Reduced Evapotranspiration from Leaf Beetle Induced Tamarisk Defoliation in the Lower Virgin River Using Satellite Based Surface Energy Balance

A thesis submitted in partial fulfillment of the Requirements for the degree of Master of Science in Hydrogeology

By

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Reduced Evapotranspiration From Leaf Beetle Induced Tamarisk Defoliation In The Lower Virgin River Using Satellite Based Surface Energy Balance

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requirements for the degree of

MASTER OF SCIENCE

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Abstract

Tamarisk (*Tamarix* spp.) is an invasive shrubby-tree native to Eurasia. Since 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 1,245 mm/yr, compared to 1,041 mm/yr for the 2011-2012 (post-beetle) period. Given the 4,700 acre riparian area, leaf beetle induced defoliation results in a mean annual ET reduction of 3,161 acre-ft. In 2011 and 2012, volumetric reductions to ET were estimated to be 817 and 5,505 acre-ft, respectively. The METRIC model was shown to be a useful tool for monitoring ET during pre- and post-beetle defoliation periods.
Table of Contents

INTRODUCTION ........................................................................................................................................... 1
    The introduction of tamarisk ......................................................................................................................... 1
    Changing perspectives on tamarisk ................................................................................................................ 3
    Tamarisk control efforts ............................................................................................................................... 3
    Biocontrol of tamarisk with *Diorhabda* spp. ............................................................................................... 4
    Estimates of tamarisk ET ............................................................................................................................. 7
    Region of Interest ....................................................................................................................................... 11
    Purpose of study ......................................................................................................................................... 12

METHODS: .................................................................................................................................................. 14
    Remote sensing with Landsat: .................................................................................................................... 14
    Ground-based weather data .......................................................................................................................... 14
    Classifying defoliated tamarisk ................................................................................................................... 16
    Estimated ET with METRIC....................................................................................................................... 20
    METRIC adjustment to account for canopy shading ................................................................................... 26

RESULTS .................................................................................................................................................... 28
    Classification of defoliated tamarisk .......................................................................................................... 28
    Healthy vs. defoliated riparian ET .............................................................................................................. 30
    Pre and post-beetle Lower Virgin Monthly ET vs. ET<sub>r</sub>......................................................................... 33
    Yearly pre and post-beetle Lower Virgin ET v. ET<sub>r</sub> ............................................................................ 34
    Comparison with Eddy Covariance Flux Station ET Estimates .................................................................... 36

DISCUSSION AND CONCLUSIONS ........................................................................................................... 38

References: ................................................................................................................................................... 41
List of Figures

Figure 1: Tamarisk flowers ........................................................................................................ 2
Figure 2: Native enemy Diorhabda spp. (leaf beetles). ............................................................... 5
Figure 3: Healthy versus defoliated tamarisk .............................................................................. 5
Figure 4: Region of Study ........................................................................................................ 12
Figure 5: Correction of incoming short wave radiation ............................................................. 15
Figure 6: Tamarisk spectral response under healthy and defoliated conditions ...................... 17
Figure 7: Measured ET,F for February to November for comparison with ET,F at satellite
overpass time .......................................................................................................................... 25
Figure 8: M-SAM classification results ..................................................................................... 29
Figure 9: SAVI maps for August 11th, 14th, and 9th of 2010, 2011, and 2012 ......................... 29
Figure 10: Lower Virgin and Muddy River METRIC ET 2010-2012 ........................................ 31
Figure 11: ET,F map for the Lower Virgin and Muddy Rivers .................................................. 32
Figure 12: ET maps for the Lower Virgin and Muddy Rivers ..................................................... 32
Figure 13: Monthly average ET pre- and post-beetle, with monthly ET..................................... 33
Figure 14: METRIC ET compared with eddy covariance ET estimates ....................................... 37
Figure 15: Scatter plot of daily eddy covariance and METRIC ET estimates ............................. 37
List of Tables

Table 1: Tamarisk evapotranspiration for various locations in the Western USA ....................... 9
Table 2: Landsat image dates used in Multi-temporal Spectral Angle Mapping analysis. ............. 20
Table 3: Monthly average METRIC ET .................................................................................. 34
Table 4: Yearly average METRIC ET .................................................................................... 35
INTRODUCTION

