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Evapotranspiration on western U.S. rivers estimated using the Enhanced Vegetation Index from MODIS and data from eddy covariance and Bowen ratio flux towers

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Abstract

We combined remote sensing and in-situ measurements to estimate evapotranspiration (ET) from riparian vegetation over large reaches of western U.S. rivers and ET by individual plant types. ET measured from nine flux towers (eddy covariance and Bowen ratio) established in plant communities dominated by five major plant types on the Middle Rio Grande, Upper San Pedro River, and Lower Colorado River was strongly correlated with Enhanced Vegetation Index (EVI) values from the Moderate Resolution Imaging Spectrometer (MODIS) sensor on the NASA Terra satellite. The inclusion of maximum daily air temperatures (T_a) measured at the tower sites further improved this relationship. Sixteen-day composite values of EVI and T_a were combined to predict ET across species and tower sites ($r^2=0.74$); the regression equation was used to scale ET for 2000–2004 over large river reaches with T_a from meteorological stations. Measured and estimated ET values for these river segments were moderate when compared to historical, and often indirect, estimates and ranged from 851–874 mm yr^{-1}. ET of individual plant communities ranged more widely. Cottonwood (*Populus* spp.) and willow (*Salix* spp.) stands generally had the highest annual ET rates (1100–1300 mm yr^{-1}), while mesquite (*Prosopis velutina*) (400–1100 mm yr^{-1}) and saltcedar (*Tamarix ramosissima*) (300–1300 mm yr^{-1}) were intermediate, and giant sacaton (*Sporobolus wrightii*) (500–800 mm yr^{-1}) and arrowweed (*Pluchea sericea*) (300–700 mm yr^{-1}) were the lowest. ET rates estimated from the flux towers and by remote sensing in this study were much lower than values estimated for riparian water budgets using crop coefficient methods for the Middle Rio Grande and Lower Colorado River.

Keywords: Evapotranspiration; Riparian; Water balance; MODIS; Saltcedar; Remote sensing

1. Introduction

Evapotranspiration (ET) by riparian vegetation is an important component of the water budget of arid and semi-arid watersheds (Dahm et al., 2002; Goodrich et al., 2000). Accurate estimates of riparian zone ET are needed to properly and soundly apportion river water for human and environmental needs (Commission for Environmental Cooperation, 1999; Congalton et al., 1998; Hansen & Gorbach, 1997; U.S. Department of Interior, 2002). In the western U.S., many rivers are now dominated by saltcedar (*Tamarix ramosissima*), an exotic shrub that has partially replaced native trees such as cottonwood (*Populus* spp.), willow (*Salix* spp.) and mesquite (*Prosopis* spp.) on floodplains (DiTomosa, 1998; Glenn & Nagler, 2005). Flow-regulated rivers have been especially susceptible to vegetation turnover (Busch & Smith, 1995; Stromberg, 2001). There is uncertainty about the amount of water used by riparian vegetation (Drexler et al., 2004; Unland et al., 1998), and in particular by saltcedar (reviewed in Glenn & Nagler, 2005). In some studies, saltcedar has exhibited higher rates of ET than native vegetation, potentially

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increasing the rate of water use by riparian vegetation on infested rivers (DiTomosa, 1998; Sala et al., 1996). On the other hand, other studies have shown moderate rates of ET by saltcedar (Cleverly et al., 2002; Nagler et al., 2004, 2005a).

Differences among studies can be attributed to differences in measurement scales (varying from leaf level to stand level). Also, because saltcedar has flexible growth habits and can occupy niches with different amounts of water availability, it can be found in varying densities and heights, and thus, the ET rate varies (Sala et al., 1996). Determining actual rates of water consumption by riparian vegetation will require knowledge of species differences, as well as broad scale estimates over large river sections. Until recently, however, it has been difficult to accurately estimate ET over riparian ecosystems, as they are a mosaic of different species associations with variable amounts of bare soil and open water.

Eddy covariance and Bowen ratio flux towers are regarded as the most accurate methods of estimating ET at scales of 0.1 to 1 km (Rana & Katerji, 2000). Flux towers have now been established on several western rivers, including the Middle Rio Grande (Cleverly et al., 2002; Coonrod & McDonnell, 2001; Dahm et al., 2002), the Upper San Pedro (Scott et al., 2004; in press), and the Lower Colorado River and associated drainages (DeMeo et al., 2003; C. Westenburg, U.S. Geological Survey (USGS), unpublished data). They provide near-real time estimates of ET and carbon flux in undisturbed stands of vegetation covering several thousand square meters. Multiple years of data have been reported for many of the main western riparian species, including cottonwood (Cleverly et al., 2002), saltcedar (Cleverly et al., 2002), velvet mesquite (*P. velutina*), giant sacaton grass (*Sporobolus wrightii*), and mixed stands of species (DeMeo et al., 2003; Scott et al., 2004; in press). The U.S. Bureau of Reclamation and other agencies charged with determining riparian water budgets are now using flux tower data to refine their estimates of riparian ET (Nichols et al., 2004).

Directly extrapolating patch-scale data from flux towers to larger landscape units can lead to biased regional estimates, because a few tower sites cannot provide a fair sampling of a whole biome (Wylie et al., 2003). Wylie et al. (2003) recommended using remote sensing and other data sources to develop statistical algorithms by which site-specific tower data can be extrapolated to similar land-cover types at a regional scale. They showed that time-integrated Normalized Difference Vegetation Index (NDVI) data, over 14 day intervals over a sagebrush-steppe ecosystem, could be combined with ground meteorological data to map regional carbon fluxes based on flux tower data. We followed that general approach in the present research.

Our goal was to estimate ET rates over large river reaches by developing empirical models of ET for the riparian vegetative community. The models were created by developing a relationship between ET from flux towers, maximum daily air temperature (T_a), and Enhanced Vegetation Index (EVI) as determined by the Moderate Resolution Imaging Spectrometer (MODIS) sensor on NASA's Terra satellite. Since its launch in 1999, MODIS has provided 16-day composite, vegetation index (VI) measurements at 250 m resolution (Huete et al., 2002), a scale which is sufficient to monitor vegetation even on narrow, western U.S. riparian corridors. We tested the feasibility of developing a single predictive equation for ET across sites and different plant associations; this is important because individual plant associations cannot be distinguished on most satellite imagery (Dahm et al., 2002; Nagler et al., 2005b). If species-specific algorithms were needed to scale tower ET data to larger areas, detailed, species-level vegetation maps of each river stretch would also be needed. These are difficult to construct even with high-resolution, aerial photography (Nagler et al., 2005b).

In previous research, Nagler et al. (2005a) developed an empirical relationship between ET, produced by eddy covariance flux towers, and EVI data collected by MODIS for cottonwood (*Populus deltoides* var. *wislezenia*) and saltcedar stands on the Middle Rio Grande. ET measurements at the tower sites were correlated with 16-day, composite EVI values for the MODIS pixel encompassing the tower site. ET was predicted from EVI and T_a by a single, empirical equation ($r^2=0.80$) across species, sites, and years.

To accomplish the present study objectives, we first extended the relationship between MODIS EVI, T_a and ET to five additional tower sites, encompassing three additional plant types, on two additional river systems. We then used MODIS EVI and T_a data to estimate ET for large stretches of the Middle Rio Grande, the Upper San Pedro River, and the Lower Colorado River, for individual plant types and land cover classes within the riparian zones.

The rivers present a contrast with respect to base flow, degree of human modification, and extent of saltcedar infestation. The Lower Colorado has a high base flow, but has been extensively modified by dams and flood control structures so that the river now rarely leaves its channel (Busch and Smith, 1995; U.S. Department of Interior, 2000). The floodplain of the river has become salinized and is dominated by saltcedar growing in association with other salt-tolerant shrubs (Nagler et al., 2004, 2005b). The Middle Rio Grande has a lower base flow than the Lower Colorado River (Dahm et al., 2002). The flow has been moderately altered by dams and flood control structures; however, annual flows are variable and overbank flooding still occurs on this river stretch. Saltcedar is co-dominant with native trees on much of this river stretch. The small amount of base flow along the Upper San Pedro is interrupted with perennial and intermittent reaches; total annual flows for this river are largely influenced by flood flows that exhibit a large degree of interannual variability (Leenhouts, in press). There are no dams along the San Pedro, and it is dominated by native trees and grasses, and at present, saltcedar is less than 3% of plant cover (Watts, 2000). Thus, this study was able to compare ET across river systems that differed markedly in human disturbance of the natural flow regime, and in degree of infestation by saltcedar.

