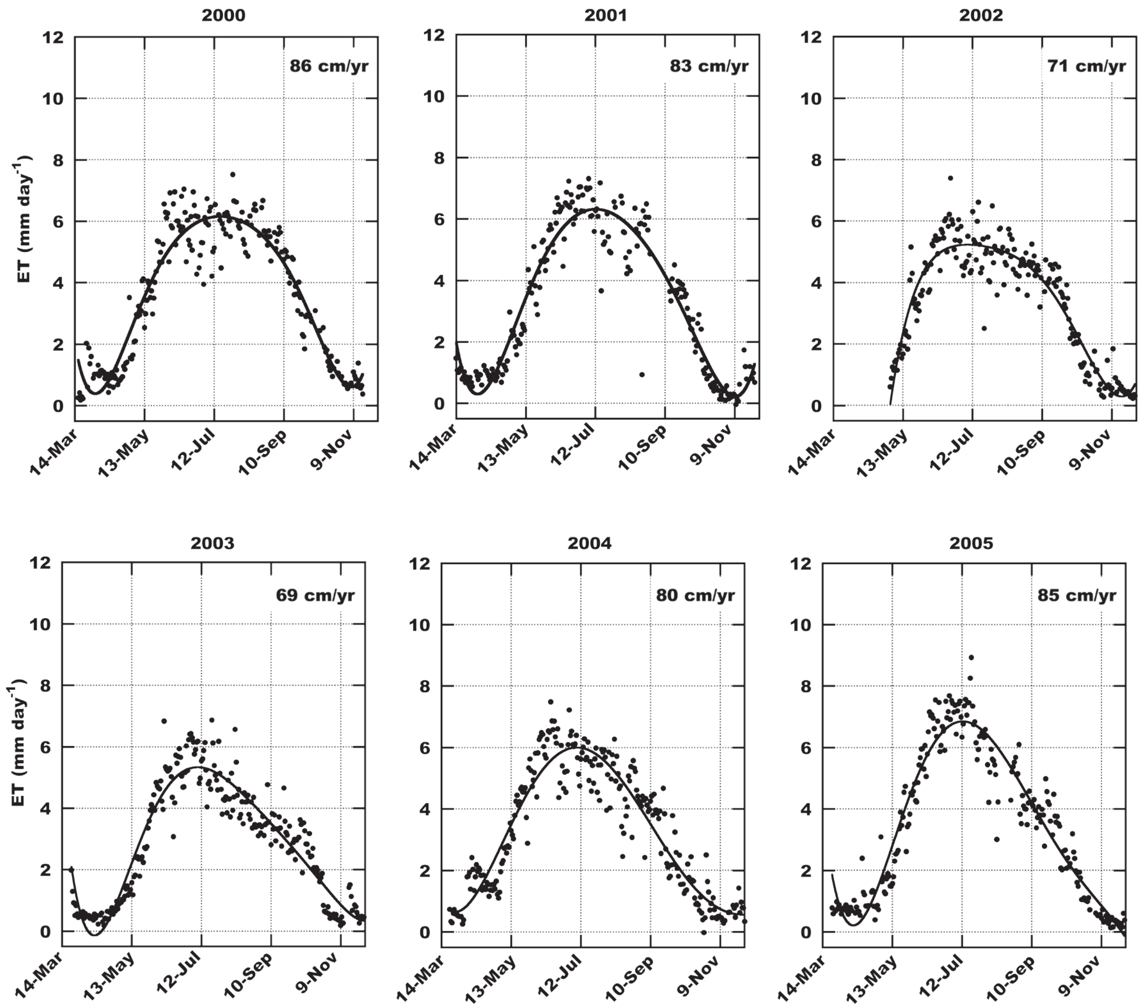

Figure 4d. Record of daily ET observations on the Sevilleta NWR. Regression line is the best-fit n^{th}-degree polynomial.