The introduction of tamarisk

Tamarisk (*Tamarix* spp.) is an invasive shrubby-tree native to Europe and Asia. The plant first made entrance into the United States in the 1800s. Soon after, the plant further dispersal through domestic nurseries (Robinson, 1965). Dr. Butterfield, agriculturist emeritus for the Agricultural Extension Service of the University of California, spoke about the availability of tamarisk and spread westward in the 19th century:

“Some eastern nurseries were listing Tamarix before we had records in California. Most of our early introductions into California came from nurseries in New York and other states. The old Downing Nursery at Newburg, N.Y., was taken over by the Saul family and in 1854 the Highland Nurseries operated by the Saul family listed Tamarix gallica, T. germanica and one called T. libanotis (p. 47 of their 1854-55 nursery catalog). James Saul was sent to California to represent the nursery and was in San Francisco in 1854 and later.” (Robinson, 1965)

The spread of tamarisk was originally encouraged due to 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 (see Figure 1) (Goldsmith & Smart 1982; Friederici, 1995). The United States Department of Agriculture (USDA) is reported to have been growing several species of tamarisk later released for cultivation (Zouhar, 2003; Horton, 1964). Furthermore, as recently as 1964 the USDA recommended tamarisk as a suitable windbreak for those living in the central Great Plains (Read, 1964).
Figure 1: Tamarisk was initially valued for the beneficial services it provided. The pink tamarisk flowers were thought to improve riparian zone aesthetics.

After introduction, tamarisk generally occupied small thickets adjacent to rivers, and locations deemed unacceptable for natives (Larner, Marshall, Phluger, & Burnitt, 1974). However, today tamarisk is considered one of the most common invasive species in the America, occurring in every major watershed (Zouhar, 2003). The timing of extensive tamarisk establishment of American riparian zones correlates well with anthropogenically induced disturbance and hydrologic regime change, namely, reservoir construction, floodplain clearance, fires, and floods (Van Hylckama, 1966; Campbell & Dick-Peddie, 1964; Harris, 1966; Turner, 1974). This would indicate that tamarisk establishment was opportunistic, rather than an active pursuit to displace natives. This is an important distinction because the plant's resilience post establishment is often used to characterize the plant as a causal agent in the initial displacement native riparian communities.
Changing perspectives on tamarisk

Complicated water law, rivalries, and competition for water resources has been a continual theme of the American southwest. During Franklin D. Roosevelt’s presidency, the New Deal spurred investigation into the potential for development of the American west (Lowitt, 1993). During this time several investigations into southwestern water resources were deployed (Chew, 2009). Since water in the American southwest is scarce, many of these studies involved the availability of water. Through these studies it was being suggested that the prevalent invasive was consuming large volumes of invaluable water (Chew, 2009; Stromberg, Check, Nagler, & Glenn, 2009). This made it easy for tamarisk to become a 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 (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, Check, Nagler, & Glenn, 2009). With these figures in mind, removal programs aimed at salvaging water through tamarisk removal were implemented.

Tamarisk control efforts

The establishment of tamarisk has caused several issues. Some of the issues include: diminished biodiversity, as tamarisk crowds out native vegetation; decreased habitat quality for birds, reptiles, and insects; alterations to river channels, as flow regime and sediment deposition
is changed; diminished water quality, as tamarisk increases salt concentration in the litter, soil, and runoff; decreased volumetric flow due to tamarisk’s high transpiration rates; and an overall reduction in recreational value (Busch & Smith, 1995; Brotherson & Field, 1987; Ellis, Molles Jr., Crawford, 1998; DeLoach, Carruthers, Lovich, Dudley, Smith, 2000).

Traditional control programs have included chemical, mechanical, and controlled burnings (Bateman et al., 2010). Widespread use of these methods becomes expensive, and has produced mixed results (Tamarisk Coalition, 2009; Dudley & Kazmer, 2005). This caused the USDA to consider biocontrol for tamarisk as early the 1970s (DeLoach, 1990; Bean, Dalin, & Dudley, 2012). Biocontrol refers to pest or weed management that employs armies of natural enemies to control undesirable weeds or insects (Hoffman & Frodsham, 1993). This method is particularly well suited for tamarisk control because it is both long lasting and relatively inexpensive (Hoffman & Frodsham, 1993).

