EFFECTIVENESS MONITORING FOR SALTCEDAR AND KNAPWEED CONTROL ON THE UPPER MUDDY RIVER FLOODPLAIN

FINAL REPORT TO THE CLARK COUNTY'S DESERT CONSERVATION PROGRAM

CONTRACT 2005-TNC-572-P

BY

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EXECUTIVE SUMMARY

The Muddy River was identified by Clark County's Multiple Species Habitat Conservation Plan and The Nature Conservancy's Mojave Desert Ecoregional Assessment as one of the most ecologically important and threatened riparian landscapes of the Mojave Desert ecoregion. Provencher et al. (2005) determined that the removal of non-native plant species followed by the restoration of native species was one of the many proposed actions with the highest return-on-investment because it was the least expensive to conduct and improved all sections and natural communities of the upper Muddy River (UMR). Most revegetation attempts, however, have failed on the UMR. The objectives of the project were to:

- Retrospective Study: Quantify the effectiveness of past tamarisk removal treatments with regard to native plant restoration, soil chemistry, breeding bird diversity, and fish abundance;
- Experimental Study: Compare the short-term effectiveness of alternative treatments of non-native invasive species control on native plant restoration and soil chemistry. Treatments were a non-removal control, traditional removal, removal with on-site chipping, and removal with native revegetation; and
- Remote Sensing: Detect areas of non-native species invasion and identify future restoration sites on the UMR.

RETROSPECTIVE STUDY

The retrospective study counter-intuitively revealed that soil salinity steadily increased for a period of 10 years after tamarisk removal. We had hypothesized that removal of the tamarisk canopy would allow successive storms to flush away accumulated salts in the soil, allow plant succession to proceed, and support increasing breeding bird abundance with time. The cover of late-successional tree species did not increase over time. Breeding bird counts decreased with time since treatment. Fish counts showed no consistent response to restoration. Limited rainfall, insufficient flooding in an incised floodplain, greater solar radiation, and enhanced wicking of soil moisture and salts to the surface after tamarisk roots were killed may have caused salinity levels to increase near the surface. Therefore, removal of tamarisk is not sufficient to achieve restoration characterized by late-succession riparian species without another process that flushes away surface salts. This process is to allow the river to periodically overflow its banks and the water table to wet the floodplain. Provencher et al. (2005) recommended reconnecting the river to its floodplain for restoring the UMR and its floodplain. There are only three areas with wide enough floodplains with few human structures in the UMR where this approach could be implemented: Southern Nevada Water Authority's (SNWA) Warm Spring Ranch, between White Narrows and Warm Springs Road, and from the old Hidden Valley Dairy to the Highway 168 Bridge in Moapa. Two approaches can be used

to reconnect the river to the floodplain: (i) Elevate the river by stepping it down using weirs in the current channel or (ii) reconstruct parts of the river channel by excavating new meanders (thus increasing sinuosity) and plug the old channel to create backwater wetlands. Both approaches have pros and cons; the first option is the least expensive. Deciding between the two options or formulating better options will require a detailed hydro-geomorphic analysis.

In the absence of reconnecting the river to its floodplain, our retrospective results would indicate that the best time to revegetate restored plots with native species is immediately after removal of tamarisk when soils are least saline, which, however, was not successful in the past. More recently, planting willows as wattles at the river's edge and mesquite equipped with slow-drip watering systems were more successful because it avoided seeding – for mesquite, however, watering columns need to be refilled periodically. Our experimental study was designed to investigate un-irrigated native revegetation on upper banks and planting willow wattles at the river's edge.

EXPERIMENTAL STUDY

The objective of the experimental study was to examine the short-term effectiveness results of tamarisk removal treatments. At most one year after implementation, it became clear that no soil chemical variables and no vegetation cover showed any response. Therefore, we highly recommend that all experimental plots be periodically resampled, probably every three years to allow for plant responses in these arid environments.

REMOTE SENSING OF WEEDS

Remote sensing of tamarisk, tall whitetop, and knapweed revealed a need for more weed control. Russian knapweed was mostly found about 2/3 mi upstream of the Highway 168 Bridge, on tribal land, and two areas on the SNWA's Warm Spring Ranch. Tall whitetop was only detected on the SNWA parcel south of Warm Spring Road (north/east side of the river) and about ½ mile upstream of the Highway 168 Bridge. Greatest areas of infestation for tamarisk were on and around the SNWA's Warm Spring Ranch, the BLM's Perkins Ranch and White Narrows area, and downstream of tribal land. Tall whitetop and knapweed were detected in relatively small areas thus it may be reasonable to dedicate resources to eradicate those areas immediately before they spread.

The new weed map generated by remote sensing should be distributed to UMR stakeholders: MRREIAC, Bureau of Land Management, SNWA, U.S. Fish and Wildlife Service, NV Power, the Moapa River Indian Reservation, and the town of Moapa. We recommend that MRRIEAC should assume a leadership role to (i) approach private owners and public land managers for eradication of Russian knapweed and tall whitetop where we detected these species and (ii) resume or maintain on-going UMR tamarisk and Russian knapweed removal efforts (i.e., continue the effort that started the retrospective study). Multiple sources of funding will be required to continue this effort.

INTRODUCTION

BACKGROUND

The Muddy River was identified by Clark County's Multiple Species Habitat Conservation Plan (MSHCP) and The Nature Conservancy's (TNC) Mojave Desert Ecoregional Assessment (TNC 2001) as one of the most ecologically important and threatened riparian landscapes of the Mojave Desert ecoregion (Figure 1). In addition to providing breeding habitat for 76 detected bird species, the Upper Muddy River (UMR) contains eight aquatic species associated with warm spring and streams found nowhere else in the world (Table 1; Sada 2000, Provencher et al. 2005).

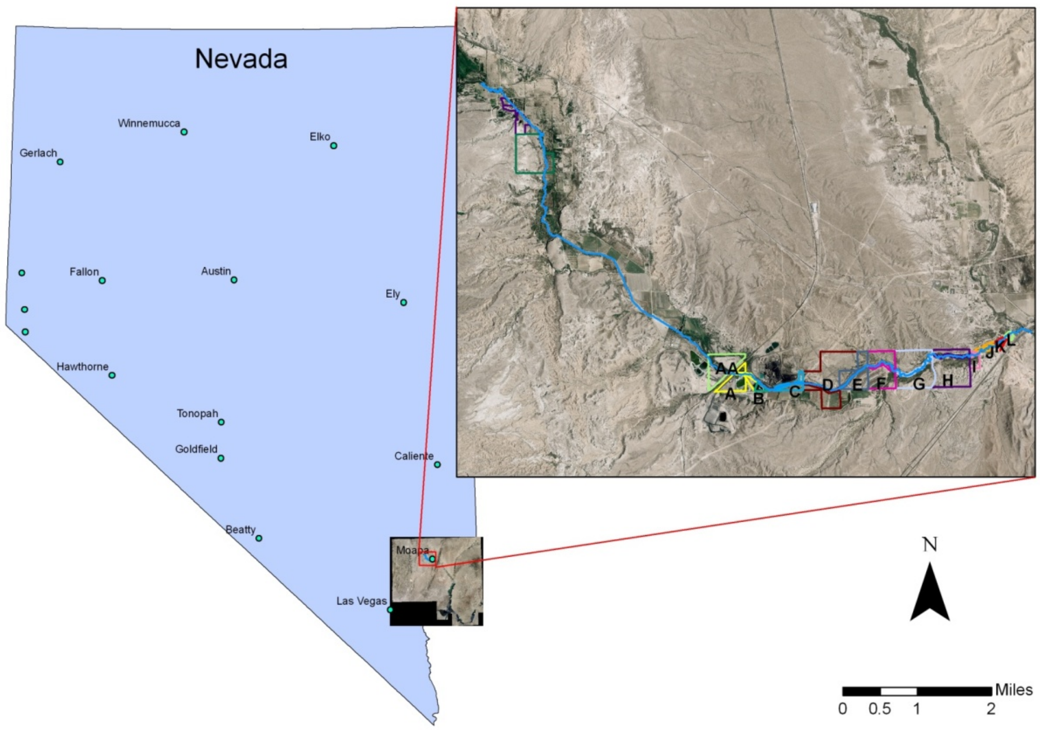

Figure 1. Location of the Upper Muddy River near the town of Moapa. The upper watershed of the Muddy River is located approximately 60 miles (96.5 km) northeast of Las Vegas in the unincorporated towns of Moapa and Glendale in Clark County, Nevada, and upstream of the Interstate 15 Bridge for approximately 14 miles (22.5 km) of the Muddy River. The Muddy River originates as a series of thermal springs in the upper valley and flows 26 miles (41.8 km) before reaching Lake Mead.

In 2005, The Nature Conservancy and Otis Bay Riverine Consultants completed a two-year bio-geomorphic assessment of the UMR for Clark County's Desert Conservation Program (Provencher and Andress 2004, Provencher et al. 2005) where three major processes explained the degradation of the river: 1) diminishing spring discharge due to water withdrawals; 2) a disconnected floodplain due to deep entrenchment, straightening, and flood and sediment control; 3) occupation of non-native invasive plant and animal species in most ecological communities.

Table 1. Upper Muddy River aquatic assemblage found nowhere else in the world.

Fish Species	
Moapa Dace	*Moapa coriacea*
Moapa White River Springfish	*Crenichthys baileyi moapae*
Invertebrates	
Moapa Pebblesnail	*Pyrgulopsis avernailis*
Moapa Turban Snail	*Pyrgulopsis carinifera*
Moapa Warm Springs riffle beetle	*Stenelmis moapa*
Moapa waterstrider	*Rhagovellia becki*
Pahranagat naucorid bug	*Pelocoris Shoshone*
Warm Springs naucorid bug	*Usingerina moapensis*

As with many other southwestern desert riparian systems, the invasion of the UMR riparian floodplain by the non-native tamarisk (*Tamarix ramosissima*) is widespread (Everitt 1980, Duncan 1994). A decade ago, nearly the entire length of the riparian corridor of the UMR, although less so around the headwater warm springs and upper watershed marshes, was occupied with varying densities of tamarisk, which diminished the abundance and diversity of native plants, such as willows (*Salix*) and honey mesquite (*Prosopis glandulosa*) that historically dominated the floodplain (Provencher and Andress 2004, Harms and Hiebert 2006). The long taproot of tamarisk allows interception of shallow groundwater at greater depths than most native plants, thus out-competing the native plants for a scarce resource (Di Tomaso 1998). Tamarisk causes excessive evapo-transpiration through high leaf area (Sala et al. 1996), eliminates native riparian shrubs and trees through competition and shading (Everitt 1980), increases ignitions with the build-up of dense and fine fuels (Everitt 1980, Di Tomaso 1998), and can increase salt concentration in the soil (Hem 1967; but see Merritt and Cooper 2000). Russian knapweed (*Acroptilon repens*), another non-native species often co-occurring with tamarisk, spreads rapidly through a combination of adventitious roots and allelopathic compounds that inhibit the growth of native plants (Weir et al. 2003).