2. Materials and methods

2.1. Study sites

The location of ET towers and descriptions of vegetation types at each tower are in Table 1. Descriptions of larger river sections, giving base flow rates, areas of coverage, and vegetation characteristics are summarized in Table 2 and are illustrated in Fig. 1. Coverage area on the Middle Rio Grande was 82,315 ha, along a 320 km stretch. A different study defined this stretch as 68,000 ha (Coonrod & McDonnell, 2001; Dahm et al., 2002); differences are because the edge of the riparian corridor is not always distinct, and our delineation differed slightly from theirs. Coverage on the Upper San Pedro was 5875 ha, along a 100 km reach from the International border to the USGS stream gauge "Tombstone," east of the city of Sierra Vista. Coverage on the Lower Colorado River was approximately 8925 ha, along a 15 km stretch of river at Havasu National Wildlife Refuge (HNWR) near Needles, California. The Middle Rio Grande contained four eddy covariance flux towers, two in saltcedar habitat and two in cottonwood habitat (Cleverly et al., 2002). The San Pedro had three eddy covariance flux towers, one in dense mesquite woodland, one in a (less dense) mesquite shrubland, and one in a sacaton grass habitat (Scott et al., 2004, in press). HNWR has three Bowen ratio towers, one in dense saltcedar, one in arrowweed (*Pluchea sericea*), and the third in mixed saltcedar, mesquite, and arrowweed. Data from the dense saltcedar and arrowweed towers were used in this study. The tower site in the mixed saltcedar and arrowweed stand was adjacent to a large, cleared area, and the MODIS pixel encompassing the tower site also contained a large amount of bare soil from the adjacent cleared area, hence this tower site was not included in the analysis.

Unfortunately, the descriptions of land cover classes in Table 2 are not uniform among river systems, because different survey and mapping systems have been used for each river system. Note that the riparian corridor of the Middle Rio Grande has considerable urban, pasture, and agriculture land in addition to riparian vegetation (Dahm et al., 2002). By contrast, HVWR and the Upper San Pedro are all riparian habitat.

2.2. ET data

ET methods have been described in detail in other publications; for the Middle Rio Grande, see Cleverly et al. (2002); Dahm et al. (2002); for the Upper San Pedro, see Scott et al. (2004, in press); and for the Lower Colorado River, see DeMeo et al. (2003). Eddy covariance flux towers, used on the Upper San Pedro and Middle Rio Grande, estimate moisture and sensible heat fluxes based on measurements in the turbulent boundary layer above the canopy (Rana & Katerji, 2000). Sensors measure air temperature, water content of the air, and the vertical component of wind speed at 10 Hz, and the fluxes of water and sensible heat are statistically determined every 30 min. Over flat terrain the mean vertical component of wind speed over the longer time scales is zero, but in any given moment the vertical component of the wind may have an upward or downward velocity. If the eddies responsible for this vertical motion move more moisture upwards on average, then a net flux of moisture from canopy to atmosphere results. The moisture flux measurements allow ET to be calculated directly, whereas additional instruments allow the surface

Table 1
Location and characteristics of the seven tower sites at which evapotranspiration (ET) was measured on the Middle Rio Grande, New Mexico and the Upper San Pedro, Arizona

Site	Longitude (°)	Latitude (°)	Elevation (m)	Vegetation
Rio Grande, Saltcedar, Flooded	−106.9	33.8	1375	Dense, monospecific saltcedar, LAI = 3.6, maximum ht = 10 m.
Rio Grande, Saltcedar, Unflooded	−106.9	34.3	1427	Saltcedar with saltgrass understory, LAI = 2.6, maximum ht. = 10m.
Rio Grande, Cottonwood, Flooded	−106.7	34.6	1465	Cottonwood overstory with sparse understory, LAI = 2.1, maximum ht. = 25 m.
Rio Grande, Cottonwood, Unflooded	−106.7	35.0	1500	Cottonwood overstory with dense understory LAI = 3.3, maximum ht. = 25 m.
San Pedro, Mesquite Woodland	−110.2	31.7	1200	Tall and dense mesquite overstory with grass/shrub understory, LAI = ~1.5; PAI = 2.0, maximum ht. = 10 m
San Pedro, Mesquite Shrubland	−110.1	31.5	1230	Sparser mesquite shrubland grass and shrub-grass understory. LAI = ~1.2; PAI = 1.5, maximum ht. = 4 m.
San Pedro, Giant Sacaton Grassland	−110.1	31.5	1230	Dense stand of giant sacaton grass, LAI = 4.2 PAI = 2.5, maximum ht. = 1.5 m
Lower Colorado, Dense Saltcedar	−114.5	34.8	133	Moderate to very dense, homogeneous saltcedar, to 6 m height.
Lower Colorado, Arrowweed	−114.6	34.8	167	Sparse to moderately dense arrowweed, with a few saltcedars.

Table 2
Characteristics of river stretches over which ET was estimated

Parameter	Middle Rio Grande	Upper San Pedro	Lower Colorado at HNWR
Length, km	320	100	15
Area, ha	82,718	5875	8925
Annual flow	Mean: 626	Mean: 31	Mean: 10,204
Volume (2000–2004), million m^3	Range: 416–779	Range: 1–95	Range: 9639–10,397
Vegetation composition	Riparian forest (8.4%), riparian scrub (7.9%), marsh/water (4.7%), cultivated (42.1%), urban/suburban (36.9%), from Dahm et al., 2002	Mesquite (43%), cottonwood/willow (11%), giant sacaton (14%), saltcedar (3%), other plants (mainly upland spp.) (27%), barren or water (2%), from U.S. Army Corp. of Engineers, 2000.	Saltcedar and arrowweed (ca. 1 : 1 ratio) (85%), willows (1.2%), bare soil (12.0%), other (1.8%), from Nagler et al., 2005b

energy balance to be calculated to check the validity of the ET measurements. A simplified energy balance at the land surface is described by the equation:

$$R_n - G = \mathrm{LE} + H \quad (1)$$

R_n is net radiation, measured above the canopy by a net radiometer. G is ground heat flux, measured with soil heat flux plates. LE is the latent heat flux (evaporation multiplied by the latent heat of vaporization), and H is sensible heat flux. Units are $W\,m^{-2}$. ET (mass per unit area per unit time) is calculated from LE by dividing it by the latent heat of vaporization of water per unit mass. ET in this paper is expressed as mm d^{-1} (length per time over any area), by converting mass of water to volume of water based on the density of water.

At many eddy covariance sites, LE+H, both of which are estimated by the eddy covariance method, are often on the average less than $R_n - G$ (Twine et al., 2000; Wilson et al., 2002). The degree to which the energy balance was not closed for the data used in this study for the Middle Rio Grande and Upper San Pedro River ranged from 10 to 30% $[1-(R_n-G)/(\mathrm{LE}+H)]$ (Cleverly et al., 2002; Dahm et al., 2002; Scott et al., 2004, in press) and was typical of other eddy covariance studies (Wilson et al., 2002). The daily mean values of LE from the tower sites on these two rivers were adjusted upwards by the degree to which the energy balance was not closed for each 24 hr period in a manner that conserves the daily ratio of H/LE (Cleverly et al., 2002; Scott et al., 2004, in press). The Bowen ratio closure method was used, in which both LE and H are increased equally (Twine et al., 2000).