Biocontrol of tamarisk with *Diorhabda* spp.

Research of tamarisk's native enemies began in 1986, and after 15 years of research *Diorhabda* spp. (leaf beetles) were selected for introduction and testing in the United States (Figure 2; Deloach et al., 2006; DeLoach et al., 2009). The specific species active in the Lower Virgin and Muddy Rivers is *Diorhabda carinulata*. The beetle controls tamarisk by eating an individual’s leaves to the point of complete defoliation (Figure 3).
Figure 2: Native enemy Diorhabda spp. (leaf beetles) which has been released in the United States for biological control of invasive tamarisk.

Leaf beetles organize their life history events according to the seasonal patterns of its native habitat, which is Fukang, China (DeLoach et al., 2006; DeLoach et al., 2009). In its native habitat leaf beetles experiences cold winters. During the winter tamarisk also defoliates itself, which leaves the beetle without its preferred food source. In order to survive these conditions, the beetle enters a form of hibernation called diapause. This process is triggered by observed
day length, which signals to the leaf beetles that winter is approaching. When a critical day length is observed, leaf beetles slow physiological processes, ceases reproductive activity, feed less, create a protective cocoon, and eventually drops into the leaf litter until desirable conditions return (Bean, Dalin, & Dudley, 2012). Since diapause is triggered by day length, the beetle will enter diapause at different times depending on latitudinal location (Dalin et al., 2010). At parallels more southern than its native habitat (e.g. the Lower Virgin and Muddy Rivers of Nevada) early triggering of diapause may produce a shift of these life history events, potentially creating a substantial disadvantage for the beetle (Bean, Dalin, & Dudley, 2012). If this shift produces an asynchronicity between leaf beetle and tamarisk phenology, the beetles may fail to establish in these river systems (Crawley, 1989; Dalin et al., 2010; Julien & Griffiths, 1999). On the other hand, success in these regions would imply that the beetle is able to adapt to more southern photo periods, indicating a greater likelihood for dispersal through the lower Colorado River (Dalin et al., 2010).

Release of leaf beetles in the American southwest is not without concern. Contact between leaf beetles and tamarisk in the Lower Virgin River is under jurisdiction of the Endangered Species Act (ESA). The Southwestern Willow Flycatcher (SWWF) is a federally listed endangered species that has made tamarisk its critical habitat. Leaf beetles harm SWWF indirectly as defoliation caused by leaf beetles leads to increased nest temperatures, increased susceptibility to predation, parasitism, and an overall decrease in brood success rates (Paxton, Theimer, & Sogge, 2011). This is an incredibly unique situation because tamarisk, which was originally detrimental to SWWF’s critical habitat, is now being protected under the same legislation. Contact between leaf beetle and SWWF critical habitat has caused a revoking of permits for future leaf beetle release until ESA issues are resolved (Gruver, 2010).
Estimates of tamarisk ET

Several recent studies reveal that high initial estimates of tamarisk evapotranspiration (ET) were likely the result of suboptimal measurement methods (Owens & Moore, 2007). Recent studies reveal that the plant ET is generally less than a well-watered reference crop (i.e. alfalfa), though its ET is highly variable (Table 1). Variability in tamarisk ET may be attributed to climatic conditions, stand density, soil properties, salinity, and the availability of water (Anderson, 1982, Glenn, Nagler, Marino, & Hultine, 2013). Further, tamarisk, like other plants adapted to arid conditions, exerts meticulous control over its stomata, quickly responding to changes in atmospheric water demand (Osmond, Borkman, & Anderson, 1980; Anderson, 1982; Devitt, Sala, Mace, & Smith, 1997; Sperry, 2000; Ogle & Reynolds, 2002). Consequentially, estimating tamarisk ET is highly site specific and poses difficulties for measurement techniques. These difficulties are not generally present for well-watered agricultural crops (Allen, Pereira, Rais, & Smith, 1998; Glenn, Nagler, Marino, & Hultine, 2013). For this reason, estimating actual tamarisk ET over entire riparian systems requires increasingly robust measurement and modeling methods.

