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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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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

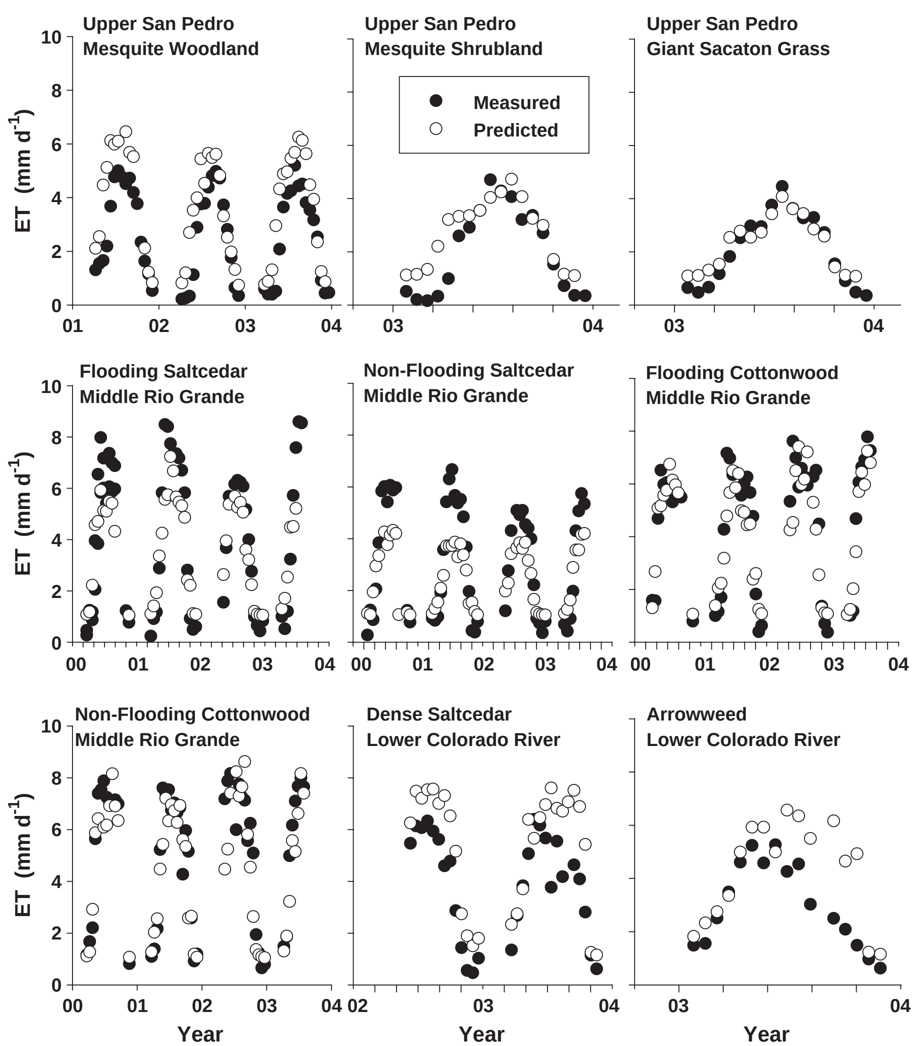

Fig. 3. Predicted (open circles) and measured (closed circles), 16-day ET values at each flux tower site. ET was predicted from EVI* and T_a.

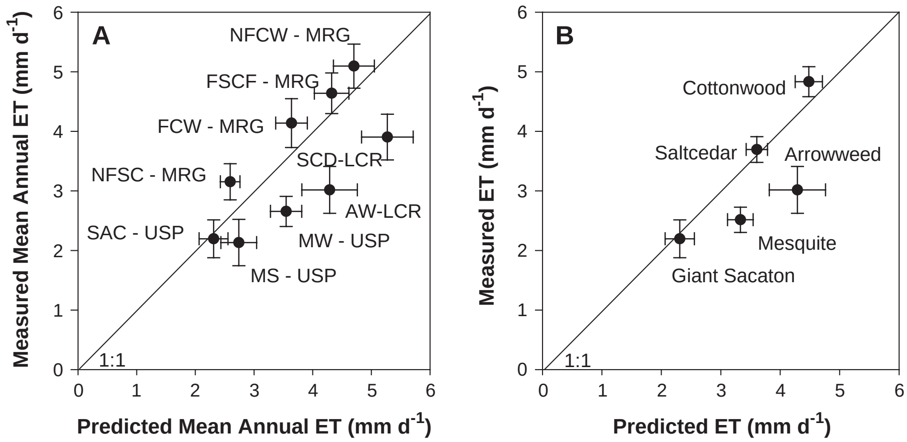

Fig. 4. Predicted and measured mean growing-season ET rates by tower site (a) and by plant species (b). Error bars are standard errors of the mean for 16-day mean values, and reflect the seasonal variation in ET. Abbreviations of tower sites refer to flooding (F) or non-flooding (NF), saltcedar (SC) 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.

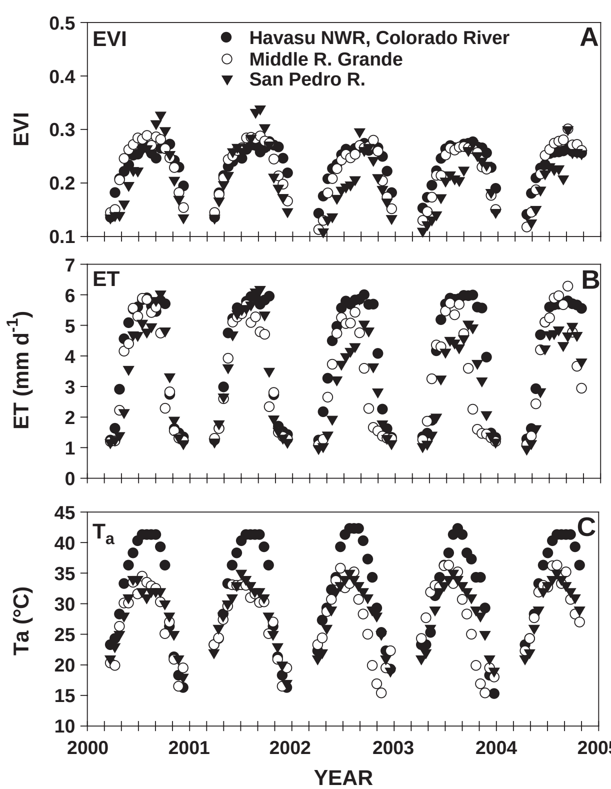

Fig. 5. Seasonal, 16-day composite, EVI (A), calculated ET values (B), and maximum daily air temperature (T_a) (C), and for Middle Rio Grande, Lower San Pedro River, and the Lower Colorado River stretches, 2000–2004.

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)

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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