Reduced evapotranspiration from leaf beetle induced tamarisk defoliation in the Lower Virgin River using satellite-based energy balance

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ABSTRACT

Tamarisk (Tamarix spp.) is an invasive shrubby tree native to Eurasia. Since its introduction to the United States, it has established itself along Southwestern American riparian systems. Control programs aimed at removing tamarisk were initiated in an effort to restore riparian areas, and potentially salvage water. Biological control of tamarisk with the Diorhabda spp. (leaf beetles) defoliates tamarisk and reduces evapotranspiration (ET). In 2009, the beetle arrived at Mesquite, Nevada, along the Virgin River, and dispersed to the Lower Virgin River riparian area in 2011. This study estimates reduced Lower Virgin River riparian ET caused by leaf beetle activity. Multi-temporal spectral angle mapper was used to detect established leaf beetle communities in the Lower Virgin River riparian area. The Mapping Evapotranspiration at High Resolution with Internal Calibration (METRIC) land surface energy balance model was used to estimate Lower Virgin River riparian ET. METRIC ET results were compared with eddy covariance ET estimates made in tamarisk along the Lower Virgin River. Comparisons indicated that METRIC accurately estimates pre-beetle ET and post-beetle reduced ET. The 2007–2010 (pre-beetle) average ET for the Lower Virgin River riparian area was 1245 mm/yr compared with 1041 mm/yr for the 2011–2012 (post-beetle) period. Given the 4700 acre riparian area, leaf beetle induced defoliation results in a mean annual ET reduction of 3161 acre-ft. In 2011 and 2012, volumetric reductions to ET were estimated to be 817 and 5505 acre-ft, respectively. The METRIC model was shown to be a useful tool for monitoring ET during pre-beetle and post-beetle defoliation periods. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS  remote sensing; evapotranspiration; surface energy balance; Virgin River; tamarisk; leaf beetle

Received 23 April 2014; Revised 13 February 2015; Accepted 23 February 2015

INTRODUCTION

Tamarisk in the USA

Tamarisk (Tamarix spp.) is an invasive shrubby tree native to Europe and Asia. The plant first made entrance into the USA as an ornamental, which led to further dispersal through domestic nurseries (Robinson, 1965). The spread of tamarisk was originally encouraged because of beneficial services provided by the plant. Rooting systems stabilized banks and controlled erosion, branches were used for firewood, animals utilized its shade, and plant flowers improved riparian zone aesthetics (Goldsmith and Smart, 1982; Friederici, 1995). As recently as 1964, the United States Department of Agriculture recommended tamarisk as a suitable windbreak for those living in the central Great Plains (Read, 1964). After introduction, tamarisk generally occupied small thickets adjacent to rivers, and locations that were unacceptable for natives (Larner et al., 1974).

The timing of more extensive riparian establishment of tamarisk correlates well with anthropogenically induced disturbance and hydrologic regime change, namely, reservoir construction, floodplain clearance, fires, and floods (Campbell and Dick-Peddie, 1964; Harris, 1966; Van Hylckama, 1966; Turner, 1974). At about the middle of the 20th century, perspectives on tamarisk began to change when it was suggested that the now prevalent invasive was consuming large volumes of water (Chew, 2009; Stromberg et al., 2009). This made tamarisk a convenient scapegoat for political issues involving water resources in the American Southwest (Chew, 2009). With economic development and public water supply at the forefront of policy maker’s attention, scientific investigation of tamarisk became focused on determining potential for water salvage upon removal of tamarisk (Chew, 2009). Of these early reports, some stated an individual tamarisk plant could transpire twice as much as a well-watered crop...
(3–4 m/yr) (Reviewed in Di Tomaso, 1998; Stromberg et al., 2009). With these figures in mind, tamarisk eradication appeared to hold great potential for alleviating Southwestern America’s water issues. This potential, along with desire for riparian restoration, spurred implementation of several removal programs. One such program was biological control of tamarisk with Diorhabda spp. (leaf beetles) (DeLoach et al., 2006). The beetles weaken tamarisk by episodically feeding on its foliage.

Several recent studies reveal that high initial estimates of tamarisk evapotranspiration (ET) were likely the result of suboptimal measurement methods (Owens and Moore, 2007). Recent studies reveal that tamarisk ET is generally less than a well-watered reference crop (i.e. alfalfa), although its ET is highly variable (Table I). Variability in tamarisk ET may be attributed to climatic conditions, stand density, soil properties, salinity, and the availability of water (Anderson, 1982, Glenn et al., 2013). Further, like other plants adapted to arid conditions, tamarisk exerts meticulous control over its stomata, quickly responding to changes in atmospheric water demand (Osmond et al., 1980; Anderson, 1982; Devitt et al., 1997; Sperry, 2000; Ogle and Reynolds, 2002). Consequently, estimating tamarisk ET is highly site specific and poses difficulties that are not present for well-watered agricultural crops (Allen et al., 2012; Glenn et al., 2013). For this reason, estimating actual tamarisk ET over entire riparian systems requires increasingly robust measurement and modeling methods.

Estimating tamarisk ET over the entire riparian systems, and evaluating the potential impact of biological control on those systems, is an important component of long-term, informed regional water management policy. This is particularly true for the Lower Colorado region, as the integrity of future supply is uncertain (Barnett and Pierce, 2008; SNWA, 2013). In this region, Lake Mead plays an important role in managing water supply for populations in Southern Nevada, Southern California, and Arizona. As a tributary to Lake Mead, the Lower Virgin River contributes to its supply and is a vital source of water for the irrigation and water districts in St George, Utah, and Mesquite, Nevada. The Lower Virgin River riparian system is dominated by invasive tamarisk, which is now being exposed to biological control by way of leaf beetles. As of 2009, leaf beetles had migrated from St George, Utah, to Mesquite, Nevada (Tamarisk Coalition, 2012). From Mesquite, the beetles continued migrating south toward Lake Mead (Tamarisk Coalition, 2012). Expert opinions remain divided regarding the potential for tamarisk control to produce significant water savings in the Colorado River Basin (Tamarisk Coalition, 2009; Nagler et al., 2010; Nagler and Glenn, 2013). It is likely that the introduction of leaf beetles to the Lower Virgin River has and will continue to alter tamarisk ET. Quantification of this change in ET provides numerous benefits ranging from supporting annual consumptive use reporting requirements by local, state, and federal agencies, water rights, and development of long-term hydrologic and biologic management policy.

