UTILIZING REMOTE SENSING TO SUPPLEMENT GROUND MONITORING OF *DIORHABDA ELONGATA* AS A CONTROL AGENT FOR *TAMARIX RAMOSISSIMA* IN DINOSAUR NATIONAL MONUMENT

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ABSTRACT

The plant *Tamarix ramosissima* has invaded significant riparian habitat along the Green River in Dinosaur National Monument. Commonly known as saltcedar or tamarisk, it was introduced from Eurasia to the Southwestern United States to prevent soil erosion along riverbanks. It has since come to affect water resources, recreation, wildlife, and ecosystem services. Various methods used to control Tamarisk's spread have had moderate success but have drained National Park Service's human and monetary resources. In June 2006, the saltcedar leaf beetle (*Diorhabda elongata*) was released as a biological control agent within the park to defoliate and ultimately eradicate the invasive species. This study examines the efficacy of using Landsat TM imagery to supplement ground monitoring of the beetle's spread and its effects on tamarisk in Dinosaur National Monument, and discusses the development of a GIS model to predict annual change in tamarisk cover and beetle populations. Through fieldwork we determined four areas of interest with favorable attributes for satellite detection. A change detection model was created by layering 2005-2008 data and quantifying mean NDVI. Results show that intra-year NDVI trends may be more effective for accurate detection than single-image year-to-year comparisons largely because intra-year environmental variability is significantly smaller. Additionally, our GIS model predicted significant growth of beetle population, implying that defoliation will become more apparent in future years. However, challenges to detecting this defoliation include the year-to-year variability of environmental factors, low spatial resolution of Landsat TM data, low visibility into parts of the Green River canyon, and the spectral mixing of tamarisk and native vegetation.

INTRODUCTION

Study Site

Dinosaur National Monument is a U.S. National Monument located on the southeast flank of the Uinta Mountains in the Uinta Basin on the border between Colorado and Utah at the confluence of the Green and Yampa Rivers. Although most of the monument area is in Moffat County, Colorado, the Dinosaur Quarry from which the pack gets its name, is located in Utah just to the north of the town of Jensen, Utah. The nearest communities are Vernal, Utah and Dinosaur, Colorado. (Figure 1)

The Uinta Basin bisected by the Green river, and extends between Vernal in the north and the town of Green River in the south and is largely inaccessible by road. Habitation in this area is restricted to the Uintah/Ouray Indian Reservation, reached only by several long dirt tracks. North of the basin, the Green River crosses from Utah into Colorado and is joined by the Yampa river, and for many miles both rivers flow through deep twisting canyons and gorges cut through the mountain range. The Green River is dammed upstream from the monument at Flaming Gorge, resulting in hydrologic disruption which has rendered the ecosystem more susceptible to tamarisk invasion (T. Naumann, pers. comm., July 2008). Tamarisk's chance of mortality increases after 24 months of inundation and after 36 months produces a 99% mortality rate (Wiedemann and Cross, 1978) which may occur naturally on an undammed river and allow for native species to out compete the invasive.

Tamarisk/Saltcedar

Over a century ago, eight different species of tamarisk were brought to North America from southern Europe and the eastern Mediterranean as a means to control erosion. Characteristic of successful exotic species, it spread rapidly throughout the Southwest and had invaded approximately 4,000 hectares (ha) of riparian habitat by the 1920s. Today the invasion continues with the Tamarisk having reached around one million ha. (Tomaso, 1998). This invasion is likely not over, with approx. 83% of the land in Utah State and 11.6% of land in Colorado at least moderately suitable for tamarisk establishment (Morisette *et al.*, 2006).