Tower sites at HNWR measured ET by the Bowen ratio energy balance (BREB) method (DeMeo et al., 2003). The BREB method measures air temperature and moisture content at two heights above the canopy to calculate LE and H fluxes based on the gradient of air temperature and

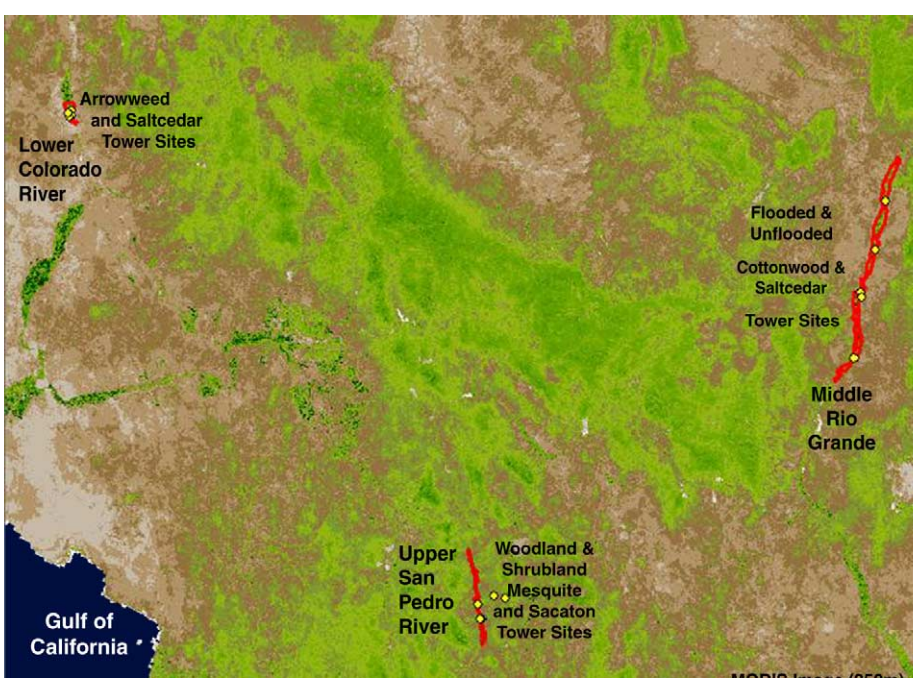

Fig. 1. Locator map for river stretches and tower sites in this study.

vapor pressure between sensors. Calculating H and LE fluxes cannot be done directly because the turbulent transfer coefficients of heat and vapor are not known. However, if they are assumed to be equal to each other, the ratio of H/LE (the Bowen ratio, β) can be calculated as the gradient of H between the two points over the canopy divided by the gradient of LE between the same points:

$$\beta = \gamma[T_l - T_u]/[e_l - e_u] \quad (2)$$

where γ is the psychrometric constant, $T_l - T_u$ is the difference temperature difference between the lower and upper temperature sensors, and $e_l - e_u$ is the vapor pressure difference between the lower and upper vapor pressure sensors. Then Eq. (1) can be solved for LE:

$$\mathrm{LE} = (R_n - G)/(\beta + 1). \quad (3)$$

The BREB method is considered an indirect method because it does not measure moisture flux directly but calculates it from the surface energy balance equation. Sensors used to calculate the Bowen ratio at each tower site included: a net radiometer to measure incoming and outgoing (emitted from surface) reflected short- and long-wave radiation; two air–temperature–humidity probes at heights of 1.5 m and 2.5 m above mean canopy height; an anemometer to measure wind speed at the upper sensor height; soil heat flux plates to measure the heat flux into or out of the ground. Temperature and humidity were measured at 30-s intervals and the position of the upper and lower sensor stations were rotated between measurements to reduce instrument bias in calculating differences between upper and lower stations. ET data were calculated as 20-min averages and summed over each day. DeMeo et al. (2003) reported excellent agreement (r^2=0.99, mean difference less than 5%) between eddy covariance and BREB methods where both methods were used over one year at the same mixed grasses site in the Mohave Desert watershed.

2.3. Collection of MODIS data

The spatial and temporal patterns of seasonality at the intensive sites and along the climate transect were analyzed with four years (2000–2004) of MODIS VI, 16-day, time series data at 250 m resolution. The MODIS VI products ingest level 2G (gridded) daily surface reflectances (MOD09 series), corrected for molecular scattering, ozone absorption, and aerosols. The 16-day VI product uses a quality assurance (QA) filtering scheme to provide improved spatial and temporal consistency in VI values on an operational basis. The NDVI, Eq. (4), and EVI, Eq. (5), are generated as:

$$\mathrm{NDVI} = (\rho_{\mathrm{NIR}} - \rho_{\mathrm{Red}})/(\rho_{\mathrm{NIR}} + \rho_{\mathrm{Red}}) \quad (4)$$

$$\mathrm{EVI} = 2.6(\rho_{\mathrm{NIR}} - \rho_{\mathrm{Red}})/(\rho_{\mathrm{NIR}} + 6 \times \rho_{\mathrm{Red}} + 7.5 \times \rho_{\mathrm{Blue}} + 1.0) \quad (5)$$

where ρ is the surface reflectance in the wavelength band, the blue and red band coefficients are to minimize aerosol variations, and has a canopy background correction term of 1.0 (Huete et al., 2002). In this research, we tested both EVI and NDVI as predictors of ET and selected EVI for the final predictive equation because it was more closely correlated with ET than was NDVI (see Results). We only used positive values of EVI so that we would eliminate open water.

2.4. Compilation of data sets and statistical methods

For calibrating ET flux data to MODIS VIs, single-pixels containing the coordinates for a tower were extracted. The location was visually confirmed by reference to high-resolution aerial photographs registered to the MODIS images. The 16-day mean values of ET and T_a measured at each tower site, which were mean daily values of 30-s measurements, were calculated for each year, for the growing season. For years 2000–2003, we used data for Day 65 to Day 337 to correlate EVI and T_a with ET at tower sites. Based on EVI values, we estimated a 18% drop in ET at the tower site and a 22% drop in ET over the whole floodplain between 2001 and 2002 (Table 4). We then conducted regression analyses, to obtain the best coefficients for predicting ET from independent variables across tower sites.

For the final predictive equation for ET across sites, we converted EVI to a scaled value (EVI*), as recommended by Choudhury et al. (1994). For EVI*, the lowest value ($\mathrm{EVI}_{\mathrm{min}}$) in the data set is set at 0 and the highest value ($\mathrm{EVI}_{\mathrm{max}}$) is set at 1.0:

$$\mathrm{EVI}^* = 1 - (\mathrm{EVI}_{\mathrm{max}} - \mathrm{EVI})/(\mathrm{EVI}_{\mathrm{max}} - \mathrm{EVI}_{\mathrm{min}}). \quad (6)$$

We based our model equation for predicting ET from EVI* on the relationship between leaf area index (LAI) and light absorption by a canopy:

$$fIRs = \left(1 - e^{-kLAI}\right) \quad (7)$$

where fIRs is the fraction of incident radiation intercepted by the canopy, IRs/Rs; Rs is the total incident solar radiation; and k is a constant determined by the leaf angles and spectral properties of the canopy (Monteith & Unsworth, 1990). LAI and k vary widely among these riparian species but Nagler et al. (2004) reported that NDVI was linearly related to $(1 - e^{-k\mathrm{LAI}})$ across species. For well-watered vegetation, ET is linearly related to net radiation (R_n) absorbed by the canopy, and therefore to fIRS (Monteith & Unsworth, 1990). When all other factors that affect ET are held constant, Choudhury et al. (1994) showed that ET is a function of VI times potential ET ($\mathrm{ET_o}$) for a reference crop, calculated from meteorological data. This relationship was found to hold for three VIs over 19 different soil types and across different crops, although effects of water stress or soil evaporation added scatter and uncertainty to the relationship (Choudhury et al., 1994). The type of function relating ET to VI depends on the VI used (Choudhury et al., 1994). Nagler et al. (2001) reported that EVI is linearly related to LAI for mixed riparian scenes along the Lower Colorado River, hence we assumed that EVI* could replace kLAI in Eq. (7).

Nagler et al. (2004) reported that T_a rather than reference crop ET_o was the meteorological variable most closely correlated with measured ET. To model the ET response to temperature, we normalized the ET data for each tower site so that the minimum ET was 0 and the maximum was 1 at each site (as in Eq. (6)), then we fit a dose response (sigmoidal) curve to the ET vs. T_a for combined data sets. This model assumes a minimum temperature below which ET approaches zero, a mid-region where ET responds to T_a in proportion to the increase in vapor pressure deficit as a function of T_a, and a maximum temperature above which ET does not increase due to an increase in physiological resistance (Jones, 1983; Monteith & Unsworth, 1990). The final predictive equation in Nagler et al. (2004) was based on EVI* and T_a took the form:

$$\mathrm{ET} = a\left(1 - e^{-bEVI^*}\right)\left(c/\left(1 + e^{-(T_a - d)/e}\right)\right) + f \quad (8)$$

where the coefficients were determined by regression analyses between ET and the independent variables. The terms a, b, c, d, e, and f are constants generated by the regression analysis to produce a curve of best fit between ET and the independent variables.