**Region of interest**

The region of interest is the riparian zone adjacent to the Lower Virgin and Muddy River systems, with a greater focus on the Lower Virgin River system (Figure 1). The Lower Virgin River stretch being studied has a length of approximately 33 km and an area of approximately 19 km² (4700 acres). The region is a hot and arid environment, with summer temperatures exceeding 45 °C and mean annual rainfall less than 10 cm (Cleverly et al., 1997). The region is also experiencing its worst drought on record, with Lake Mead water level dropping more than 30.48 m since the year 2000 (SNWA, 2013).

**Estimating tamarisk ET**

Most studies have aimed at characterizing site-specific tamarisk ET. Bowen ratio energy balance stations, sap flux

<table>
<thead>
<tr>
<th>Location</th>
<th>Method</th>
<th>ET (mm/yr)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin River, NV</td>
<td>Bowen ratio</td>
<td>700–1400</td>
<td>Devitt et al. (1998)</td>
</tr>
<tr>
<td>Lower Colorado, CA</td>
<td>Bowen ratio</td>
<td>400–1400</td>
<td>Chatterjee (2010)</td>
</tr>
<tr>
<td>Lower Colorado, CA</td>
<td>Bowen ratio</td>
<td>780–980</td>
<td>Nagler et al. (2005b)</td>
</tr>
<tr>
<td>Rio Grande, NM</td>
<td>Eddy covariance</td>
<td>800–1200</td>
<td>Nagler et al. (2005a)</td>
</tr>
<tr>
<td>Lower Colorado, CA</td>
<td>Sap flux</td>
<td>307–1460</td>
<td>Nagler et al. (2009a)</td>
</tr>
<tr>
<td>Pecos River, TX</td>
<td>Sap flux</td>
<td>700</td>
<td>Owens and Moore (2007)</td>
</tr>
<tr>
<td>Dolores River, UT</td>
<td>Sap flux</td>
<td>220</td>
<td>Hultine et al. (2010b)</td>
</tr>
<tr>
<td>Pecos River, TX</td>
<td>Groundwater fluctuation</td>
<td>420–1180</td>
<td>Halter and Hart (2009)</td>
</tr>
<tr>
<td>Lower Colorado, CA and NM</td>
<td>Remote sensing</td>
<td>447–1155</td>
<td>Murray et al. (2009)</td>
</tr>
<tr>
<td>Upper Colorado, NV, WY, and UT</td>
<td>Remote sensing</td>
<td>220–580</td>
<td>Nagler et al. (2011)</td>
</tr>
<tr>
<td>Humboldt River, NV</td>
<td>Sap flux sensors, remote sensing</td>
<td>518 pre-beetle, 297 post-beetle</td>
<td>Patterson et al. (2012a, 2011b)</td>
</tr>
<tr>
<td>Truckee River, NV</td>
<td>Eddy covariance flux tower</td>
<td>400–500</td>
<td>Snyder et al. (2012)</td>
</tr>
</tbody>
</table>
sensors, eddy covariance turbulent flux stations, and monitoring groundwater fluctuations have contributed much to the current understanding of tamarisk water consumption (Table I). Other studies have aimed at integrating ground-based measurements with moderate resolution (250–500 m pixels) optical remote sensing in an effort to estimate the spatial distribution of tamarisk ET (Murray et al., 2009; Nagler et al., 2005a; Nagler et al., 2005b; Nagler et al., 2009b). When characterizing ET over an entire riparian system with site specific information, spatial variability is difficult, if not impossible, to quantify. The larger spatial scale introduces complexity in canopy, stand density and thermal regimes, variability in soil properties, salinity, and variability in available water. Further, when considering suitability for long-term estimates of tamarisk ET, cost becomes an important factor distinguishing different methods. Site-specific methods usually require expensive instrumentation that is only available for a set period of time. This makes long-term (5–10+ years) evaluation often impractical. Remote sensing methods utilizing moderate resolution sensors allow for more frequent images with higher spectral resolution over large areas. However, 250–500 m pixels are generally too large to resolve many of the narrow tamarisk corridors lining southwestern rivers. Remote sensing methods that estimate ET from vegetation indices are also prone to miss different stressors limiting tamarisk ET, such as plant disease and salinity, and do not account for bare soil evaporation contributing to ET. When these issues are considered, it appears the most desirable approach for long-term analysis of tamarisk-dominated riparian system ET are methods that utilize high-spatial resolution imagery, are able to account for heterogeneities that influence ET through environmental and biological stressors, and can account for bare soil evaporation that may increase under defoliated conditions. A potential approach is a satellite remote sensing at field scale resolution (30–120 m), which relies on thermal and optical imagery as well as ground-based weather data. However, such methods still introduce uncertainty. This is particularly true in arid regions where midday depression of ET caused by reduced water availability, increased vapor pressure deficit, and stomatal control may be observed (Nagler et al., 2009; Taghvaeian, 2011; Geli, 2012).

**Purpose of study**

This study aims to evaluate the reduction in ET due to biological control of tamarisk using a remotely sensed
surface energy balance model applied over a 33-km stretch of the Lower Virgin River. The Mapping Evapotranspiration at High Resolution with Internal Calibration (METRIC) model (Allen et al., 2007) uses remotely sensed thermal and optical imagery and ground-based weather data to estimate the spatially distributed surface energy balance. The model then solves for latent energy (i.e. ET) as a residual. METRIC is able to resolve both temporal and spatial variability of ET within the tamarisk-dominated riparian system, the presence of environmental and biological stressors potentially limiting ET at overpass time, and bare soil evaporation that contributes to system-wide ET. The study estimates monthly and yearly ET for the Lower Virgin and Lower Muddy River systems from 2007-2012. Spatially distributed results of pre-leaf and post-leaf beetle ET for the Lower Virgin River are compared. These estimates are also compared with ET estimates of a reference crop (alfalfa). Validation of METRIC-estimated ET is presented through comparison with eddy covariance ET obtained at a station installed in tamarisk along the Lower Virgin River (Sueki et al., 2015). Due to the timing of the study, we evaluate the effect of tamarisk defoliation on Lower Virgin River ET compared with healthy tamarisk in the nearby Lower Muddy River (Figure 1). The Lower Muddy River encountered beetles after they migrated through the Lower Virgin River.

