

Remote Sensing of Saltcedar Biological Control Effectiveness

Ray Carruthers, Ecologist and Research Leader, USDA-ARS, Exotic and Invasive Weed Research Unit, Albany, CA

Gerald Anderson, Ecologist and Remote Sensing Specialist, USDA-ARS Northern Plains Agricultural Research Lab in Sidney, MT

Jack DeLoach, Research Entomologist and Lead Scientist, Saltcedar Biological Control Project at the USDA-ARS, Grasslands Soil and Water Research Laboratory, Temple, TX

Jeff Knight, State Entomologist, Nevada Department of Agriculture, Reno, NV

Shaokui Ge, Research Affiliate, University of California Berkeley, CA

Peng Gong, Professor and Co-Director, Remote Sensing Lab, University of California, Berkeley, CA

Abstract—Saltcedar (*Tamarix spp.*) is a major invasive weed found throughout the Western United States and Mexico. Introduced into North America in the 1800s, this shrub to small tree, now infests many riparian areas where it displaces native vegetation, increases fire hazards, uses extensive amounts of water, increases flooding during high water events and thus has caused extensive damage to urban, agricultural and natural areas. In 2001, scientists from the United States Department of Agriculture released a Chinese leaf beetle (*Diorhabda elongata*) into test areas in six states to initiate and evaluate a new biological control program for saltcedar. A combination of ground-based sampling and remote sensing has been used to monitor impacts caused by this biological control program. Both color aerial photography and hyperspectral remote sensing were used to successfully classify and quantify saltcedar populations and the effectiveness of the biological control program, including beetle spread and defoliation within monotypic stands of saltcedar and in areas where saltcedar is mixed with native vegetation.

Introduction

Saltcedar (*Tamarix spp.*) is an exotic weed that has invaded many riparian areas across western North America. In the absence of natural enemies and disease causing organisms, saltcedar grows very aggressively (DeLoach and others 2000) and is highly competitive with native vegetation (Smith and others 1998, Sala and others 1996, Shaforth and others 1995). Therefore, many of the nation's most productive and diverse ecological regions are being negatively affected by the invasion of this exotic invasive plant (Lovich and DeGouvenain 1998). Common methods used to control saltcedar include herbicide application, burning and bulldozing, all of which are expensive and highly detrimental to non-target flora and fauna. Although these approaches may be successful in the short run, they do not provide permanent control of the problem as the saltcedar often grows back or reinvades from surrounding areas.

Over the past decade, biological control of saltcedar has been a major research effort within the

USDA-Agricultural Research Service. A consortium of scientists and land managers has recently field tested the use of this new technology in several western states including CA, CO, MT, NM, NV, OR, TX, UT, and WY (DeLoach and others, this proceedings). A leaf beetle from Eurasia, *Diorhabda elongata*, has now been tested at several locations, where it has established reproductive populations, increased dramatically in numbers and spread extensively across saltcedar infested areas where the beetles have caused extensive defoliation of saltcedar for multiple seasons (fig. 1). In these test locations, the leaf beetles are significantly impacting saltcedar growth and development, while no non-target plants have been negatively affected (DeLoach and others, this proceedings).

Ground sampling of beetle populations and their impact on target saltcedar and adjacent beneficial species was conducted at all of the release sites for several years; however the scale of impact quickly made ground-based field sampling both difficult and expensive. Previous studies (Everitt and DeLoach 1990) have documented



Figure 1. Saltcedar defoliation caused by *Diorhabda elongate* in Lovelock, Nevada (September 2003).

the effective use of remote sensing for the assessment of saltcedar infestations. In support of the overall project monitoring and assessment efforts (DeLoach and others, this proceedings), further remote sensing was conducted to characterize saltcedar infestations, to follow beetle establishment, impact and spread, and eventually to document the return of beneficial vegetation into areas where saltcedar has been controlled.