Partially-cleared understory in Albuquerque's South Valley

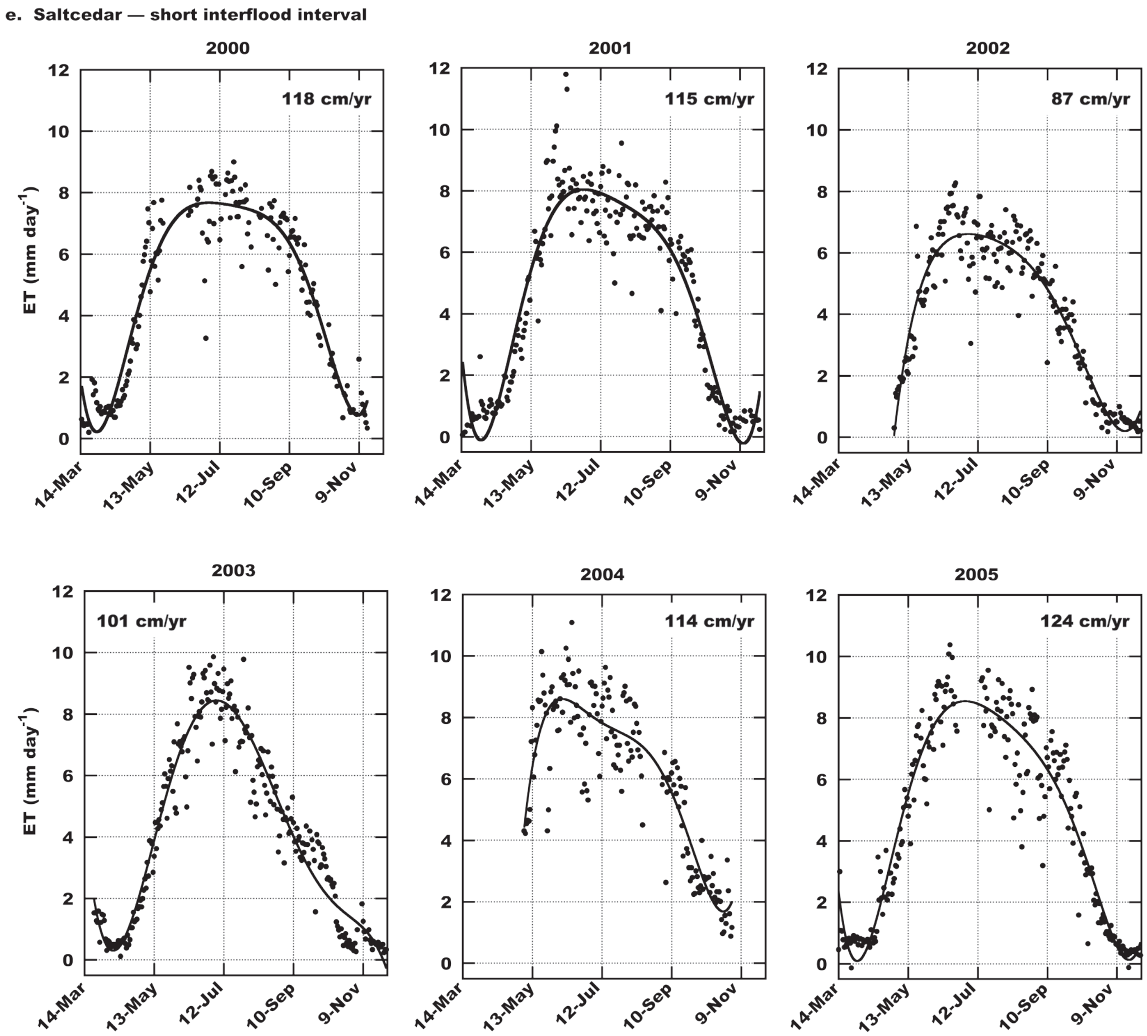

Figure 4e. Record of daily ET observations on the Bosqsue del Apache NWR. Regression line is the best-fit n^{th}-degree polynomial.