Estimating tamarisk ET over 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 Lower Colorado Region water, as the integrity of future supply is uncertain (Barnett & 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, as well as 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 southbound 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 (Nagler & Glenn, 2013; Nagler et al., 2010; Tamarisk Coalition, 2009). It is likely that the introduction of leaf beetles to the Lower Virgin River will alter tamarisk ET, and it is possible that alterations to tamarisk ET will increase available water in the system. Quantification of this change 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.
Table 1: Tamarisk evapotranspiration for various locations in the Western USA (Nagler & Glenn, 2013)

<table>
<thead>
<tr>
<th>Location</th>
<th>Method</th>
<th>ET (mm/yr)</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Virgin River, NV</td>
<td>Bowen Ratio</td>
<td>700-1400</td>
<td>Devitt et al. (1998)</td>
</tr>
<tr>
<td>Low. Colorado, CA</td>
<td>Bowen Ratio</td>
<td>400-1400</td>
<td>Chatterjee (2010)</td>
</tr>
<tr>
<td>Low. Colorado, CA</td>
<td>Bowen Ratio</td>
<td>780-980</td>
<td>Nagler et al. (2005a)</td>
</tr>
<tr>
<td>Rio Grande, NM</td>
<td>Eddy covariance</td>
<td>800-1200</td>
<td>Nagler et al. (2005b)</td>
</tr>
<tr>
<td>Low. 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 &amp; 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>GW fluctuations</td>
<td>420-1180</td>
<td>Halter &amp; Hart (2009)</td>
</tr>
<tr>
<td>Humboldt River, NV</td>
<td>Sap flux, Remote</td>
<td>518 pre-, 297 post-</td>
<td>Pattison et al. (2011a, 2011b)</td>
</tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Truckee River, NV</td>
<td>Eddy covariance</td>
<td>400-500</td>
<td>Snyder et al. (2012)</td>
</tr>
</tbody>
</table>

Most studies have aimed at characterizing site-specific tamarisk ET. Bowen ratio energy balance stations, sap flux sensors, eddy covariance turbulent flux stations, and monitoring groundwater fluctuations have contributed much to the current understanding of tamarisk water consumption (Table 1). 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., 2009a; 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 water consumption, such as plant disease and salinity. When these issues are considered, it appears the most desirable method for analyzing long-term tamarisk ET is one that has higher spatial resolution, and is also able to account for local variability that influences ET through environmental and biological stressors. A potential solution is remote sensing methods that utilize sensors with agricultural field scale resolution (30 – 120 m), remotely sensed thermal and optical imagery, as well as weather data collected on the ground. However, such methods still introduce uncertainty. This is particularly true in arid regions where midday depression of ET caused by reduced water availability and increased vapor pressure deficit may be observed. (Taghvaeian, 2011; Geli, 2012).
Region of Interest

The region of interest is the riparian zone adjacent to the Lower Virgin and Muddy River systems (Figure 4). The Lower Virgin River stretch has a length of approximately 33 km. The Lower Virgin River riparian zones being investigated represent an area of approximately 19 km² (4,700 acres). The region is a hot and arid environment, with summer temperatures exceeding 45 C and mean annual rainfall less than 10 cm (Cleverly, Smith, Sala, & Devitt., 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).
Figure 4: Region of Study, the Lower Virgin River and Muddy Rivers with polygons of riparian areas being analyzed by METRIC in green and orange, respectively. Moapa and Overton weather stations as well as the eddy covariance station are also marked. The inset presents the approximate eddy covariance footprint area used for METRIC analysis in red, and a green point for the location of the eddy covariance station.

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, Tasumi, & Trezza, 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 and post-leaf beetle ET for the Lower Virgin River are compared. These estimates are also compared to 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 to healthy tamarisk in the nearby Lower Muddy River (Figure 4). The Lower Muddy River encountered beetles after they migrated through the Lower Virgin River.
METHODS:

Several subsections of the methods section follow Liebert et al. (2015).