METHODS

Remote sensing with Landsat

The study utilizes Landsat 5 and Landsat 7 imagery, acquired by the Thematic Mapper and Enhanced Thematic Mapper Plus sensors, respectively. The sensors have a spatial resolution of 30 m in the visible and infrared, and 120 and 60 m in the thermal region, respectively. The imaging return interval is 16 days for each satellite, but 8 days when Landsat 5 and 7 satellites are used together. This helps increase the number of quality (i.e. no clouds, haze, or smoke) images available to quantify monthly and seasonal ET. Landsat 5 and 7 images used in the study are for the years 2007–2012.

Ground-based weather data

Weather stations in Moapa Valley (Lat: 36°34’11” Long: 114°27’32’”) and Overton (Lat: 36°32’46” Long: 114°26’44”), Nevada, provided ground-based weather data necessary to apply the METRIC model. Data from both stations are available through the Western Regional Climate Center (www.wrcc.dri.edu). Hourly observations of incoming solar radiation, wind speed, air temperature, relative humidity, and precipitation were all used in reference ET and METRIC computations. Precipitation is used in a daily time step soil-water balance model that estimates bare soil evaporation due to recent rainfall (Allen, 2011). Bare soil evaporation estimates are later used in the calibration of METRIC (discussed in section 2.4). Weather data were subjected to quality control prior to being used in any computations. Quality control followed recommendations by ASCE-EWRI (2005) and Allen (1996).

Quality control included correction of hourly incoming solar radiation for sensor drift and malfunction, and visual inspection of hourly temperature, humidity, and wind speed. Incoming solar radiation was compared with theoretical clear sky solar radiation, and corrections were made following Allen (1996). Wind speed measurements were scanned for consistently low or high measurements, which would indicate potential sensor malfunction. Measurements of air temperature and vapor pressure were validated by scanning the record of observation for behavior typical for winter and summer seasons (i.e. air temperature reaching dew point more frequently in the winter than in the summer months). Quality control also involved analyzing data for outliers and to ensure hourly air temperature did not drop below the dew point.

Classifying defoliated tamarisk

Multi-temporal Spectral Angle Mapping (M-SAM) was used by way of the ENVI 5.0 image processing platform’s Spectral Angle Mapper tool as a way to determine the presence and southward extent of established leaf beetle communities. The goal of M-SAM application was to determine locations within Landsat images where Lower Virgin River ET pre-beetle and post-beetle exposure could be compared. When the beetle initially arrives to a region, defoliation is typically partial, localized, and sporadic. Consequently, few pixels will exhibit full defoliation, and ET reductions will be limited. Upon the second year, defoliation is more extensive and widespread. As a result, more pixels will exhibit full defoliation, and ET reductions are likely to be more substantial (Dudley in: Robison, 2012). With this in mind, the M-SAM classifier was applied to detect established communities through classification of full defoliation (Figure 2).

Tamarisk defoliation caused by leaf beetles involves the removal of chlorophyll and accessory pigments responsible for absorption of photosynthetically active radiation in the visible region of the electromagnetic spectrum. It also involves the removal of spongy mesophyll tissues responsible for high reflectance in the near infrared. M-SAM uses the optical spectral signature of healthy tamarisk at some base date before tamarisk defoliation in conjunction with the optical spectral signature of fully defoliated tamarisk to create multi-temporal reference spectra with a total of 12 bands and their respective surface reflectance values. In the multi-temporal spectra, the first six surface reflectance values (blue, green, red, near
beetles alters the spectral signature of tamarisk. In particular, increasing defoliation during the period of beetle activity produces corresponding changes in tamarisk spectral response. Full defoliation for the pixel being analyzed was experienced in 14 August 2011.

Infrared, and two short wave infrared bands) correspond to spectral data collected at the base date, while the last six surface reflectance values correspond to spectral data collected at some date within the range of beetle activity (approximately June to September). The multi-temporal reference spectra become the spectral signature for tamarisk changing from healthy to fully defoliate in the presence of leaf beetles. The reference spectra used for classification was 27 June 2011, in conjunction with 14 August 2011 (Figure 2).

Tamarisk Coalition observations reported that the beetle arrived in Mesquite, Nevada, in 2009. Generally, it takes the beetle 2 years to become widely established in a given region (Dudley in: Robison, 2012), which suggested that 2011 would be an appropriate year to expect widespread tamarisk defoliation in the Lower Virgin River riparian system. Reference spectra for defoliated conditions were selected based on observation of defoliated tamarisk at the eddy covariance station in 2011 (Sueki et al., 2015), Tamarisk Coalition observations from 2011 (Tamarisk Coalition, 2012), analysis of spectral behavior, and National Agriculture Imagery Program imagery from 2011. These observations were also supported by evidence of beetle migration through the Lower Virgin River observed by Nagler et al. (2014), which revealed partial defoliation of tamarisk at the southernmost riparian areas of the Lower Virgin River in July 2011, and full defoliation in June 2012.

The M-SAM approach analyzes pixels from images that have been prepared using ENVI’s layer stacking tool, which produces multi-temporal images. M-SAM analyzes pixels proposed for classification (test spectra) by comparing them to the multi-temporal reference spectra that exhibits an optical response deemed representative of tamarisk under fully defoliated conditions (reference spectra). Reference and test spectra values are used to create vectors that are projected into multidimensional space, where the angles between them can be analyzed (Campbell and Wynne, 2011). In this case the multidimensional space is $\mathbb{R}^{12}$. When vectors are composed of sufficiently similar spectral values, they will also have similar directions, and the angle between them will be within a user defined classification threshold. The angle ($\beta$) between the reference spectra and test spectra vectors is determined by the following relation, which is simply derived from the k-dimensional dot product:

$$\beta = \cos^{-1}\left(\frac{\sum_{i=1}^{k}r_i t_i}{\sqrt{\sum_{i=1}^{k}r_i^2 \sum_{i=1}^{k}t_i^2}}\right)$$

where $k$ is the number of bands composing the vectors, $r_i$ is the $i^{th}$ band of reference spectra and $t_i$ represents the $i^{th}$ band of the test spectra.