Note that to test the closeness of the relationships among variables we chose to report correlation coefficients (r), while for predictive, regression equations we chose to report coefficients of determination (r^2), which gives the proportion of variability in the dependent variable that can be explained by the independent variables (Sokal & Rohlf, 1995).

2.5. Extrapolation of ET over large river stretches and for different plant associations

Once a relationship between EVI*, T_a, and ET at the tower sites was established, we used EVI* and T_a data to estimate ET over larger areas for the years 2000 to 2004. For extracting EVI values for whole river stretches, data layers outlining the riparian corridor of each river section were prepared from MODIS images with ArcMap (ESRI, Redlands, CA) and ERDAS (Leica Geosystems, Atlanta) software. For individual plant associations, representative patches of each plant type were first located on 2002 aerial images (1 m resolution) available for the Upper San Pedro and HNWR (Nagler et al., 2005b). The MODIS EVI pixel corresponding to each vegetation patch was located by first registering the aerial image to a 2002 MODIS EVI image; then the exact pixels encompassing the vegetation patch were identified by visually aligning landmarks such as river bends and patterns of vegetation density on the aerial image and the MODIS image, using split-screen viewers in ERDAS Imagine. EVI data for pixels representing each vegetation patch were extracted for Days 65–337, 2002. We selected sample sites to represent, as far as possible, the range of biomass intensities for each plant type. For the saltcedar comparison, we selected 15 sites on a photomosaic of HNWR along a gradient running from the wetted marsh edge, to the upper bench several kilometers away from the wetted edge (Nagler et al., 2005b). Twelve patches of arrowweed at HNWR were also sampled. Only a single patch of willow, approximately 50 ha in area at HNWR, was large enough to extract MODIS EVI data that was not mixed with other plant types. Six pixels in that patch were sampled. Fifteen (dense) woodland mesquite and 15 (less dense) shrubland mesquite sites on the Upper San Pedro were sampled. Twelve giant sacaton grassland sites were also sampled on the Upper San Pedro. We were unable to locate cottonwood stands on either river that were large enough to cover a MODIS EVI pixel, hence they were not sampled.

We did not have aerial photography for the Middle Rio Grande, hence individual plant types were not sampled. However, the Middle Rio Grande has agricultural, urban, and suburban land within the riparian corridor in addition to riparian vegetation, and these can be distinguished on Landsat satellite images (Dahm et al., 2002). Representative patches of each land cover type were identified on an August, 2002, Enhanced Thematic Mapper (ETM+) image, then the corresponding EVI pixels were extracted from the 2002 MODIS images for Days 65–337. Approximately 150 MODIS pixels (ca. 940 ha) per land cover class, at sites distributed along the length of the river, were randomly sampled. Urban land, such as parts of Albuquerque that are within the floodplain, was excluded. However, suburban residential lots, which are partially forested and cover approximately 10,000 ha in the floodplain (Dahm et al., 2002) were included.

3. Results

3.1. Correlation between ET, NDVI, EVI*, and Ta

Eight of the nine tower sites showed a strong correlation ($r > 0.80$) between ET and EVI* (Table 3). ET was only moderately correlated with EVI* at the arrowweed site at HNWR ($r = 0.64$). This species is evergreen (Ferren et al., 1996), whereas the other species are either deciduous or winter-dormant (giant sacaton). Hence, for arrowweed, EVI* remained high through November because leaves were retained on the plant even though ET had slowed, whereas for the other species ET and EVI* followed the same seasonal curve. EVI and EVI* gave identical results in all cases. ET was also significantly ($P < 0.05$) correlated with NDVI for all tower sites but not as strongly as with EVI*. ET was also strongly correlated with T_a at all sites. When EVI* and T_a were combined in a multiple linear regression equation, for most sites the correlation with ET

Table 3
Correlation coefficients between ET and vegetation indices (EVI and NDVI) and air temperature (T_a) at the seven eddy covariance flux tower sites on the San Pedro and Rio Grande rivers and two Bowen ratio towers on Lower Colorado River

ET tower site	EVI	NDVI	T_a	EVI+T_a
San Pedro, Charleston mesquite	0.87	0.83	0.77	0.88
San Pedro, Lewis Spring mesquite	0.86	0.82	0.77	0.90
San Pedro, Lewis Spring sacaton	0.94	0.82	0.82	0.97
Rio Grande saltcedar flooding	0.83	0.68	0.84	0.88
Rio Grande saltcedar nonflooding	0.84	0.52	0.82	0.89
Rio Grande cottonwood flooding	0.84	0.74	0.86	0.90
Rio Grande cottonwood nonflooding	0.82	0.77	0.89	0.89
HNWR dense saltcedar	0.83	0.64	0.92	0.92
HNWR arrowweed	0.64	0.50	0.76	0.79
All sites combined	0.77	0.66	0.75	0.84

All correlation coefficients are significant at $P<0.05$.

was improved over either variable alone (Table 3). For the combined data sets, both EVI* and T_a were significant terms in the multiple regression equation ($P<0.001$). The correlation coefficient between ET and EVI* plus T_a for combined data sites was 0.84, only slightly lower than for individual tower sites (mean=0.89). Hence, this analysis supported the use of the EVI* and T_a for estimating ET across sites and species.

3.2. Predictive equations for ET

The multiple linear regression model assumes that EVI* and T_a are additive and independent in determining ET. More logically, ET should be dependent on light intercepted by the canopy (e.g., EVI*), times a scaling factor to account for the effect of T_a. The combined data sets showed a curvilinear relationship between ET and EVI* (Fig. 2A). We fit a curve in the form of Eq. (4) (a hyperbolic rise to a maximum) between ET and EVI*. In contrast to the linear correlation analysis, in which EVI* and EVI were equivalent, in the nonlinear analysis EVI* provided a better fit to ET than EVI ($r^2=0.62$ and 0.56, respectively). We fit a