Saltcedar regrowth in Albuquerque's South Valley

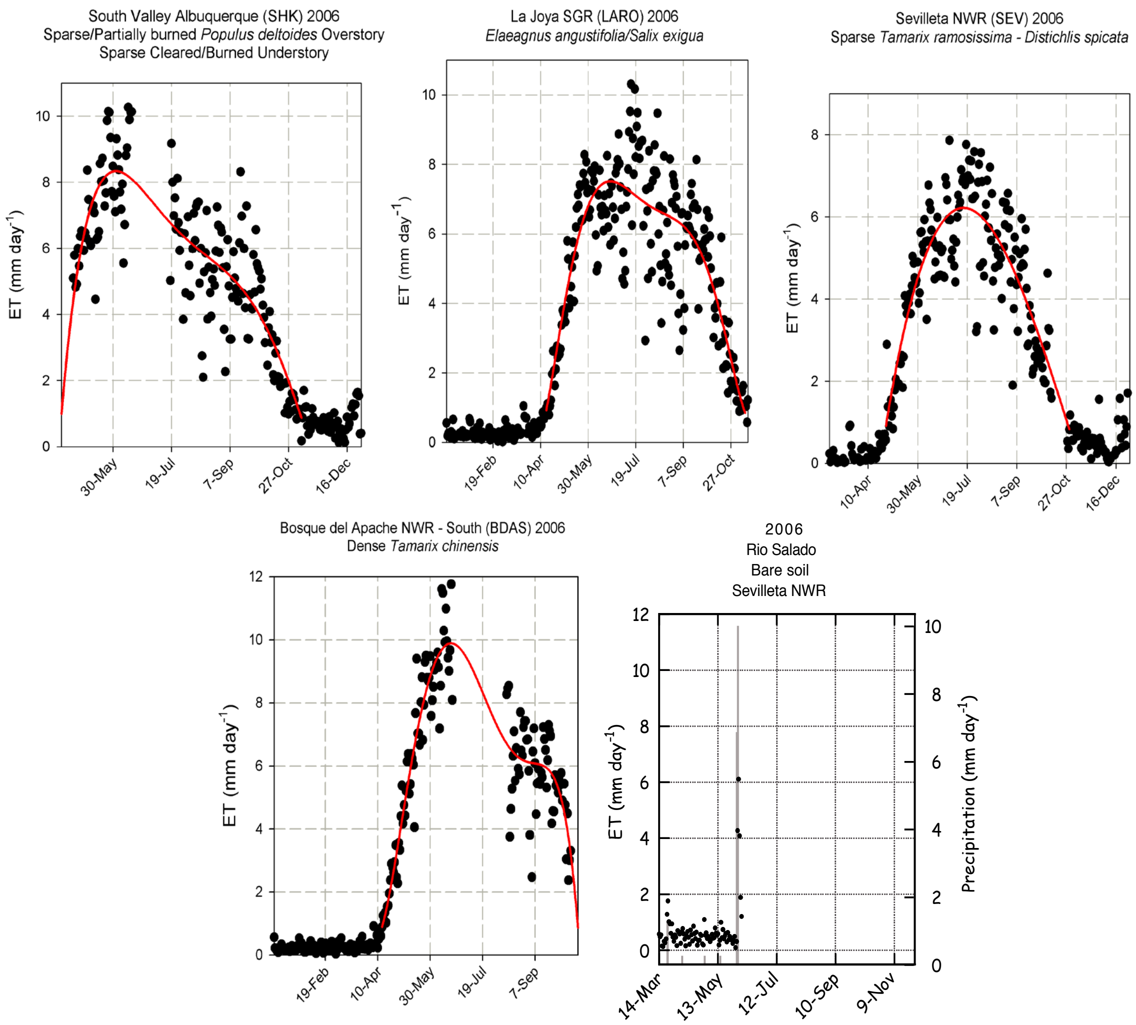

Figure 4f. Record of daily ET observations at all sites in 2006. Regression line is the best-fit n^{th}-degree polynomial.

3D Sonic Eddy Covariance (3SEC) system

The tower near Belen and Rio Communities, situated in a marginal native cottonwood forest, was vandalized beyond repair before the beginning of the growing season in 2004. This site was a total loss, and the insurance claim has been recently completed from which a replacement system was established over bare soil in the Rio Salado. A flood greater in magnitude than the 100 yr flood in the Rio Salado destroyed the initial system placed high on a terrace. A more remote location for a replacement of that system has been located and we expect to begin collecting data again later in 2007.

The influence of advection in this semi-arid region created some special case conditions in the boundary layer. Cooper et al. (2003) observed stable thermal stratification of the boundary layer at about 3-m above the canopy under stable conditions. This cap on the surface layer entrains humidity at the divergence point along the 3-m thermocline and establishes the conditions favorable for evaporative cooling of the canopy and surface layers, as Cooper et al. (2000) demonstrated over and adjacent to a cottonwood canopy. Evaporative cooling of the cottonwood canopies was observed in every year (Fig. 5). The saltcedar canopy at Bosque del Apache, where Cooper et al.'s (2003) research was conducted, showed measurable H < 0 in some years and not others, illustrating that evaporative cooling occurs over saltcedar canopies under some but not all conditions (Fig. 5). The energy balance inverted part way through the 2003 growing season at the La Joya site such that the canopy was a heat sink during the spring and switching to a heat source later in the summer. Ground heat flux was negligible at all sites and in all years (Fig. 5) due to shading of the soil surface.