Tamarisk has been successful in the United States for several reasons. It has no native predators, is able to tolerate highly saline conditions, and can redistribute salt from the soil profile to the soil surface. Through secreting salt from its leaves Tamarisk can redistribute salt from the soil profile to the soil surface inhibiting germination and growth of other plant species (Tomaso, 1998). Tamarisk is able to tolerate salt concentrations up to 18,000 - 36,000 ppm (Jackson *et al.*, 1990) and elevations of up to 2100 m (USDA, 2008). Tamarisk's patterns of seed dispersal contribute to its prolificacy. The flowers produce seeds that can be carried long distances by wind or water. As an r-strategist, each tamarisk plant is capable of producing up to 2.5 x 10^8 seeds per year (USDA, 2008). The seeds must come in contact with moisture a few weeks after dispersal to germinate (Tomaso, 1998). As a phreatophyte, Tamarisk can send roots deep into groundwater sources effectively lowering the water table and modifying local floristic composition in the process. Water consumption and evapotranspiration rates of tamarisk have been debated but are estimated at 200 gallons of water per day (Owens and Moore, 2007). This is not particularly exceptional compared to other herbaceous plants with an abundant water supply but saltcedar's presence in areas where normally only xeric plants would grow results in additional water consumption (Anderson, 1977). Tamarisk stands also spread farther and their root systems go deeper than native plants, such as willows and cottonwoods resulting in additional groundwater depletion (Busch and Smith, 1995). A typical tamarisk stand will have a 5m tap root (Brotherson and Field, 1987). Native box elder (*Acer negundo* L.) proves to be the most competitive plant within the majority of Dinosaur National Monument's upstream riparian system, successfully coexisting with and in some cases shading out tamarisk stands. Further downstream, the sandbar willow (*Salix exigua)* proves to be the more dominant native crowding out tamarisk on riverbanks (T. Naumann, pers. comm., July 2008).

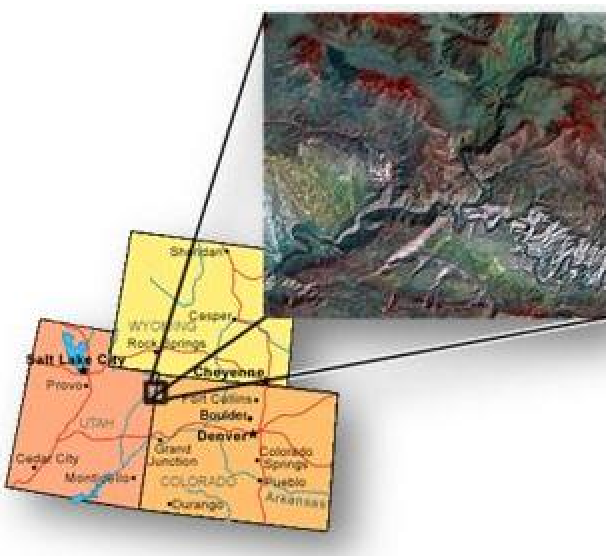

Figure 1. Dinosaur National Monument, located in Utah and Colorado.

Since Tamarisk has the ability to spread vegetatively through rhizomes and develop adventitious roots from submerged or buried stems, traditional methods of removal such as hand pulling, prescribed burns and bulldozing have done little to inhibit growth (Deloach *et al.*, 2000). When used as a control method, fire can even stimulate plant propagation if its intensity is low and although burning may top-kill a plant, several new plants may sprout vegetatively in its place (USDA, 2008). Hand pulling is also resource-intensive, as tamarisk stands can thrive in inaccessible terrain and often form dense thickets which can not easily be navigated by foot. Tap roots have been measured to reach 100 feet in depth making it challenging for a work crew to successfully remove an entire plant without causing massive soil disturbance. Herbicides are the most effective man-made solution, but are costly and exact an ecological toll on sensitive riparian ecosystems (US Department of Interior, 2005). Since Dinosaur National

Park is under the jurisdiction of National Park Service, control methods must be in compliance with the National Environmental Policy Act (NEPA). Herbicides can only be safely used in accordance with yearly water levels which influence the chemical's ability to reach native vegetation. Due to the limited timeframe and risks to native vegetation, alternative methods to chemical utilization are encouraged.

Integrated Pest Management (IPM) is quickly becoming the favored method of tamarisk control. Thus, in 2006 the biological control program began and the Salt Cedar Leaf beetle was released in five locations of Dinosaur National Monument's canyon area. These locations are Lower Disaster Falls (river mile 236.4) and Lower Lodore Canyon (226.5) in 2007 and Echo Park (225) and Lower Echo Park (223.75) in 2006. In June 2008 there was a release of 12,000 beetles at Brown's Park National Wildlife Refuge at Grime's Bottom (248).