Provencher et al. (2005) determined that the removal of non-native plant species followed by the restoration of native species was one of the many proposed actions with the highest return-on-investment because it was the least expensive to conduct and improved all sections and natural communities of the UMR. Tamarisk removal would gradually improve recruitment of mesquite, cottonwood, willow and native forbs, which in turn could increase habitat complexity and diversity for the fauna. Moreover, the UMR watershed itself is sufficiently limited in extent (the 500-year floodplain is approximately 3,500 acres [1,420 ha]) to feasibly allow for the long-term control of tamarisk and, perhaps, other non-native invasive species such as Russian knapweed, tall whitetop

(*Lepidium latifolium*), and fan palms (*Washingtonia filifera*) (Provencher and Andress 2004).

Since 1995, the Muddy River Regional Environmental Impact Alleviation Committee (MRREIAC), a not-for-profit corporation dedicated to rural community based protection and restoration of desert watersheds, riparian areas and wetlands, has operated a demonstration tamarisk and knapweed removal project using hand-felling and herbicides on sections of approximately 9.6 km (6 miles) of private lands of the UMR. Artificial native plant restoration following tamarisk and knapweed removal has also been attempted by MRREIAC, but with varying and surprising outcomes. Despite the use of dry water polymers on deeply entrenched river banks, willow and cottonwood cuttings drilled to the water table, hand irrigation, and best advice on desert riparian vegetation restoration most revegetation attempts have failed. While artificial native vegetation restoration efforts have generally not been successful, native quailbush-dominated vegetation has naturally established in removal areas with an increasing presence of mesquite, willows, and cottonwood within 5-10 years.

OBJECTIVES

There is a need to understand why artificial native plant revegetation efforts fail, what happens to plant succession when artificial revegetation fails, and whether the cause of failures is elevated salt content in soils, lack of sufficient soil moisture, or other factors. There is also a need to understand if tamarisk removal affects animal species; indeed, animals require structure or thermal cover when native riparian shrubs and trees have been replaced by tamarisk. For example, the listed Southwestern Willow Flycatcher will use dense tamarisk patches when willow is absent (USFWS 1993). Therefore, managers may sometimes need to compromise between the desirable removal of a non-native invasive species to achieve long-term system-wide conservation goals and short-term loss of habitat for species at risk. Assuming tamarisk removal will continue on the UMR floodplain, probably at an elevated rate, stakeholders have also expressed the desire to test better and less expensive ways of restoring the native vegetation of treated areas (hand-felling followed by painting fresh stumps with Garlon 4 has proven very effective at killing tamarisk [Neill 1990 and 1996] within the logistic and regulatory constraints of the UMR). Therefore, this study had the primary objectives of monitoring the effectiveness of a) past tamarisk and knapweed removal efforts and b) alternative experimental methods. An additional objective was to find new locations of infestation to treat with improved control methods.

We divided the project into three parts: a) the retrospective study monitoring of MRREIAC's previous control efforts, b) the experimental study testing new treatments, and c) remote sensing to locate current infestations of tamarisk, knapweed and tall whitetop.

The objectives of the project were as follows:

- Retrospective: Quantify the effectiveness of past non-native invasive species treatments by MRREIAC with regard to native plant restoration, soil chemistry, breeding bird diversity, and fish abundance;
- Experimental: Compare the short-term effectiveness of alternative treatments of non-native invasive species control on native plant restoration and soil chemistry; and
- Remote Sensing: Detect areas of non-native species invasion and identify future restoration sites on the UMR.

METHODS AND MATERIALS

RETROSPECTIVE

While MRREIAC has implemented several small scale restoration projects, success of removal and native plant restoration from the past 13 years has not been documented quantitatively. We returned to areas treated in different years to monitor the effectiveness of past efforts by measuring the change in soil chemistry, native and non-native plant species cover, and fish and bird species abundance. All areas were heavily infested with mature tamarisk prior to treatment and generally lacked a native understory, although a few remnant willow and mesquite were preserved.

Late successional plants were important to this project because they provide the structure, cover, and food that will support Clark County priority species. This group would include any species that require longer periods to grow such as ash or mesquite trees. On the other hand species such as quailbush or inland salt grass are considered early successional species, which wildlife are not likely to take advantage of due to lack of available cover for nesting or thermal protection. An intermediate group of species which requires more time to grow are termed mid-successional species which may include alkali sacaton, arrowweed or willow which may provide better habitat for wildlife.

Nine private property river reaches (Table 2, Figure 2) were retained for sampling the past removal activities of MRREIAC, including permanent no treatment controls on the Pulsipher property (I) and Riverview property (L; formerly Pulsiper). These segments offer unique combinations of treatment years and property locations adjacent to the UMR from the Moapa River Indian Reservation to Highway 168. The control plots on Riverview L and Pulsipher I will not be shared between the retrospective and experimental in order to retain control plots for bird and fish assessments in their second year of sampling. To increase the consistency between the retrospective and experimental components of this study, the unit of vegetation and soil sampling was tailored to the size of the smallest experimental sampling unit, which was 10m long. The total sampling area was segmented in 10m linear units of river front and five 10m units per year × property combination were randomly selected for sampling, and if the plot was not feasible, other plots were opportunistically selected.

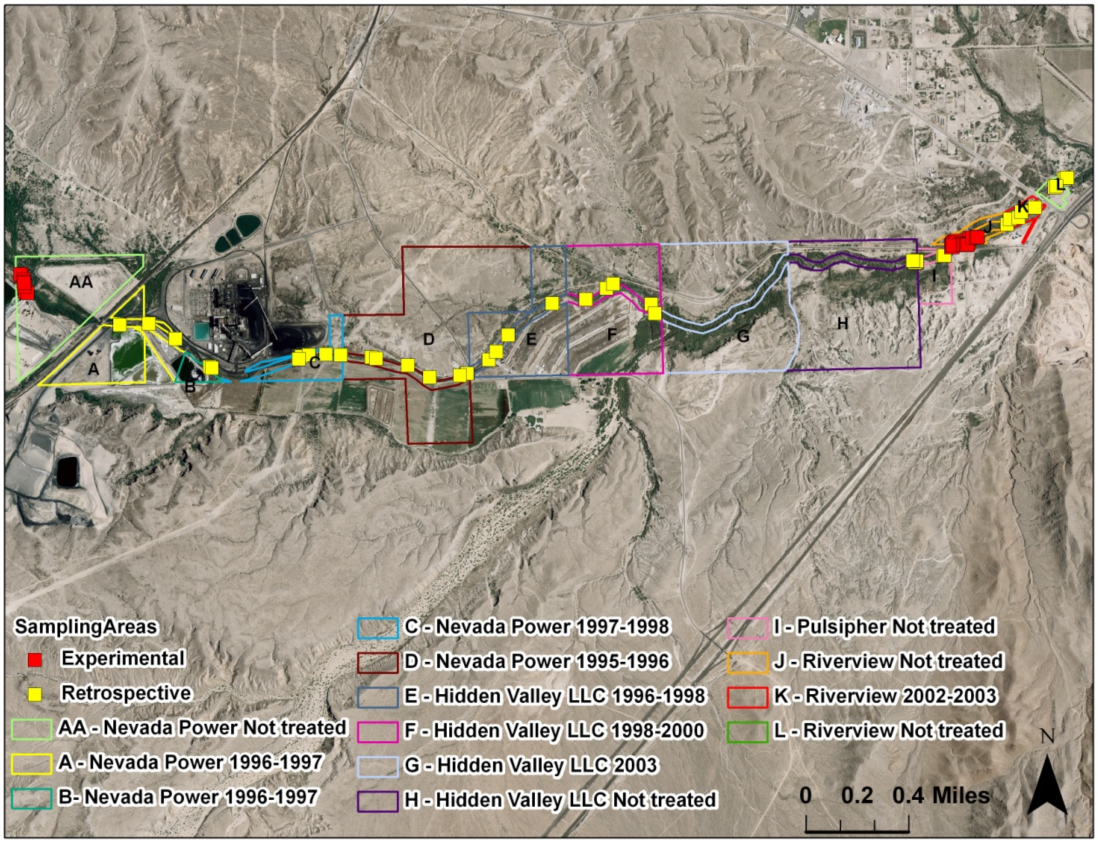

Figure 2. Locations of retrospective monitoring plots and experimental treatments along the Muddy River.

Table 2. Properties studied in the retrospective study.

Property	Year Treated	Parcel Identification
Nevada Power	1996-1997	A
Nevada Power	1996−1997	B
Nevada Power	1997-1998	C
Nevada Power	1995- 1996	D
Hidden Valley LLC	1996-1998	E
Hidden Valley LLC		F
Riverview (formerly Pulsipher) Property K	2002-2003	K

We established four 10m parallel line transects (also parallel to the river) separated by ~1m with transect #1 closest to the river's edge (Figure 3). Vegetation cover of understory and midstory herbaceous and woody species was measured on these transects using the line-intercept method (Elzinga et al. 1998, Herrick et al. 2002). Cover per plant species was calculated from the total number of centimeters from the four 10m transects. If different species overlap vertically, the cover of each will be measured and the relative vertical layer occupied by the species will be noted. Bare ground, litter, and woody debris were also measured if no vegetation was present. We defined woody debris to be any woody material greater than 5 cm in diameter including tree trunks if they were taller than 2 m in height in order to prevent those trees from being double-counted in the densiometer readings.

The height of each native tree species in a plot was visually estimated to the closest 1m interval and the species noted. For tamarisk, we visually estimated the average height of the stand. This last measurement only applied to the dense control plots of the retrospective study. Canopy cover was measured with a spherical densitometer (manufactured by Dr. Paul E. Lemmon; Lemmon 1956 and 1957) by taking one reading from the center of each plot.

Soil samples were collected at approximately 2m and 8m on each transect with a spade to a depth of 10cm. The eight soil samples will be combined in one sealable plastic bag and mixed for soil analysis. Soil samples were sent to A & L Western Agricultural Laboratories in Modesto, CA, for analysis of pH, B, Cl, Ca, Mg, Na, SO_4, $C0_3$, HCO_3, electrical conductivity (E.C.), soil adsorption ratio (SAR), exchangeable sodium percentage (ESP), and saturation percent (Sat%).

One photograph from each end of a plot was taken facing inwards between the second and third transects. A small dry-erase photo-board was placed approximately 2m inside the plot to identify the plot and provide a sense of proportion. GPS (NAD 83 UTM 11S) coordinates of the beginning and end of the 1^{st} and 4^{th} transects were taken with a MobileMapper CE Thales unit with sub-meter precision.