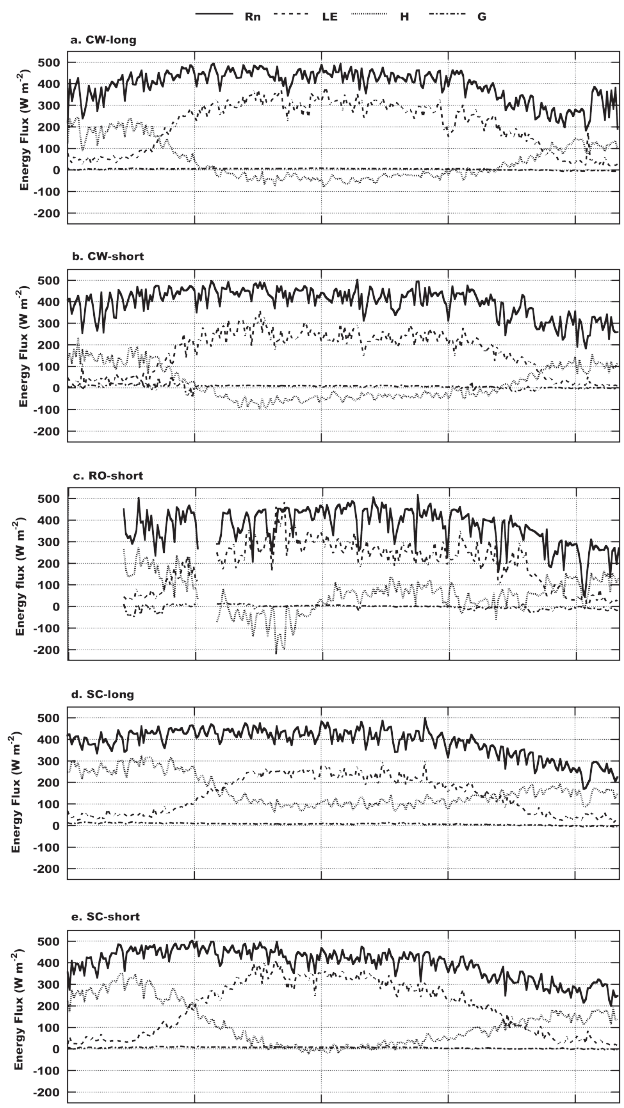

Figure 5. Record of average daytime ($R_n > 0$) energy balance at each site. Values for all sites other than the La Joya Russian olive site were the average flux for that day of the year in all years. Energy fluxes for La Joya were measured in 2003.

Penman calibration coefficients (ET Toolbox Calibration targets)

Monthly Kc values computed for every month in which ET was measured (Table 1). Some of the winter months had fewer days of ET measurements due to re-calibration cycles for the major instrumentation. Values of Kc were typically lower in the winter, but small sample sizes generated considerable variability (Table 1).

Values of Kc during the growing season are illustrated in Figure 6. Onset of actual ET was delayed in both saltcedar sites in all years (Fig. 6). Greening delay in the saltcedar at these sites is related to greater cold air drainage in that region of the MRG (Cleverly et al. 2006). Kc at the Albuquerque site was undiminished during 2002 (Fig. 6), indicating that this was the only site at which ET did not decline during the extreme drought (Fig. 2). As the drought was alleviated in 2004 and 2005, values of Kc markedly increased at all sites (Fig. 6).

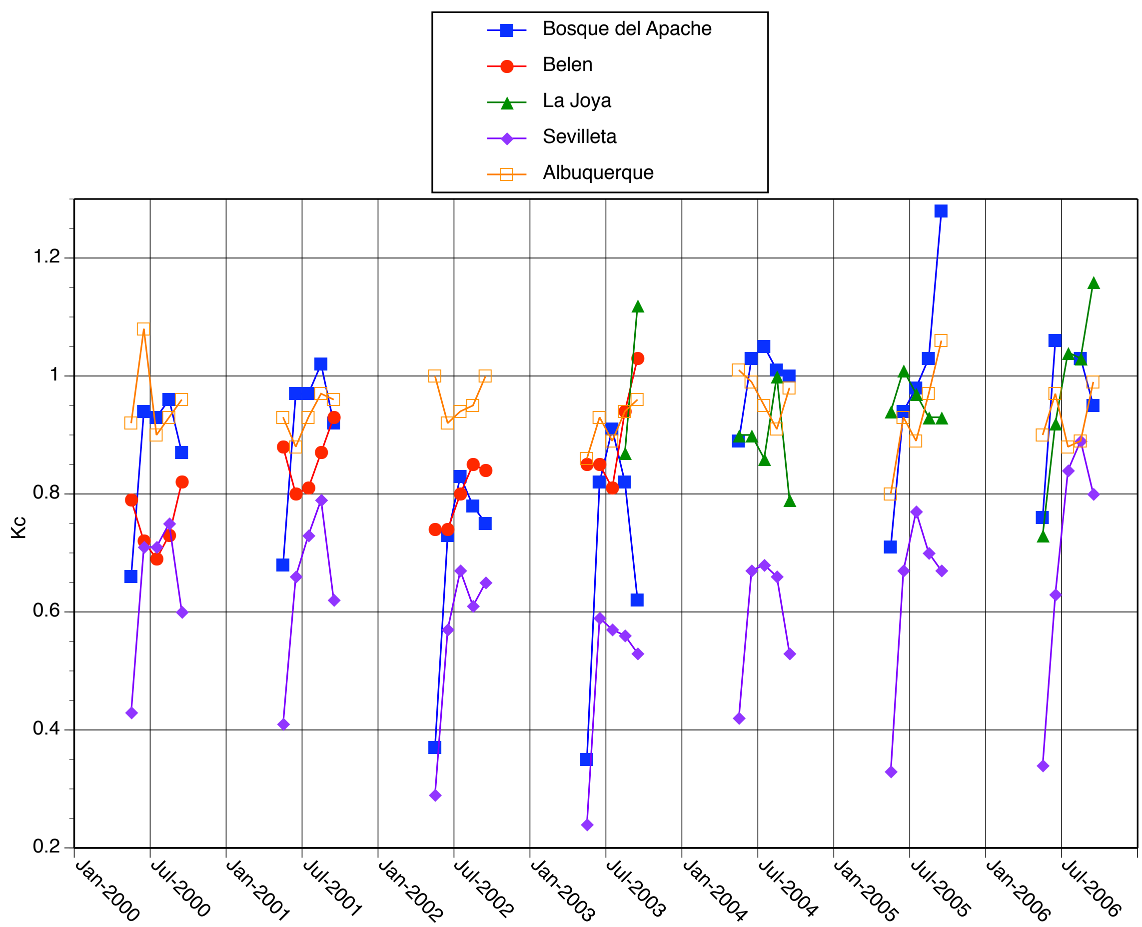

Figure 6. Values of Kc for the months of May through September of each year.