Saltcedar Leaf Beetle

The saltcedar leaf beetle (*Diorhabda elongata* Brullé subspecies *deserticola*) is a tiny, winged beetle that is native to parts of Asia and the Mediterranean. All three stages of larvae (instars) and adults feed on foliage. Theoretical population doubling time for the beetle is 6.2 days (Lewis *et al.*, 2003). Early studies of the leaf beetle's defoliating effect on tamarisk and its strict dietary preference for the plant has shown the biological control method to be promising (Deloach *et al.*, 2006). While there may be no way to eliminate all of the tamarisk stands near the area of a release, the beetle may be able to manage the plant's spread. Removal of photosynthetic tissue by defoliation has been documented to lower carbohydrate storage reserves and reproductive capacity in some plants (Hudgeons *et al.*, 2007). Although tamarisk re-foliates within two weeks of defoliation by the beetle, re-growth is often spotty and unhealthy. Canopy cover and especially ground (shrub) cover is highly limiting to beetle population growth due to predation from insects living in native vegetation (Peter Williams, pers. comm. July 2008). Through years of repeated defoliation the beetle has effectively controlled the plant's growth and spread in test sites (Deloach, 2006).

Perhaps the most notable limitation to beetle survivability in the North America has been day length. In the initial trials conducted by the United States Department of Agriculture both of the sites below the 38th parallel failed to sustain beetle populations (Deloach, 2006). In both of these locations, day lengths shorter than 14 hours 45 minutes during the late summer caused the beetles to enter into diapause, fail to overwinter successfully and disrupt synchrony between the life cycle of the beetle and host plant availability (Bean *et al.*, 2007). While our study site at 40.3˚ N was safely above the 38˚ line, one concern was that the canyon created by the Green River might create significant areas where the beetles could not prosper due to excessive shadowing.

The goal of this project is to develop a system of monitoring the beetle's progress using satellite imagery. Detecting vegetation health through near infra-red (NIR) and the Normalized Difference Vegetation Index (NDVI) has been done in the past and has been proven effective (Geraci, 2006) And while this general method is well established, questions specific to our study site include whether there will be portions of the canyon not visible to the satellite as well as how much year-to-year variation of ecosystem factors will affect change detection readings.

METHODOLOGY

Field Work

During the second week of July 2008, our team took GPS point data of significant tamarisk stands and/or beetle presence where it was possible on the Green River route as was instructed by the lead Botanist in Dinosaur National Monument, T. Naumann and her National Park Service team who were also the raft operators. Along with GPS points and site locations and description, point data was recorded using the following values:

1.) Tamarisk: present or absent **2.)** River mile and direction: river left/right **3.)** Tamarisk: defoliated or healthy **4.)** Beetles: present or absent **5.)** Rate of defoliation on a scale of 0-5, 0= no defoliation, 5=no healthy foliage **6.)** Stages of beetles present (eggs, first, second and third instars, adults) **7.)** Rate of beetle cover on tamarisk from 0-5, 0= no beetles, 5= completely covered **8.)** Rate of alternative (native) vegetation influence 0-5, 0= no natives present to influence the vegetation in image pixels, 1-2= sparse native presence, 3-5= coverage significant enough to disrupt a satellite reading.

Percentage of tamarisk ground cover was broken up into three categories: <20, 20-50, >50. The protocol for estimating this was taken from Geraci (2006). This estimation helped determine how well the evaluated stands would appear in moderate-resolution satellite imagery.

From these ground observations we then isolated areas of interest and three control sites. Our control sites are a worksite near Limestone Campground (river mile 227.5) where stands were physically removed by Dinosaur National Park's Weed Warrior program. This point provided control due to the complete absence of tamarisk in the

2008 layer of our change detection model which we compared NDVI to defoliated stands and non-defoliated stands elsewhere in the canyon. The large island below Limestone campground (228) showed full tamarisk ground cover with no defoliation. This large stand allowed us to compare pixels with mixed vegetation to detect spectral differentiation. An infested riverbank at the confluence of the Green and Yampa river served as the third control point for the specific 2008 June-August change detection model (we predict it will become a major defoliation site in the coming years) due to its significant beetle population yet lack of defoliation, >50 tamarisk ground cover and absence of native species. This serves as control to the extremely defoliated area of tamarisk at the confluence.