The classification threshold was determined so as to minimize classification of natural variation within riparian zones as a false positive for defoliation. Calibration of the threshold was determined using Landsat 5 Thematic Mapper imagery collected from May to September for years 2007–2009, which are years when the Tamarisk Coalition (2012) reported that the beetle was not in the study area. Images dates used for analysis are presented in Table II. The dates used for M-SAM analysis are intended to capture the approximate window of beetle activity. Land use maps and National Agriculture Imagery Program images were used to verify that classifications remained within riparian zones. A classification threshold of 0.075 radians was determined most suitable for this region, and over the years evaluated. Accuracy of classification results was considered robust in light of tamarisk coalition reports (2012), on ground observation by Sueki et al. (2015), spatial distributions of the vegetation indices, and results of Nagler et al. (2014). Limited data was available to produce a more robust accuracy assessment for classification. The optimal classification threshold of 0.075 radians was selected because it minimized classification of defoliation during years that were reported to be free of beetles.

Figure 2. Progression of tamarisk spectral response under pre-beetle (2010, left) and post-beetle (2011, right) conditions. The figure on the left shows the spectral response of tamarisk under pre-beetle conditions remains relatively constant. The figure on the right shows that defoliation of tamarisk by leaf beetles alters the spectral signature of tamarisk. In particular, increasing defoliation during the period of beetle activity produces corresponding changes in tamarisk spectral response. Full defoliation for the pixel being analyzed was experienced in 14 August 2011.
Table II. Landsat image dates used in Multi-temporal Spectral Angle Mapping analysis.

<table>
<thead>
<tr>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
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<tbody>
<tr>
<td>5/28</td>
<td>5/23</td>
<td>5/26</td>
<td>5/20*</td>
</tr>
<tr>
<td>6/29</td>
<td>6/8</td>
<td>6/27</td>
<td>6/5*</td>
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<td>7/15</td>
<td>6/24</td>
<td>7/13</td>
<td>6/21*</td>
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<td>8/24*</td>
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<td></td>
<td></td>
<td></td>
<td>9/25*</td>
</tr>
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</table>

Landsat 7 images are marked with an*.

Estimated ET with METRIC

The METRIC model computes ET for each Landsat pixel in the riparian system by solving for latent energy as a residual of the surface energy balance:

\[ LE = R_n - G - H \]  \hspace{1cm} (2)

where \( LE \) is the flux of latent energy, \( R_n \) is the net radiation at the surface, \( G \) is the ground heat flux, and \( H \) is the sensible heat flux. The METRIC computes each of these variables based on a series of calculations involving weather data, thermal radiance and optical reflectance, incoming solar radiation, vegetation indices, and other surface variables and parameters (Allen et al., 2007; Allen et al., 2012). Net radiation is computed using incoming shortwave radiation from the weather station along with Landsat derived surface temperature, emissivity, and surface albedo. Ground heat flux is estimated using Landsat derived surface temperature and vegetation indices. Sensible heat flux is determined with Landsat derived surface temperature, estimates of momentum roughness length \( z_{om} \) derived from the National Land Cover Database (Jin et al., 2013), and the Calibration using Inverse Modeling at Extreme Conditions (CIMEC) procedure (Allen et al., 2007, 2011). Momentum roughness lengths of 0.1 and 0.4 m were assumed to correspond to woody wetlands and herbaceous wetlands, respectively (Allen et al., 2012). Once \( R_n, G, \) and \( H \) are computed, \( LE \) is calculated as a residual. The instantaneous ET rate at satellite overpass time \( (ET_{inst}) \) is calculated by dividing \( LE \) by the latent heat of vaporization for water:

\[ ET_{inst} = 3,600 \frac{LE}{\lambda} \]  \hspace{1cm} (3)

where 3600 is a factor for time conversion from seconds to hours and \( \lambda \) is the latent heat of vaporization, which is a function of surface temperature. This value is used to compute the ratio of \( ET_{inst} \) to alfalfa reference ET \( (ET_r) \). The resultant ratio \( (ET,F) \) is analogous to a crop coefficient and is computed for each pixel in the image. \( ET_r \) is computed using weather station data and the ASCE Standardized Penman–Monteith equation (ASCE-EWRI, 2005). ET for the 24-h period \( (ET_{24i}) \) for day \( i \) is estimated as

\[ ET_{24i} = ET_r F_i \times ET_{r,24i} \]  \hspace{1cm} (4)

where \( ET_{r,24i} \) is the 24-h reference ET for day \( i \), and \( ET,F_i \) is the fraction of reference ET for the \( i^{th} \) day. Estimated ET over extended time periods is computed with the following equation:

\[ ET = \sum_{i=n}^{m} ET_r F_i \times ET_{r,24i} \]  \hspace{1cm} (5)

where \( n \) is the first day of the desire time period and \( m \) is the last day of the desired time period.

Daily per-pixel \( ET,F \) is estimated through linear interpolation of \( ET,F \) values between image acquisition dates and is multiplied by weather station-based \( ET_{r,24i} \) values for the respective day \( i \) to finally estimate the daily \( ET_{24i} \) per pixel. In this formulation, the METRIC assumes that ET in the riparian zone changes in proportion to the change in \( ET_{r,24} \) at the weather station. In this case, \( ET_{r,24} \) is used as an index for relative change based on weather conditions, while pixel specific information about the actual ET relative to \( ET_r \) is carried in \( ET,F \) values. In the case of riparian and irrigated environments, relying on \( ET_r \) to represent a daily index of relative change according to daily weather conditions is fairly robust given that these environments are more energy limited than water limited.