Table 1. Monthly values of Kc.

Month	Bosque del Apache NWR Kc	n	Belen Kc	n	La Joya SGR Kc	n	Sevilleta NWR Kc	n	Albuquerque Kc	n
Jan-2000										
Feb-2000										
Mar-2000	0.16	15	0.31	8			0.16	12	0.31	12
Apr-2000	0.19	29	0.32	29			0.16	28	0.40	29
May-2000	0.66	24	0.79	30			0.43	31	0.92	31
Jun-2000	0.94	11	0.72	29			0.71	30	1.08	30
Jul-2000	0.93	27	0.69	31			0.71	27	0.90	27
Aug-2000	0.96	18	0.73	28			0.75	25	0.93	28
Sep-2000	0.87	30	0.82	30			0.60	28	0.96	30
Oct-2000	0.55	19	0.94	21			0.44	20	1.16	22
Nov-2000	0.42	11	0.42	11			0.33	13	0.39	8
Dec-2000										
Jan-2001										
Feb-2001										
Mar-2001	0.12	12	0.20	17			0.16	17	0.23	16
Apr-2001	0.18	28	0.36	27			0.16	28	0.42	29
May-2001	0.68	28	0.88	29			0.41	28	0.93	29
Jun-2001	0.97	29	0.80	30			0.66	29	0.88	30
Jul-2001	0.97	28	0.81	30			0.73	24	0.93	21
Aug-2001	1.02	25	0.87	26			0.79	23	0.97	27
Sep-2001	0.92	27	0.93	29			0.62	17	0.96	26
Oct-2001	0.40	29	0.55	30			0.24	29	0.95	30
Nov-2001	0.17	18	0.09	22			0.16	19	0.35	27
Dec-2001										
Jan-2002										
Feb-2002										
Mar-2002										
Apr-2002										
May-2002	0.37	31	0.74	28			0.29	29	1.00	28
Jun-2002	0.73	29	0.74	24			0.57	30	0.92	30
Jul-2002	0.83	31	0.80	31			0.67	31	0.94	31
Aug-2002	0.78	30	0.85	31			0.61	31	0.95	31
Sep-2002	0.75	29	0.84	27			0.65	27	1.00	27
Oct-2002	0.43	27	0.48	27			0.34	28	0.91	31
Nov-2002	0.16	27	0.08	27			0.19	28	0.35	29
Dec-2002	0.56	8	0.11	2			0.33	4	0.76	11
Jan-2003										
Feb-2003										
Mar-2003	0.35	2	0.26	10			0.15	10		
Apr-2003	0.07	22	0.34	17			0.07	29	0.38	26
May-2003	0.35	31	0.85	31			0.24	31	0.86	31
Jun-2003	0.82	30	0.85	30			0.59	30	0.93	26

Table 1 continued. Monthly values of Kc.