Methods and Materials

The Study Areas

Saltcedar biological control release sites were located in nine different western states including California, Colorado, Montana, New Mexico, Nevada, Oregon, Texas, Utah, and Wyoming (DeLoach and others 2004). Some states such as California, Nevada, and Texas included three or more different release sites while the other states only had a single test site. In this paper, we will present results from two of over a dozen specific research sites examined. We will discuss detailed assessments of aerial photography from Cache Creek, CA and hyperspectral imagery from Lovelock, NV. However these two types of remote sensing technology, along with videography and satellite imagery are being used to assess saltcedar infestations and biological control impacts at most of our research locations in all of the states where *Diorhabda elongata* has been released.

Cache Creek is a small river that is located north and west of Woodland, CA (38° 40' 02"N latitude and 128° 45' 30"W longitude). The stream course is highly infested with *Tamarix parviflora* intermixed with a diverse

combination of native flora including many species of willows, cottonwood, and other common riparian plant species. This area is also infested with other exotic plant species of interest to our research team, including *Arundo donax*, *Lepidium latifolium* and *Centaurea solstitialis* that are also being assessed using remote sensing. Cache Creek is of primary interest to us as *T. parviflora* blooms in distinctive purplish-red blossoms (fig. 2) early in the spring prior to leaf-out of saltcedar and most other riparian vegetation. Thus, the saltcedar is easily identified visually on the ground and in the air, making it possible for us to separate it from other vegetation at this time of the year. During mid-season, however it is difficult to

separate *T. parviflora* from other green vegetation as the plants are then without flowers and are often intermixed and hard to see due to visual barriers caused by adjacent plant canopies. This area was chosen as one of our primary study sites because an extensive historical record of aerial photography exists for this location.

The saltcedar infestation on Cache Creek runs along approximately 50 miles of river channel, much of which is hard to access and thus is very difficult to map and manage. The use of remote sensing to assess and develop comprehensive distributional maps would better allow local land managers to implement saltcedar removal,

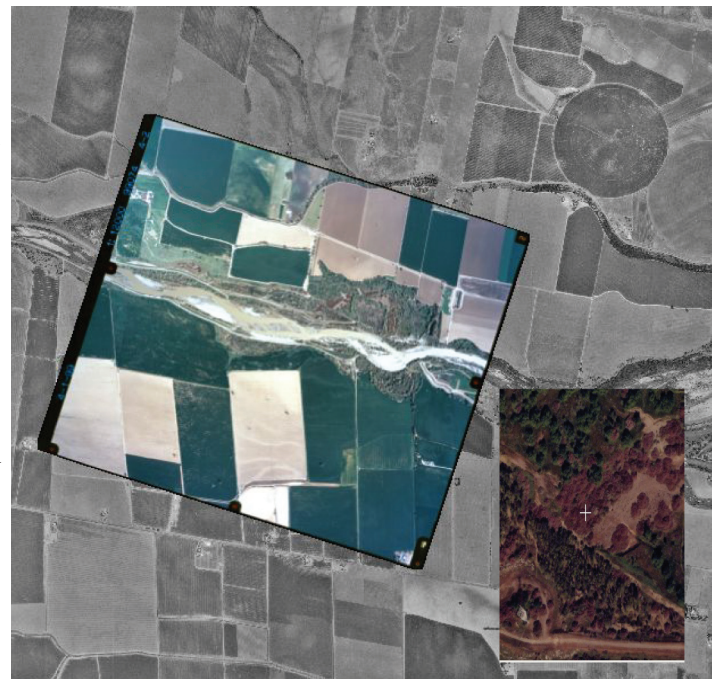


Figure 2. An orthorectified color aerial photograph of a saltcedar infested portion of Cache Creek, CA. Inset shows blowup with individual purple colored saltcedar (*Tamarix parviflora*) in bloom.

allow our team to better assess biological control impacts, and would additionally provide a saltcedar base-map for future midsummer saltcedar assessments using hyperspectral imagery. Hyperspectral image collection has already been conducted in this area but has not yet been analyzed. We are conducting this additional research in Cache Creek (where we now have accurate saltcedar base maps) as new methods of aerial identification of saltcedar using midsummer foliage would be very helpful in the development of identification and separation techniques for other species of saltcedar. This is important as most *Tamarix* spp. (other than *T. parviflora*) do not have such a temporally concentrated bloom period and thus, need to be recognized with or without flowers.