Remote sensing with Landsat:

The study utilizes Landsat 5 and Landsat 7 imagery, acquired by the Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) sensors, respectively. The sensors have a spatial resolution of 30 m in the visible and infrared, and 120 m 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 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. Weather data was subjected to quality

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 to theoretical clear sky solar radiation, and corrections were made following Allen (1996) (Figure 5).

Figure 5: Correction of biased low short wave radiation caused by sensor drift at the Overton station in 2010. The measured values are presented in the top figure, where it is clear that the sensor is consistently underestimating incoming short wave radiation. The corrected values are presented in the bottom figure.
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- and post-beetle exposure could be compared. When the beetle initially arrives to a region defoliation is typically partial, localized, and sporadic. Consequentially, 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 6).
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 6 surface reflectance values (blue, green, red, near infrared (NIR), and two short wave infrared (SWIR) bands) correspond to spectral data collected at the base date, while the last 6 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 becomes the spectral signature for tamarisk changing from healthy to fully
defoliated in the presence of leaf beetles. The reference spectra used for classification was June 27, 2011 in conjunction with August 14, 2011 (Figure 6).

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 (NAIP) 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 mulit-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 & 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 ($\theta$) between
the reference spectra and test spectra vectors is determined by the following relation, which is
simply derived from the $k$-dimensional dot product:

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

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 TM 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 2. The dates used for M-
SAM analysis are intended to capture the approximate window of beetle activity. Land use maps
and NAIP 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.

Table 2: Landsat image dates used in Multi-temporal Spectral Angle Mapping analysis.

<table>
<thead>
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<th>2009</th>
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<td>9/15</td>
<td>8/24*</td>
<td>9/25*</td>
</tr>
</tbody>
</table>

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:

\[ LE = R_n - G - H \]
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. 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, Tasumi, & Trezza, 2007; Allen, Tasumi, Trezza, & Kjaersgaard, 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, Tasumi, & Trezza, 2007; Allen, Tasumi, Trezza, & Kjaersgaard, 2012). Momentum roughness lengths of 0.1 m and 0.4 m were assumed to correspond to woody wetlands and herbaceous wetlands, respectively (Allen, Tasumi, Trezza, & Kjaersgaard, 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:

\[
ET_{inst} = 3,600 \frac{LE}{\lambda}
\]

where 3,600 is 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 (\( ET_{rF} \)) 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 (ASCI-EWRI, 2005). ET for the 24-hour period (ET$_{24}$) for day $i$ is estimated as:

$$ ET_{24i} = ET_r F_i \times ET_{r,24} $$

where ET$_{r,24i}$ is the 24-hour reference ET for day $i$, and ET$_r F_i$ is the fraction of reference ET for the $i^{th}$ day. Estimated ET over extended time periods is computed with the equation:

$$ ET = \sum_{i=n}^{m} ET_r F_i \times ET_{r,24i} $$

where $n$ is the first day of the desire time period, $m$ is the last day of the desired time period.

Daily per-pixel ET$_r F$ is estimated through linear interpolation of ET$_r F$ values between image acquisition dates, and is multiplied by weather station based ET$_{r,24i}$ values for respective day $i$ to finally estimate the daily ET$_{24}$ per pixel. In this formulation, 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$_r F$ 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$_r F$ obtained at image overpass time remains relatively constant throughout the day and is equal to the 24-hour ET$_r F$. 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 due to 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 regards to these larger areas, midday depression of ET was sufficiently compensated by nighttime transpiration and guttation, so that the application 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, 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-hour average ET, F were evaluated using eddy covariance derived ET, and weather station derived ET,
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 7 presents the results of this analysis, along with the three year average hourly ET,F. From Figure 7 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 three year, 24-hour average measured ET,F was 0.48, and the three year 10 am and 11 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 am and 11 am measured ET,F values. Given that the average 24-hour 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, since midday depression of ET would serve to reduce estimates obtained through the METRIC model.
Figure 7: Measured February through November hourly average ET,F for 2010, 2011, and 2012, and the three 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-hour average ET,F is very close to 10 am to 11 am values.