An assumption of the METRIC model is that \( ET,F \) obtained at image overpass time remains relatively constant throughout the day and is equal to the 24-h \( ET,F \). However, it has been observed that environmental stresses like salinity, variability in depth to water, and increased vapor pressure deficit can lead to depression of midday tamarisk ET because of stomatal control (Glenn et al., 2013). A study of tamarisk ET at a site along the Lower Colorado River (Cibola National Wildlife Refuge (CNWR); Nagler et al., 2009b), which is similar to the site studied here, reported that tamarisk leaf-area transpiration and stomatal conductance varied markedly between different sites. A number of physical properties were also monitored during their study, including soil texture, depth to groundwater, groundwater salinity, and groundwater temperature. Despite these detailed measurements, environmental factors controlling tamarisk ET in the CNWR were not fully understood (Nagler et al., 2009b). Accordingly, Nagler et al. (2009b) state that the assumption of a constant \( ET,F \) did not accurately project ET at any given site. However, Nagler et al. (2009b) also observed that the assumption of constant \( ET,F \) held sufficiently true for mixed scenes aggregated over larger areas. In regard to these larger areas, midday depression of ET was sufficiently compensated by nighttime transpiration and gusation, so that the applica-
tion of their vegetation index-based approach produced an error term of about 20%, which is within the accuracy of other remote sensing methods (15–30%) (Nagler et al., 2009b). The Lower Virgin River area being studied is similar to that of the CNWR in the sense that they have similar climates and are tamarisk dominated, and the area of interest is relatively large. Accordingly, depression of midday ET in the Lower Virgin River may be sufficiently moderated by nighttime transpiration and guttation when considering ET estimates over the larger Lower Virgin River riparian area.

To further evaluate midday depression of ET within the Lower Virgin River study area, differences between ET,F at the time of Landsat overpass (about 10:15 AM), and 24-h average ET,F were evaluated using eddy covariance-derived ET and weather station-derived ET, (ASCE-EWRI, 2005). Hourly average ET,F was evaluated within the eddy covariance station footprint area from February through November; for each year, the eddy covariance station was active (2010, 2011, and 2012). Figure 3 presents the results of this analysis, along with the 3-year average hourly ET,F. In Figure 3, it can be seen that depression of tamarisk ET is most pronounced during morning hours. However, by Landsat overpass time the ET,F is largely depressed and remains fairly constant throughout the afternoon. The 3-year, 24-hour average measured ET,F was 0.48, and the 3-year 10:00 and 11:00 AM average measured ET,F was 0.53 and 0.46, respectively. The approximate 10:15 AM measured ET,F value was 0.51, which was determined by linearly interpolating between 10:00 and 11:00 AM measured ET,F values. Given that the average 24-h ET,F was 0.48 and the approximate 10:15 AM ET,F was 0.51, along with observations presented in Nagler et al. (2009b), it was determined that the assumption of constant ET,F introduces a minimal amount of uncertainty in this study. If significant depression happens after the time of satellite overpass, at the very least, the assumption of constant ET,F produces estimates that can be seen as an upper-bound on system-wide ET estimates, because midday depression of ET would serve to reduce estimates obtained through the METRIC model.

Calibration of the model is done through the selection of two anchor pixels for the CIMEC process. The anchors consist of a ‘hot’ and ‘cold’ pixel, each of which exhibits optical and thermal properties indicative of particular evaporative conditions (Morton et al., 2013). The hot pixel is identified as a bare agricultural field with little or no vegetation cover, surface heating, and little evaporative cooling (Morton et al., 2013). ET,F at the hot pixel is specified, and dependent on evaporation estimates from a weather and precipitation-driven bare soil evaporation model (Allen, 2011). The cold pixel is identified within an agricultural field that is well watered with full vegetation cover, where all available energy is used for ET (i.e. H is 0, or slightly negative under advective conditions) (Morton et al., 2013). The CIMEC procedure is then employed to iteratively solve for H in the energy balance equation using the anchor pixels (Allen et al., 2007; Morton et al., 2013). The CIMEC process within METRIC reduces possible biases in estimated ET due to uncertainties in atmospheric correction of surface temperature and reflectance, aerodynamic stability correction, and estimated z,com. Additionally, it has been found that estimated METRIC ET is not very sensitive to the estimated value of z,com (Tasumi et al., 2008).

**METRIC adjustment to account for canopy shading**

The METRIC was primarily developed to estimate ET from agricultural areas. These areas generally exhibit some degree of homogeneity and predictability because they are relatively well watered and well maintained. For this reason, some enhancement may be necessary for METRIC to address the behavior of more complex vegetative communities (Allen et al., 2012). Natural tamarisk stands are one such example. Variability in stand height and density, along with the altitude of the sun at Landsat overpass time (about 10:15 AM), cause shadowing that is visible from the near nadir-viewing Landsat sensor. When viewed from near nadir, shadows cause the albedo for tall vegetation to be biased low as compared with a full hemispherical albedo that should be used when computing net Rn. Based on how shadows impact the estimation of near nadir albedo, compensation for lowering of near nadir albedo during defoliation and resultant increased shadowing was found to be important. The effects of shadows on albedo and land surface energy budget estimation have been well documented (Betts and Ball, 1997; Strahler et al., 1999; Dobos, 2006; Barlage et al., 2005; Wang and Zeng, 2008).

![Hourly ET,F for February through November](Image)

**Figure 3.** Measured February through November hourly average ET,F for 2010–2012 and the 3-year ET,F average. Depression of tamarisk ET,F at the eddy covariance station is most dramatic during the morning, and remains relatively constant through the afternoon. Tamarisk ET,F is at an almost fully depressed state at the time of Landsat overpass (about 10:15 AM), and the 24-h average ET,F is very close to 10:00 to 11:00 AM values.
The METRIC model estimates broadband albedo ($\alpha$) following Tasumi et al. (2008), which uses spectral radiance to compute at-satellite reflectance values that are then corrected on a band by band basis to obtain at-surface reflectance values. Albedo is then calculated by summing weighted surface reflectance values over Landsat bands 1–7. Weighting coefficients were used from Tasumi et al. (2008). The reader is referred to that paper for a more detailed explanation of the method for estimating albedo used in this study. Albedo is used to estimate $R_n$, which is used to estimate $LE$ in Equation (2). If albedo is biased low by the presence of shadows, it will increase $R_n$, and the resulting $LE$ will be biased high. To compensate for this, a method for estimating albedo based on normalized difference vegetation index (NDVI) was developed and applied for such conditions following recommendations of Allen et al. (2012). In the Lower Virgin River, the relationship between NDVI and albedo under healthy and defoliated conditions (natural and leaf beetle induced) had a coefficient of determination of 0.67. The formula used to estimate albedo as a function of NDVI is

$$\alpha = -0.3\text{NDVI} + 0.335$$

This formulation was derived assuming albedo values of 0.155–0.275 correspond to NDVI values of 0.60–0.20, respectively. These albedo and respective NDVI values were chosen following suggestions outlined in Allen et al. (2012) for shadowed conditions and when long narrow leaves are oriented more vertically than horizontally, along with estimates of albedo and corresponding NDVI for sparse tamarisk stands and surrounding bare soil in the Lower Virgin River riparian area.