Assessment of the use of remote sensing to characterize beetle defoliation has concentrated on the use of hyperspectral imagery that was collected at insect releases sites near Lovelock, Nevada (40° 1' 20"N latitude and 118° 31' 24"W longitude). The Lovelock site is near the Lovelock and Oreana Valleys and adjacent to the Humboldt River, just upstream from the Humboldt Sink. The Lovelock Valley is one of Nevada's primary agricultural areas where alfalfa is grown primarily for seed production. Saltcedar heavily infests the Humboldt River and side irrigation channels in this area, where it extend up-stream for approximately 100 miles. Saltcedar is especially damaging in this drainage, as it both reduces available water for agriculture and blocks channel flow during times of heavy runoff. Local agricultural producers have been fighting saltcedar all along the Humboldt River channel for the past two decades and are losing the battle. Saltcedar leafbeetle releases in this area have been extremely successful. The beetles have highly defoliated the saltcedar, and have now spread many miles from the release site over the past four years. Beetle impact now can be easily evaluated only by using aerial reconnaissance.

Remote Sensing Data Acquisition

Aerial Photography—A total of 42 natural color aerial photographs were taken at a scale of 1:12,000, along Cache Creek in April of 2001 and 2002. At the time of photography, the saltcedar was in full bloom and was purplish-red in color, making it distinctive from other associated riparian vegetation and the physical background in the study area (fig. 2). However, because the photographs were taken in response to flowering, it is possible to confuse saltcedar with some blooming fruit trees in adjacent agricultural orchards and thus careful analysis between riparian zones and agricultural fields was conducted. For analysis, the photos were scanned at a 1-foot resolution (1000 dpi) using full color with three (blue, green, and red) digital channels. These digital

images were then resampled at 1-meter resolution using a nearest neighbor algorithm. Once processed for analysis, images were orthorectified and georeferenced to 1-meter resolution DOQs from USGS using a second order polynomial function. Each individual digital image was then evaluated for saltcedar (see subsequent section on image analysis), classified then mosaiced to provide an area-wide map of the saltcedar infestation.

Hyperspectral Imaging—Hyperspectral aerial imagery was acquired over study areas using a CASI II hyperspectral imaging system on 2 July 2002, 29 August 2002, 18 July 2003, and 10 September 2003 (2004 images have also been acquired but not yet analyzed). The CASI II is a line scanner covering 545 nm, between 400 to 1000 nm. The system can be modified to acquire different spatial and spectral resolutions. CASI records calibrated radiance values, which were used in this study. Conversion to reflectance using ground targets is possible; however, the objectives of the project could easily be achieved using radiance alone.

Spectral and spatial coverage were changed over the course of the study to best accommodate biological control damage assessment. On 2 July 2003, imagery was acquired at an altitude of 1,500 m above ground level (AGL) obtaining a 2 m pixel resolution and 48 bands, with band centers ranging from 426.7 nm to 965.1 nm with a 5.9 nm bandwidth. The area covered was approximately 1,697 ha along the Humboldt River release site. Imagery collected on 29 August 2002 was acquired at an altitude of 750 m AGL, producing a 1 m resolution. Spectral resolution was dropped from 48 to 36 bands with a 7.9 nm band-width to accommodate the additional data (band centers ranged from 428.6 to 963.2 nm) and the area covered was 1,212 ha. On 18 July 2003 the area flown was reduced to focus in on the damage detected in August of 2002. Approximately 610 ha were imaged near the release site using the same band configurations and imaging altitude as the August 2002 flight. Spectral bands for the September 2003 flight were again reduced (to 32 bands) to accommodate the need to image a much larger area. Band centers ranged from 422 nm to 954 nm with an 8.8 nm band-width. Images were again taken at 750 m AGL, which produced a 1 m pixel resolution over approximately 3,170 ha.

Geographic coordinates for each line of the CASI images were recorded in real time using a differential global positioning system (GIS) coupled with the systems inertial momentum unit (IMU).