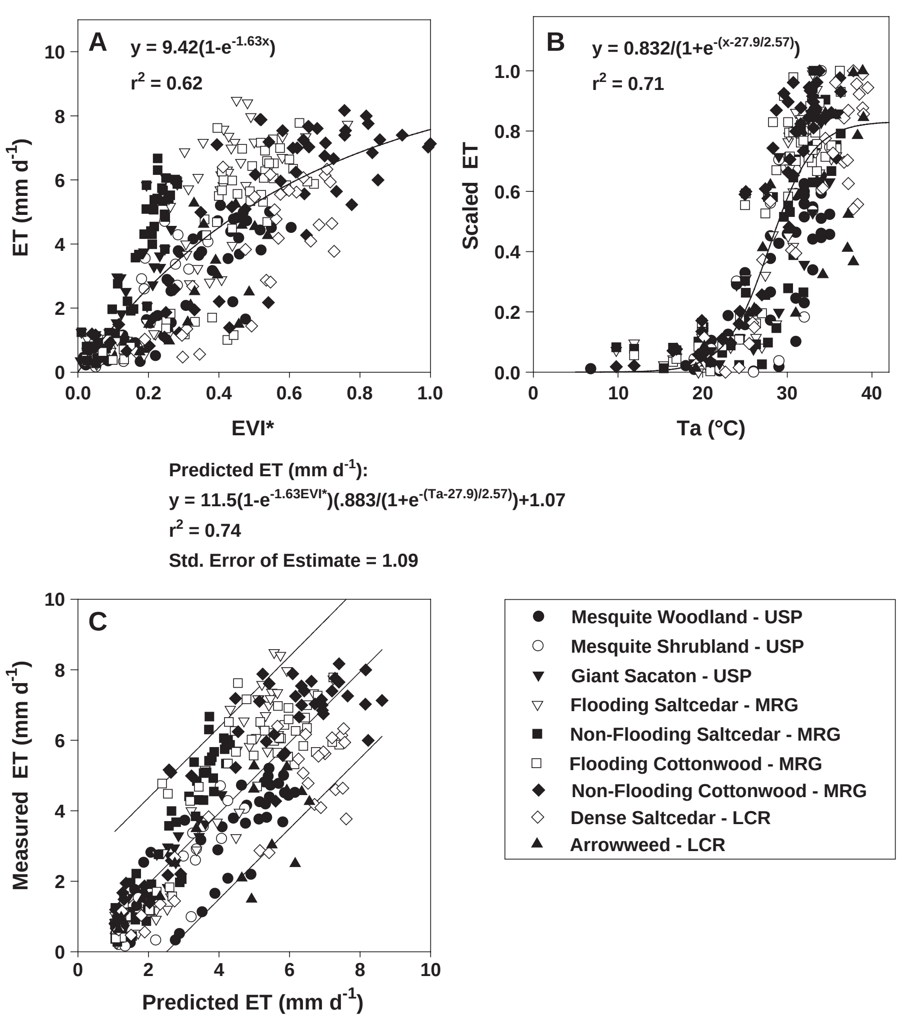

Fig. 2. Regression equations for ET vs. scaled EVI (EVI*) (A); scaled ET vs. maximum daily air temperature (T_a) (B); and measured vs. predicted ET based on EVI* and T_a (C) at nine flux towers on the Upper San Pedro, Middle Rio Grande, and Lower Colorado rivers. Data points are 16-day values for EVI*, T_a, and ET at each tower site. Lines around data points in (C) show the 95% prediction intervals. River abbreviations in the legend are USP = Upper San Pedro River; MRG = Middle Rio Grande; and LCR = Lower Colorado River at Havasu National Wildlife Refuge.

sigmoidal curve to the ET vs. T_a data (Fig. 2b). Temperatures below about 20 °C supported negligible ET, while ET appeared to approach a maximum value at approximately 35 °C. The two equations were then multiplied together and subjected to linear regression to produce a single predictive equation as in Nagler et al. (2005a):

$$ET = 11.5\left(1 - \exp^{-1.63EVI^{*}}\right) \times \left(0.883/\left(1 + \exp^{(-T_a - 27.9)/2.57}\right) + 1.07. \quad (9)$$

The r^2 was 0.74 and the root mean square error was 1.09 mm d^{-1} (Fig. 2c). The y-intercept value, 1.07, is the mean value of ET when EVI* approaches 0 or T_a is below 20 °C. Midwinter values for ET were approximately 0.6 mm d^{-1}, lower than the minimum for Days 65–337 expressed in Eq. (9). According to Eq. (9) the maximum possible ET when EVI*=1 and T_a=35 °C is 8.8 mm d^{-1}, similar to the observed maximum.

Measured ET and predicted ET at each tower site are plotted across measurement periods in Fig. 3. In general the measured and predicted seasonal curves are in good agreement. However, on the Middle Rio Grande, measured peak summer values of saltcedar ET were lower than predicted values. This is due to more drought stress and water limitations than the other sites. Both measured and predicted ET tended to peak in August or September at sites on the Upper San Pedro and Middle Rio Grande. At HNWR, which has a consistent water supply and lower elevation relative to the other rivers, measured values of ET peaked in June or July, whereas predicted values peaked in August. Arrowweed maintained high EVI* values as late as November, leading to spuriously high values for predicted late season ET.

We conducted an anaysis of variance of the residuals (observed– predicted values). Residuals were not randomly distributed, but differed by tower site (Fig. 4A) and species (Fig. 4B)(P<0.05). Predicted values were significantly (P<0.05) higher than observed values at the HNWR sites. The observed values were not corrected for energy closure as were values for the other tower sites. When plotted by species, predicted and observed values

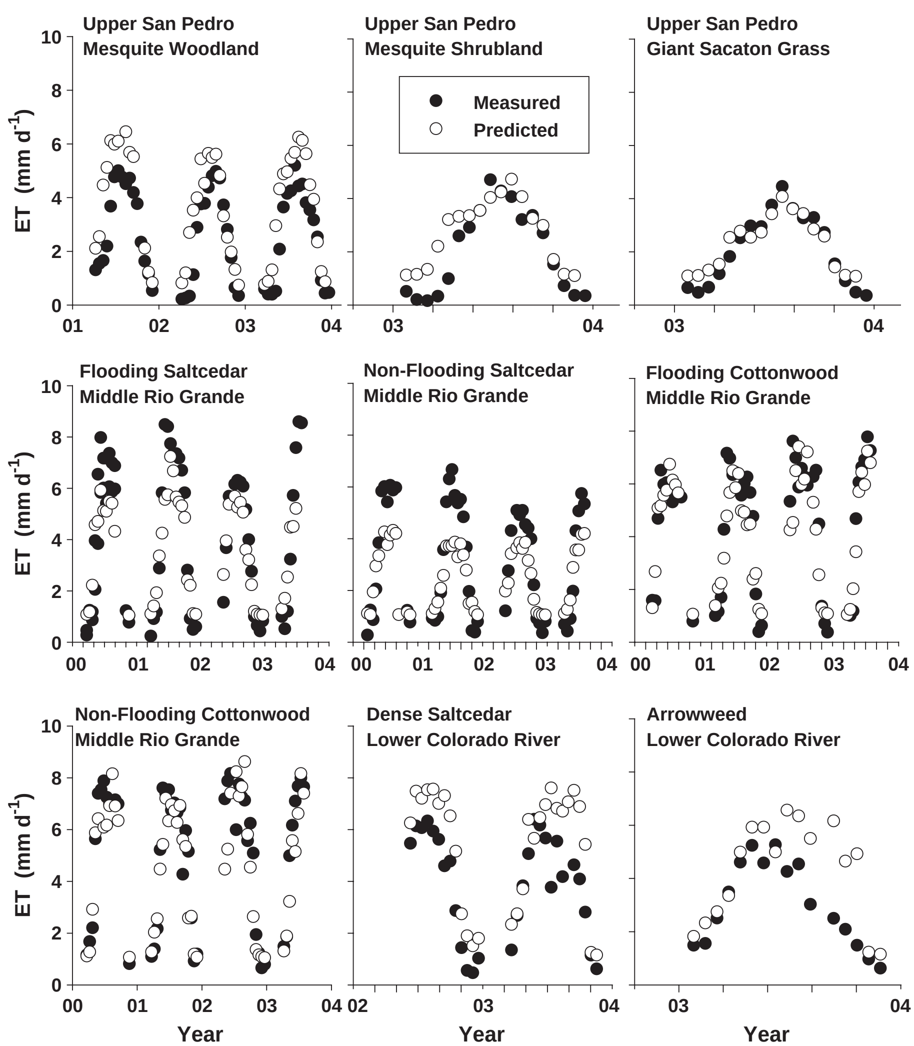

Fig. 3. Predicted (open circles) and measured (closed circles), 16-day ET values at each flux tower site. ET was predicted from EVI* and T_a.

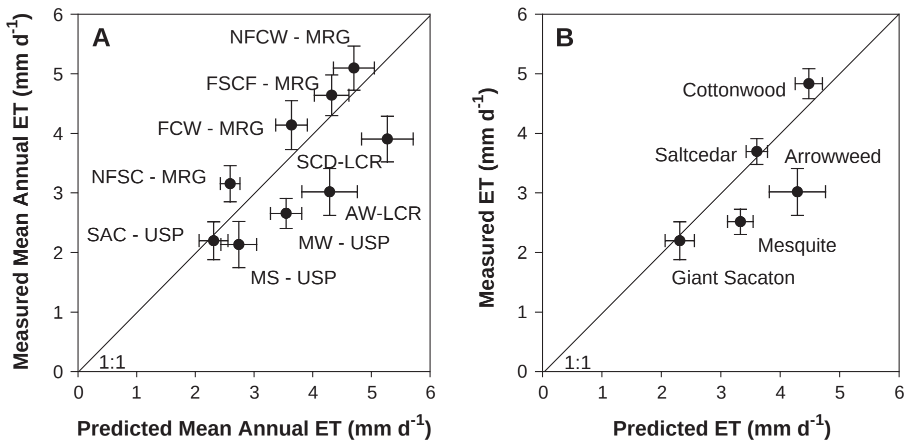

Fig. 4. Predicted and measured mean growing-season ET rates by tower site (a) and by plant species (b). Error bars are standard errors of the mean for 16-day mean values, and reflect the seasonal variation in ET. Abbreviations of tower sites refer to flooding (F) or non-flooding (NF), saltcedar (SC) or cottonwood (CW) sites on the Middle Rio Grande (MRG); saltcedar or arrowweed (AW) sites on the Lower Colorado River (LCR); and mesquite woodland (MW), mesquite shrubland (MS), or giant sacaton grass (SAC) sites on the Upper San Pedro River (USP).

were within 25% of the 1:1 line for all species except arrowweed, for which predicted ET values were 40% higher than measured values.

