Defoliation effects of *Diorhabda carinulata* on tamarisk evapotranspiration and groundwater levels

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ABSTRACT

*Diorhabda carinulata* (northern tamarisk beetle) has been released in the western United States as a biological control agent for the invasive plant *Tamarix* spp. (tamarisk). A few studies have been conducted analysing the effects of beetle defoliation on tamarisk water consumption, but predefoliation and post-defoliation comparison based on field data is scarce. The question of whether beetles substantially alter tamarisk water consumption is still open for discussion. In this study, an eddy covariance station and groundwater monitoring well were installed in a tamarisk stand along the Virgin River near Mesquite, NV, in 2010 to observe the impacts of tamarisk defoliation on evapotranspiration (ET) and groundwater levels. ET was calculated using the eddy covariance method and the White method and supported by Landsat remote sensing estimates. Data collected in 2010 established a baseline since the beetles arrived at the site in late 2010 and started feeding on foliage causing tamarisk trees to turn to brown during 2011. Repeated defoliations in 2011 and 2012 show that post-defoliation ET values and magnitude of diurnal groundwater-level fluctuations decreased compared with the predefoliation values. Estimated annual ET and annual average daily groundwater fluctuations were reduced by 18% and 35%, respectively. However, the magnitude of effects of defoliation was dependent on the growth stage of tamarisk at the time of defoliation. Also, ET recovered within a month as tamarisk established new leaves. Results from this study suggest that long-term changes in ET are highly dependent on repeated defoliation occurrences over several years. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS eddy covariance; White method; Virgin River; *Tamarix*; saltcedar; leaf beetle

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INTRODUCTION

The Virgin River is a tributary of the Lower Colorado River system and is an important source of domestic and agricultural water in Nevada, Arizona, and Utah (SNWA, 2013). The demand for Colorado River water has increased with population growth and the prioritization of maintenance and development of ecological habitats (Bernhardt et al., 2005; Follstad Shah et al., 2007; Cohen, 2011). This issue is compounded by the fact that the Colorado River system is currently facing the worst 11-year drought in the last century (Bureau of Reclamation, 2012). The decade from 2000 to 2009 has had the lowest 10-year running average flows (Woodhouse et al., 2010). For these reasons, careful attention has been given to alternative strategies for conserving water. For example, in 2007 the Southern Nevada water authority funded the ‘Study of the Long-Term Augmentation Options for the Water Supply of the Colorado River System’ to examine water resource augmentation options (SNWA, 2009). One of the several options was vegetation management, which included tamarisk control. Southern Nevada water authority estimated that 20 000 acre-feet per year of water is potentially available through the control of tamarisk along the Virgin River (SNWA, 2008).

Tamarisk (also known as saltcedar, *Tamarix* spp.) is an invasive, mostly deciduous, and shrubby tree native to Europe and Asia. Tamarisk first entered the United States as an ornamental, which led to further dispersal through nurseries (Robinson, 1965). Dispersal was later encouraged because of beneficial services provided by the plant, such as its suitability as a windbreak (Read, 1964). It was also noted that rooting systems could stabilize river...
banks, animals could utilize its shade, branches could be used for firewood, and the plant’s flowers improved riparian zone aesthetics (Goldsmith and Smart, 1982; Friederici, 1995).

After introduction and dispersal, tamarisk did not immediately dominate riparian zones (Everitt, 1980). Rather, the plant occupied small thickets adjacent to rivers, and locations deemed unacceptable for natives (Robinson, 1965; Larner et al., 1974). In several places, extensive establishment of tamarisk along Southwestern riparian zones corresponds to anthropogenically induced disturbance and hydrologic regime change (i.e., reservoir construction, floodplain clearance, fires, and floods) (Campbell and Dick-Peddie, 1964; Harris, 1966; Turner, 1974; Graf, 1982). Tamarisk now occupies hundreds of thousands of hectares of North American riparian zones (Nagler et al., 2012). Along such riparian zones, tamarisk can be observed forming vast monocultures or in communities composed of other salt-tolerant shrubs. Along the Lower Colorado River floodplain, tamarisk may be seen in communities with arrowweed (Pluchea sericia), while along the San Pedro, the Rio Grande, and the Colorado River delta in Mexico, tamarisk may be seen in mixed stands with cottonwood (Populus spp.) and willow (Salix spp.) trees (Glenn and Nagler, 2005).

During the middle of the 20th century, after tamarisk had established in many locations, perceptions of tamarisk began to change (Robinson, 1965; Hughes, 1968; Chew, 2009; Stromberg et al., 2009). The changing sentiment was motivated by competition for water in the Southwest (Stromberg et al., 2009). Early investigation of tamarisk was aimed at determining potential for water savings through its removal (Graf, 1992). Results of these investigations included estimates of tamarisk evapotranspiration (ET) as high as 3–4 m per year per plant, which is up to twice that of a reference crop (DiTomaso, 1998). These findings fueled policy geared toward eradicating tamarisk to reclaim water for economic development, copper mining (for national defense), and public water supply (Chew, 2009). As perception changed, tamarisk was depicted as a nuisance, responsible for the degradation and consumption of valuable natural resources (Bowser, 1957; Harris, 1966; Stromberg et al., 2009). However, recent research raises important questions regarding whether such labels are warranted. For example, the 3–4 m per year per plant values reviewed by DiTomaso (1998) are improbable, likely being the result of suboptimal measurement methods (Owens and Moore, 2007). In fact, it has been noted that under some circumstances, tamarisk actually uses less water than certain natives, such as cottonwood and willow (e.g. Naglere et al., 2003, 2010; Shafroth et al., 2005; Owens and Moore, 2007). The Tamarisk Coalition (2009) reported that tamarisk water consumption largely depends on the composition of native communities, stand density, and site conditions (Nagler and Glenn, 2013). Consequently, tamarisk ET is highly variable, and experts remain divided on whether worthwhile water savings are possible with tamarisk eradication (Tamarisk Coalition, 2009; Nagler et al., 2010; Nagler and Glenn, 2013). However, it is clear that if plants do not return to occupy invaded tamarisk areas, then a potential for water savings through tamarisk control is possible.

Despite this newly realized uncertainty, initially perceived opportunity for water savings and the potential for ecological and environmental rehabilitation and protection prompted the development of tamarisk removal strategies. Traditional control of tamarisk via chemical (Duncan and McDaniel, 1998), mechanical, and fire-based methods (Shafroth et al., 2005) has had mixed results, is generally expensive, and can cause environmental issues of their own (Bateman et al., 2010). For these reasons, in the 1970s, tamarisk was considered a suitable candidate for biological control (Watts et al., 1977; DeLoach, 1989). Diorhabda elongata (Brulé) sensu lato leaf beetles (Coleoptera: Chrysomelidae), now commonly referred to as Diorhabda carinulata, whose larvae and adults feed on leaf foliage and petioles, which results in desiccation and eventual loss of leaves (Pattison et al., 2011a), were selected, and open field test began in 2001 (DeLoach, 1989; DeLoach et al., 2003). One successful release site is located in St George, UT, on the banks of the Virgin River. The release took place in 2006, leading to the large-scale establishment of the beetles along the Lower Virgin River. Colonies originating in St George arrived at the Overton arm of Lake Mead in 2011 (Tamarisk Coalition, 2012).

The relatively rapid progression of these beetles down the Lower Virgin River into the Overton arm provides a unique opportunity to directly assess if the beetles are providing any water savings. The effect of defoliation has been reported in recent years. However, the lack of a baseline condition (prebeetles’ defoliation) is a common issue in these studies (Hultine et al., 2010; Pattison et al., 2011b; Snyder et al., 2012). The migration of beetles through the Lower Virgin River provides opportunity to compare tamarisk ET during baseline conditions with tamarisk ET measured under defoliated conditions.

The objective of this study was to determine the effect of beetles’ defoliation on tamarisk water consumption. An eddy covariance tower was installed along the Lower Virgin River, enabling the capture of both predefoliation and post-defoliation ET estimates. ET estimates were based on eddy covariance data and groundwater-level fluctuations to assess differences in ET associated with predefoliation and post-defoliation periods. In addition, the Landsat satellite derived land surface energy balance, and vegetation index data were used to support our interpretations of
result. This study helps to assess potential water salvage resulting from biocontrol of tamarisk in the Lower Virgin River and has important implications for the Colorado River system.

METHODS

In 2010, an eddy covariance tower was installed along the corridor of the Lower Virgin River to measure net radiation (Rn), ground heat flux (G), sensible heat flux (H), and latent heat flux (LE) (Figure 1). The tower is located approximately 20 km southwest of Mesquite, NV, (36°42′09″N, 114°15′29″W) and is surrounded mostly by tamarisk, which extends along the river’s floodplain for approximately 1.1 km and is about 120 m wide. The Lower Virgin River flows along the west side of the study site, and pasture land bounds the tamarisk stands to the east of the study site (Figure 1). The site consists of a groundwater monitoring well and the equipment necessary to estimate available energy (Rn – G) and apply the eddy covariance technique for estimating turbulent fluxes of ET. Even though the study site location was not optimal because of a nearby pasture, the site contained the largest tamarisk stand in the area where defoliation was observed, and ET from the surrounding tamarisk could be measured. The turbulent fluxes obtained from the site were carefully evaluated to make sure that the peak contribution was within the tamarisk stand.

The eddy covariance tower includes a three-dimensional sonic anemometer (model CSAT3), an open-path infrared gas analyser (model LI-7500), a net radiometer (model NR-LITE), two soil heat flux plates (model HFP01SC), two soil thermocouple probes (model TCAV-L), two soil water reflectometers (model CS616), and a combination of air temperature/relative humidity probe (model HMP45C-L). Groundwater levels were monitored with a CS408 pressure transducer installed in a 1.8-m depth piezometer screened between 1.9 and 2.8 m. Precipitation was measured with a tipping bucket rain gage, TE525WS-L, Texas Electronics. The anemometer and gas analyser were placed approximately 3.8 m above the ground surface (1 m above canopy) with a fetch toward the dominant wind direction, which is east–southeast. The tower configuration and its orientation were determined based on historic wind patterns to obtain optimal fetch from the tamarisk stands. Data were compiled into several tables including the original 10-Hz time series and 30-min average humidity, temperature, and net radiation and ground heat flux data. The data were monitored, compiled, and stored in a Campbell Scientific CR5000 data logger. Data collection occurred monthly during maintenance site visits, at which time, sensors were cleaned and checked and full memory cards were exchanged with newly formatted cards. Additionally, hand measurements of the groundwater levels were made during site visits and cross checked with pressure transducer measurements.

Turbulent fluxes were processed and corrected using EddyPro, LI-COR Inc. Axis rotations for tilt correction, time lag compensation, turbulent fluctuations with block averaging and compensation of density fluctuations were applied to the raw data. Raw data were also screened to identify anomalies that may include spikes, amplitude resolution, dropouts (gaps), absolute limits, skewness, and kurtosis. Spectra were calculated with the Fast Fourier Transform method.
Transform, with Hamming window and low/high-frequency range corrections applied. Fluxes were also checked for quality based on steady-state and turbulent conditions. Flux values deemed to have poor quality were discarded based on the screening mentioned previously. Processed and corrected turbulent fluxes were then calculated as 30-min averages from 10-Hz data. Linear interpolation was used for gap filling if gaps are fewer than 4 hours. If gaps were more than 4 hours and there was no preceding precipitation event within 12 h, missing data for a respective hour were filled by taking the average value computed from the previous and next day values for that hour. If a precipitation event or change in trend line occurred before the gap, the simple average was calculated using values from 2 days after the gap. When there were large continuous gaps in the flux data, those gaps were not filled. There were three data gaps not filled. The first gap was caused by a major winter storm at the end of December 2010 that flooded the study site, prompting malfunction of the tower’s power supply; however, data collection was restored in January of 2011. Another significant data gap occurred from 1 March to 20 April and 26 November to 31 December in 2012 because of malfunction of the data logger. The footprints were calculated using EddyPro. If peak contribution distance was beyond the tamarisk fetch, those data were excluded and gap filled as mentioned previously. Overall, 14% of data were gap filled.

Groundwater water levels were measured at 30-min intervals. Depth to water hand measurements were made during the site visit and used to calibrate pressure transducer drift. The corrected water level data were then converted to total head using land surface elevation at the site. Elevation of the site was obtained from National Elevation Dataset, U.S. Geological Survey. Groundwater-level time series were used to calculate diurnal fluctuations and to estimate ET using the White method (White, 1932; Loheide et al., 2005), which assumes that diurnal groundwater fluctuations are caused by phreatophyte water extraction. The White method estimates the ET rate, averaged over a 24-h period, by multiplying the specific yield by the sum of the daily change in storage and the net inflow rate. The specific yield was estimated to be 0.085 based on a soil texture observed at the site while constructing the well, depth to water, volumetric soil moisture, and the range that Loheide et al. (2005) has suggested for similar site conditions. Loheide et al. (2005) provided guidelines for estimating specific yield based on numerical simulations and typical hydraulic properties for different textural types. Specific yield is dependent on the water table depth, soil moisture, duration of drainage, and sediment texture (Martinet et al., 2009). Loheide et al. (2005) suggested that time-varying specific yield can be approximated by knowing the water content of soil profile, soil hydraulic conductivity, pore size distribution index, and change in water table elevation. They also reported that specific yield can be substantially lower if the depth to water is less than 1 m depending on the soil type. For instance, specific yield is reduced by 50% if the water depth is reduced from 1 to 0.5 m for silt texture and a 3% reduction for sand texture. Gillham (1984) also outlined the concept of variable specific yield, where the specific yield of the unsaturated zone above the water table is considered a variable, with values of specific yield decreasing as the water table approaches the ground surface. In the case where the capillary fringe extends from the water table to the ground surface, the effective specific yield is near zero. Depth to water at the Virgin River study site was between 1.4 and 0.6 m below ground surface, with an average of 0.96 m and the shallowest depth to water occurring during winter months when tamarisk and beetles are dormant. Therefore, the assumption of a constant specific yield may overestimate ET in the winter months. However, in this study, because of the lack of detailed soil hydraulic property analyses and the fact that winter time was not the main focus period of the study, a single value was chosen and used for all 3 years. Soil texture near the water table is a mixture of silt and clay and is a mixture of sands and gravels at the bottom of the well. A relatively low specific yield value of 0.085 was used because of the silt and clay soil texture, high soil water content (~0.33 m$^3$ m$^{-3}$), and relatively shallow depth to water at the site (Gillham, 1984; Loheide et al., 2005; Logsdon et al., 2010).

The daily change in storage was calculated as the difference between the daily maximum on the day of interest and the same value on the following day. Similar to Loheide et al. (2005), the net inflow rate was calculated from the slope of the line best fitting the graph of groundwater-level data between midnight and 4 a.m., assuming that groundwater consumption by plants is negligible at this time.

Reference ET (ET0) was computed using the standardized Penman–Monteith reference ET equation, for a grass reference surface (ASCE-EWRI, 2005). Grass reference-based ET0 was calculated with hourly incoming shortwave radiation measured at the Overton Community and Environmental Monitoring Program weather station located 30 km to the west of the study site and with hourly temperature, humidity, and wind speed measured at the study site.

Classification of fully defoliated tamarisks was examined using optical imagery from the Landsat satellite and the Multitemporal Spectral Angle Mapping algorithm by comparing the known defoliated multitemporal spectra with the nondefoliated spectra. The soil-adjusted vegetation index (SAVI) was also calculated to support interpretations of predefoliation and post-defoliation areas and time series of measured and remotely sensed ET.
Remote sensed ET for predefoliation and post-defoliation periods for the eddy covariance tower footprint and entire riparian area was estimated using the mapping evapotranspiration at high resolution with internal calibration (METRIC) land surface energy balance model with Landsat data. The METRIC land surface energy balance model uses Landsat thermal and optical imagery and ground-based weather data to estimate LE (Allen et al., 2007). The model solves for LE as a residual of the surface energy balance and estimates the instantaneous ET rate at the satellite overpass time. Then, the fraction of reference ET (ETrF) is calculated per pixel by dividing the instantaneous ET by alfalfa reference ET (ETr). The ETrF is used to calculate daily ET by multiplying ETrF by the daily reference ET for the study area. METRIC ET estimates were made over the study area from 2007 to 2012. More information on remote sensing background and application specifics for this study can be found in Liebert et al. (2015).

RESULTS

To better understand the causes of seasonal ET differences for each year, monthly average weather and net radiation measured at the eddy covariance tower were analysed for 2010, 2011, and 2012 (Figure 2). While the study region is water limited, the study site fetch area is largely energy limited because of the presence of shallow groundwater and riparian vegetation. In such environments, ET is largely a function of the available energy (Rn – G) and advective conditions (i.e. drying power of the air) and therefore generally follows daily ETo estimates. All of these factors make it important to analyse weather and energy variables when evaluating seasonal ET and annual ET changes from year to year. The average energy balance closure (H + LE/Rn – G) calculated based on the monthly averaged data in 2010, 2011, and 2012 was 0.94, 0.92, and 0.91, respectively. Uncertainties associated with measurements of Rn and G, heat storage, and regional scale exchange processes prevented confidently closing the energy balance by adjusting either H or LE, or both; therefore, the energy balance was left unclosed.

In 2010 and 2011, the highest monthly precipitation occurred in February (39 in 2010 and 34 mm in 2011), while the highest monthly precipitation in 2012 occurred in August (30 mm). Temperature in the spring of 2012 showed slightly higher values than in 2010 and 2011, which likely led to higher vapor pressure deficit (VPD) being measured in the spring of 2012 compared with 2010 and 2011 (Figure 2a and 2b). As expected, the seasonality of VPD corresponds well with precipitation and temperature because of the temperature dependence of saturation vapor pressure and subsequent evaporation of precipitation, thereby reducing the VPD, advection, and reference ET of the regional air mass (Huntington et al., 2011; Beamer...
et al., 2013). The temperature dependence of VPD is more obvious than the precipitation dependence. However, as seen in August of 2011 and 2012, the temperature is similar, but VPD in 2012 is lower than that of 2011, which can be explained by higher precipitation in 2012 compared with that of 2011.

Figure 2b illustrates monthly averaged air temperature and net radiation. Net radiation in February 2010 was substantially lower than that of the subsequent years in our study. This is largely due to a higher number of rainy days throughout the month of February compared with 2011 and 2012. Furthermore, rain in 2010 occurred mostly in the afternoon, while it mostly occurred during morning hours in subsequent years.

Average monthly wind speed shows that wind is stronger in winter and spring compared with the summer months. Average monthly wind directions at the site were east–southeast in the winter and southeast–south in the summer months (Figure 2c); however, sometimes, daytime westerly wind dominated both summer and winter seasons. Fetch analysis indicated that daytime peak contribution point of flux footprint was at 25±9 m (± one standard deviation) upwind from the tower. Wind direction can vary depending on a day. Tamarisk cover around the tower was about 50 m in both east and west directions and over 500 m in the north and south directions. As illustrated in Figure 2d, monthly average ET0 is highest in 2012 (8.0 mm per day), which corresponds to 2012 having low precipitation and high VPD in May, June, and July. The precipitation in May, June, and July of 2012 was 0, 0, and 10 mm, respectively, and the VPD in May, June and July of 2012 was 2.4, 3.4, and 2.9 kPa, respectively.

Figure 3 illustrates groundwater levels measured at 30-min intervals in 2010, 2011, and 2012. The smaller oscillations superimposed on the larger oscillations represent diurnal fluctuations in the water table because of phreatophytic groundwater consumption. Peaks and valleys of the diurnal fluctuations roughly correspond to daily times of 0600 and 1600h, respectively. Dampening of the diurnal fluctuations was observed once in 2011 (30 June to 16 August) and twice in 2012 (22 May to 20 June and 27 July to 14 August) and corresponds to defoliation events as observed by the clear departure from hourly ET0 (Figure 4). Satellite-derived ET (Liebert et al., 2015), and eddy covariance ET. Note that 28 and 29 June experienced high ET0 because of high wind during daytime hours.

Daily ET0 and eddy covariance estimated ET for 2010 (prebeetle arrival), 2011, and 2012 are illustrated in Figure 5. Daily ET was slightly lower than ET0 during winter and early spring each year because of the dormant period of tamarisk. During 2011, daily ET was substantially less than ET0 during summer months and gradually approached ET0 by September. In July, precipitation was higher in 2011 than in 2010 and vice versa in August. Temperature and ET0 differences between 2010 and 2011 in July and August were minor. Therefore, results indicate that differences in ET were not caused by variations in precipitation, temperature, or ET0 but rather by tamarisk defoliation and recovery. In 2012, the reduction of daily ET caused by defoliation was less evident than in 2011. Results indicate that a reduction in ET occurred twice in 2012 because of defoliation (May – late June and mid-July – August). Given that higher than average precipitation occurred in August 2012, it is possible that the initial reduction in ET was caused by weather and reduced ET0. However, as illustrated in Figure 5, ET0 was higher than ET throughout the entire month of August 2012, implying defoliation. These results are supported by the findings of Liebert et al. (2015) and Bateman et al. (2013), which illustrate reduced vegetation vigor during summer months of 2011 and 2012 derived from Landsat and MODIS satellite data.

The similar seasonal and defoliation trends observed in daily ET estimated from eddy covariance data were also recognized in total daily ET estimated using the White method (Figure 6), which reflect the trends of diurnal water level changes illustrated in Figure 3. In 2011, daily ET, calculated using the White method, was substantially reduced by the beginning of July, and noticeable reductions in ET occurred twice, June and August in 2012. These reductions were generally more pronounced as compared with daily eddy covariance estimated ET. The White method resulted in wider ranges of daily ET than that of the eddy covariance data. The highest daily ET value was about 8 mm per day for eddy covariance data and about
15 mm per day for the White method. Although the 15 mm per day computed by the White method may be an exceptional event, on average, the peak ET values are approximately 10 mm per day, which is still slightly higher than values computed using the eddy covariance method. On the other hand, daily ET in some cases was estimated as zero using the White method, which mostly appeared during winter and early spring because of less pronounced diurnal fluctuation of groundwater depth. During winter and early spring periods, daytime reduction of groundwater levels was minimal, leading to only slight increase or almost no increase in net inflow.

Total ET and ETo from 21 April to 26 November were calculated for each year (Figure 7). This time period was chosen for year-to-year comparison of total ET; since 2012, eddy covariance data were limited to this time period. Eddy covariance estimated total ET was 953, 795, and 873 mm, while White estimated total ET was 976, 696, and 789 mm, for 2010, 2011, and 2012, respectively. For both methods, the highest total ET was observed in 2010 followed by 2012, and the lowest total ET was in 2011. On the other hand, the highest total ETo within the same time period was observed in 2012 (1216 mm) followed by 2011 (1154 mm) and 2010 (1077 mm).
The combination of diurnal water level measurements and ET estimates illustrated in Figures 3–6 and remote sensing of vegetation vigor and ET at the study site (Liebert et al., 2015; Bateman et al., 2013) supported that defoliation occurred once in 2011 (midsummer) and twice in 2012 (early spring and late summer). Defoliated tamarisk in the beginning of July 2011 had refoliated by the beginning of September 2011 and maintained in a refoliated state until fall senescence. In 2012, the first defoliation occurred at the end of May, and tamarisk had refoliated by the end of June. There was a second defoliation at the end of July 2012, and the tamarisk had refoliated by the end of August.

Comparison of ET estimated from the eddy covariance data to 5-day moving average METRIC ET estimates for the eddy tower footprint area was well matched, showing similar seasonal and defoliation trends in each year. The remotely sensed reduction of ET in 2011 corresponds to a reduction in SAVI and ETrF of 0.12 (36% of healthy value) and 0.37 (54% of healthy value), respectively. In 2012, there were two defoliation events. The first defoliation event corresponds to reductions in SAVI and ETrF of 0.14 (36% of healthy value) and 0.31 (48% of healthy value), respectively. The second defoliation event corresponds to reductions in SAVI and ETrF of 0.10 (20% of healthy value) and 0.08 (24% of healthy value), respectively (Liebert et al., 2015). Even though defoliation occurred twice in 2012, the extent of defoliation was smaller in 2012 compared with 2011 as represented by SAVI and ETrF, which corresponds well with ET estimated by eddy covariance method. Annual reduction in ET in 2011 was about 17%, while the reduction in 2012 was about 8%.

**DISCUSSION**

Results from this study at the Virgin River clearly demonstrate the impact that tamarisk defoliation has on plant transpiration. However, these periods were short, lasting about 2–4 weeks, and the magnitude of the defoliation effects was not consistent from year to year. Short-term decreases of tamarisk ET due to defoliation has also been observed in recent studies by Dennison et al. (2009), Hultine et al. (2010), and Snyder et al. (2012). Snyder et al. (2012) estimated tamarisk ET along the Truckee River, near Nixon, NV, using the eddy covariance technique over a 3 and a half-year period, where the beetles defoliated the tamarisk every year. They observed that there were distinct periods of reduced ET in all 3 years but the periods of reduced ET were only about 2–4 weeks in duration, with no definitive long-lasting effect. Hultine et al. (2010) conducted a sap flux study in southeastern Utah along the Dolores River and reported that tamarisk defoliation decreased stem sap flux density for about 6–8 weeks. Dennison et al. (2009) estimated ET using remote sensing and measured sap flux density during periods of defoliation in eastern Utah along the Colorado River. Their results showed a reduction of ET caused by defoliation, with a partial recovery after 20 days as defoliated branches began to regenerate new leaves.

Hultine et al. (2010) also pointed out that the sap flux densities in the second year of defoliation lacked the rapid reduction in early summer observed in the first year. These observations closely correspond with ET results from the Virgin River site. Snyder et al. (2012) noted that cumulative growing season ET did not indicate any specific trend, likely due in part to fluctuations in beetle density. Their cumulative growing season total ET from eddy covariance fluxes from 2008 to 2010 did not show consistent reduction. Highest ET was observed during third-year defoliation, and the lowest ET was in the second-year defoliation. Our post-defoliation cumulative ET from 21 April to 26 November in 2011 and 2012 was reduced when compared with predefoliation conditions. However, cumulative ET in 2011 (795 mm) was lower than that of 2012 (873 mm). Difference in the cumulative ET was also likely due to fluctuations in beetle density, as well as timing of defoliation. In 2011, there was a widespread defoliation that took place in midsummer, when there was a good amount of healthy foliage that sustained expanding beetle populations. In 2012, on the other hand, the first defoliation event occurred in the early spring when tamarisk just started establishing healthy foliage leading to less foliage for the beetles to consume. Therefore, it is likely that beetle populations could not increase to the size experienced in 2011. However, the tamarisk quickly refoliated, and the second defoliation occurred by late summer of 2012 before beetles started overwintering.

Nagler et al. (2014) reported that the MODIS satellite-based normalized difference vegetation index near our eddy covariance tower dropped more than 30% over 48 days in 2011, the first-noted defoliation in their survey.
This reduction in normalized difference vegetation index is comparable with the Landsat-based reduction in SAVI of 36% and ETf of 54% over the footprint area for 2011. For a further comparisons and discussion between remote sensing and eddy covariance ET estimates over the study area, see Liebert et al. (2015).

As pointed out by several researchers, tamarisk has highly variable water use. Stand-level estimates of tamarisk ET have been reported to range from 0.75 to 1.45 m per year depending on local climate, weather, and stand density (Nagler et al., 2010). Previously reported growing season tamarisk ET rates along the Virgin River and Lower Colorado River range from 0.3 to 12 mm per day (Devitt et al., 1998; DeMeo et al., 2008). Devitt et al. (1998) estimated annual tamarisk ET using the Bowen ratio energy balance to be 0.75 in 1994 and 1.45 m in 1996, with maximum daily ET of 10–12 mm per day. DeMeo et al. (2008) estimated an annual average tamarisk ET rate of 1.19 m per year using Bowen ratio energy balance along the Virgin River approximately 10 km from the study area. Bateman et al. (2013) reported that a peak ET rate estimated using satellite imagery of 2.5 mm per day for post-defoliation along the Virgin River near Mesquite, NV, roughly 22 km away from the study area. Daily and total ET estimated in this work falls within the range of previously reported values in the area under both foliated and defoliated conditions. Average daily eddy covariance estimated ET between July and August was approximately 6.2 in 2010, 3.7 in 2011, and 4.8 mm per day in 2012. Total ET estimated from eddy covariance data from 21 April to 26 November was 0.95 in 2010, 0.80 in 2011, and 0.87 m in 2012.

Differences in predefoliation and post-defoliation total ET from April to November calculated from the eddy covariance data showed 0.16 m in 2011 and 0.08 m in 2012, approximately 17% and 8% reductions, respectively. On the other hand, differences in predefoliation and post-defoliation total ET from April to November calculated using the White method showed 0.28 m in 2011 and 0.19 m in 2012, approximately 29% and 19% reductions, respectively. Hultine et al. (2010) reported that their stem sap flow measurements showed beetle-induced defoliation lead to about a 16% reduction in annual water use over two consecutive growing seasons. In this work, about a 12% reduction in eddy covariance estimated ET and about a 24% reduction for the White estimated ET averaged over two consecutive growing seasons were observed. Hultine et al. (2010) reported that the decreases in annual tamarisk water use were about 0.04 m per year in southeastern Utah, which is less than results from this work. In another study

Figure 8. Groundwater (GW) depth from ground measured at 30-min intervals and gage height in Littlefield, AZ, (a) from 2010–2012, (b) 4 days in summer of 2010, and (c) 4 days in winter of 2011.
reported by Allander et al. (2009), the estimated annual ET values for predefoliation and post-defoliation were about 0.52 and 0.28 m (2-year average), respectively, which equates to a 0.24 m per year or 46% reduction. Because tamarisk is known to have a highly variable water use and varies depending on climatic and weather conditions, it is difficult to quantify the exact amount of water usage or water savings from tamarisk defoliation. However, what is common across all tamarisk defoliation studies is that beetle-induced defoliation does temporarily reduce consumptive water use of tamarisk.

Evapotranspiration values calculated with the White method had higher variability than that of the eddy covariance data. These results are support by recent studies and are attributed to the sensitivity of the White model to changes in specific yield (Loheide et al., 2005; Lautz, 2007; Gribovszki et al., 2008; Martinet et al., 2009). Martinet et al. (2009) also reported higher variability of White estimated ET when compared with eddy covariance estimated ET, which was attributed to a combination of factors including the uncertainty and temporal dependencies of specific yield and net inflow estimation. These uncertainties and dependencies are similar in this study. Furthermore, as reported in Martinet et al. (2009) and Zhu et al. (2011), groundwater-level fluctuations respond to surface water stages, which may result in erroneous ET values when there are rapid changes in river stage. Figure 8 shows groundwater depth recorded in the study period and stream discharge obtained from the nearby U.S. Geological Survey gage station (Virgin River at Littlefield, AZ, site #09415000), located upstream to the study site approximately 37 km away. The figure illustrates that monthly groundwater-level changes are related to the changes in the river stage but not at hourly or daily time scales. This is due to the distance between the river and the well location. Therefore, it is unlikely that daily fluctuations of groundwater levels are significantly impacted by daily changes in river stages. There are agriculture fields near the study site, which are irrigated. This might violate the assumption that constant rate of flow into the near-well region occurs over the entire day and could affect daily groundwater fluctuations. Unfortunately, this could not be validated because irrigation information was not available. Additionally, precipitation events also can cause sudden increases in groundwater levels, therefore reducing the estimated ET using the White method as shown in Figure 9. Similar precipitation induced changes in groundwater levels, and estimated ET were reported by Lautz (2007) who found that more than 1 mm per day of precipitation led to large reductions in estimated ET and sometimes resulted in erroneous negative ET estimates because of measureable response to recharge at their field site.

While recognizing the uncertainties in both the White method and eddy covariance estimated ET, both approaches show clear reductions in ET because of defoliation. Although application of the White method showed larger variability and contains some uncertainty, the trend of daily and annual ET was similar to that obtained from eddy covariance data. This supports that groundwater-level changes were mostly caused by phreatic groundwater consumption, in this case, tamarisk groundwater uptake.

CONCLUSIONS

This study evaluated the impact of tamarisk defoliation on ET. ET was calculated using eddy covariance data and the White diurnal groundwater fluctuation method. Post-defoliation ET estimates, along with magnitude of diurnal groundwater fluctuations, decreased compared with the predefoliation estimates. Repeated defoliations observed at the site in 2011 and 2012 clearly show that post-defoliation ET values and magnitude of diurnal groundwater-level fluctuations decreased compared with the predefoliation values. Estimated annual ET and annual average daily groundwater fluctuations were reduced on average by 18% and 35%, respectively. However, magnitude of the effects of defoliation seemed to be dependent upon the growth stage of tamarisk at the time of defoliation. Also, the defoliation periods were short lived as tamarisk quickly recovered and established new growth. The magnitude of ET slightly differed between the two approaches, but the changes in ET caused by beetle defoliation were well matched. These results were also supported by Landsat satellite-derived ET, SAVI, and ETrF estimates. Results of both approaches clearly highlight that tamarisk groundwater uptake, and subsequent ET, was reduced for limited amounts of time because of beetle defoliation. Based on these results, long-term changes in ET will depend on repeated defoliation occurrences over several years and the ability of tamarisk to withstand beetles’ defoliation. Water
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savings may lower depending on replacement of tamarisk with other vegetation.

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