Image Analysis

Aerial Photography—Based on the color similarity and relationships among various types of native vegetation and the invasive species, vegetation was initially

divided into eight types: *T. parviflora*, evergreen trees, non-evergreen trees, shrubs, crops, bare fields (including agriculture and rangeland), water bodies (including wetlands), rocks and roads. Initially, color patterns alone were used to separate and classify the saltcedar from the other categories of habitat. This provided inaccurate identification of saltcedar along the stream channel and thus more complex methods of analysis were required. Thus, the image processing to distinguish saltcedar from associated vegetation and background required four distinct steps beyond just the use of color differentials. The following analysis used: (1) Texture extraction using six texture measures; (2) Texture subset selection based on separability measured by Bhattacharya distances (BD); (3) Best texture determination based on classification accuracy; and (4) Post-classification processing based on invasive habitats. After these classification procedures were applied, the original eight categories were reduced to six categories by merging rocks and roads with bare fields and bare hills. Finally, ground-truthing was conducted from the up-stream, middle reach, and down-stream segments along the creek, to assess classification accuracy. For more details on the analysis and classification procedure, see Ge and others (2004).

Hyperspectral imagery—Image to image registration was performed to compensate for much of the spatial registration error that confounds temporal difference analysis. Images were then transformed to the normalized difference vegetation index (NDVI) and a change detection algorithm was used to determine differences between images collected over the period of study. Areas showing change were photo-interpreted and matched to ground observations on beetle occurrence to ensure the change was the result of *Diorhabda elongata* feeding damage to saltcedar. All areas of saltcedar that had been defoliated were subsequently masked as a region of interest (ROI) and the impacted area was quantified (ha).

Results and Discussion

Aerial Photography of Saltcedar Infestations

Based on the scanned images, all eight covers were compared based on their quantized numerical values of color (pixel by pixel), using analysis of variance. Although we found significant differences overall, tonal confusion existed among some covers, including saltcedar. For example, saltcedar sometimes was confused with water and other shrub-like plants because of their similar color and the variability caused by shading. Bhattacharya distance (BD) was applied to represent the separability between class pairs of samples. BD values

range between 0 and 2.00. If it is less than 1.00, the two cover classes are very similar and thus hard to separate. A BD value between 1.00 and 1.9 means that the two classes might be classified as two different cover types. A BD value between 1.90 and 2.00 indicates very good separation between the two classes. The separability of saltcedar with other shrub covers using color alone was only 1.88. *Tamarix* separability with water was even less with a BD of only 1.03. Therefore, using color alone, it was not possible to accurately separate saltcedar from the surrounding habitats, even though it was easily recognizable using the human eye due to large-scale pattern recognition. Pattern recognition was then evaluated using four different window sizes (3x3, 5x5, 7x7, and 9x9 pixel dimensions) focused around each one meter pixel. This was done to evaluate the effectiveness of patterning or texture as an added component in the analysis. After significant comparative analyses, a window size of 5x5 pixels was found to provide the best overall accuracy in correctly classifying saltcedar. Using this window size, the overall average separability was improved from a BD of 1.87 to 1.99, and even more significantly, the separability of saltcedar from adjacent water was increased from a BD 1.03 to 1.96, which approaches the maximal BD value of 2.0. Based on this improved separability, habitat classification errors were minimized and covers compared to actual observed plant distributions (fig. 3). Comparisons made between this automated saltcedar recognition process and human interpretation of the photos