Eq. (9) is similar in form to the predictive equation developed for the four tower sites on the Middle Rio Grande (Nagler et al., 2005a). When the equation developed in that study was applied directly to the expanded data set in the present study, the coefficient of determination was nearly as great as Eq. (7) ($r^2=0.70$), but predicted ET was about 1 mm d^{-1} higher than measured ET across sites. The previous work assumed a linear response between ET and T_a, whereas Eq. (9) accounts for the apparent non-linearity of the response below 20 °C and above 35 °C in the expanded data set.

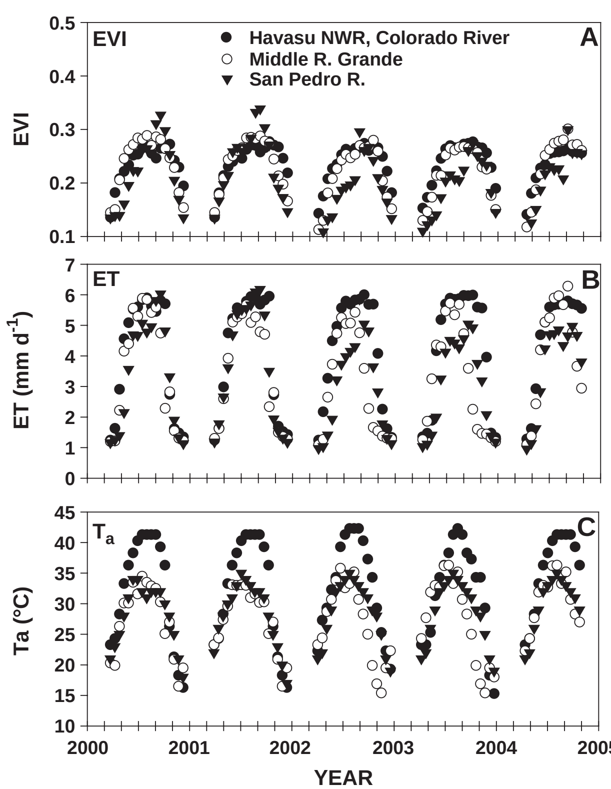

Fig. 5. Seasonal, 16-day composite, EVI (A), calculated ET values (B), and maximum daily air temperature (T_a) (C), and for Middle Rio Grande, Lower San Pedro River, and the Lower Colorado River stretches, 2000–2004.

3.3. Estimation of ET along river stretches

Eq. (9) was used to predict ET values along the river stretches in Table 1 using MODIS imagery. Data layers outlining each river stretch were overlaid on MODIS images, and EVI values for Days 65–327, Years 2000–2004, were extracted. T_a data for each river stretch was derived from meteorological station data. EVI and ET values were similar for the three river stretches (Fig. 5A,B), even though the Lower Colorado had significantly higher T_a (Fig. 5C). Annual ET, calculated for each river stretch from data in Fig. 5B, was 851–874 mm yr^{-1} for all river systems (Table 4) (2004 data were incomplete so that year was omitted). Year-to-year variation was low for the Middle Rio Grande and Lower Colorado River, but somewhat higher for the San Pedro, which is not flow regulated (see Table 2).

Table 4
Calculated annual ET values for river stretches, based on EVI and T_a

Year	Middle Rio Grande	Upper San Pedro	Lower Colorado at HNWR
2000	937	881	832
2001	934	973	846
2002	791	763	881
2003	832	790	844
Mean (SEM)	874 (74)	852 (95)	851 (21)

3.4. EVI and ET of different cover classes

Individual plant associations were compared for 2002, the year where we had both MODIS data and finer-resolution aerial or ETM+imagery to identify particular plant and land cover classes (Fig. 6). MODIS pixels were extracted for days 65–337, 2002, and T_a data was from meteorological stations. Willow trees had the highest projected ET (mean = 1309 mm yr^{-1}), followed by dense, woodland mesquite (mean = 1046 mm yr^{-1}). These values are higher than measured at the woodland mesquite tower site (i.e., Fig. 4) because they represent dense patches with complete or nearly complete ground cover.

Saltcedar was next highest (mean = 750 mm yr^{-1}), but it exhibited a wider range of ET values than the other plants, as it could grow in dense stands with no water shortage, or in less-dense, mixed saltcedar and arrowweed stands with water shortage. ET rates for giant sacaton grass, shrubland mesquite, and arrowweed were 646, 428, and 491 mm yr^{-1}, respectively. These ET estimates rank the plants similarly to data from tower sites (i.e., Fig. 4B).

For the Middle Rio Grande, we sampled the broader land cover classes defined for that river in other studies (e.g., Dahm et al., 2002) (Fig. 6). Considerable land conversion has taken place along the Middle Rio Grande, and cover classes included riparian forest vegetation, agricultural fields and pastures, and suburban land. Agricultural land had the highest mean projected ET (1050 mm yr−1), despite the fact that approximately 30% of the fields were fallow at any given time. Riparian mean ET (mixed saltcedar and native trees) was 640 mm yr^{-1}, while suburban land was nearly as high, 570 mm yr^{-1}. Mean riparian ET was lower than the mean value of saltcedar and cottonwood tower sites, because it included areas of sparse vegetation and bare soil as well as thickly vegetated areas typical of the tower sites.

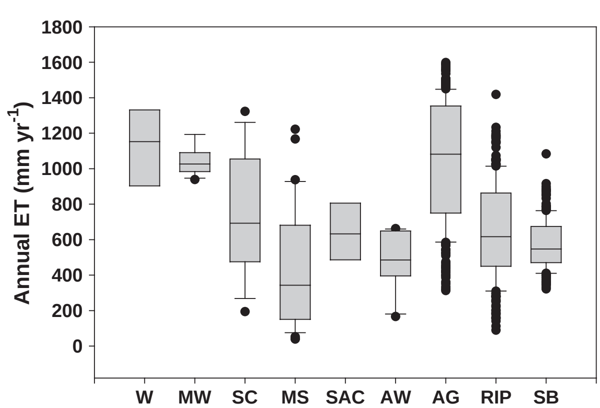

Fig. 6. Estimated growing-season ET for different riparian plant types and land cover classes on western U.S. rivers. Individual plant types were sampled on the Upper San Pedro and the Lower Colorado River. Agricultural, riparian forest, and suburban land cover classes were sampled on the Middle Rio Grande. SC = saltcedar; W = willow; MW = mesquite woodland; MS = mesquite shrubland; SAC = giant sacaton grass; AW = arrowweed; AG = agricultural and pasture land; RIP = riparian forest; SB = suburban land. Box plots show the median (center line), upper and lower 25% quartiles (shaded boxes), 95% quartiles (error bars), and outlier data points. Middle Rio Grande land classes had more outliers than individual plant types due to larger sample size.

4. Discussion

4.1. Validity of using MODIS EVIs and Ta for estimating riparian ET

Several methods are available for estimating ET from remote sensing data. In general they fall into two categories: surface energy balance methods (Gillies et al., 1997) and VI methods (Choudhury et al., 1994). Energy balance methods typically estimate LE by estimating the sensible heat flux using the difference between air temperature and the land surface temperature (LST), estimated by remote sensing (Inoue, 2003; Moran et al., 1994). This estimate of the sensible heat flux is combined with an estimate of the available energy ($R_n - G$) to estimate ET as a residual. Energy balance methods have the advantage of being physically based, so the same methods can be applied to different ecosystems and climate conditions. By combining LSTs with VIs, under favorable conditions they can account for both plant transpiration and soil moisture evaporation (Carlson et al., 1995; Gillies et al., 1997). Some of these methods have been applied to western riparian corridors in preliminary research (Cooper et al., 2000; Kustas et al., 2002; Prueger et al., 2001, 2004). However, they require unbiased radiometric measurement of land surface temperatures. MODIS LSTs (1 and 5 km pixel size) or AVHRR LSTs (1 km) do not have the needed resolution for narrow riparian corridors and they capture adjacent, non-riparian land that tends to have a high surface temperature in arid and semi-arid landscapes (Coonrod & McDonnell, 2001; Nagler et al., 2005a). On the other hand, finer-resolution satellite imagery, such as ETM+, does not have the needed temporal resolution to make frequent estimates of ET. Each satellite overpass produces a single, instantaneous, estimate of ET, which is subject to error due to temporal variability in energy fluxes from a vegetated surface (Kustas et al., 2002). Hence, multiple images are needed to get a clear picture of ET. Further research is needed to develop these methods as working tools for estimating riparian ET.