**RESULTS**

**Classification of defoliated tamarisk**

Between 2010 and 2012, M-SAM classification detected an increase in defoliated tamarisk along the Lower Virgin River, while tamarisk along the Lower Muddy River was unchanged in 2010 and 2011 (Figure 4). The timing of maximum full defoliation for the Lower Virgin River was observed on 9 August 2012, when 3 km$^2$ (731 acres) of tamarisk was classified as fully defoliated. On 14 August 2011, 2.1 km$^2$ (510 acres) of Lower Virgin River tamarisk was classified as fully defoliated. In August of 2010, which corresponds to the approximate timing of maximum classified defoliation in 2011 and 2012, less than 0.004 km$^2$ (about 1 acre) of Lower Virgin River tamarisk was classified as fully defoliated. This supports Tamarisk Coalition observations that in 2009, the beetle arrived in Mesquite, Nevada, and that it takes approximately 2 years for the beetle to establish. The small area classified as defoliated during 2010 may be attributed to either classification error arising from natural variation, or localized sporadic defoliation events typical of initial leaf beetle arrival to a region. Although data was limited for a more robust classification accuracy assessment, M-SAM results for detection of defoliated tamarisk resembled changes in canopy biomass revealed by way of soil adjusted vegetation index (SAVI) maps (Figure 5), as

![Figure 4. Multi-temporal Spectral Angle Mapping classification results for fully defoliated tamarisk on 11 August 2010, 14 August 2011, and 9 August 2012, respectively. The dates correspond to the timing of maximum classification for respective years. Landsat bands of 7, 4, and 3 are assigned to red, green, and blue channels. Results for 2012 utilize Landsat 7 Enhanced Thematic Mapper Plus imagery, which is impacted by the malfunctioning scan line corrector (Off).](https://example.com/figure4.png)
well as the progression of leaf beetles through the Lower Virgin River as reported by the Tamarisk Coalition (2012).

Classification results indicate that in 2011, the Lower Virgin River was experiencing defoliation, while the neighboring Muddy River remained unaffected. This confirmed what was expected to occur because of the north–south migration of the beetle. These circumstances provided an opportunity to study the impacts of tamarisk defoliation on ET rates by comparing Lower Virgin River

Figure 5. Soil adjusted vegetation index (SAVI) for respective years during the timing of maximum M-SAM classification on 11 August 2010, 14 August 2011, and 9 August 2012, respectively. The greatest SAVI reductions presented in (a), (b), and (c) correspond well with Multi-temporal Spectral Angle Mapping classification at the same dates shown in (a), (b), and (c) of Figure 4.

Figure 6. Comparison of Lower Virgin River and Muddy River daily tamarisk ET rates in 2010–2012. (a) Year 2010 was pre-beetle as determined by Multi-temporal Spectral Angle Mapping classification and supported by Tamarisk Coalition on-ground observation. It can be seen that evapotranspiration (ET) rates for the Lower Virgin River and Muddy River are relatively similar. (b) In 2011, the Lower Virgin River experienced tamarisk defoliation, while tamarisk in the Muddy River remained healthy. Divergence of ET rates in June, with recovery in October, reveals the impact of tamarisk defoliation through reduced ET. (c) In 2012, Lower Virgin and Muddy Rivers both experience reduced ET from tamarisk defoliation. (d) The progression of Lower Virgin River ET during 2010 (pre-beetle) and 2011 and 2012 (post-beetle). Comparison of years reveals that 2012 exhibited the most reduced ET rates.
ET rates during defoliation with those from healthy tamarisk areas in the neighboring Lower Muddy River under the same weather conditions.

**Healthy versus defoliated riparian ET**

For June to September (the approximate timing of beetle activity) of 2007–2010, ET rates averaged over Lower Muddy and Virgin River riparian areas shown in Figure 1 reveal that the ET is higher in the Lower Virgin River because of higher tamarisk density (Figure 6(a)). For 2007–2010, average SAVI for the Lower Virgin River and the Lower Muddy River was 0.37 and 0.34, respectively. Figure 6(a) and (b) present ET for 2010 and 2011, where it is evident that beetle activity caused reductions in ET for 2011, most notably from June to September. This is further supported by M-SAM classification results and reductions in SAVI during the same time period (Figures 4 and 5). From June to September of 2007–2010 (pre-beetle), the average ET rate for the Lower Virgin River riparian area was 6.14 mm/day, and for the Lower Muddy River riparian area, it was 5.31 mm/day. Over this time, the average Lower Virgin River ET rate was 0.83 mm/day greater than the Muddy

![Figure 7](image_url)

**Figure 7.** Map of $ET_{RF}$ for the Lower Virgin and Muddy River regions in 2010–2012. $ET_{RF}$ is the average of Mapping Evapotranspiration at High Resolution with Internal Calibration results from February through November.

![Figure 8](image_url)

**Figure 8.** Evapotranspiration (ET) maps computed with the METRIC for August 2010–2012 in mm/month. August is the month that experienced greatest reduced ET from leaf beetle-induced defoliation.
River. This difference in ET is likely due to tamarisk density differences as observed from SAVI distributions for respective riparian areas (Figure 5(a)). During the period of tamarisk defoliation in the Lower Virgin River, the 2011 ET rate from June to September was 5.57 mm/day and 5.96 mm/day, for the Lower Virgin River and Lower Muddy Rivers, respectively. The difference in ET between Lower Muddy and Lower Virgin riparian areas during this period was 0.39 mm/day, which was due to a combination of defoliation and density differences. When considering heightened pre-beetle Lower Virgin River average ET from 2007–2010, the decrease in 2011 ET is approximately 1.22 mm/day, which is due to defoliation alone. This reduction equates to 2300 acre-ft of reduced ET due to defoliation in the Lower Virgin River. The spatial distribution of METRIC ET,F and ET estimates are illustrated in Figures 7 and 8, respectively, and highlight these results.