	Bosque del Apache NWR		Belen		La Joya SGR		Sevilleta NWR		Albuquerque	
Month	Kc	n	Kc	n	Kc	n	Kc	n	Kc	n
Jul-2003	0.91	31	0.81	29			0.57	31	0.89	30
Aug-2003	0.82	31	0.94	30	0.87	31	0.56	31	0.94	23
Sep-2003	0.62	30	1.03	28	1.12	27	0.53	28	0.96	26
Oct-2003	0.47	30	1.02	29	0.94	26	0.44	30	0.91	27
Nov-2003	0.19	25	0.16	21	0.37	26	0.17	25	0.25	6
Dec-2003	0.14	30	0.17	3	0.17	28	0.12	28		
Jan-2004	0.10	13			0.20	22	0.22	29		
Feb-2004							0.14	1		
Mar-2004					0.16	7	0.08	11		
Apr-2004					0.61	18	0.34	27		
May-2004	0.89	26			0.90	19	0.42	31	1.01	17
Jun-2004	1.03	30			0.90	30	0.67	30	0.99	30
Jul-2004	1.05	31			0.86	6	0.68	31	0.95	13
Aug-2004	1.01	16			1.00	27	0.66	31	0.91	21
Sep-2004	1.00	29			0.79	30	0.53	29	0.98	21
Oct-2004	0.55	31			0.64	25	0.34	29	0.87	31
Nov-2004	0.25	1					0.29	25	0.51	2
Dec-2004	0.22	28			0.26	17				
Jan-2005	0.39	28			0.53	13				
Feb-2005	0.67	10			0.30	23				
Mar-2005	0.20	23			0.21	30	0.13	8	0.31	5
Apr-2005	0.24	30			0.41	30	0.11	26	0.31	22
May-2005	0.71	31			0.94	30	0.33	30	0.80	31
Jun-2005	0.94	24			1.01	29	0.67	30	0.93	30
Jul-2005	0.98	17			0.97	31	0.77	31	0.89	31
Aug-2005	1.03	31			0.93	31	0.70	20	0.97	31
Sep-2005	1.28	29			0.93	29	0.67	29	1.06	30
Oct-2005	0.68	30			0.91	28	0.57	28	1.01	28
Nov-2005	0.14	30			0.26	26	0.12	25	0.53	15
Dec-2005	0.11	31			0.11	30	0.12	28		
Jan-2006	0.08	30			0.11	29				
Feb-2006	0.06	27			0.06	28				
Mar-2006	0.04	28			0.07	29	0.05	23		
Apr-2006	0.18	30			0.15	29	0.06	28	0.71	5
May-2006	0.76	31			0.73	31	0.34	31	0.90	31
Jun-2006	1.06	20			0.92	30	0.63	30	0.97	15
Jul-2006					1.04	30	0.84	31	0.88	13
Aug-2006	1.03	20			1.03	31	0.89	31	0.89	29
Sep-2006	0.95	29			1.16	30	0.80	30	0.99	30
Oct-2006	1.00	11			0.90	29	0.47	16	0.69	30
Nov-2006					0.35	14	0.19	30	0.29	29
Dec-2006							0.29	25	0.40	27

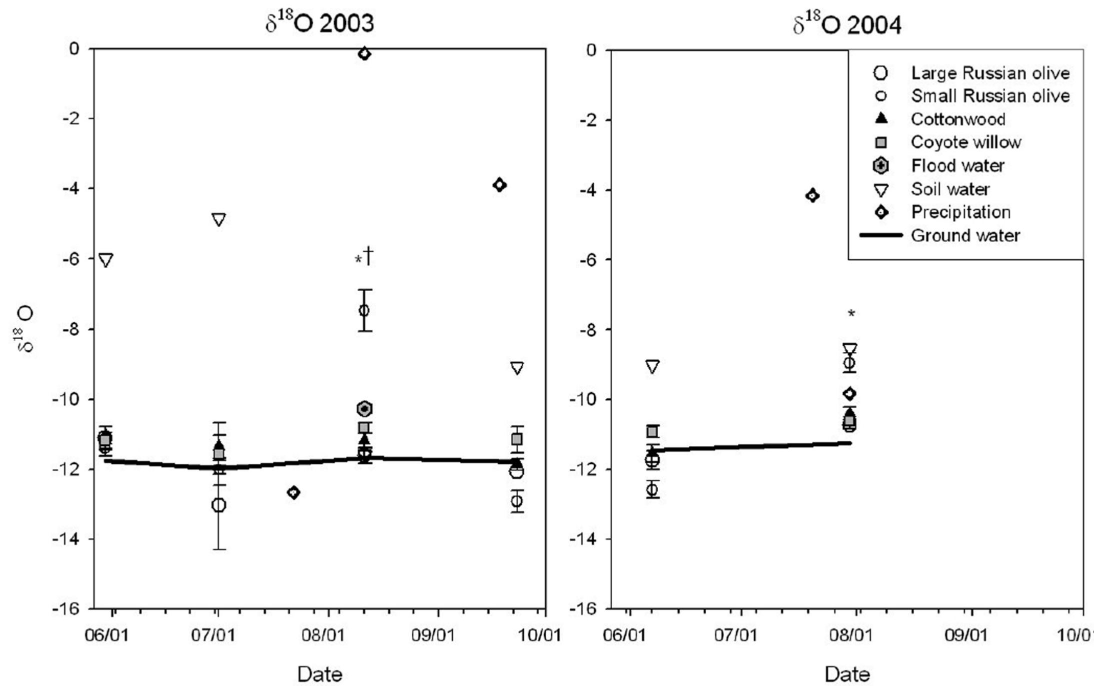

Figure 7. $\delta^{18}O$ of the three species and various source waters. The solid line shows groundwater values. * Small Russian olive significantly differs from groundwater. † Coyote willow significantly differs from groundwater. Soil water is at 5 cm depth on all dates except 8/11/03, when 30 cm depth was used due to lack of oxygen data for the 5 cm sample. Figure 6 in Trafton thesis (attached). (All data were collected at La Joya SGR.)