VI methods are empirical in nature, and depend on the relationship between foliage density and unstressed ET for a particular range of species and meteorological conditions. Current methods, such as those used in the Lower Colorado River Accounting System (LCRAS) (Congalton et al., 1998; U.S. Department of Interior, 2002), or the ET Toolbox used on the Middle Rio Grande (Brower, 2005), use the red and near infrared bands from Landsat imagery to divide the riparian corridor into biomass intensity and use crown closure to determine species or vegetation community. Then a crop coefficient (K_c), which is the ratio of crop ET to ET_o, is assigned to each class.

We developed a method following the approach of Wylie et al. (2003), in which VIs measured at frequent intervals are combined with meteorological data (T_a in our case) to estimate ET over a growing season. We calibrated our estimates with ET measurements from flux towers. Hence, our method uses remote sensing to scale ground measurements of ET rather than to directly estimate ET by a physical model. In selecting an empirical approach for estimating ET in western riparian corridors, we accept that the results cannot be extrapolated to other ecosystems or climate regimes. However, VI methods have the advantage that they measure a biophysical parameter, foliage density, that is directly related to potential ET under a given set of meteorological conditions (Choudhury et al., 1994; Monteith & Unsworth, 1990), and that has a damped temporal response to atmospheric conditions compared to LSTs.

The strong correlation between MODIS EVI and ET at eight of the nine tower sites on the Upper San Pedro River, Middle Rio Grande, and the Lower Colorado allowed us to estimate ET over three river systems that have similar vegetation types with a root mean square error of approximately 25%. The error or uncertainty of the estimates come from 1) errors and uncertainties in the ET measurements; and, 2) simplifying assumptions made in extrapolating ET over larger areas using EVI and T_a.

Within the last decade, ET estimates have improved in accuracy due to new methods and better instrumentation, but there is still considerable error and uncertainty inherent in each method (Drexler et al., 2004). Flux towers in arid and semi-arid riparian ecosystems are subject to errors due to the less-than-homogeneous nature in both horizontal and vertical extent of the typical multi-storied riparian canopy. Furthermore, the areal extent of vegetation cover or fetch is often limited and so the measurements may sometimes not be representative of vegetation of interest (Devitt et al., 1998). The BREB method has reduced accuracy when the gradient of H or LE between sensor stations is low (Drexler et al., 2004). Comparative measurements between fixed and portable Bowen ratio instrument sets showed a spread in values of about 20% even under uniform measurement conditions in cropped fields in Kansas (Nie et al., 1992). Unland et al. (1998) estimated that site-specific errors were about 20% for Bowen ratio measurements over a mesquite woodland on the Santa Cruz River in Arizona, while instrument limitations resulted in a loss of as much as 50% of the data.

Unlike the BREB method, the validity of the eddy covariance's estimate of ET and H can be checked for energy balance closure. The quantity, $ET+H$, measured by eddy covariance is often less than the quantity, R_n-G (Wilson et al., 2002). There is still much debate as to why this is the case and what to do about it (e.g., Brotzge & Crawford, 2003; Twine et al., 2000). The lack of closure in the surface energy balance is on the order of 10–30% for the riparian sites used in this study, and they can vary seasonally and also interannually, confounding comparisons of ET even at the same site over seasons and among years (Scott et al., 2004). A reasonable upper limit to the accuracy of remote sensing methods for obtaining ET is about 20% (Jiang et al., 2004). In the present study we combined data from different sites and collected by different operators, hence the variance is expected to be larger than for a single site measured over time. Therefore, although they represent the best current technology for estimating ET over areas of hundreds to thousands of square meters, Bowen ratio or eddy covariance flux towers have potential errors of as high as 25%, a value close to the limit described in Jiang et al. (2004) and similar to the prediction error in our calibration equation between EVI* and ET from flux towers.

ET is a complex function of R_n, atmospheric water demand, foliage density, bare soil evaporation, and aerodynamic and physiological (stomatal) resistances (r_a and r_s, respectively) of the canopy (Monteith & Unsworth, 1990). In estimating ET from EVI* and T_a only, we are implicitly assuming that soil evaporation is low compared to transpiration, and that canopy resistance factors are equal among species. These assumptions appear to be reasonable approximations for unstressed plants in these riparian zones (Nagler et al., 2005a). All of the plants in this study have been observed to be phreatophytic (making use of ground water), though some are facultative rather than obligate. Thus, if ground water levels are sufficiently close to the surface, then plants can have unlimited access to moisture from the alluvial aquifer rather than the surface. Rainfall is low on these rivers, and overbank flooding occurs infrequently, so the soil under the plant canopy is normally dry. Therefore, transpiration is the dominant component of ET. For open, tall, and non-uniform canopies such these mixed tree and shrub associations, r_a is usually low (Jones, 1983; Kustas et al., 2002; Monteith & Unsworth, 1990), so differences in canopy architecture among species may not be important in determining ET. Under non-stressed conditions, several studies have reported that the main riparian species on these rivers (mesquite, arrowweed, saltcedar, cottonwood, and willow) have similar rates of ET as a function of leaf area (Nagler et al., 2004; Sala et al., 1996; Smith et al., 1998). However, the simplifying assumptions can not be expected to hold under stress conditions. Saltcedar maintains much higher ET rates than the native trees species under salinity or water stress (Glenn & Nagler, 2005; Nagler et al., 2004; Sala et al., 1996; Smith et al., 1998). Over short time periods, therefore, EVI* would be a poor predictor of ET under stress conditions. Over a period of weeks, however, these plants reduce their LAI in response to stress, so stress would ultimately be detected as a decrease in EVI* and therefore ET. Sala et al. (1996) compared two stands of saltcedar along the Virgin River, Nevada, one growing in saline soil and the other in non-saline soil. The stand in saline soil had an LAI of 1.0 while the stand in non-saline soil had an LAI of 3.5, but both maintained similar rates of ET per unit LAI. Reduction of LAI in response to water stress has been reported for cottonwoods and willows (Smith et al., 1998).

The only species that did not show a strong correlation between EVI* and ET was arrowweed, the only evergreen species. However, it should still be valid to estimate annual or peak arrowweed ET from EVI* data, as ET should be related to foliage density, as measured by peak summer EVI*.

These estimates can undoubtedly be improved by incorporating energy-balance and other physical approaches that allow real time estimation of actual ET into the equations to detect stress, and by better physiological models relating ET to foliage density and atmospheric water demand of individual species. The most critical need is for more, and better distributed, ET data for the entire range of riparian plant associations, including aquatic species as well as terrestrial species. As more ET data becomes available, the relationship between ET, meteorological data, and VIs can be improved, and adjusted for differences among species and river systems. The scaling method we used can be applied to LIDAR and other emerging methods for ET estimation (Drexler et al., 2004) as well as to tower data. MODIS EVI appears to have the needed spatial and temporal resolution to scale ground-based ET measurements over large river areas. Ultimately, remote sensing data combined with ground measurements of T_a may be sufficient to monitor riparian ET.

4.2. Comparison with other estimates of riparian ET

Annual ET rates ranged rather narrowly over the rivers, from 851–874 mm yr^{-1}, despite differences in plant types, flow rates, and meteorological conditions among the rivers. ET rates were also fairly constant year-to-year, despite variability in annual flow rates for the San Pedro River and Middle Rio Grande (see Table 2).