Areas of interest (Figure 2) include the Bottom of Hell's Half mile (231) where a point polygon was taken during fieldwork. This site shows a significant beetle population with >50 tamarisk ground cover and emerging signs of defoliation. This point is to be observed into the later days of July and August to determine defoliation patterns of establishing beetle populations. The Rippling Brook Island area (230.5) and the area above Whirlpool Canyon (222.5) exhibit >50 Tamarisk cover, all stages of instars and adult beetle presence, heavy defoliation and lack of native presence. Our main area of concern was a central point for release sites, Echo Park, located at the confluence of the Green and Yampa (225) where there was the most severe defoliation.

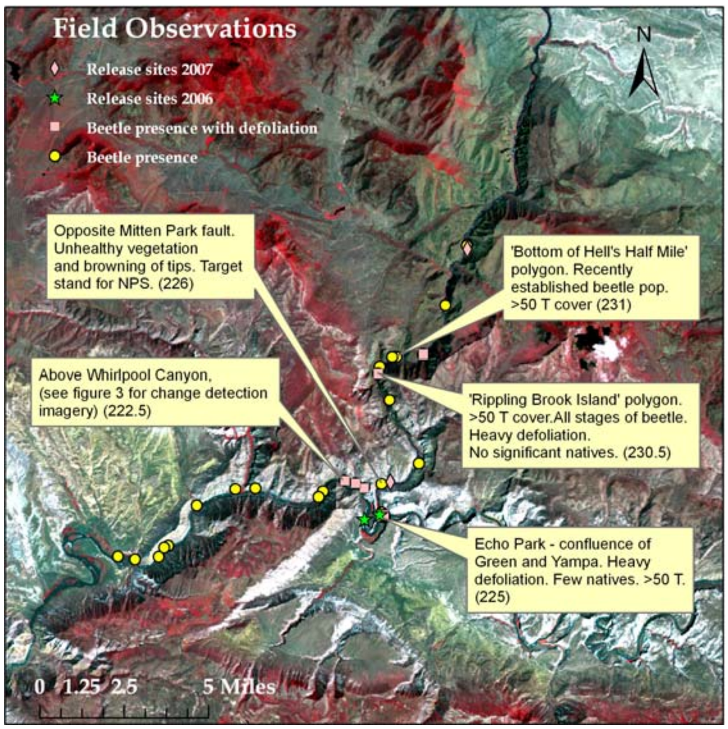

Figure 2. Map combining areas of beetle presence/defoliation, areas of interest, and release sites.

Digital Image Processing

Landsat Thematic Mapper (TM) imagery was obtained using the tools provided by USGS National Map Seamless Server site and funding through the DEVELOP program at NASA Ames Research Center. Four scenes were acquired for a four-year period (dates: 07/07/2005, 06/24/2006, 07/13/2007, 06/29/2008). We requested near-anniversary dates to preserve temporal consistency/resolution, vegetation cycles, and to reduce seasonal error. All data were received in a raw format and corrected using a Digital Elevation Model (DEM) along with ground control points in ERDAS. We used image algebra change detection in our study and took the difference in pixel value and put it in a percentage of change increase or decrease. We also compared band 4/NIR wavelengths and NDVI. Images were all related and adjusted to the same conditions as the 2005 reference image. Tamarisk plant health was measured through vegetation indices. NIR was used to reflect vegetation health through false-color composites and Normalized Difference Vegetation Index (NDVI) was calculated using this formula:

$$\text{NDVI} = \frac{\rho_{TM4} - \rho_{TM3}}{\rho_{TM4} + \rho_{TM3}}$$

This relationship shows overall health of vegetation scaled from -1 to 1. (Figure 3)

Figure 3. This site is located above Whirlpool canyon (222.5). The background image is a false-color composite. Ground cover is >50 Tamarisk. White pixels show a slight overall decrease in vegetation health.