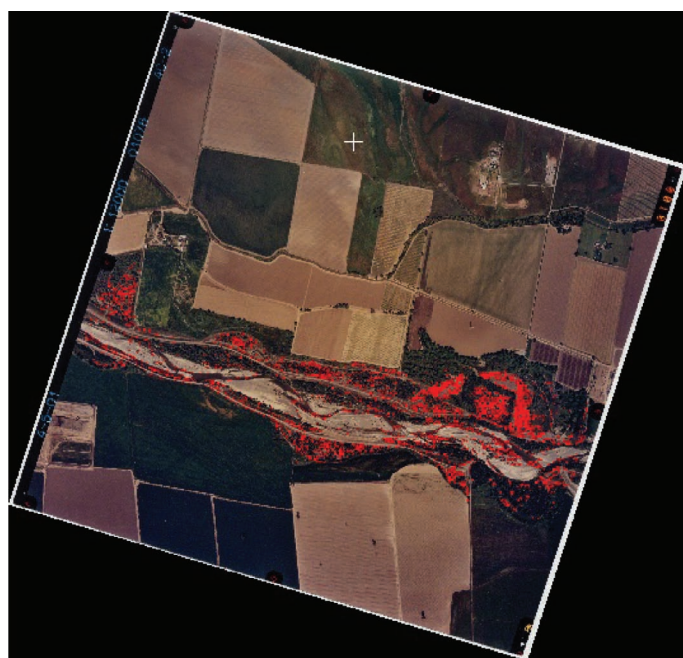


Figure 3. Classified image showing saltcedar infested areas highlighted in red. A combination of color and texture analysis was necessary to identify the saltcedar.

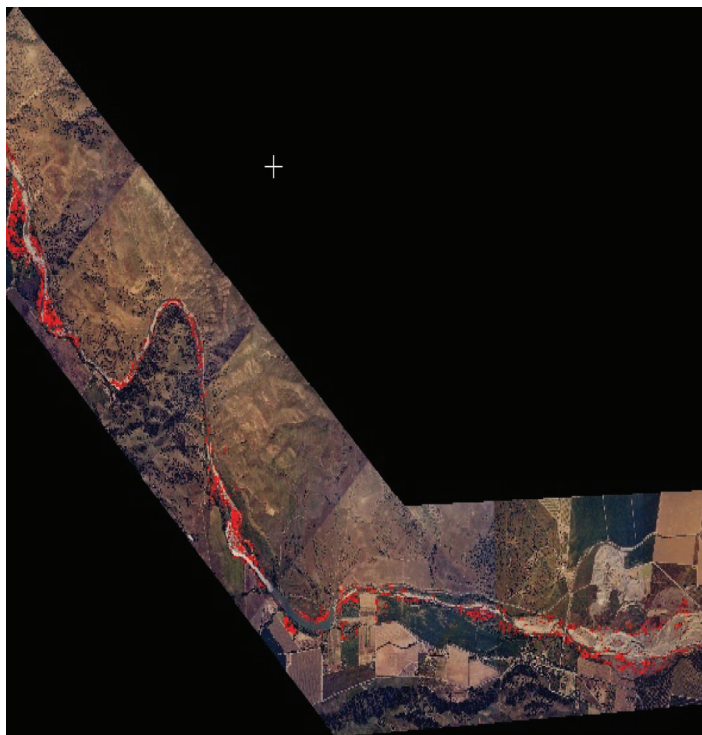


Figure 4. A mosaiced series of saltcedar classified images showing infestation areas along Cache Creek.

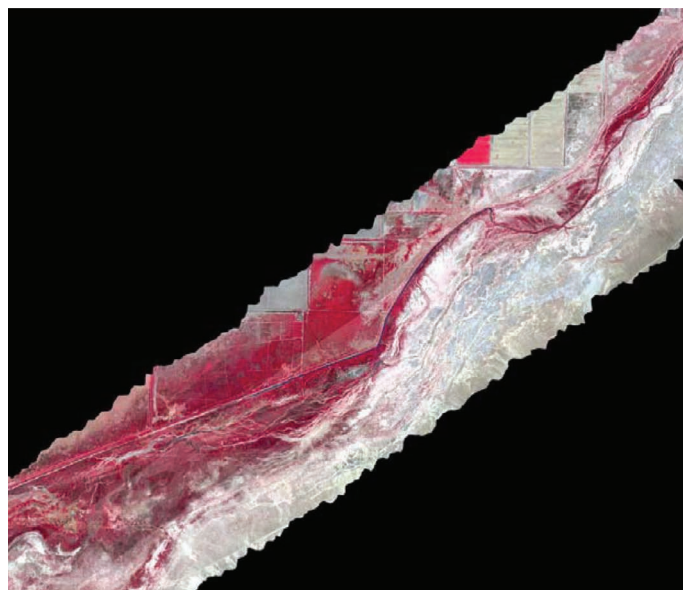


Figure 5. The entire area near Lovelock, Nevada that was imaged in July 2002 (1,697 ha). This monoculture of healthy saltcedar (depicted in red) showed no signs of beetle defoliation from the air.

resulted in an approximate 90 percent accuracy. Although full field validation is still underway, this classification also provided an approximate 90 percent accuracy in preliminary field assessments.