Calibration of the model is done through the selection of two anchor pixels for the CIMEC process. Anchors consist of a “hot” and “cold” pixel, each of which exhibit 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, Tasumi, & Trezza, 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 $z_{om}$. Additionally,
is has been found that estimated METRIC ET is not very sensitive to the estimated value of $z_{om}$
(Tasumi, Trezza, & Allen, 2005; Tasumi, Trezza, Allen, & Wright, 2008).

**METRIC adjustment to account for canopy shading**

METRIC was primarily developed to estimate ET from agricultural areas. These areas
generally exhibit some degree of homogeneity and predictability since 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, Tasumi,
Trezza, & Kjaersgaard, 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 to a
full hemispherical albedo that should be used when computing net $R_n$. 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 & Ball, 1997; Dobos, 2003; Wang & Zeng, 2008; Barlage, Zeng, Wei, & Mitchell., 2005;
Strahler & Muller, 1999).

The METRIC model estimates broadband albedo ($\alpha$) following Tasumi, Trezza, Allen, &
Wright (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, Trezza, Allen, & Wright (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 the primary energy balance equation. 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 NDVI was developed and applied for such conditions following recommendations of Allen, Tasumi, Trezza, & Kjaersgaard (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:

$$\alpha = -0.3NDVI + 0.335$$

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, Tasumi, Trezza, & Kjaersgaard (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

Several subsections of the results section follow Liebert et al. (2015).

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 8). The timing of maximum full defoliation for the Lower Virgin River was observed on August 9th of 2012 when 3 km² (731 acres) of tamarisk was classified as fully defoliated. On August 14th of 2011, 2.1 km² (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 km² (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 9), as well as the progression of leaf beetles through the Lower Virgin River as reported by the Tamarisk Coalition (2012).
Figure 8: M-SAM classification results for fully defoliated tamarisk on August 11\textsuperscript{th}, 14\textsuperscript{th}, and 9\textsuperscript{th} of 2010, 2011, and 2012, respectively. 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 ETM+ imagery, which is impacted by the malfunctioning scan line corrector (SLC Off).

Figure 9: SAVI for respective years during the timing of maximum M-SAM classification on August 11\textsuperscript{th}, 14\textsuperscript{th}, and 9\textsuperscript{th} of 2010, 2011, and 2012, respectively. Greatest SAVI reductions presented in a, b, and c correspond well with M-SAM classification at the same dates shown in a, b, and c of figure 8.
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 due to 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 ET rates during defoliation to those from healthy tamarisk areas in the neighboring Lower Muddy River under the same weather conditions.

**Healthy vs. 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 4 reveal that the ET is higher in the Lower Virgin River due to higher tamarisk density (Figure 8a). For 2007-2010, average SAVI for the Lower Virgin River and the Lower Muddy River was 0.37 and 0.34, respectively. Figures 10a and 10b 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/d, and for the Lower Muddy River riparian area it was 5.31 mm/d. Over this time, the average Lower Virgin River ET rate was 0.83 mm/d greater than the Muddy River. This difference in ET is likely due to tamarisk density differences as observed from SAVI distributions for respective riparian areas (Figure 10a). During the period of tamarisk defoliation in the Lower Virgin River, the 2011 ET rate from June to September was 5.57 mm/d and 5.96 mm/d, 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/d, 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/d, which is due to defoliation alone. This reduction equates to 2,300 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 11 and 12, respectively, and highlight these results.

Figure 10: Comparison of Lower Virgin River and Muddy River daily tamarisk ET rates in 2010 through 2012. (a) 2010 was pre-beetle as determined by M-SAM classification and supported by Tamarisk Coalition on-ground observation. It can be seen that 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.
Figure 11: Map of ET$_{rF}$ for the Lower Virgin and Muddy River regions 2010, 2011, and 2012. ET$_{rF}$ is average of METRIC results from February through November.

Figure 12: ET maps computed with the METRIC for August 2010, 2011, and 2012 in mm/month. August is the month that experienced greatest reduced ET from leaf beetle induced defoliation.
Pre and post-beetle Lower Virgin Monthly ET vs. ET_r

Average monthly ET results for the Lower Virgin and Lower Muddy Rivers are presented in Table 3. Monthly results for the Lower Virgin River ET pre- and post-beetle arrival, as well as ET for an alfalfa reference surface, ET_r, are illustrated in Figure 13, where it is evident that alfalfa ET remained substantially higher than tamarisk ET under healthy conditions. For years post-leaf beetle arrival it can be seen that Lower Virgin River ET is less than Lower Virgin River ET pre-leaf beetle. 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 13.