The Solar Radiation Model in Brief

Due to the nature of the canyon in our study site there may be areas, which do not get the required amount of sunlight to prevent the beetles from entering early diapause and unsuccessfully overwintering. To test this theory, our team analyzed the ground data taken by the DEVELOP team and the NPS team. We first used a solar radiation algorithm based on (Dubayah and Rich, 1995) along with a DEM and Latitude/Longitude data for collection points to find the total amount of solar radiation at each point during a normal growing season (May 15 to October 15). We then regressed this figure against both our set of data points for presence/absence and a beetle colony health index created from a set of points provided by the NPS which we digitized from large scale river maps.

Habitat Suitability Map - GIS Methodology and Layer Information

Layers:

1. 10m absolute DEM
2. Average monthly precipitation raster
3. Soil water capacity
4. Soil hydrologic group
5. Soil drainage class
6. Soil Salinity
7. Soil pH
8. Optimum proximity to stream polygon

Tamarisk Suitability Map. The model used two 10m resolution DEMs, one with relative elevation used to create slope and aspect rasters and one with absolute elevation later obtained and used in the final suitability GIS. We reclassified the absolute DEM with a maximum elevation of 2100m to reflect the tamarisk threshold. The relative DEM was used to create hydrological flow direction, flow accumulation and stream order images. The four highest orders of the stream were highlighted and polyline vectors were constructed manually of each of these orders. Established theory on water tables describes a quadratic equation of surface and water table, with water table depth the resulting function. This equation was modeled with a logarithmic relationship found between the two variables. So for each stream order vector (with each order denoting a stream twice the size of the previous order) two buffer polygons were created showing the optimum and high potential tamarisk areas adjacent to each stream. The four optimum and four high potential buffers were joined respectively using a union tool to create two individual polygons. The monthly 10m precipitation images from the GIS data were averaged using the raster calculator to give a monthly average raster for a full year. The polygons used for the elevation data to extract the areas under the max threshold (2100m) were again used to extract the relevant areas of the precipitation image.

Soil data were imported from a number of the National Resource Conservation Service (NRCS) Soil Data Mart publications for Dinosaur National Monument. Six choropleth maps were created and converted into raster format for analysis, one for each variable: texture, hydrologic group, drainage class, available water capacity to 5ft depth, pH and salinity. Both an optimum suitability and a high potential suitability map were constructed by normalizing the variables, extracting areas of each layer that corresponded with plant suitability parameters found through research, and compiling them into one raster. The pixels of this raster which fell into the areas of either the optimum or high potential stream proximity polygon were extracted and two final GIS layers were output.

Current Sites. 'Tamarisk Thicket' polygons were extracted from the NPS Dinosaur National Monument Vegetation Map. A 'thicket density' attribute was extracted for the polygons and a maximum potential annual spread distance for each of the three density categories (15%, 40% and 60%) was estimated from measured yearly spread rates in the canyon and the literature (Graf, 1978). The estimates were 1km for 60% density, 660m for 40% and 250m for 15% cover.

Year One. The 'high potential' tamarisk suitability map was added to the GIS. A buffer was constructed around the tamarisk polygons showing the maximum (100%) potential spread for one growing season (over one year) based on the density attribute field. Buffers were then created for 50, 25, 13, 6 and 3% spread - an exponential decline in spread related to falling categories of 'growth suitability' from the suitability map. Therefore with suitability ranging from 9 to 33, there were 6 equal classes of suitability created e.g. 29 to 33, each relating to a buffer, in this case 100% spread. For each category, the raster calculator was used to extract only the areas with suitability within that category, then the 'extract by mask' function was used to extract only those areas of the specific raster image which fell within the associated buffer.

So for the example, only those pixels of the suitability map that fell into the 29 to 33 category were extracted. These new areas were then limited further by extraction into the area of the 100% buffer. When this process had been completed for each of the 6 category/buffer partnerships, each new image was reclassified into a constant image of value=1 to remove interfering pixels and overlaps, using the 'conditional' function. The six images were then compiled into a single image of 'one years spread' using the 'mosaic to single raster' function and limited into the confines of the canyon using the 'high potential' stream order polygon. This was then converted into a polygon vector file for use in mapping of further years.