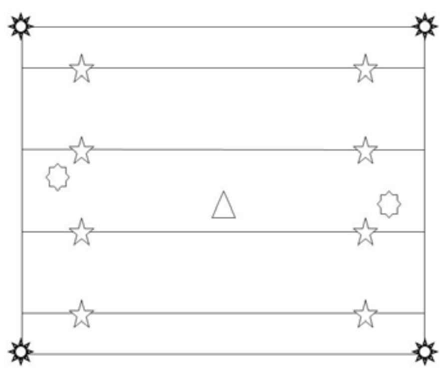

Figure 3. A diagram of a retrospective plot. Lines represent line transect locations. Triangle represents the location of a densiometer. Stars represent where soil samples were collected. Eight-point starts represent where photos were taken of the plot. Suns represent where GPS UTM locations were collected.

Breeding bird surveys were conducted by a team of experienced birding volunteers (Bruce Lund, Jeanne Tinsman, Kevin DesRoberts, John Hiatt, Caroline Titus, Rita Schlageter, and Carl Lundblad) in the first year. Breeding bird surveys were conducted using an area search of the full length of the riparian corridor for each river reach that corresponds to a time since tamarisk removal, including the controls. The observer noted the species, either visually or by auditory cues, and approximate location of birds on a printed aerial photography map of the plots. Bird and vegetation sampling stations were not matched in space. All plots were sampled five times during the breeding bird season. Breeding bird surveys in the second year were conducted by subcontractor, Carl Lundblad, and followed the same protocol as in the first year.

Fish species were sampled by NDOW staff and data shared by Southern Nevada Water Authority, following standard fish sampling protocols used in the same river reaches sampled for breeding birds. Sampling protocol did not differ between the two years of sampling. At least two hoop-nets paired with minnow traps were set per river reach. The nets and traps were pulled the following day and fish captured were recorded.

We proposed the following null and alternative hypotheses to explain the recovery of native plant, bird, and fish species:

Soil salinity with time since removal of tamarisk

Null: Soil salinity does not change with time

Alternative #1: Soil salinity decreases with time due to dilution of surface soil salts by storms

Late-succession plant species cover recovery with time since removal of tamarisk

Null: The cover of late-succession plant species does not increase with time;

Alternative: The cover of late-succession species increases with time.

The cover of late-succession plant species vs. soil salinity

Null: The cover of late-succession plant species is not influenced by soil salinity;

Alternative: The cover of late-succession plant species increases with decreasing soil salinity (and conversely for increasing soil salinity).

Breeding bird species count and richness with time since tamarisk removal

Null: Breeding bird counts and species richness does not change with time;

Alternative #1: Breeding bird counts and richness initially decrease and then increase with time as late-succession species grow;

Alternative #2: Breeding bird counts and richness decrease with time.

Breeding bird species count vs. vegetation cover

Null: There is no relationship between breeding bird abundance and the cover of late-succession species, shrubs, and herbaceous;

Alternative #1: Breeding bird counts increases with the cover of late-succession species;

Alternative #2: Breeding bird counts decreases as herbaceous species cover increases (indicating a very open woody canopy).

Fish abundance with time since tamarisk removal

Null: Fish abundance does not change with time;

Alternative #1: Fish abundance increase with time due to greater light penetration and aquatic primary productivity.

Simple and multiple linear regressions (Sokal and Rohlf 1981), and Non-metric Multidimensional Scaling ordination (NMS, Kruskall 1964, Kenkel and Orlóci 1986) were used to test the hypotheses. For NMS, we removed variables that were mostly zero to avoid disjunctions, which occur when a variable's data are dominated by zeros (Kenkel and Orlóci 1986). Only three ordination axes were retained. Furthermore, each variable was tested for homogeneous variances, transformed if variances were heterogeneous, and rechecked for successful transformation (Zar 1984: 236-242).

EXPERIMENTAL

Experimental plots were located on the Shirley Perkins property, Alamo property, Riverview J (formerly Pulsipher) property, Nevada Power property, and Bureau of Land Management (BLM)-Perkins property (Table 3, Figure 2, Figure 4). We used a complete randomized block design to test the effects of alternative tamarisk/knapweed control treatments and native plant species restoration (Steel and Torrie 1980). Fifteen blocks were established, each comprised of four spatially randomized treatments along the river's edge (Table 3, Figure 4).

Table 3. Properties and number of experimental blocks per properties on the UMR floodplain.

Properties	Blocks
Alamo	1
Perkins	3
BLM- Perkins	2
Nevada Power	3
Riverview	6

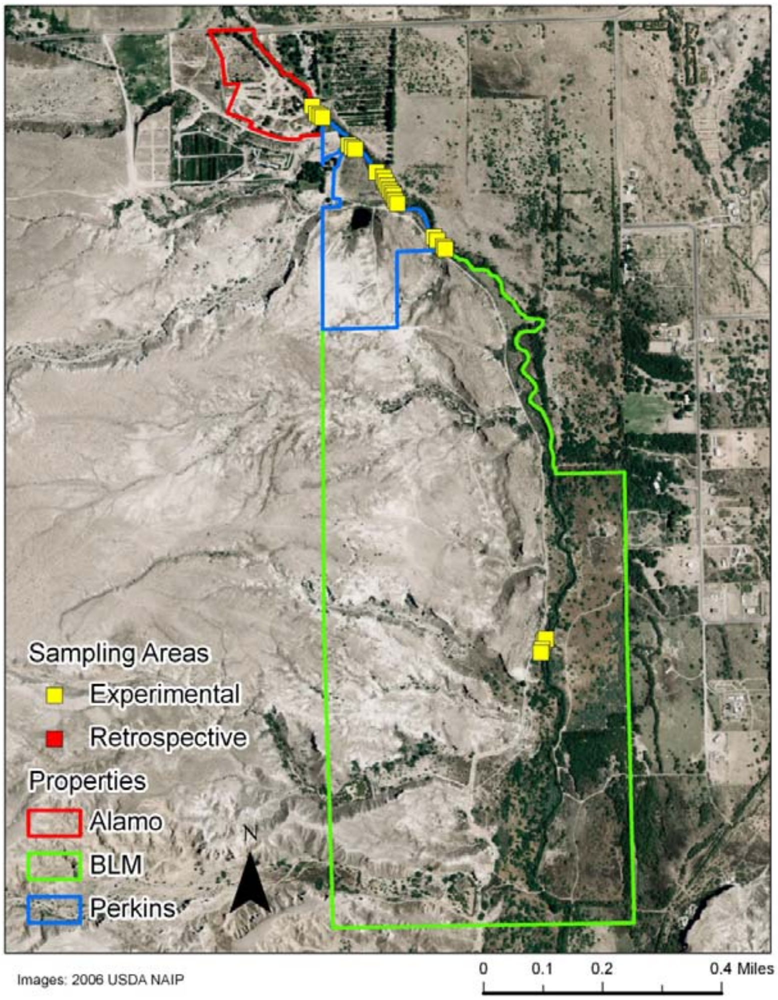

Figure 4. Location of experimental treatments on upper Muddy River properties.

Each treatment replicate was 10m wide along the river's edge; therefore, a block is made of four 10m plots (Figure 5). Timing of treatments varied from immediately after tamarisk removal to a couple of months post tamarisk removal, due to multiple factors such as availability of NDF crews, appropriate season to collect willow cuttings and weather-related issues including rain and wind events. Tamarisk treatments were: no removal control (hereafter *Control*), chainsaw felling followed by painting stumps with Garlon 4 and spraying knapweeds with Thordon (hereafter *Removal*), traditional *Removal* + *Chipping* spread on-site (*Removal* + *Chipping*), and traditional removal coupled with artificial native plant species regeneration (*Removal* + *Seeding*). The depth of chipping application was not specified, and as a result varied with tamarisk density. Artificial native plant restoration consisted of spreading one or more bales, depending on the width of the plot, of *Sporobolus airiodes* on the surface of the plot and installing one willow wattle per plot parallel to the stream along the bank. Neither the native grass nor the willow wattles received any watering. The bales of native grass were provided to MRREIAC via BLM. Seeds were collected locally within the Las Vegas BLM district, and were grown at the Native Plant Materials Center in Tucson, Arizona.   Willow cuttings were collected along nearby stretches of the river where abundant.

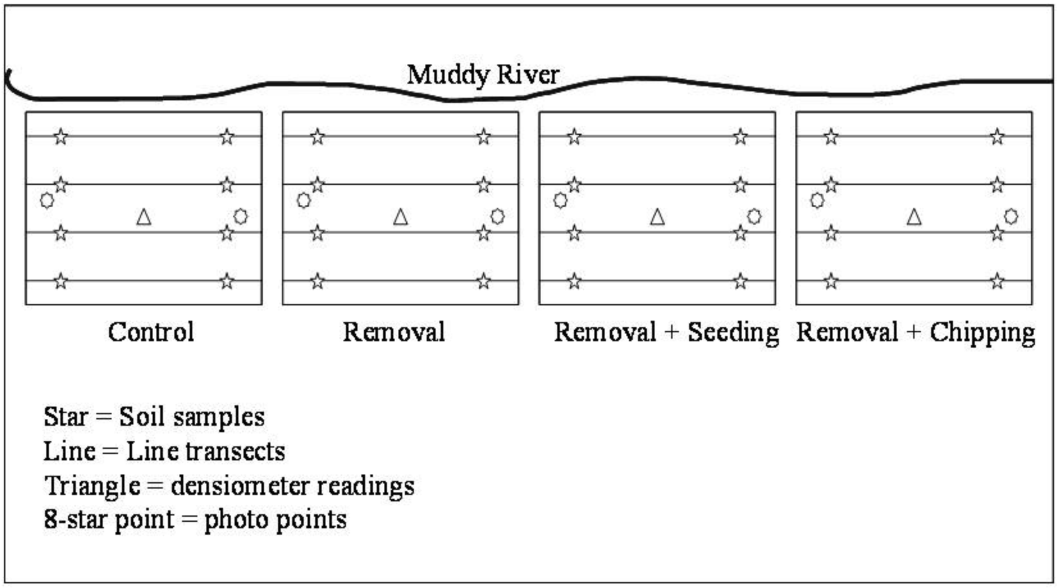

Figure 5. Example of an experimental block and its randomized treatments with locations of sampling transects, soil collection, densiometer reading, and photographs. Different blocks can have different spatial randomization of treatments.

Sampling was conducted pre-treatment and one year post-treatment. Due to the limited availability of NDF inmate crews and law enforcement issues on the BLM property, not all plots were treated during the first year. Three blocks on Nevada Power property, and two blocks on BLM Perkins property were not treated until the second year. Sampling of plots proceeded exactly as described in the Retrospective study (Figure 3).

We proposed the following null and alternative hypotheses to explain the effects of experimental treatments;

Soil salinity among treatments one year after removal

Null: Soil salinity does not vary among treatments;

Alternative: Soil salinity is greater in the *Control* than the three removal treatments.