Figure 13: Monthly mean Lower Virgin River tamarisk ET pre- and post-beetle arrival compared to 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 and post-beetle Lower Virgin ET v. ETₚ

Average yearly ET results for the Lower Virgin and Lower Muddy Rivers are presented in Table 4. The pre-beetle mean yearly (2007-2010) ET for the Lower Virgin River was 1,246 mm/yr.

Table 3: Monthly average evapotranspiration for the Lower Virgin River and Lower Muddy River for pre-beetle (2007-2010) and post-beetle (2011-2012) arrival in mm/month.

<table>
<thead>
<tr>
<th>Month</th>
<th>L. Mudy pre-beetle</th>
<th>L. Muddy post-beetle</th>
<th>L. Virgin pre-beetle</th>
<th>L. Virgin post-beetle</th>
<th>L. 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>41.10</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>88.50</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>
and the post-beetle mean yearly (2011-2012) ET for the Lower Virgin River was 1,041 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) to mean 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 5,505 acre-ft. Comparing 2011 Lower Virgin River ET (1,193 mm/yr) to mean 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 mean yearly ET for pre-beetle (2007-2012) and post-beetle (2011-2012) periods resulted in a reduction of 3,161 acre-ft. Mean ET, from 2007-2010 was 2,219 mm/yr, and for 2011-2012 mean ET, was 1,875 mm/yr. When compared to Lower Virgin River mean pre- and post-beetle tamarisk ET rates for respective periods, ET is 973 mm/yr and 834 mm/yr less that ET, respectively.

Table 4: Yearly Lower Virgin and Lower Muddy River evapotranspiration with respective differences in mm/year.

<table>
<thead>
<tr>
<th>Year</th>
<th>ET$_r$</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>
Comparison with Eddy Covariance Flux Station ET Estimates

For validation purposes, METRIC ET was compared to ground based ET estimates obtained by an eddy covariance flux station installed in tamarisk on the Lower Virgin River (Figure 4) (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 4). The footprint was approximated based on daytime fetch derived from the analytical models of Kljun, Calanca, Rotach, & Schmid (2004) and Kormann & 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 14 illustrates the time series comparison of METRIC ET and eddy covariance estimates, where it is evident that METRIC ET estimates compare well to eddy covariance ET estimates for pre- and post-defoliation periods ($r^2 = 0.86$; Figure 15). 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.
Figure 14: Comparison of 5-day moving average METRIC 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, c). Comparison of METRIC yearly ET from 2010-2012 for the footprint area reveals that ET increased in 2012 versus 2011, which are both post-beetle (d). Comparing Figure 10d to Figure 6d 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.

Figure 15: Scatter plot of daily eddy covariance and METRIC 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.
DISCUSSION AND CONCLUSIONS

Several subsections of the methods section follow Liebert et al. (2015). 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/d and post-beetle arrival peak summer ET was 2.0 mm/d. This study reports a pre-beetle peak summer ET of 6.1 mm/d and a post-beetle peak summer ET of 3.4 mm/d. Nagler et al. (2014) reports yearly pre-beetle ET (2007-2009) was 903 mm/yr (4.09x10^7 m^3/yr over 4,531 ha), and yearly post-beetle ET (2012) was 419 mm/yr (1.9x10^7 m^3/yr over 4,531 ha). This study reports yearly pre-beetle ET (2007-2009) of 1,225 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 MODIS 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 to eddy covariance ET estimates suggest 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 14d). These result are opposite to those for the larger Lower Virgin River riparian area as a whole, where METRIC ET for 2011 was greater than 2012 (Figure 10d). This difference is likely the result of less tamarisk defoliation within the eddy covariance footprint as compared to the larger Lower Virgin River riparian area as shown in the ET time series of Figures 10 and 14, increases in 2012 M-SAM classification of defoliation (Figure 8), and SAVI reductions for 2012 (Figure 9). 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 upon 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 & 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.
References:


