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Original Articles

Remote sensing of tamarisk beetle (*Diorhabda carinulata*) impacts along 412 km of the Colorado River in the Grand Canyon, Arizona, USA

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A B S T R A C T

Tamarisk (*Tamarix* spp.) is an invasive plant species that is rapidly expanding along arid and semi-arid rivers in the western United States. A biocontrol agent, tamarisk beetle (*Diorhabda carinulata*), was released in 2001 in California, Colorado, Utah, and Texas. In 2009, the tamarisk beetle was found further south than anticipated in the Colorado River ecosystem within the Grand Canyon National Park and Glen Canyon National Recreation Area. Our objectives were to classify tamarisk stands along 412 km of the Colorado River from the Glen Canyon Dam through the Grand Canyon National Park using 2009 aerial, high spatial resolution multispectral imagery, and then quantify tamarisk beetle impacts by comparing the pre-beetle images from 2009 with 2013 post-beetle images. We classified tamarisk presence in 2009 using the Mahalanobis Distance method with a total of 2500 training samples, and assessed the classification accuracy with an independent set of 7858 samples across 49 image quads. A total of 214 ha of tamarisk were detected in 2009 along the Colorado River, where each image quad, on average, included an 8.4 km segment of the river. Tamarisk detection accuracies varied across the 49 image quads, but the combined overall accuracy across the entire study region was 74%. Using the Normalized Difference Vegetation Index (NDVI) from 2009 and 2013 with a region-specific ratio of > 1.5 decline between the two image dates (2009NDVI/2013NDVI), we detected tamarisk defoliation due to beetle herbivory. The total beetle-impacted tamarisk area was 32 ha across the study region, where tamarisk defoliation ranged 1–86% at the local levels. Our tamarisk classification can aid long-term efforts to monitor the spread and impact of the beetle along the river and the eventual mortality of tamarisk due to beetle impacts. Identifying areas of tamarisk defoliation is a useful ecological indicator for managers to plan restoration and tamarisk removal efforts.

1. Introduction

Tamarisk species (*Tamarix* spp.), commonly identified as saltcedar, arrived in North America from Asia and Europe in the mid-1800s and were used to mitigate riverbank erosion and as ornamental plants (Brock, 1994; Chew, 2009). In the western United States (U.S.), management of many rivers for flow regulation (e.g., hydropower), flood control, and flow diversion (e.g., for crop irrigation) have interacted with biological factors to provide invasive advantages for tamarisk to expand in riparian areas (Di Tomaso, 1998; Mortenson et al., 2012; Stevens and Siemion, 2012; Stromberg, 1998; Vandersande et al., 2001). As a result, tamarisk expanded to many southwestern U.S. rivers by the early 20th century where native riparian woody vegetation was primarily willows (*Salix* spp.), cottonwood (*Populus fremontii*), and the western honey mesquite (*Prosopis glandulosa*) (Infalt, 2005). Biological attributes that make tamarisk a successful invader include small seeds that are transported by wind and water, and that germinate quickly in moist floodplain substrates (Di Tomaso, 1998; Grotkopp and Rejmanek, 2007; Mortenson et al., 2012; Reichard and Hamilton, 1997; Stevens and Siemion, 2012). Once established, its long tap root enables the species access to groundwater (Hart, 2009) making tamarisk a drought-tolerant species. The salt exudates on the deciduous leaves also increase soil salinity and inhibit seed germination of other plant species associated with free flowing river systems (Ladenburger et al., 2006; Merritt and Shafroth, 2012). Tamarisk species are still expanding by an estimated rate of > 25 km per year along segments of arid and semi-arid rivers in the western U.S. (Nagler et al., 2014).

To reduce the footprint of tamarisk species on the landscape and to promote native riparian plant restoration, a biocontrol agent, tamarisk beetle (*Diorhabda carinulata*), was released in 2001 in Texas, Wyoming, Colorado, Utah, Nevada, and California. The biocontrol agent was considered a more economical and effective tamarisk control method

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than other mechanical, chemical, and burning treatments (Bean et al., 2012; Hultine et al., 2010). Herbivory by the tamarisk beetle defoliates the leaves of the tamarisk. Herbivory can occur multiple times per year and frequent episodes of defoliation progressively weakens the plants (Snyder et al., 2010). Studies of the beetle before its release as a biocontrol agent suggested that the beetle's reproductive cycle was limited by day length and temperature (Bean et al., 2012; DeLoach et al., 2003; Dudley, 2005) which would limit its distribution to geographic areas north of the 38th parallel, approximately 111 km north of the Utah-Arizona State boundary. In their native habitats in China, Tunisia, Turkmenistan, and Greece, the tamarisk beetle requires 10 h of daily sunlight to maintain populations. During diapause, the beetle begins to hibernate when the amount of day light falls below a particular length of time (Bean et al., 2012). However, five years after beetle release, two patterns were documented in the western U.S.: 1) the beetles were remaining active later into the year, and 2) beetle populations at more southern-latitudes were entering diapause significantly later in the year than populations at more northern latitudes (Bean et al., 2012). Currently, the Northern Tamarisk Beetle is estimated to be expanding at a rate of 40 km per year (Nagler et al., 2017).

By 2009, the tamarisk beetle had traveled further south than projected and was observed in the Colorado River ecosystem within Glen Canyon National Recreation Area (GCNRA) and Grand Canyon National Park (GCNP). Important ground-based monitoring has been carried out to document the spread and impact of the tamarisk beetle along the Colorado River within GCNP and GCNRA (Jamison and van Riper, 2015; Jamison, 2016; Johnson et al., 2012). However, no comprehensive study documents the total beetle-impacted area in this iconic landscape.

There are multiple environmental consequences of tamarisks being impacted by the beetle, some of which are already occurring along the Colorado River in GCNRA and GCNP, such as altered plant communities, changes in vegetation structure, hydrological processes, carbon and nutrient cycling, as well as impacts to recreation (Hultine et al. 2010; Sherry et al., 2016). For example, decline of tamarisk stands can decrease habitat quality for fauna such as the endangered southwestern willow flycatcher (*Empidonax traillii extimus*) (herein referred as SWFL) and other riparian breeding birds (Darrah et al., 2017; Hatten, 2016; Holmes et al., 2005; Hultine et al., 2010; Johnson et al., 2012; Malakoff, 1999; Sogge et al., 2008; Yard et al., 2004). Furthermore, other factors may discourage native vegetation establishment in beetle-impacted tamarisk stands. Native riparian vegetation might have difficulty colonizing naturally due to changes in salinization of floodplain soils (Bay and Sher 2008; Glenn et al., 1998; Shafroth et al., 2008). Native riparian vegetation also might have difficulty establishing naturally in locations where tamarisk thrived previously by accessing deeper alluvial water with long taproots (Di Tomaso, 1998; Fenner et al., 1985), though native xeric or facultative riparian vegetation that require less water could potentially inhabit such areas (Reynolds and Cooper, 2011; Sherry et al., 2016). Furthermore, native riparian vegetation may also have difficulty establishing naturally downstream of dams whose operations curtail winter and spring floods that are critical to germination, seedling establishment, and growth of some species such as willows and cottonwoods, particularly when salinity, rooting depth to groundwater, distance from the river channel, or other influencing factors are limiting (Fenner et al., 1985; Glenn et al., 1998; Glenn and Nagler, 2005; Glenn et al., 2012; Glenn et al., 2013; Nagler et al., 2005, 2008, 2009; Stromberg, 1998, Stromberg et al., 2009; Vandersande et al., 2001). Any or all of these factors, no doubt, might affect successful seed germination and establishment of native vegetation within dead or defoliated tamarisk stands along the Colorado River downstream of Glen Canyon Dam.

Researching the effects of tamarisk beetle impacts on tamarisks using ground-based and remote sensing data is important, because of the societal and ecological roles tamarisks play along the Colorado River ecosystem in GCNRA and GCNP (Cross et al., 2011). Tamarisk is one of the dominant woody riparian plants along the Colorado River in GCNRA and GCNP (Ralston et al., 2008; Sankey et al., 2015a), and has a large influence on resources and ecosystem services (Dennison et al., 2009; Lewis et al., 2003). For example, the expansion of tamarisk in the riparian zone and sandbars has impacted recreation uses such as boating, fishing and camping (Grotkopp and Rejmanek, 2007; Penny, 1991; Zavaleta, 2000). Defoliation events by the leaf-eating beetles can be detected with remotely sensed data because the change in leaf color and loss of leaf area are noticeable in the visible and near-infrared portions of the electromagnetic spectrum (Dennison et al. 2009; Fletcher, 2013; Glenn et al., 2008). Defoliation and eventual tree mortality specifically decrease photosynthetic activity and biomass, which have been relatively commonly detected in many river segments of the western U.S. using various image classification and change detection methods including vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) (Bateman et al., 2013; Dennison et al., 2009; Jarchow et al., 2017; Nagler et al., 2014, 2017; Sankey et al., 2016).

A comprehensive remote sensing analysis and mapping of tamarisk-beetle impacts does not currently exist for the 412 km segment of the Colorado River that flows within GCNRA and through GCNP. Remote sensing of riparian environments is especially challenging in this iconic deep-canyon environment, in large part because high quality, synoptic satellite image acquisitions are not viable due to the extreme spatial variability of dark shadows resulting from the spatiotemporal interaction of the narrow, sinuous, and rugged canyon topography with inter-daily solar incidence angles. Instead, acquisitions of very high spatial resolution multispectral imagery from a fixed wing aircraft are periodically conducted by the U.S. Geological Survey (USGS) to image the entire river corridor and enable accurate and consistent monitoring of the Colorado River ecosystem from Lake Powell reservoir to Lake Mead reservoir as part of the Glen Canyon Dam Adaptive Management Program (https://www.usbr.gov/uc/rm/amp/index.html). It is only very recently that a pre- and post-tamarisk beetle multispectral image time-series (Davis, 2012, 2013; Durning et al., 2016) has been available to synoptically assess beetle impacts on tamarisk for the entire length of the river from Glen Canyon Dam, within GCNRA and through the GCNP.

The study objectives were to: 1) classify tamarisk stands along 412 km of the Colorado River from the Glen Canyon Dam within GCNRA and through GCNP using aerial, high spatial resolution multispectral imagery, and 2) quantify changes in tamarisk stands between 2009 and 2013 due to defoliation by tamarisk beetle using the time-series of aerial imagery. Synoptically mapping tamarisk and defoliation provides extremely useful ecological indicators for the status and trends of riparian resources for land managers (Hultine et al., 2010). The information can aid long-term efforts to monitor: (i) the spread and impact of the beetle along the river, (ii) the eventual mortality of tamarisk due to beetle impacts, (iii) the subsequent succession of riparian vegetation in stands of weakened or dead tamarisk, and (iv) the continued expansion of tamarisk where still occurring. Identifying areas of tamarisk defoliation also enables managers to plan restoration and tamarisk removal efforts that will be undertaken by the National Park Service over the next two decades as part of the Glen Canyon Dam Long-Term Experimental and Management Plan (U.S. Department of the Interior, 2016a,b).

2. Methods

2.1. Study region

The study region covers the Colorado River from Glen Canyon Dam in GCNRA through the western boundary of GCNP (Fig. 1). The total length of the Colorado River included in this study region is 411.7 river kilometers (km). Of these, 25.4 river km are within GCNRA (from Glen Canyon Dam at the Lake Powell Reservoir downstream to Lees Ferry