Herbaceous species cover among treatments one year after removal

Null: Grass and forb species cover does not vary among treatments;

Alternative #1: Grass and forb species cover is greater in removal treatments compared to the *Control*;

Alternative #2: Grass and forb species cover is greater in the *Removal + Seeding* treatment compared to the other removal treatments;

Alternative #3: Grass and forb species cover is greater in the *Removal + Chipping* treatment compared to the *Removal + Chipping* treatment.

Shrub species cover among treatments one year after removal

Null: Shrub cover does not vary among treatments;

Alternative #1: Shrub cover is greater in removal treatments compared to the *Control*;

Alternative #2: Shrub cover is lowest in the *Removal + Chipping* treatment compared to other removal treatments*.*

Woody debris cover among treatments one year after removal

Null: Woody debris cover does not vary among treatments;

Alternative: Woody debris cover is greater in the *Control* than in removal treatments.

Litter and bare ground cover among treatments one year after removal

Null: Litter and bare ground cover do not vary among treatments;

Alternative 1: Litter and bare ground cover are greater in the removal treatments compared to the *Control*;

Alternative 2: Litter cover is greatest, and bare ground cover the smallest in the *Removal + Chipping* treatment compared to other removal treatments.

We used a mixed model two-way univariate and multivariate analysis of variance (random effect for blocks, fixed effects for treatments) to test for treatments effects (respectively, ANOVA and MANOVA; Steel and Torrie 1980) on soil chemistry variables and plant and substrate cover. The correct error term was the interaction of the block and treatment effect (Steel and Torrie 1980). Due to the very patchy distribution of plant species one year after treatment, only the functional groups herbaceous cover, shrub cover, tree cover, and the cover of the most abundant species were retained for statistics. When pre-treatment data were available (covariate), we used analysis of covariance (respectively, ANCOVA and MANCOVA). Because of the high correlation among soil chemistry variables, we first performed simple correlations and only kept for analysis variables that were uncorrelated to one another and that were highly correlated to others not retained for analysis. As above, variables were transformed if variances were heterogeneous. MANCOVA was used twice; once for the largely uncorrelated soil chemistry variables and secondly for plant cover variables, and the cover of litter, woody debris, and bare ground.

REMOTE SENSING

While monitoring the effectiveness of past and near future desert riparian vegetation restoration methods is needed to learn and demonstrate success, there is also a need to detect areas of non-native species invasion to identify future restoration, as well as identify small areas of weeds before they spread further. On the UMR, these areas may be undetected by ground inventories because access to private properties may not be available, surrounding vegetation is too dense to permit ground detection, patches of weeds may be too small to be easily detected, or not enough staff are available to map weeds. Under these conditions, mapping of non-native invasive species by remote sensing may be the most appropriate and feasible approach.

Spatial Solutions was subcontracted to conduct the remote sensing portion of the project for a fixed-price of $17,425. Aerial photography was generously provided by the Southern Nevada Water Authority. Four-band (red, blue, green, and near infrared) multi-spectral aerial imagery was captured in June 2008 at 6" spatial resolution. All processing was completed using Erdas® Imagine software. Analysis of imagery was restricted to within the UMR floodplain boundary (Figure 6).

The 500-year floodplain boundary was selected for three reasons: (i) In 2004, we needed to delineate a floodplain area large enough to qualify as a minimum commercial order for capture of new satellite imagery; although this was eventually not needed, Figure 6 represents that first delineation; (ii) the 500-year floodplain reflects the historical area of river, wetlands, and potential wetlands prior to water diversion for agricultural and pumping in order to analyze the area in a landscape context; and (iii) the 500-year floodplain also represents the area where patches of invasive weeds may initially become established after significant rain events because where water may recede from other areas, there may still be residual moisture within portions of the floodplain.

Spectral signatures of various known location of Russian knapweed, tamarisk, and tall whitetop were identified with an unsupervised classification approach. Extensive visual analysis of the imagery and simultaneous manual editing occurred to remove obvious areas that did not represent invasive species which resulted in the most effective and consistent representation of occurrence of these species. All areas of potential infestation were mapped and TNC staff verified presence/absence and species of infestation. The map was iteratively refined through field verification.

Figure 6. The 500-year floodplain of the Upper Muddy River.

RESULTS

RETROSPECTIVE

Regression analyses Soil salinity was primarily measured by electrical conductivity (Rivelli et al. 2002, Li et al. 2001). All other measures of soil chemistry were generally positively correlated to it, except calcium that showed no pattern with time since removal. The alternative hypothesis that soil salinity decreased with time since removal of tamarisk was rejected; the square-root of electrical conductivity increased steadily from about 2.75 to 6.25 $\sqrt{d.S/M}$ in 10 years since removal, but then declined slightly in years 11 and 12 after removal (r^2 = 0.38; Figure 7). Several observations were outside the 95% confidence interval (CI) and electrical conductivity was generally below the average 8 years after removal. The highest value of electrical conductivity was about 84 d. S/m recorded in the 10th year after removal. The lowest value was about 2 d. S/m found under the canopy of tamarisk. Boron, which was hypothesized to concentrate under tamarisk, showed the same relationship as electrical conductivity (Figure 8); however, the highest boron concentration was found in year 11 of removal. As for electrical conductivity, many observations were not in the 95% CI as expressed by the lower r^2 of 0.25 for the square-root of boron compared to the square-root of electrical conductivity. The lowest and highest untransformed values of boron concentration, respectively, were about 1.2 and 61 ppm.

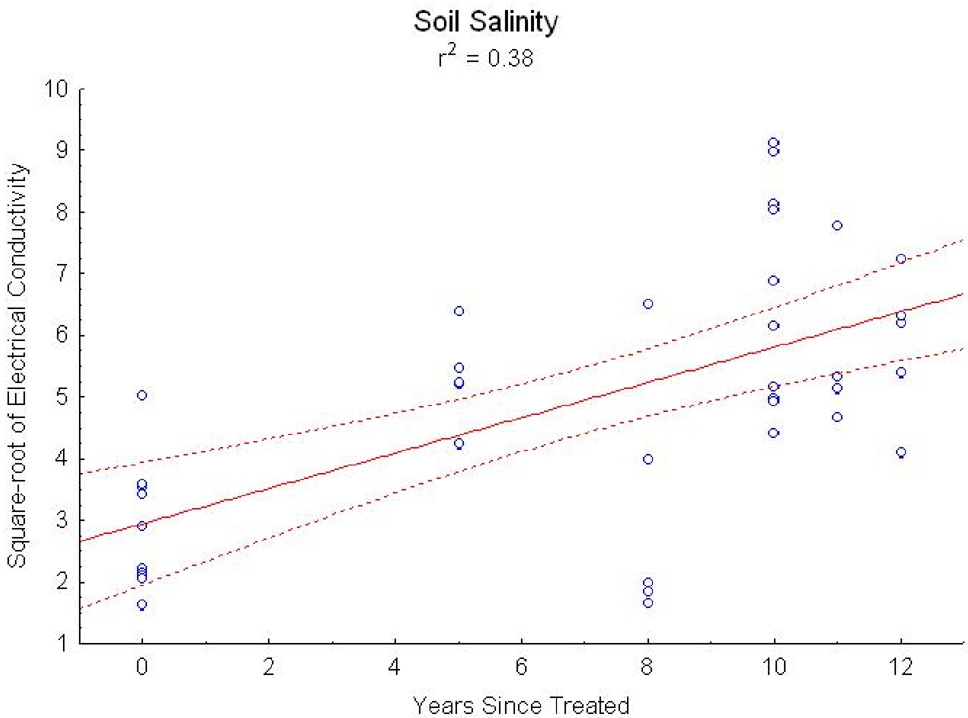

Figure 7. Electrical conductivity with years since tamarisk removal. Year 0 represented the control with no tamarisk removed. The square-root of electrical conductivity was used to homogenize variances. Units are $\sqrt{d.S/M}$.

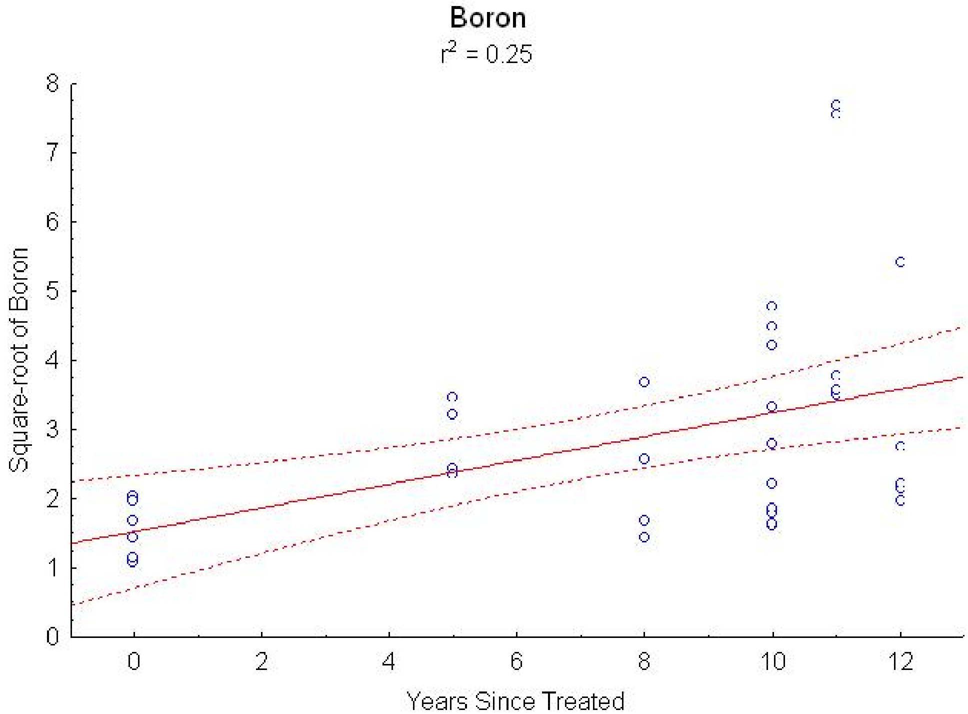

Figure 8. Boron with years since tamarisk removal. Year 0 represented the control with no tamarisk removed. The square-root of Boron was used to homogenize variances. Units are $\sqrt{ppm}$.

We hypothesized that the cover of late-succession species would increase with time since removal of tamarisk, and, conversely, the cover of quailbush, a dominant early-succession shrub, would decrease with time. The cover of late-succession species, which had patchy distributions, and quailbush did not significantly change with time as regressions slopes were flat and the dispersion of observations highly scattered around the average (r^2 = 0.01 for late successional species and r^2 = 0.03 for quailbush); thus the alternative hypotheses were invalidated (Figure 9, Figure 10). This hypothesis was based on the primary assumption that soil salinity decreased with time since tamarisk removal, which we also rejected. One anomaly to the non-significant regression slopes was a greater than average cover of late-successional species 8 years after removal of tamarisk, which was the same year we observed the lower than average soil salinity. Therefore, we rejected the overall hypothesis but strong deviations from the average for electrical conductivity and late-successional species cover on year 8 lend support to the negative relationship between soil salinity and cover of late-successional plant species.

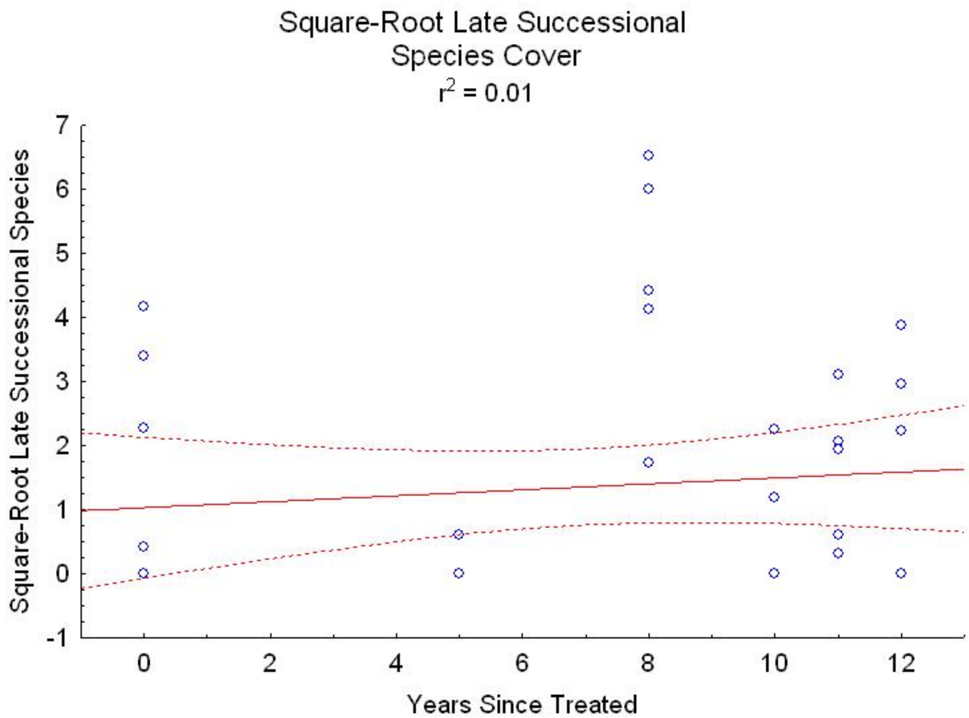

Figure 9. Cover of late-succession species with years since tamarisk removal. Year 0 represented the control with no tamarisk removed. The square-root of cover was used to homogenize variances.

Figure 10. Cover of quailbush with years since tamarisk removal. Year 0 represented the control with no tamarisk removed. The square-root of cover was used to homogenize variances.

We hypothesized that soil salinity would decrease with years since removal of tamarisk and that late-successional species cover would increase, but we did not claim that quailbush cover would decrease with soil salinity. It is reasonable to assume, however, that late-successional species would shade out and displace quailbush. Interestingly, the relationship between the cover of quailbush and electrical conductivity was parabolic with a peak of about 3 $\sqrt{\%}$ around 5 $\sqrt{d.S/M}$ after removal of tamarisk and zero average quailbush cover at electrical conductivity square-root values of 1.5 and 8.5 $\sqrt{d.S/M}$ (Figure 11). Many observations were outside the 95% CI and of these several had zero cover of quailbush. There was no relationship between quailbush and boron (results not shown).

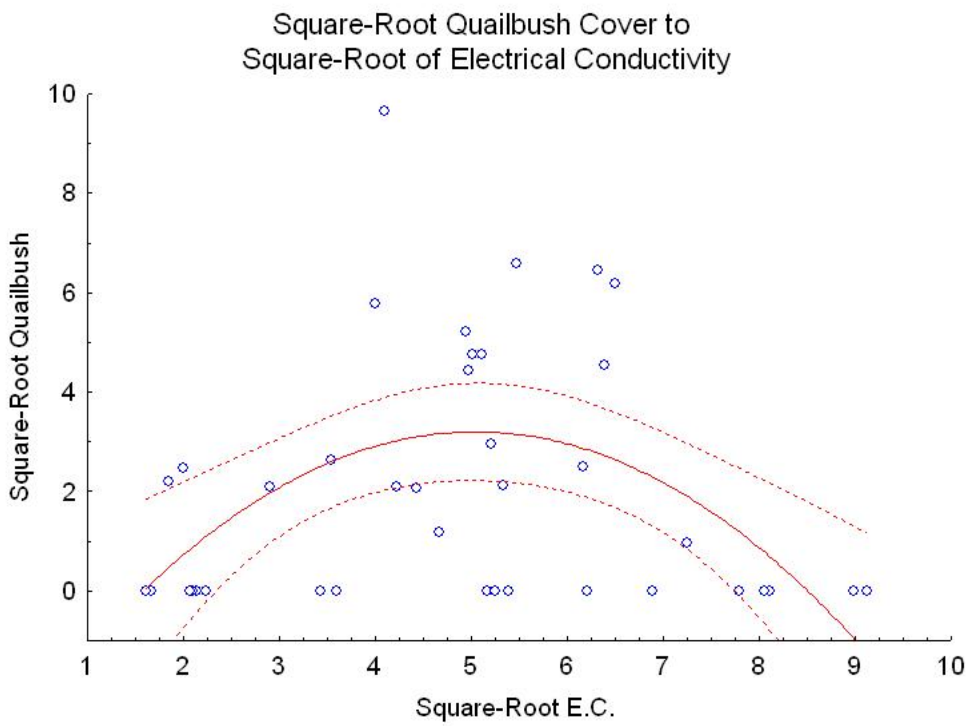

Figure 11. Cover of quailbush to electrical conductivity. Square root of electrical conductivity and quailbush were used to homogenize variances.

As predicted by the alternative hypothesis, we found a negative relationship between the square-root cover of late-succession species and the square-root of electrical conductivity (r^2 = 0.22; Figure 12). Highest cover of late-successional species was observed at the lowest electrical conductivity values. The relationship with electrical conductivity was noisy, especially at low electrical conductivity values, as suggested by the moderately low r^2 with many observations having zero cover of late-successional species. The same relationship was found for boron; however, the negative regression slope with boron was more shallow and even noisier than the previous one (Figure 13).

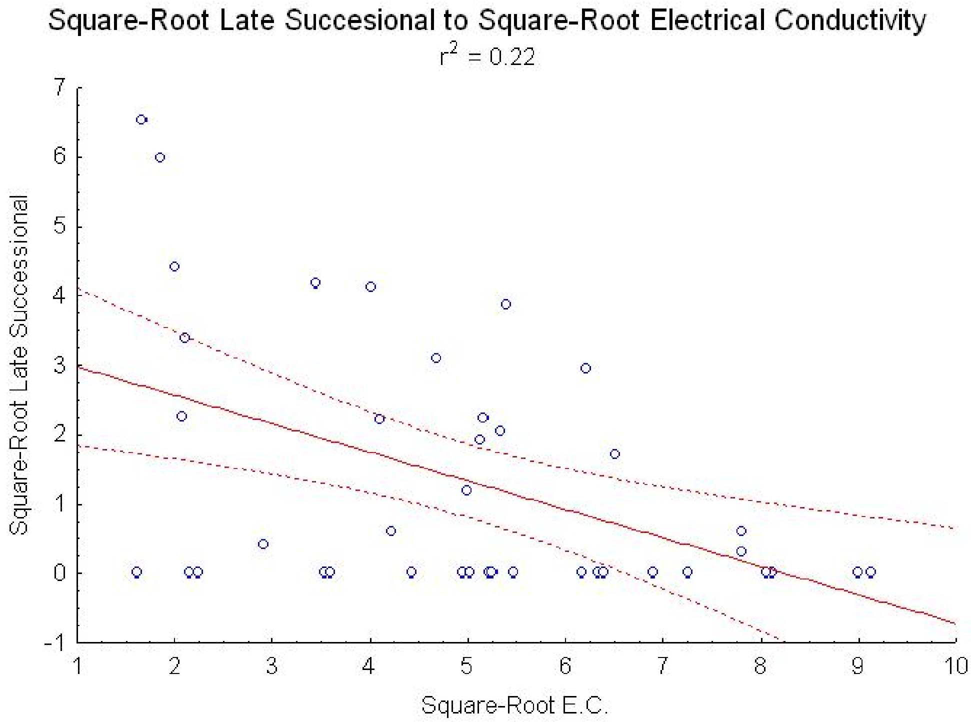

Figure 12. Relationship between the cover of late-succession species and electrical conductivity. Year 0 represented the control with no tamarisk removed. The square-root of cover and electrical conductivity were used to homogenize variances.

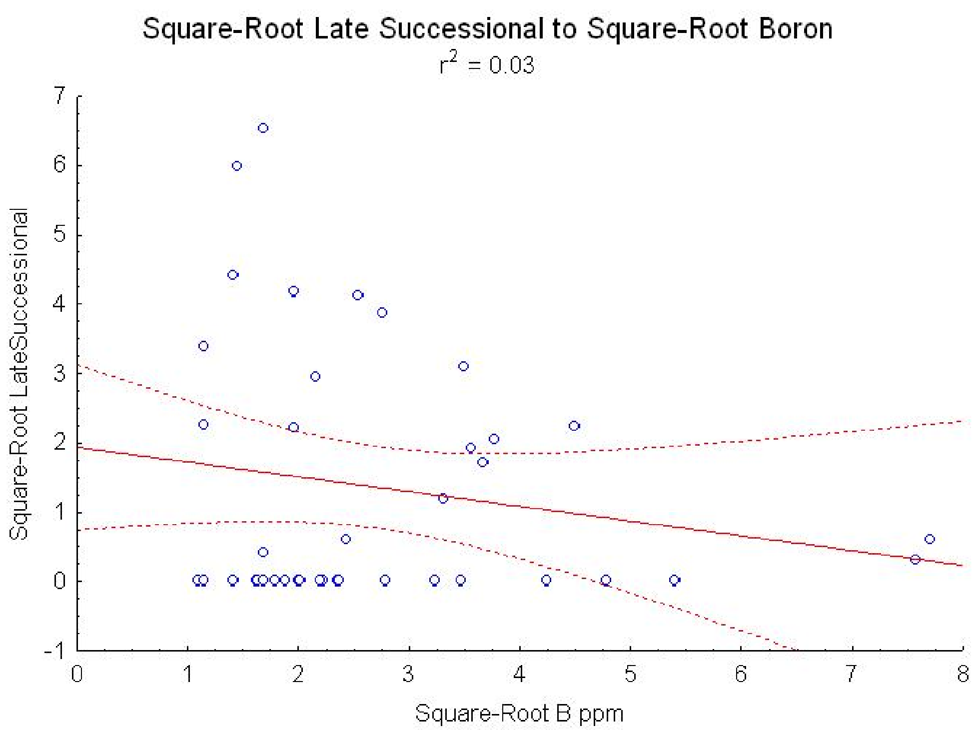

Figure 13. Relationship between the cover of late-succession species and boron. Year 0 represented the control with no tamarisk removed. The square-root of cover and boron were used to homogenize variances.

The next series of hypotheses concerned the recovery of breeding bird and fish species. Alternative hypotheses predicted an increase in the count of breeding bird species only in later years after removal of tamarisk, whereas the abundance of fish would more rapidly respond to increased light and aquatic primary productivity. An associated hypothesis was that Clark County priority species would also be favored by the recovery of late-successional species after removal of tamarisk. There was a negative relationship between the count of breeding bird species and time since removal of tamarisk in both 2008 (r^2 = 0.024; Figure 14) and 2009 (r^2 = 0.20; Figure 15). In both graphs, data points were sparse but generally contained within wide 95%CIs. The control plots (year 0) with untreated tamarisk contained both the highest and one of lowest bird counts. Differences between 2008 and 2009 were minor, with the exception of overall greater counts in 2009.

Breeding bird species richness was not responsive to time since treatment in 2008 (r^2 = 0.01; Figure 16); richness weakly decreased with years since tamarisk removal in 2009 (r^2 = 0.10; Figure 17). In addition to having relatively flat slopes, data observations were widely dispersed around the mean in both years of sampling; however, most observation points were contained within the 95% CI.

Figure 14. Relationship between the breeding bird point count and years since tamarisk removal in 2008. Year 0 represented the control with no tamarisk removed.

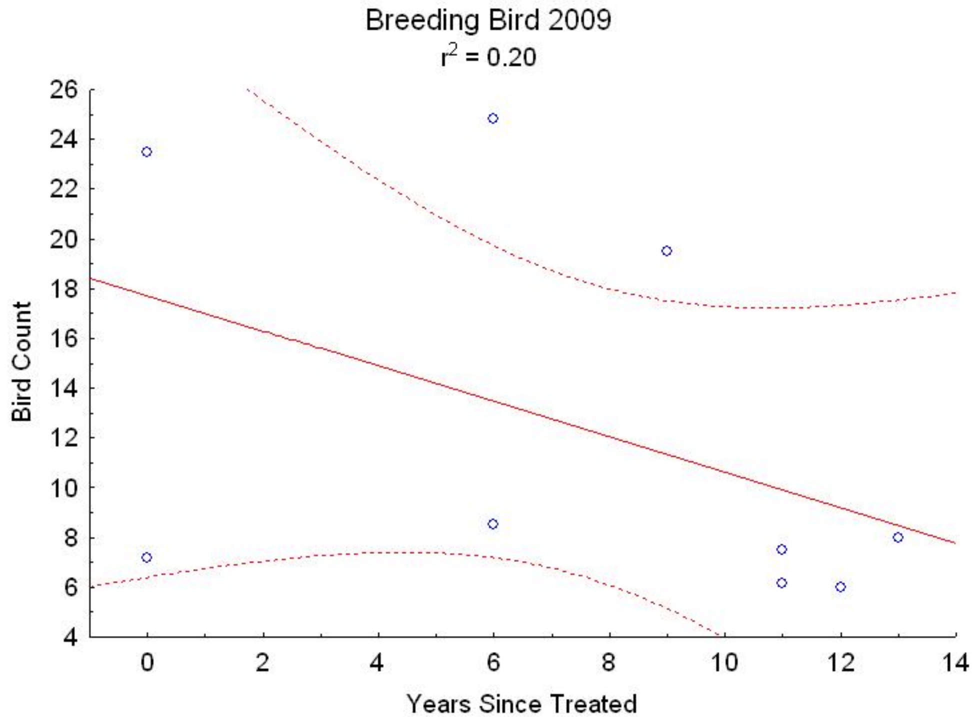

Figure 15. Relationship between the breeding bird point count and years since tamarisk removal in 2009. Year 0 represented the control with no tamarisk removed.

Figure 16. Relationship between the breeding bird species richness and years since tamarisk removal in 2008. Year 0 represented the control with no tamarisk removed. The logarithm base 10 was used to homogenize variances of species richness.

Figure 17. Relationship between the breeding bird species richness and years since tamarisk removal in 2009. Year 0 represented the control with no tamarisk removed. The logarithm base 10 was used to homogenize variances of species richness.

Of the Clark County priority bird species, we detected the following covered species: Arizona Bell's Vireo, Blue Grosbeak, and Phaenopepla. In addition, the only evaluation species we detected was Crissal Thrasher. No watch list species were detected. These species were detected infrequently and in plots with different periods of recovery following tamarisk removal. Arizona Bell's vireo was detected three of four times in control plots (untreated tamarisk). A list of breeding bird surveys can be found in Appendix A.

Multiple regression of total breeding bird count against the cover of tree, shrub, and herbaceous species in 2008 and 2009 revealed only a stronger negative (B = -3.87 for 2008 and B = -7.75 for 2009) relationship with herbaceous cover (r^2 = 0.76, p = 0.053 in 2008 and r^2 = 0.65, p = 0.10 in 2009; Table 4).The 2009 effect of herbaceous cover on bird count was not significant due primarily to the small number of data points.

Greater bird count was found in plots with the lowest herbaceous cover in 2008 and 2009 (Figure 18, Figure 19) because greater herbaceous cover generally indicated low structural diversity of mostly open areas. With one exception in 2009, all observations were within their 95% CIs. One data point had a strong influence on the regression in both years where total bird count was highest (about 14 in 2008 and 32 in 2009) at the lowest herbaceous cover of about 0.6%. The lowest total bird count was about 2 in 2008 and 5 in 2009.

Table 4. Multiple regression of total breeding bird count against the cover of trees, shrubs, and herbaceous (grasses and forbs) species. Sample size = 7 plots.

	B	STE of B	p-level
	2008		
Intercept	14.68	3.42	0.023
Tree Cover	0.02	0.33	0.961
Shrub Cover	0.27	1.19	0.834
Herbaceous Cover	-3.87	1.24	0.053
	2009		
Intercept	31.10	9.13	0.042
Tree Cover	-0.24	0.89	0.801
Shrub Cover	0.50	3.17	0.885
Herbaceous Cover	-7.75	3.31	0.101

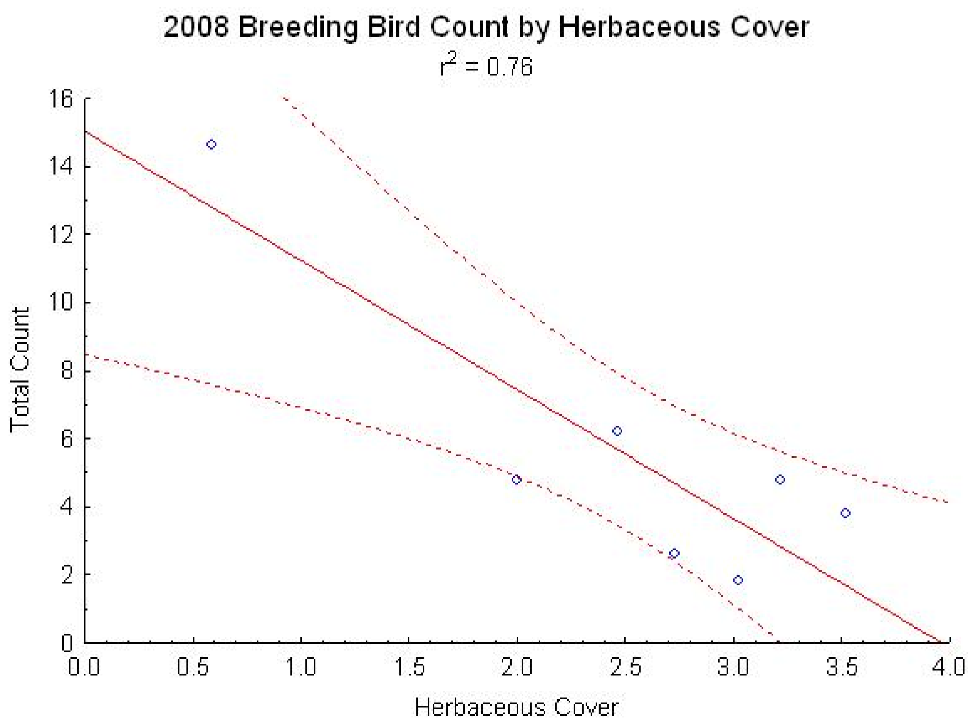

Figure 18. Relationship between the breeding bird count and herbaceous species cover in 2008.

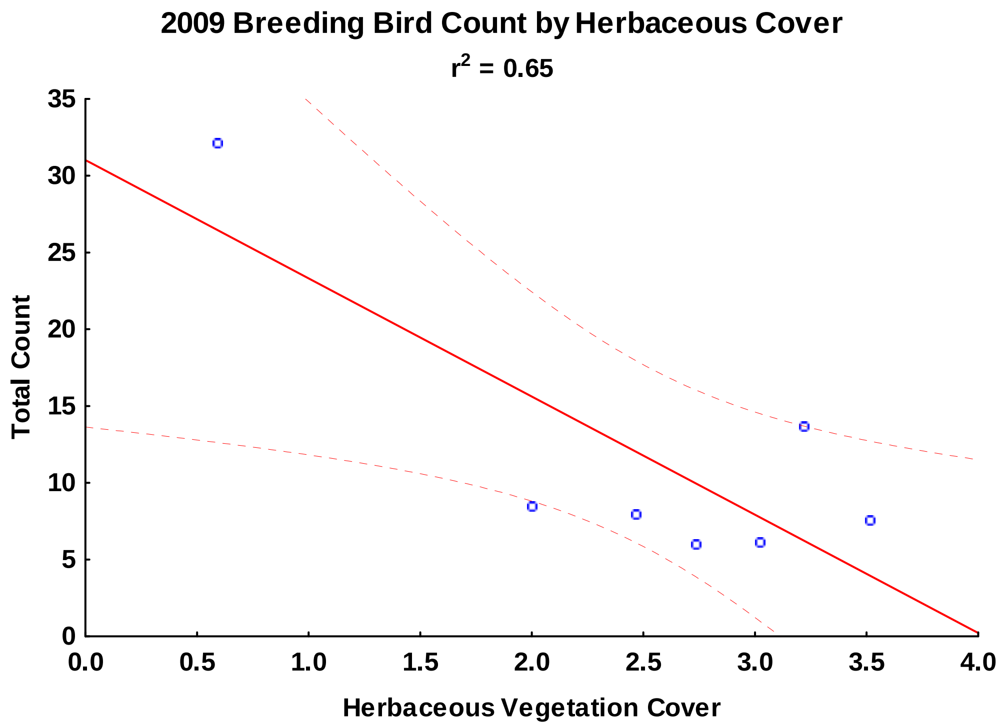

Figure 19. Relationship between the breeding bird count and herbaceous species cover in 2009.