Finally, these classified images were mosaiced across the study area in order to provide comprehensive

infestation maps and to estimate the invasive saltcedar cover in a 40 km subset of the Cache Creek drainage. The total area of saltcedar infestation for this single 40 km section of stream was estimated to be 398 ha. These maps (fig. 4) are now being used by local land managers in their saltcedar control programs and as a basis for comparison against more detailed hyperspectral analyses being conducted during the summer of 2004.

Hyperspectral Image Analysis

Analysis for the 2 July 2002 imagery indicated a total imaged area of approximately 1,697 ha (fig. 5). During this sample period there was no visible saltcedar damage. Significant defoliation of saltcedar was identified by ground crews prior to the August 2002 flight. The area was relatively small and localized, so adjustments were made to increase spatial resolution to 1 m by reducing the number of bands from 48 to 36 and decreasing the image area (1,697 ha to 1,212 ha) and the flight altitude. Change detection between the July 2002 and August 2002 image pairs (figs. 5 and 6, respectively) indicated that the biological control agents had defoliated approximately 0.35 ha over the two-month period (fig. 6). This measure represents only the actual area of canopy cover of the saltcedar trees, not the larger surface area (open ground) infested by saltcedar. In July of 2003 the total canopy area of saltcedar defoliated increased to 4.3 ha (fig. 7), and in the interval between the 18 July 2003 flight and the 10 September 2003 flight (62 days) *Diorhabda elongata* had defoliated (or mostly defoliated) approximately 76.7 ha (fig. 8). Between the initial flight, 2 July 2002, and the last flight, 10 September 2003, the defoliation progressed approximately 2.8 km from the original release site and produced an impact span of approximately 5.2 km (southwest to northeast). The beetles themselves have actually spread much further along the Humboldt drainage. Results indicate an exponential rate of beetle population growth and saltcedar defoliation (fig. 1). A total of nine other sites are being monitored using the same technique (not reported here). These areas are more typical of riparian vegetation with a mixture of saltcedar and other plants. Defoliation rates in these areas indicate that impacts to saltcedar are somewhat slower across most of the plant's range, but that insect establishment has occurred, that the beetle populations are building and saltcedar is being negatively impacted at almost all of the test locations (DeLoach and others, this proceedings).

Summary

A comprehensive assessment program has used a combination of color aerial photograph and hyperspectral

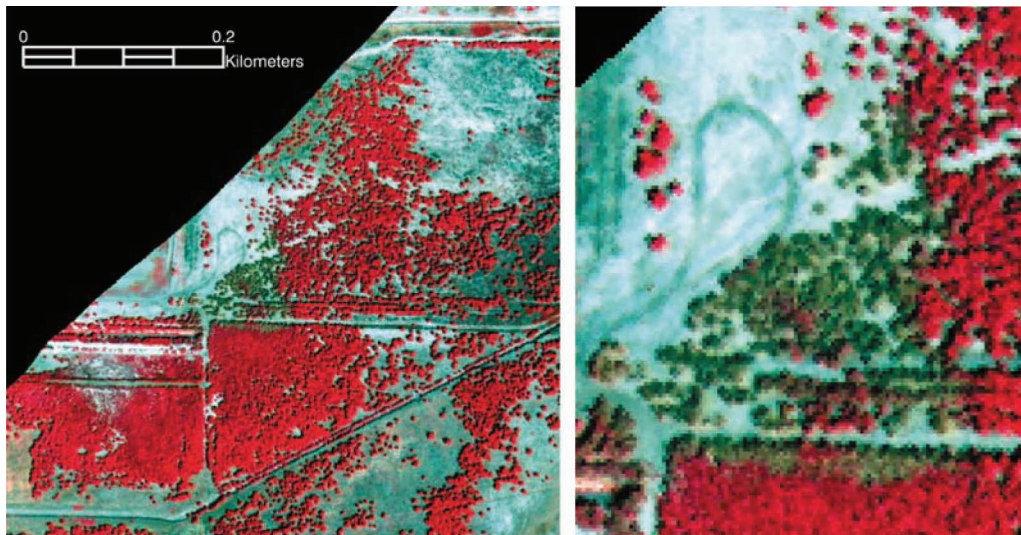


Figure 6. Beetle defoliation in August 2002 is shown in green in this false color simulated infrared image. The healthy saltcedar is shown in red. The enlarged section of the defoliation revealed an approximate 0.3 ha impacted by the beetle when it was first noted using aerial reconnaissance.