Year Two. As the number and size of tamarisk polygons had now changed from the initial ones extracted from the NPS vegetation map, the same process could not be repeated exactly. It was assumed that the density of an initial tamarisk stand would apply quite accurately to those stands that had developed from it over the year. Therefore the density of a 'one year' stand was input manually depending on the density of the current stand in closest proximity to that stand. After this, the same processes of buffering and raster extraction based on the suitability map were applied to the new polygons and a compiled raster for the second year was created.

Beetle Suitability Map. The first layer compiled point data on tamarisk locations, release sites and beetle attributes (presence/absence/larval grade). The first set was the field GPS points, second were digitized from NPS maps and third were digitized release sites. Three variables were interpolated spatially: larvae grade, beetle presence and defoliation grade, and added to produce a "beetle work" raster. Second layer was vegetation map from NPS. Vegetation types were assigned a grade from 1-5 based on limitation to beetle survival through canopy/ground cover. The final layer was the high potential tamarisk suitability map due to the routing of beetles based on future tamarisk spread. This gave three layers: a layer of current beetle patterns, a native vegetation layer highlighting potential competition for the beetles and the high potential tamarisk suitability map.

Beetle Spread Year One. Data points of current beetle/larval presence were compiled into a single layer. The distance from each of these points to the nearest beetle release site was measured and added to the data along with the number of beetles released at that nearest site. This gave a good indication of the state of the beetle population at each point (the further a point from a release site with a lower number of beetles released, the fewer the beetles at that location and the less advanced the community). From looking at all the data available, a max annual distance of 10km was found for beetle spread, while the average was approx. 3000m. The two variables, proximity to release site and number of beetles released, were formatted and standardized in a way that a maximum distance of spread (given movement into areas of highest suitability) was calculated for each point based on these factors.

In the same way that spread was calculated for the tamarisk previously, the suitability map was split into five categories (range of values ~5-31, therefore 10-, 11-15, 16-20, 21-25, 26+) which each related to a distance of spread. For example, 26+ related to 100% spread (so over the max distance already calculated) and 21-25 related to 50% spread, 16-20 to 25% etc. A complete (for all points) buffer was then created for the 100% down to 6% spread distances. For each buffer the area inside the buffer that fell into the associated category was then extracted (using the same techniques as for the tamarisk earlier). This whole process can be described as creating a 'weighted buffering system'. The extracted areas for all buffers were compiled into a single raster of beetle spread in the first year (2008-09).

Beetle Spread Year Two. Much as was done with the tamarisk spread, the first year beetle raster was converted to a vector file (of about 70 polygons). The distance of each of these polygons to the nearest release site was again measured with the number of beetles released at that site again given. The max distance was then calculated for each point based again on these two factors, however the 'weight' of the distance variable on the final figure was taken as being half as potent due to beetle communities becoming more stable in new locations and therefore depending half as much on where they initially came from (relation decreases exponentially with time). The same processes were then taken to create a 'weighted buffering system' for the second year of beetle spread.

Net Future Tamarisk Growth/Decay (Final Output). Both the two tamarisk spread rasters and the two beetle spread rasters (for 2008-09 and 2009-10) were integrated in a single GIS. Using the 'Erase' function, the areas in which the first year beetle locations overlayed the first year tamarisk locations were removed, leaving areas of tamarisk growth taking into account the biocontrol. This was repeated for the second year layers. These final first and second year layers were then compared with the layer of current tamarisk locations to show future plant growth, migration or defoliation. Final outputs are an optimum suitability map and a high potential suitability map.

RESULTS

An examination of the changes in mean NDVI from 2007 to 2008 shows that while an expansion in beetle area throughout the monument was observed during fieldwork, the index of vegetation health actually increased between the two years in the study sites (Figure 4). This increase in vegetation health was remarkably uniform across the different study sites, implying that the increase in NDVI was not a localized phenomenon. Additionally, the increase was quite significant; leading our team to question what other variables might be responsible.