Native total fish counts weakly increased with time since tamarisk removal for surveys conducted in 2008 (r^2 = 0.10; Figure 20). The only native species on the Clark County priority species list we collected was the Virgin River Chub (Appendix B). The slope of the 2008 regression was only positive because of one river reach located in a plot where tamarisk was removed 12 years prior; otherwise the slopes would be flat. This plot was sampled by a contractor, whereas all other plots were sampled by the Nevada Department of Wildlife staff.

Native total fish counts decreased with time since tamarisk removal for surveys conducted in 2009 (r^2 = 0.24; Figure 21). Similarly to the 2008 surveys, the only native fish on Clark County's priority species list caught was the Virgin River Chub. Results of fish surveys between 2008 and 2009 varied substantially without an explanation for possible causes. Major differences are in year 12, which was sampled by a SNWA contractor in both years.

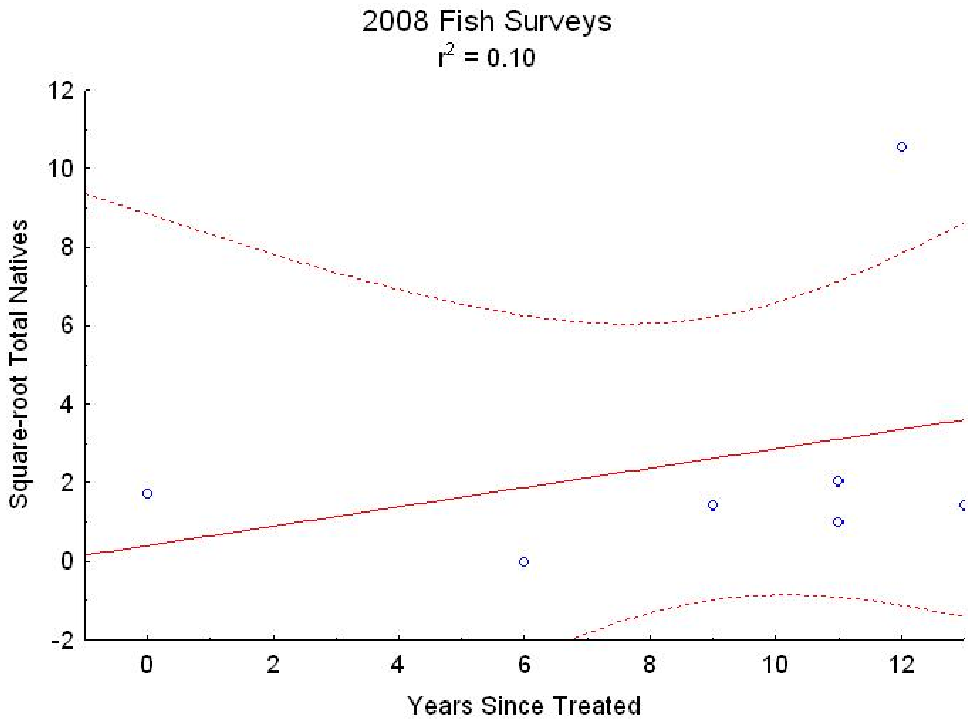

Figure 20. Total native fish count since years of tamarisk removal in 2008. The square-root of fish counts was used to homogenize variances.

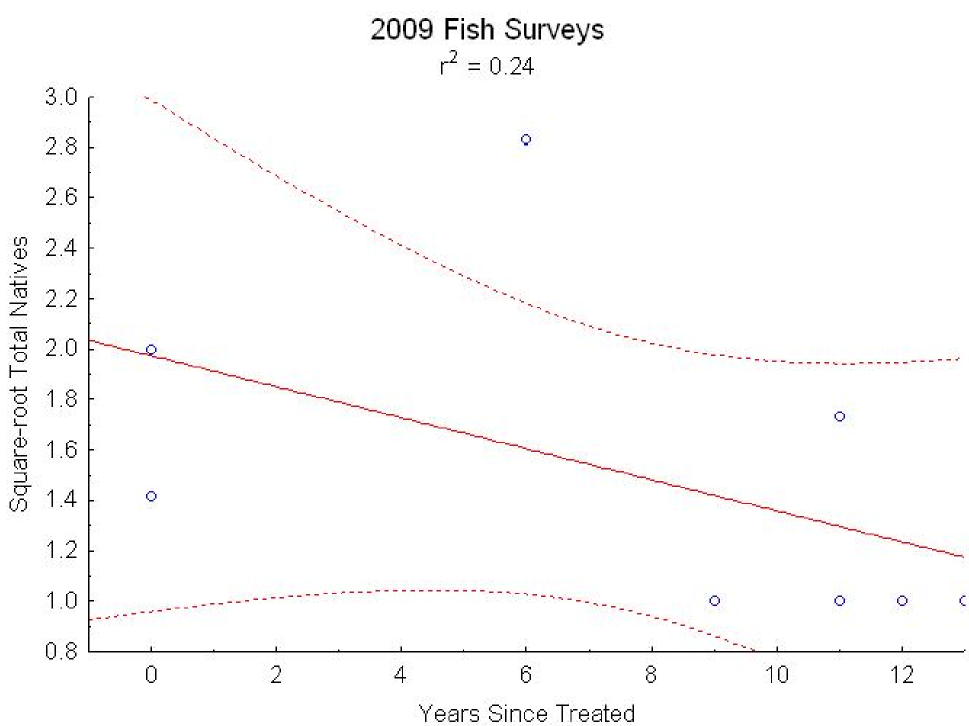

Figure 21. Total native fish count since years of tamarisk removal in 2009. The square-root of fish counts was used to homogenize variances.

Ordination analysis Non-metric multidimensional scaling ordination of vegetation cover (primary data matrix) and soil chemistry variables (secondary matrix) produced three ordination axes accounting cumulatively for about 85% of the variance (Table 5). The third axis explained the majority of the variance, followed by the second axis. To visualize ordination results, we use a biplot that displays plots (for example, REC4 is "Retrospective Control plot 4"). The position of a plot along an axis is determined by a vector whose entries correlate to the contribution of independent variables of cover and soil chemistry. Overlaid on this plot are the projected contributions of each explanatory variable shown by a line for chemistry and as a named point for cover variables. The farther the point (line or named point) from the centroid of the biplot, the stronger the contribution is. Because we display results from three axes, we need two biplots for axis 3 vs. axis 2 and axis 2 vs. axis 1.

Table 5. Percent variance explained by axes from non-metric multidimensional scaling of vegetation and soil matrices.

	R^2	
Axis	Increment	Cumulative
1	0.16	0.16
2	0.26	0.42
3	0.43	0.85

The third axis was strongly negatively correlated with grass cover (non-parametric correlation tau = -0.32), mostly inland saltgrass (*Distichlis spicata*), and strongly positively correlated to shrubs (tau = 0.71; Figure 22, Table 6). This axis was negatively explained by soil salinity (tau for pH = -0.4, tau for CO_3 = -0.36; Figure 22, Table 7); more saline plots had greater grass cover. More saline or grassier plots are situated in the lower part of the biplot. Plots dominated by shrubs (quailbush) were in the upper part of the biplot.

The second axis was positively correlated to forbs (tau = 0.65) and negatively correlated to litter (tau = -0.35) and woody debris (tau = -0.48); therefore, plots to the left of axis 3 are control plots (Figure 22, Table 6), but plots to the right contain more forbs, and less litter and woody debris. Soil calcium was also higher in plots with greater litter and woody debris (tau = -0.29), whereas electrical conductivity was positively correlated to axis 2 with more forbs (tau = 0.33; Figure 22, Table 7).

The first axis of the ordination contributed least to the explained variance (Table 5) and was formed of plots with positive correlation to litter (tau = 0.52) and forb cover (tau = 0.25) and negative correlation to woody debris (tau = -0.40) and grass cover (tau = -0.22; Table 6). The only soil chemistry variable with any explanatory strength for axis 1 was HCO_3 (tau = -0.23; Figure 23), which indicates soil ranging from slightly acidic (pH = 6) to alkaline (pH = 10). More alkaline soils were associated with grassier plots with more woody debris.

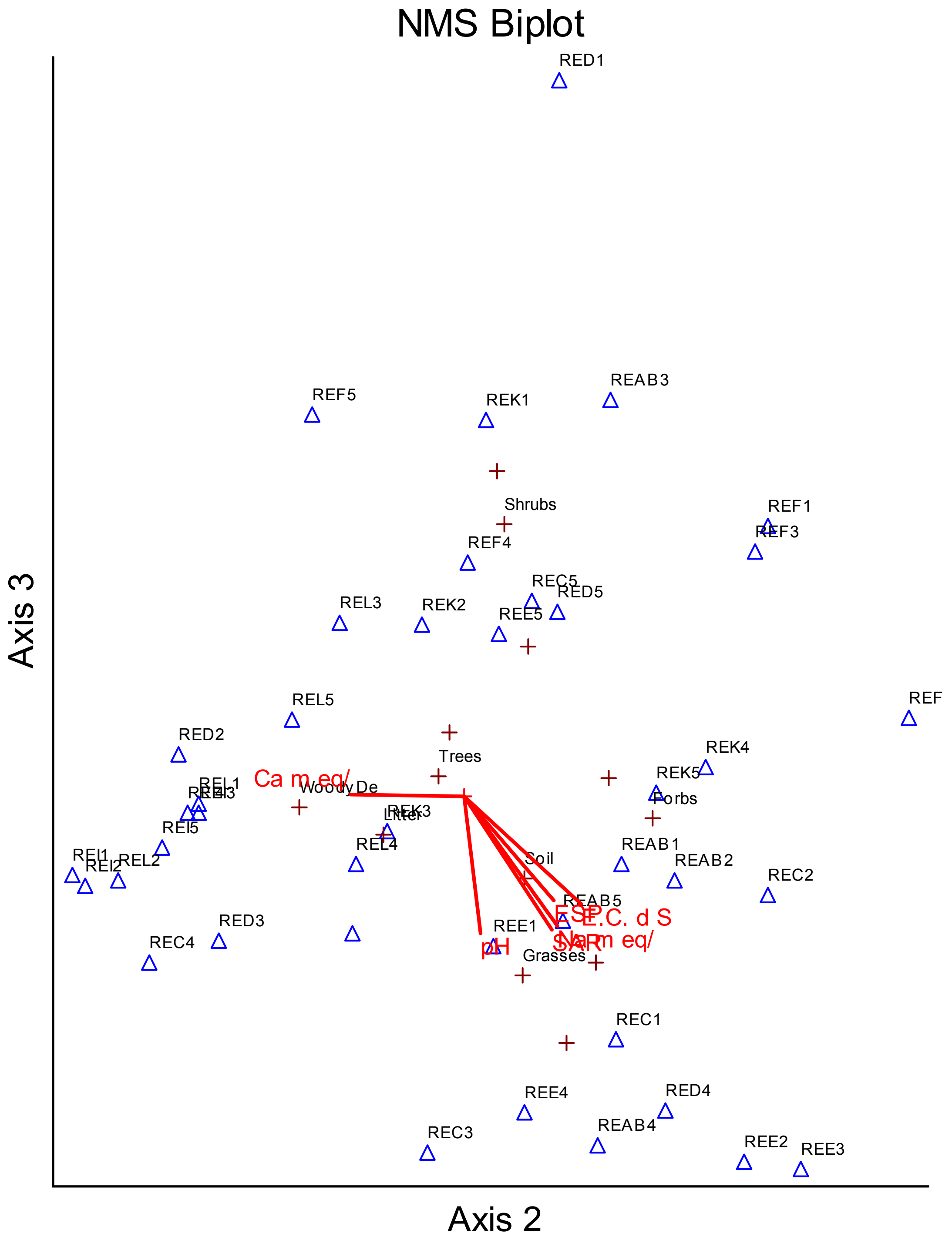

Figure 22. Biplot of axes 2 and 3 from the non-metric multidimensional scaling ordination of vegetation cover and soil chemistry data from the retrospective study.