Pre-beetle and post-beetle Lower Virgin Monthly ET versus ETr

Average monthly ET results for the Lower Virgin and Lower Muddy Rivers are presented in Table III. Monthly results for the Lower Virgin River ET pre-beetle and post-beetle arrival, as well as ET for an alfalfa reference surface, ETr, are illustrated in Figure 9, where it is evident that alfalfa ET remained substantially higher than tamarisk ET under healthy conditions. For years, it can be seen that Lower Virgin River ET post-leaf beetle arrival is less than Lower Virgin River ET pre-leaf beetle arrival. Reduced monthly ET occurs when the beetle is active, with full recovery taking place as late as November. The maximum reduction of ET occurs in August as shown in Figure 9.


<table>
<thead>
<tr>
<th>Month</th>
<th>Lower Muddy pre-beetle</th>
<th>Lower Muddy post-beetle</th>
<th>Lower Virgin pre-beetle</th>
<th>Lower Virgin post-beetle</th>
<th>Lower Virgin difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>13.54</td>
<td>19.84</td>
<td>17.54</td>
<td>20.55</td>
<td>−3.01</td>
</tr>
<tr>
<td>February</td>
<td>16.82</td>
<td>25.91</td>
<td>17.64</td>
<td>25.29</td>
<td>−7.65</td>
</tr>
<tr>
<td>March</td>
<td>30.10</td>
<td>41.1</td>
<td>35.24</td>
<td>43.28</td>
<td>−8.04</td>
</tr>
<tr>
<td>April</td>
<td>79.28</td>
<td>92.45</td>
<td>94.66</td>
<td>96.19</td>
<td>−1.53</td>
</tr>
<tr>
<td>May</td>
<td>134.93</td>
<td>165.45</td>
<td>177.99</td>
<td>183.04</td>
<td>−5.05</td>
</tr>
<tr>
<td>June</td>
<td>172.57</td>
<td>194.66</td>
<td>208.14</td>
<td>180.36</td>
<td>20.78</td>
</tr>
<tr>
<td>July</td>
<td>177.16</td>
<td>167.95</td>
<td>199.34</td>
<td>155.66</td>
<td>43.68</td>
</tr>
<tr>
<td>August</td>
<td>164.24</td>
<td>153.49</td>
<td>192.26</td>
<td>116.18</td>
<td>76.08</td>
</tr>
<tr>
<td>September</td>
<td>129.69</td>
<td>104.30</td>
<td>142.20</td>
<td>88.5</td>
<td>53.70</td>
</tr>
<tr>
<td>October</td>
<td>78.20</td>
<td>72.47</td>
<td>89.64</td>
<td>73.37</td>
<td>16.27</td>
</tr>
<tr>
<td>November</td>
<td>38.99</td>
<td>33.21</td>
<td>46.26</td>
<td>37.56</td>
<td>8.70</td>
</tr>
<tr>
<td>December</td>
<td>20.93</td>
<td>25.85</td>
<td>24.57</td>
<td>20.68</td>
<td>3.89</td>
</tr>
</tbody>
</table>

The difference for pre-beetle and post-beetle Lower Virgin River ET is also presented in mm/month.

Figure 9. Monthly mean Lower Virgin River tamarisk evapotranspiration (ET) pre-beetle and post-beetle arrival compared with mean monthly alfalfa reference ET. It can be seen that post-beetle monthly ET is substantially less than pre-beetle monthly ET during the months of June to November, which marks leaf beetle emergence from diapause in June and tamarisk recovery in November. Alfalfa reference ET remains greater than Lower Virgin River tamarisk ET for all months.

Yearly pre-beetle and post-beetle Lower Virgin ET versus ETr

Average yearly ET results for the Lower Virgin and Lower Muddy River are presented in Table IV. The yearly pre-beetle (2007–2010) mean ET for the Lower Virgin River was 1246 mm/yr and the yearly post-beetle (2011–2012) mean ET for the Lower Virgin River was 1041 mm/yr. This translates to a reduction of 205 mm/yr. The greatest reduction in yearly ET due to defoliation was observed in 2012. Comparing 2012 Lower Virgin River ET (889 mm/yr) with yearly pre-beetle ET resulted in a reduction of 357 mm/yr. Considering the acreage of the Lower Virgin River riparian area, this difference resulted in a reduction of 5505 acre-ft. Comparing 2011 Lower Virgin River ET...
(1193 mm/yr) with yearly pre-beetle ET resulted in a reduction of 53 mm/yr. Considering the acreage of the Lower Virgin River riparian area, this difference resulted in a reduction of 817 acre-ft. The difference in yearly mean ET for pre-beetle (2007–2012) and post-beetle (2011–2012) periods resulted in a reduction of 3161 acre-ft. Mean $E_T$ from 2007 to 2010 was 2219 mm/yr, and for 2011 to 2012, the mean $E_T$ was 1875 mm/yr. When compared with Lower Virgin River mean pre-beetle and post-beetle tamarisk ET rates for the respective periods, ET is 973 mm/yr and 834 mm/yr less than $E_T$, respectively.

Comparison with eddy covariance flux station ET estimates

For validation purposes, METRIC ET was compared with ground-based ET estimates obtained by an eddy covariance flux station installed in tamarisk on the Lower Virgin River (Figure 1) (Sueki et al., 2015). A polygon encompassing the approximate eddy covariance flux station footprint was used to spatially average METRIC ET estimates within the footprint at daily time steps (Figure 1). The footprint was approximated based on daytime fetch derived from the analytical models of Kljun et al. (2004) and Kormann and Meixner (2001) which rely on atmospheric stability, wind speed, and wind direction. The comparison spanned the period of 2010–2012, which is when the flux station was in operation. Figure 10 illustrates the time series comparison of METRIC ET and eddy covariance estimates, where it

<table>
<thead>
<tr>
<th>Year</th>
<th>$E_T$</th>
<th>Lower Virgin</th>
<th>Lower Muddy</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>2372</td>
<td>1229</td>
<td>1082</td>
<td>147</td>
</tr>
<tr>
<td>2008</td>
<td>2181</td>
<td>1194</td>
<td>884</td>
<td>310</td>
</tr>
<tr>
<td>2009</td>
<td>2232</td>
<td>1251</td>
<td>1140</td>
<td>111</td>
</tr>
<tr>
<td>2010</td>
<td>2092</td>
<td>1311</td>
<td>1119</td>
<td>192</td>
</tr>
<tr>
<td>2011</td>
<td>1829</td>
<td>1193</td>
<td>1159</td>
<td>34</td>
</tr>
<tr>
<td>2012</td>
<td>1920</td>
<td>889</td>
<td>1028</td>
<td>−139</td>
</tr>
</tbody>
</table>

$E_T$ is also presented in mm/year.