Point/location	Year	Mean NDVI
9- eddy below Triplet Falls	2007	.34
	2008	.73
35- confluence of Green and Yampa	2007	.33
	2008	.74
33- opposite of Mitten Park Fault	2007	.31
	2008	.73
40- top of Whirlpool Falls	2007	.33
	2008	.71

Figure 4. NDVI values for the areas of interest show a dramatic overall increase from 2007 to 2008.

We were also able to note areas with shading problems across the images, though this issue did not affect the areas we used in the analysis. These areas between river miles 242 and 240 above Winnie's Rapid, river left at proposed Echo Park Dam site, and river left between river miles 221 and 222, present an obstacle to future analysis, but one that can be overcome in the monitoring task by simply looking at other major adjacent tamarisk stands.

For the hillshade model, the regressions showed day length was neither a useful variable for prediction of beetle presence/absence nor for community health. R^2 values for the regressions were 0.0022 and 0.01279 with p values of 0.81 and 0.773 respectfully, implying that solar radiation is not a driver of beetle population in the park. If it were an important driver, one would expect a precipitous decline in beetle population health and increased beetle absence in the bottom tier of fieldwork sites in reception of solar radiation some of which received as few as eight hours of direct sunlight at the summer solstice. However, a stronger proof of beetle indifference to solar radiation in the park would require observations at beetle emergence during the spring and early summer, or at a minimum, more comprehensive fieldwork than what was conducted.

Remote sensing, survey data, and predictive spatial models are important tools for developing efficient and effective containment strategies for non-native species over large areas (Morisette, 2006). So perhaps the most readily applicable part of our team's analysis, the GIS model predicts significant spread of both the beetle and the tamarisk over the next two years. The tamarisk is predicted to spread most noticeably in Island Park, cover increasing by 750% and 1600% in 2009 and 2010, respectively, as compared with cover in 2008. This is due to a lack of beetle spread this far down the Green River, and it will be a prime site for manual or herbicidal removal, conducted by the National Park Service. However, in Echo Park, where the beetle is forecasted to populate in numbers, tamarisk cover will increase by only 170% in 2009, with little growth in 2010. This is compared to predicted spread of 600% and 920% in 2009 and 2010, respectively, if the biological control had not been released. (See Figure 5)