Water budget summaries for the Middle Rio Grande for the period 1972–1997 estimated that riparian vegetation covered 20,000 ha of floodplain and consumed 150 to 375 million m^3 yr^{-1} of water at annual ET rates of 730 to 1825 mm yr^{-1} (Middle Rio Grande Water Assembly, 1999). Those estimates were based on indirect, water balance and crop-coefficient methods rather than direct estimates of ET (Hansen & Gorbach, 1997). Our estimates for total ET from agriculture, suburban lots, and riparian vegetation in the floodplain from 2000 to 2004 ranged from 510 to 600 million m^3 yr^{-1} of water at mean annual ET rates of 820 to 950 mm yr^{-1} (accepting the area estimates in Dahm et al., 2002). However, riparian vegetation accounted for only 130 million m^3 yr^{-1} (15%) of the total, at a mean rate of 640 mm yr^{-1} according to data in Fig. 6. This value is lower than values directly extrapolated from ET towers (i.e., 150 to 250 million m^3 yr^{-1} at rates of 740 to 1200 mm yr^{-1}) (Dahm et al., 2002), because the towers are sited in areas of uniform vegetation cover that tend to have higher EVI values than the mean EVI value over the floodplain.

ET for riparian vegetation on the San Pedro River has been estimated by several methods (Goodrich et al., 2000; Scott et al., in press). Goodrich et al. (2000) combined remote sensing data, a Penman–Monteith model calibrated with cottonwood and willow sap flow data, and BREB measurements from mesquite and sacaton to estimate the withdrawal of groundwater by riparian ET on the Upper San Pedro River. They estimated that mesquites and cottonwoods withdrew 8 million m^3 yr^{-1} of groundwater from a stretch of river extending from the U.S.–Mexico border to the Tombstone gauge. They concluded that other vegetation, such as giant sacaton grass, mainly used annual precipitation for ET. Mesquites and cottonwoods occupy 43% and 11% of the riparian corridor, respectively (Watts, 2000). By our estimates, total ET on this river stretch from 2000–2004 was 27–36 million m^3 yr^{-1} over 4500 ha, of which (accepting their area estimates) 14–19 million m^3 yr^{-1} was from mesquites and cottonwoods. Assuming the mesquites and cottonwoods utilized precipitation (2000–2003 mean = 370 mm yr^{-1}) as well as groundwater, discharge from groundwater was 6.4–9.0 million m^3 yr^{-1} based on EVI and tower ET data, similar to estimates in Goodrich et al. (2000). Scott et al. (2004) compared annual ET rates for mesquite stands along the San Pedro for 2001 and 2002, a wet year and dry year, respectively. They reported a 16% drop in mesquite ET from 2001 to 2002. Based on EVI values, we estimated a 22% drop in ET over the whole floodplain between 2001 and 2002 (Table 4). The good agreement in results suggests that MODIS EVI could be a useful tool for monitoring the riparian ET component of the water budget for this river.

ET has been estimated for the Lower Colorado River by the U.S. Bureau of Reclamation, using crop coefficients for different intensities (low, medium, high) of phreatophyte vegetation (U.S. Department of Interior, 2002). For the stretch of river from Davis Dam to Parker Dam, encompassing HNWR, phreatophyte ET was estimated at 220 million m^3 in 2001 at an annual ET rate of approximately 1700 mm yr^{-1}. Our estimate is much lower, approximately 110 million m^3 at a rate of 854 mm yr^{-1} over the same area. The LCRAS estimates (U.S. Department of Interior, 2002) assume annual ET rates of 1400 to 1800 mm yr^{-1} for sparse to dense saltcedar stands, much higher than our range of estimates, or from direct measurement from flux towers in HNWR. The flux tower data for HNWR, commissioned by the U.S. Bureau of Reclamation to refine estimates of ET, show that the crop coefficients that were set by expert opinion based on small-scale ET studies (M. Jensen, USDA-ARS, unpublished data) were too high.

These first-order comparisons show that ET values extrapolated over large river stretches by MODIS EVI are similar to direct estimates made by ground measurements in the case of the San Pedro River. On the other hand, they are lower than values estimated by the crop coefficient methods that have been used to set values for riparian ET in water budgets up to the present (Congalton et al., 1998; Hansen & Gorbach, 1997; U.S. Department of Interior, 2002; Brower, 2005). Nichols et al. (2004) were commissioned by the U.S. Bureau of Reclamation to compare the accuracy of different ET estimation methods for the Middle Rio Grande. They compared direct measurements of ET made at an eddy covariance flux tower with ET estimates based on crop coefficients and concluded that crop coefficient methods are unsuitable for use on riparian vegetation in arid environments. They pointed out that the methods had virtually no predictive power, since K_c is set once then stays the same, whereas actual vegetation responds to water flows, stress, and other factors. They recommended that crop coefficients be replaced by some on-going measure of the state of the canopy, such as by obtaining satellite measurements of LAI over extended areas of the riparian corridor, to provide more realistic and accurate measurements over the growing season. The present study shows that this goal can be accomplished with MODIS EVI data calibrated with flux tower data. Because towers grossly under sample the heterogeneity of the population, remotely sensing is a very important tool for capturing the spatial and temporal dynamics of these ecosystem functions.

4.3. ET of individual plant associations and other land cover classes

Saltcedar ET has been estimated to be as high as 3000–4000 mm yr^{-1} in some studies, while other studies reported much lower rates (reviewed in DiTomosa, 1998; Glenn & Nagler, 2005). Using sap flow methods, Sala et al. (1996) reported short-term rates of ET for saltcedar of 1.6–2.0 times ET_o on the Virgin River, Nevada. The U.S. Department of Interior (2002) uses a crop coefficient of 1.2 times ET_o to estimate mid-summer rates of saltcedar ET on the lower Colorado River, resulting in ET values of 1400–1800 mm yr^{-1}. On the other hand, eddy covariance (Cleverly et al., 2002) and BREB (Devitt et al., 1997) methods have produced values of 740–1500 mm yr^{-1}. Nagler et al. (2004) reported low to moderate LAI and NDVI values for saltcedar stands along a 350 km stretch of the Lower Colorado River. The present study shows that saltcedar ET rates (based on direct tower measurements and EVI* extrapolations) are in the range of 300–1300 mm yr^{-1}, depending on stand density. The ratio of mean annual saltcedar ET to ET_o is approximately 0.5 over the range of estimates in this study.

Based on ET extrapolated from EVI* values, willow has a mean ET rate approximately twice as high as saltcedar. Cottonwood has similar LAI as willow (Nagler et al., 2004), and ET in the range of 1000–1200 mm yr^{-1} at tower sites (Cleverly et al., 2002). Mesquite and saltcedar are intermediate, while sacaton grass and arrowweed are lowest. The results derived from EVI* are similar to rankings reported with respect to LAI and light interception by natural and constructed canopies (Nagler et al., 2003, 2004), and for rankings based on individual tower data over different plant stands (Fig. 4B) (Cleverly et al., 2002; Scott et al., 2004, in press). For the broader land cover classes on the Middle Rio Grande, agricultural fields have higher EVI and projected ET than riparian forest. Suburban land, consisting of partially cleared forest within the floodplain, had ET nearly as high as riparian forest land, and occupies twice as much land as riparian forest in the Middle Rio Grande (Dahm et al., 2002).

4.4. Conclusions

MODIS EVI data, combined with ground measurements of T_a and ET, can produce estimates of ET valid over large stretches of western U.S. riparian habitat, and for individual plant associations within the riparian corridor, within a potential error of plus or minus 25%. Arrowweed, an evergreen species, was the only species tested for which ET was not strongly correlated with 16-day-composite MODIS EVI values. The method could be improved by increasing the number of ground measurement sites for ET and by accurately mapping the vegetation associations with finer resolution imagery than MODIS provides (Nagler et al., 2005b). Also, the EOS-1 Terra and Aqua satellite data may be combined to provide 8-day composite MODIS EVI values, which would offer more timely data. The first-order estimates of riparian ET reported here are much lower than the official annual estimates that are currently used in water management decisions by government agencies (Hansen & Gorbach, 1997; U.S. Department of Interior, 2002; Brower, 2005). The combination of MODIS imagery, quantitative vegetation maps, and ground ET towers should be able to provide more accurate and timely estimates of riparian ET than are currently available to river operations and natural resource managers.

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