ET is also presented in mm/year.

Figure 11. Scatter plot of daily eddy covariance and Mapping Evapotranspiration at High Resolution with Internal Calibration (METRIC) evapotranspiration (ET) estimates for years 2010–2012. The $r^2$ value of 0.86 reveals there is a strong correlation between METRIC ET and eddy covariance estimated ET. When the best fit line is forced through the origin, the best fit line had the equation $y = 0.95x$, indicating minimal average bias.

Figure 10. Comparison of 5-day moving average Mapping Evapotranspiration at High Resolution with Internal Calibration (METRIC) evapotranspiration (ET) with eddy covariance estimates for 2010–2012 for the footprint area within tamarisk. Comparison of 2010–2012 reveals that METRIC compares well with eddy covariance estimates ([a], [b], and [c]). Comparison of METRIC yearly ET from 2010–2012 for the footprint area reveals that ET increased in 2012 versus 2011, which is both post-beetle ([d]). Comparing Figures 10(d) with 6(d) reveals the importance of considering the spatial variability of defoliation when estimating reduced tamarisk ET, where the larger Lower Virgin River riparian area ET is most reduced in 2012.
isevident that METRIC ET estimates compare well to eddy covariance ET estimates for pre-defoliation and post-defoliation periods ($r^2 = 0.86$; Figure 11). In addition, it is clear that both METRIC and the eddy covariance station ET estimates have close correspondence through the defoliation and recovery periods of 2011 and 2012, giving confidence in both approaches for estimating reduced ET during defoliation.

**DISCUSSION AND CONCLUSIONS**

Yearly estimates of tamarisk-dominated Lower Virgin River ET are within the range of values obtained from previous studies (Table 1). METRIC ET results from this study reinforce results of tamarisk ET for the Lower Virgin River presented in Nagler et al. (2014). Nagler et al. (2014) found that pre-beetle arrival peak summer ET was 4.3 mm/day and post-beetle arrival peak summer ET was 2.0 mm/day. This study reports a pre-beetle peak summer ET of 6.1 mm/day and a post-beetle peak summer ET of 3.4 mm/day. Nagler et al. (2014) reports yearly pre-beetle ET (2007–2009) was 903 mm/yr (4.09×$10^7$ m$^3$/yr over 4531 ha), and yearly post-beetle ET (2012) was 419 mm/yr (1.9×$10^7$ m$^3$/yr over 4531 ha). This study reports yearly pre-beetle ET (2007–2009) of 1225 mm/yr, and post-beetle ET (2012) of 889 mm/yr. Differences in peak summer and yearly ET rates summarized by Nagler et al. (2014) and reported by this study can potentially be explained by differences in the methods applied, as well as the areas over which the analysis was conducted. Nagler et al. (2014) used vegetation indices to estimate ET using Moderate-resolution Imaging Spectroradiometer optical imagery at 250 m spatial resolution, while this study applied a surface energy balance model using Landsat thermal and optical imagery at 60–120 m (thermal) and 30 m (optical) spatial resolution. The surface energy balance model approach includes evaporation from bare soil and transpiration from riparian vegetation, while the vegetation index approach does not directly consider bare soil evaporation. This may be why ET results for post defoliation periods reported in this study are higher than those reported by Nagler et al. (2014). Nagler et al. (2014) also considered a larger stretch of the Lower Virgin River, which likely has vegetation communities of different densities. These two primary differences (methods applied and areas analyzed) may explain why results from this study differ from those of Nagler et al. (2014).

Comparison of METRIC with eddy covariance ET estimates suggests that METRIC is accurate for estimating ET and reduced tamarisk ET caused by leaf beetle-induced defoliation within the eddy covariance footprint area. This suggests that the surface energy balance approach of METRIC may be suitable for estimating ET and reduced ET due to defoliation of tamarisk over the larger Lower Virgin River riparian area. METRIC ET estimates averaged over the eddy covariance footprint revealed that 2012 was greater than 2011 (Figure 10(d)). These results are opposite to those of the larger Lower Virgin River riparian area as a whole, where METRIC ET for 2011 was greater than 2012 (Figure 6(d)). This difference is likely the result of less tamarisk defoliation within the eddy covariance footprint as compared with the larger Lower Virgin River riparian area as shown in the ET time series of Figures 10(c) and 6(c), increases in 2012 M-SAM classification of defoliation (Figure 4), and SAVI reductions for 2012 (Figure 5). This suggests that site-specific estimates of defoliated tamarisk ET have potential to improperly characterize the impacts of defoliation on ET for the larger riparian area.

Long-term reductions in Lower Virgin River riparian area ET will largely depend on the long-term composition of plant communities. Biocontrol efforts do not generally result in complete mortality of the target species but rather seek to create a system where native species regain some competitive advantage (DeLoach and Carruthers, 2004). Accordingly, the future riparian system is likely to have some increased mix of tamarisk and native species. Monthly and yearly METRIC ET over the Lower Virgin River riparian area reveals that tamarisk is consuming substantially less than a reference crop. A restored riparian system would only provide long-term reductions in ET if the ET for the restored system was less than that of the tamarisk-dominated system. It is possible that a restored system will evaporate and transpire about the same or even more than it did under tamarisk dominated conditions, based on the ET of native plants (USBR, 2011). The METRIC model can be a useful tool to monitor riparian ET for both tamarisk-dominated and native systems.

**ACKNOWLEDGEMENTS**

This project was funded by the Desert Research Institute Maki Endowment for enhancing water resources in Southern, Nevada, and U.S. Geological Survey 2012 to 2017 Landsat Science Team funding.

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