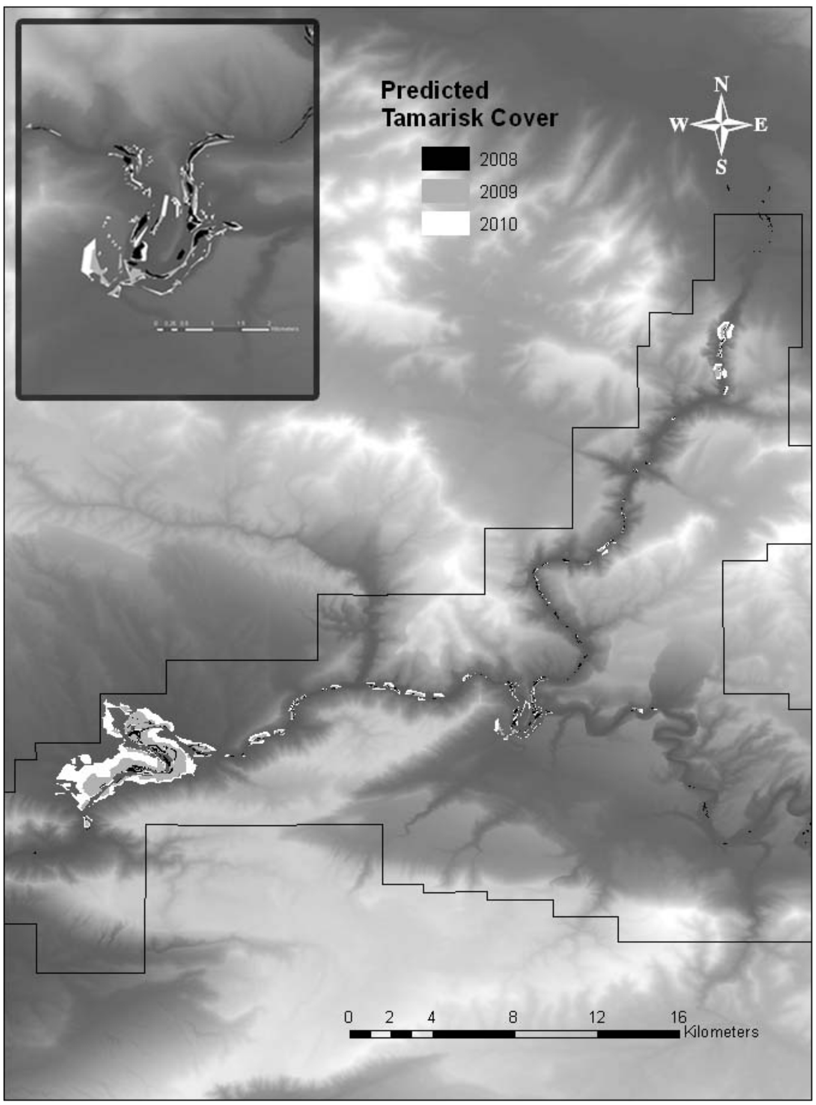

Figure 5. Comprehensive tamarisk growth prediction through years 2008-2010.

DISCUSSION

The surprising result of the remote sensing work led our team to look for other reasons behind the increase in NDVI across the years. The most notable reason found for increased vegetation health was the incredible variation in precipitation, and thus river flow, which occurred between the years. Water discharge records from the USGS for our site over the years 2005-2008 show 2008 to be an exceptionally wet year (See Figure 6). This had an extremely large effect on riparian vegetation as compared with the baseline from the other years.

Water Year	Daily mean values at data acquisition dates			
	June 24	June 29	July 7	July 13
2005	9570	8380	5290	3580
2006	3410 (estimate)	2500	2060	2250
2007	2820	2190	1470	1180
2008 (daily average)	11700	10125	6955	4875

Figure 7. USGS Water data measurements of mean daily values of discharge (cf/s) taken at the Green River water station at Jenson, Utah. Values correspond to data acquisition dates to show yearly variability of water level. Year 2008 is shown to be an extremely high water year causing an overall increase in vegetation health during the early defoliation days in which data were acquired.

To contend with this year-to-year variability we suggest that NDVI and NIR comparisons must be made within the same study year, preferably with data from the June, July and August months. Peak green-up for vegetation in the area occurs in late June. July is a month where defoliation is rampant. The NPS team advised us during our field work (7/8-7/11/2008) that peak defoliation would occur between late July and early August. Photographic evidence showed this to be true, but satellite data could not be acquired in time for this publication. August is a time of partial refoliation of the plant and images from this time could be used to assess the ability of the plant to come back from beetle infestation. The 16-day coverage of Landsat, together with the relatively cloud-free climate of the semi-arid ecosystem in the summer add to the ability to conduct such an analysis. Evaluation could be done at the end of the summer season based on that year's patterns of defoliation compared to the previous year's patterns, but not by actual values of NDVI which may be heavily influenced by environmental factors other than beetle presence.

A validation of the predictive model for beetle and tamarisk spread also should be conducted before the GIS model described here is incorporated more fully into a policy–advising framework. Some variables considered in the model were assumed to influence the tamarisk and beetle in ways that may not be applicable to the specific environment of Dinosaur National Monument. With further understanding of beetle population dynamics within the canyon, increasingly accurate GIS techniques can be created to model beetle spread.

The analysis conducted with the solar radiation model shows how some of these variables can have effects different from those assumed in the literature. Remotely sensed images should play a key role in this validation, as month to month analyses of defoliation may eventually serve as a test for beetle presence or absence, something that along with the results of additional fieldwork can be checked against the model predictions.

Overall, our work shows that remote sensing can play a key role in the monitoring of the bio-control of tamarisk in Dinosaur National Monument. Establishing intra-year comparisons will be critical to this effort however, and predicting the beetle's movements may eventually allow the National Park Service to increase their resource allocation efficiency, increasing their ability to keep the invasive tamarisk under control.

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