Vegetation Factors controlling ET

By shading the soil, dense vegetation along the MRG can limit soil evaporation. The dominant pathway for water loss from the ground to the atmosphere is through the vegetation (Fig. 7). Exceptions to this general rule were observed in August 2003, in which small Russian olive individuals and coyote willow (*Salix exigua*) had access to a mixture of groundwater, soil water, and precipitation water (Fig. 7). Because LE was reduced during August 2003 period when $H > 0$ (see Fig. 5), groundwater ET (as opposed to soil water ET) was reduced beyond the simple reduction in our measured ET rates, indicating that sites with small-stature riparian vegetation is transpiring less water from the river than larger phreatophytes during drought periods.

ET is further limited by restrictions on r_s, especially at high VPD (Fig. 8). At a given VPD, r_s has an upper limit but not a lower limit (Fig. 8), illustrating the importance of groundwater access in ameliorating stressful atmospheric conditions around the leaves and canopy. At low VPD, r_s was less restricted at the cottonwood site in Albuquerque's south valley than at the saltcedar and Russian olive sites (Fig. 8). There appeared to be a threshold restriction on r_s at high R_n, but that relationship was moderated by the direct relationship between VPD and r_s (Fig. 8). The flux of carbon dioxide (F_c) related to daytime photosynthesis is also restricted at high r_s, although there is very little correlation between r_s and F_c at low r_s. In general, photosynthetic carbon fluxes are lesser at the Bosque del Apache saltcedar site than at the La Joya Russian olive site. (Negative values of F_c represent CO_2 fluxing toward the surface as it occurs when pho-

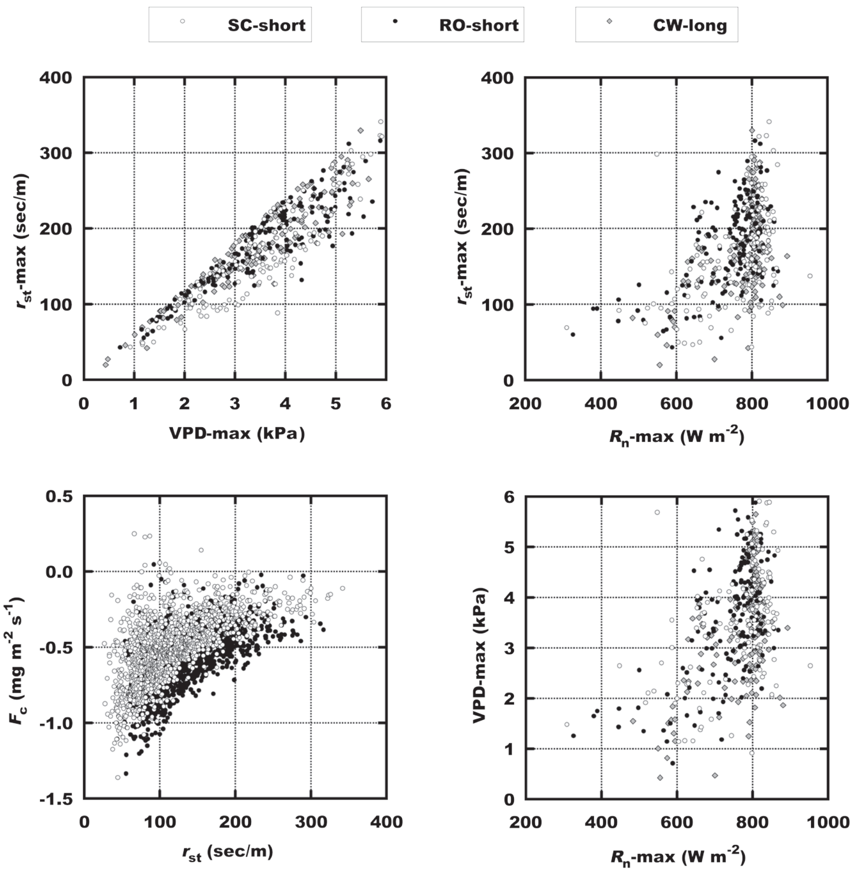

Figure 8. Bulk stomatal resistance (r_s) shown as a function of VPD and R_n. F_c: daytime flux of carbon.

tosynthesis is creating a demand for carbon.) Measured uptake of carbon during the day was four to five times the respiratory carbon flux that was measured at night. Measurements of nighttime F_c are confounded by reduced turbulence in the boundary layer at that time.

Contributions of Individual Phreatophyte Species

Sapflux measurements of the contributions of individual species was also pursued at the La Joya Russian olive site. With a medial density but very high transpiration rates per stem, Russian olive trees consume the most water of these three major riparian species (Table 2). So, as the contribution of Russian olive increases through time, ET at the La Joya site also increased (Fig. 4). Willow stems, which are smaller in stature but more numerous than cottonwood stems, average out to having an equivalent ET contribution at the La Joya site (Table 2). Individual stems and collective thick-

Table 2. Model of stand level transpiration with differing relative cover scenarios. Table 4 in Trafton thesis (attached).