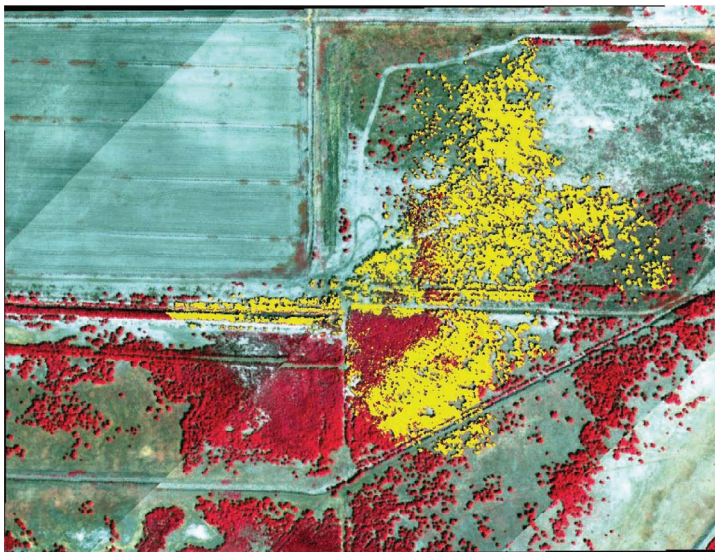


Figure 7. Areas appearing bright yellow are the saltcedar plants defoliated by the biological control agents in July 2003. The red areas are the healthy non-defoliated plants. The approximate area defoliated was 4.3 ha.

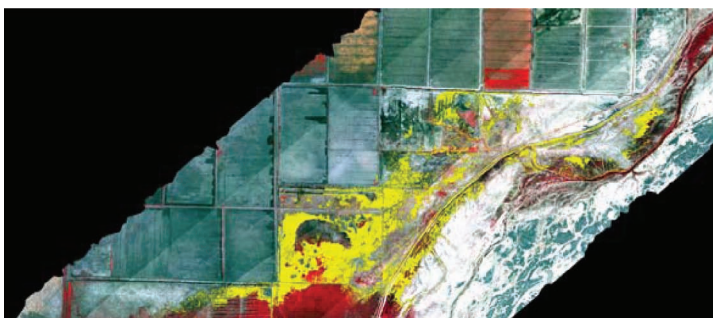


Figure 8. The yellow highlight indicates the area of saltcedar defoliation occurring between the first flight (2 July 2002) when no defoliation was detected and the 10 September 2003 flight when approximately 76.6 ha of saltcedar had been defoliated

imagery to assess saltcedar populations prior to beetle release and to follow beetle defoliation patterns from the original release sites across wide areas of impact. A combination of color and texture analysis was used to identify, classify, and map invasive *Tamarix parviflora* during spring bloom, along a 50 mile segment of Cache Creek in central California with an estimated 90 percent accuracy. An on-going effort is further evaluating the use of hyperspectral imagery during mid-summer to identify saltcedar interspersed with other background native vegetation in this and other infested areas. Additional use of hyperspectral image assessment and GIS mapping has allowed biological control specialists to track and evaluate beetle performance at many pilot release sites where the beetles have spread across thousands of acres. A combination of aerial and ground sampling has clearly documented the success and safety of this project in multiple study areas; however, due to the scope of the beetle defoliation, aerial reconnaissance seems to now be the only practical method of assessing the full magnitude of impact. Based on these trials and remote sensing assessments, several State and Federal agencies are highly enthusiastic about saltcedar biological control and have initiated efforts to use this technology over wide areas. Remote sensing is expected to play a major role in the continued assessment of this beneficial invasive species management project.

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