Average daily rate (cm^3 hr^{-1})		Estimated stems per m^2	Species water consumption (mm day^{-1})	Proportion of total cover- Scenario 1	Scenario 2	Scenario 3	Scenario 4
Russian Olive	178	2.30	4.9	0.00	0.10	0.35	0.60
Cottonwood	128	1.70	2.6	0.60	0.60	0.35	0.20
Willow	57	3.30	2.3	0.20	0.10	0.10	0.00
	Total Community water use (mm day^{-1})			**2.02**	**2.28**	**2.51**	**3.20**
	*assuming 80% vegetation cover, dense stand						

ets of saltcedar are well known to vary widely, from much less than the results in Table 2 to as much or more than Russian olive (Cleverly et al. 2002). Indeed, ET at the two saltcedar sites was both extremely high and very low (Fig. 4). To properly manage water resources along the MRG, Kc values need to reflect not only the range of variation between species, but in different types of saltcedar thickets.

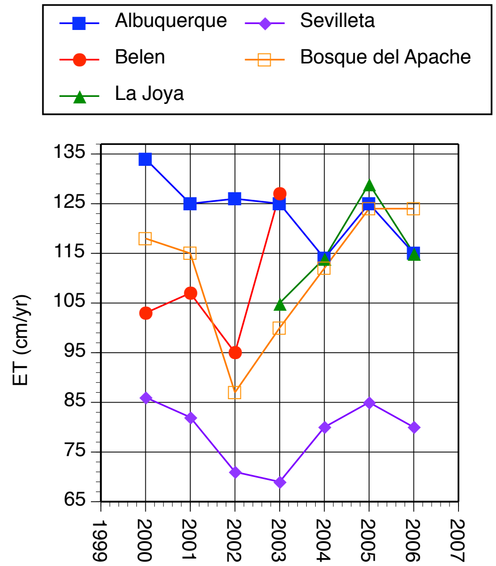

Figure 10. Pattern of annual ET at all sites. 2003: Partial removal. 2004: Removal and herbicide application to the cut stumps completed. 2005: Regrowth of saltcedar and Russian olive. 2006: Forest fire in early June.

Restoration

Removal of saltcedar and Russian olive from beneath the cottonwood canopy in Albuquerque's south valley resulted in an immediate change in the daily pattern of energy flux (Fig. 9). Before the understory was removed, scant insolation was incident on the soil surface, being intercepted by transpiring tissue instead. Then, beginning in 2003, morning H was positive, illustrating increased sunlight directly on the soil surface where evaporation is restricted by minimal surface soil moisture.

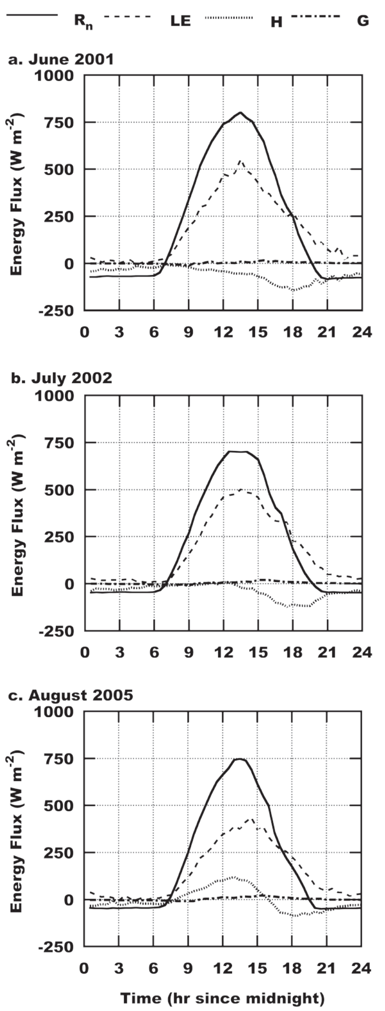

Figure 9. Daily pattern of energy fluxes in Albuquerque's south valley. Lines represent the monthly average flux for a given 30-min period.

Neither Kc nor ET was reduced at the Albuquerque south valley cottonwood site in 2002, the first year of the drought (Figs. 2, 6, & 10). However, in 2004, when an increase in ET and Kc was observed at the reference sites (Figs. 6 & 10), ET declined by 9% at the completely restored site in Albuquerque (Fig. 10). ET at the reference sites increased by 12% from 2003 to 2004. The total reduction in 2004 ET due to restoration was 21%, or 26 cm. Without the restoration work, ET at the Albuquerque site was expected to also increase by 12% and also returning to pre-drought rates.

No water savings were observed at this site following 2004 (Fig. 10). Equivalent increases in ET generated from restoration and reference sites between 2004 and 2005 are representative of the returning contribution of saltcedar and Russian olive as the vegetation re-sprouted from cut stumps and root crowns. This result illustrates the crucial importance of funding multi-annual return treatments to continue reaping the benefit of restoration on the water budget. On an optimistic note, ET rates in Albuquerque's south valley have not returned to their extravagant pre-drought levels (Fig. 10).

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