Table 6. Correlation (Kendall's tau) between primary variables and ordination axes. N = 41.

Primary Variables	Axis		
	1	2	3
Grasses	-0.22	0.09	-0.32
Forbs	0.25	0.65	-0.04
Shrubs	-0.19	0.04	0.71
Trees	-0.01	-0.10	-0.03
Litter	0.52	-0.35	-0.16
Woody Debris	-0.40	-0.48	0.01
Soil	0.17	0.12	-0.24
Quailbush	-0.11	0.11	0.51
Heliotrope	0.18	0.05	0.36
Unknown Forb	0.27	0.02	0.09
Tamarisk	-0.03	-0.06	0.04
Saltgrass	-0.25	0.16	-0.43
Mojave Seablite	-0.03	0.35	-0.33

Table 7. Correlation (Kendall's tau) between secondary variables and ordination axes. N = 41.

Secondary variables	Axis		
	1	2	3
SAR	-0.06	0.28	-0.26
ESP	-0.06	0.28	-0.26
Na	-0.05	0.28	-0.25
Ca	-0.04	-0.29	0.10
Mg	-0.04	0.16	-0.10
pH	-0.03	0.25	-0.40
CO3	-0.06	0.13	-0.36
HCO3	-0.23	0.32	-0.01
E.C.	-0.05	0.33	-0.25
Cl	-0.01	0.23	-0.15
B	0.13	0.22	-0.08
Sat%	0.09	0.21	0.00

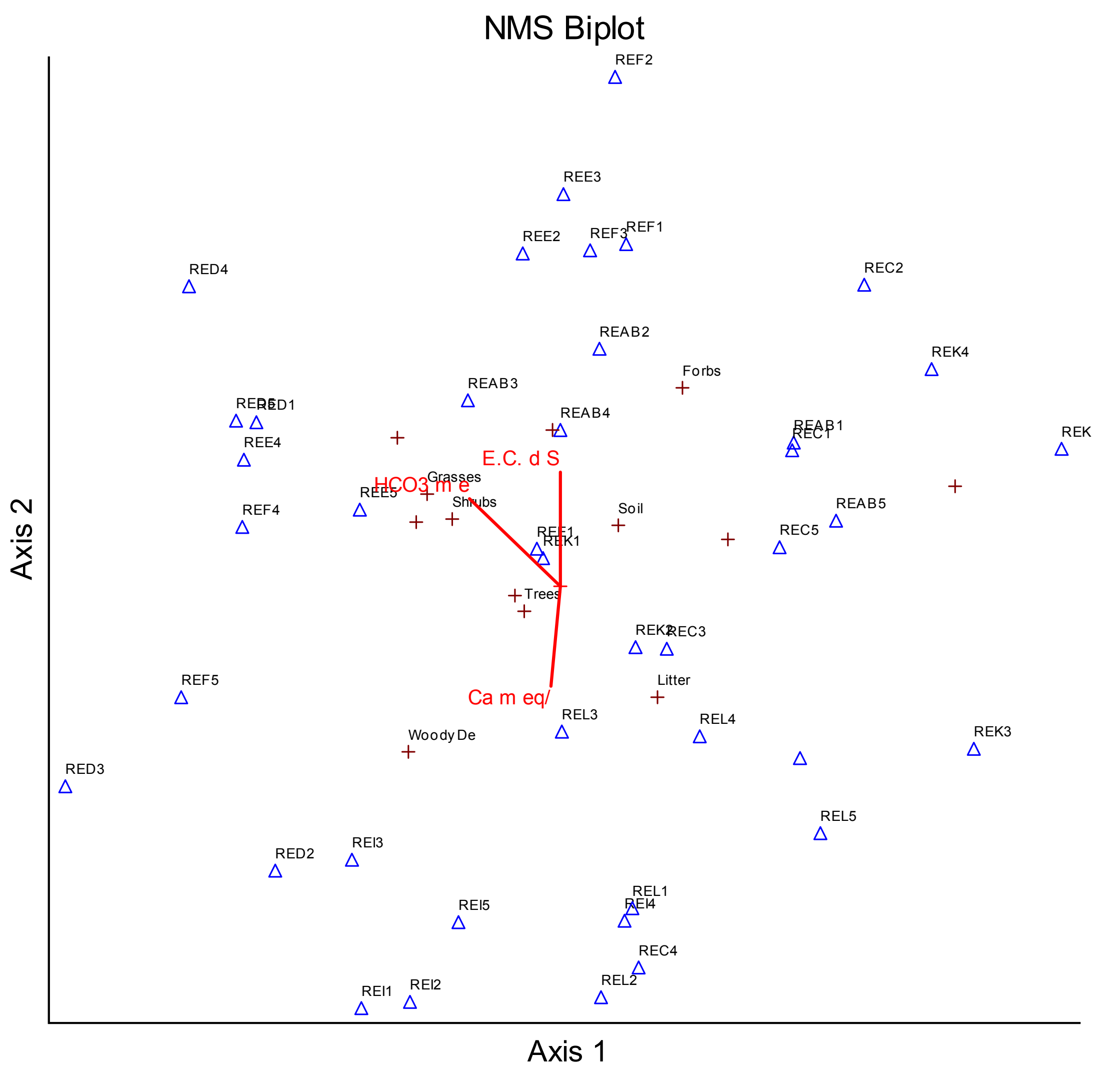

Figure 23. Biplot of axes 1 and 2 from the non-metric multidimensional scaling ordination of vegetation cover and soil chemistry data from the retrospective study.

EXPERIMENTAL

Correlation analysis of all soil chemical variables determined that saturation percentage, boron, calcium, carbonate, bicarbonate and electrical conductivity (EC) were not correlated among themselves, but were highly correlated to all other variables (Table 8). These uncorrelated variables were retained for all other analyses. The correlated variables are less useful for statistical analyses because they are too co-dependent to meet test assumptions. Moreover, these variables would already be explained by the more independent, uncorrelated variables.

Table 8. Correlation matrix (Kendall's tau) for soil attributes. Units for Na Ca, Mg, CO_3, HCO_3, and Cl are meq/L. Units of E.C. are dS/m, and ppm for B.

	SAR	ESP	Na	Ca	Mg	pH	CO_3	HCO_3	E.C.	Cl	B	Sat%
SAR	1.00	0.99	0.94	0.07	0.59	0.51	0.25	0.32	0.66	0.57	0.56	0.26
ESP	0.99	1.00	0.93	0.11	0.61	0.55	0.24	0.32	0.68	0.58	0.56	0.29
Na	0.94	0.93	1.00	0.06	0.81	0.40	0.17	0.33	0.81	0.72	0.49	0.14
Ca	0.07	0.11	0.06	1.00	0.07	0.52	0.11	0.12	-0.05	0.04	0.08	-0.15
Mg	0.59	0.61	0.81	0.07	1.00	0.25	0.00	0.26	0.89	0.77	0.24	-0.02
pH	0.51	0.55	0.40	0.52	0.25	1.00	0.31	0.05	0.34	0.13	0.41	0.23
CO_3	0.25	0.24	0.17	0.11	0.00	0.31	1.00	0.20	0.04	-0.02	0.48	0.23
HCO_3	0.32	0.32	0.33	0.12	0.26	0.05	0.20	1.00	0.31	0.17	0.58	0.50
E.C.	0.66	0.68	0.81	-0.05	0.89	0.34	0.04	0.31	1.00	0.87	0.25	0.09
Cl	0.57	0.58	0.72	0.04	0.77	0.13	0.02	0.17	0.87	1.00	0.11	0.03
B	0.56	0.56	0.49	0.08	0.24	0.41	0.48	0.58	0.25	0.11	1.00	0.40
Sat%	0.26	0.29	0.14	0.15	0.02	0.23	0.23	0.50	0.09	0.03	0.40	1.00

A multivariate analysis of covariance (MANCOVA) of the uncorrelated soil variables revealed that treatment application was the only significant effect (p = 0.01; Table 9). Because the overall treatment effect was significant, we explored univariate analyses of covariance (ANCOVA) to find the source of significance.

Table 9. MANCOVA of treatment effects on post-treatment soil chemical variables. Pre-treatment soil chemical variables were used as covariates. N = 15 blocks.

	Wilks λ	F	DF Effect	DF Error	p
Block	0.008	3.97	70		
Treatment	0.423	2.23	15	91.5	**0.010**
Calcium	0.828	1.37	5	33.0	0.260
HCO3	0.823	1.41	5	33.0	0.244
SQRT EC	0.752	2.17	5	33.0	0.081
SQRT Boron	0.923	0.55	5	33.0	0.737
Square Saturation	0.938	0.44	5	33.0	0.819

ANCOVA for electrical conductivity (EC) did not detect a significant treatment effect (p = 0.8, Table 10; Figure 24, Figure 25), although the pre-treatment effect of EC was significant (p < 0.001; Table 10); indeed, mean EC looked quite different among treatments after tamarisk removal (Figure 25), but the same differences existed before tamarisk removal (Figure 24). Therefore, removal of tamarisk had nothing to do with among treatment differences. Highest EC was observed in the no-removal *Control* (CO) and *Removal + Chipping* (RC) plots prior to removal. The regression between pre- and post-treatment EC was strong (r^2 = 0.38; Figure 26), confirming that past results explained current ones. Despite the strong regression, several data points were scattered outside the 95% CI at lower and intermediate pre-removal EC values.

Table 10. ANCOVA of treatment and pre-treatment effects for E.C. (d S/m). Square-root of pre-treatment EC values was used to homogenize variances.

	SS	DF	MS	F	p
Block	965.69	14	68.98		
Treatment	33.66	3	11.22	0.32	0.811
sqrt(EC0)	752.95	1	752.95	21.41	**<0.001**
Error	1441.51	41	35.16		

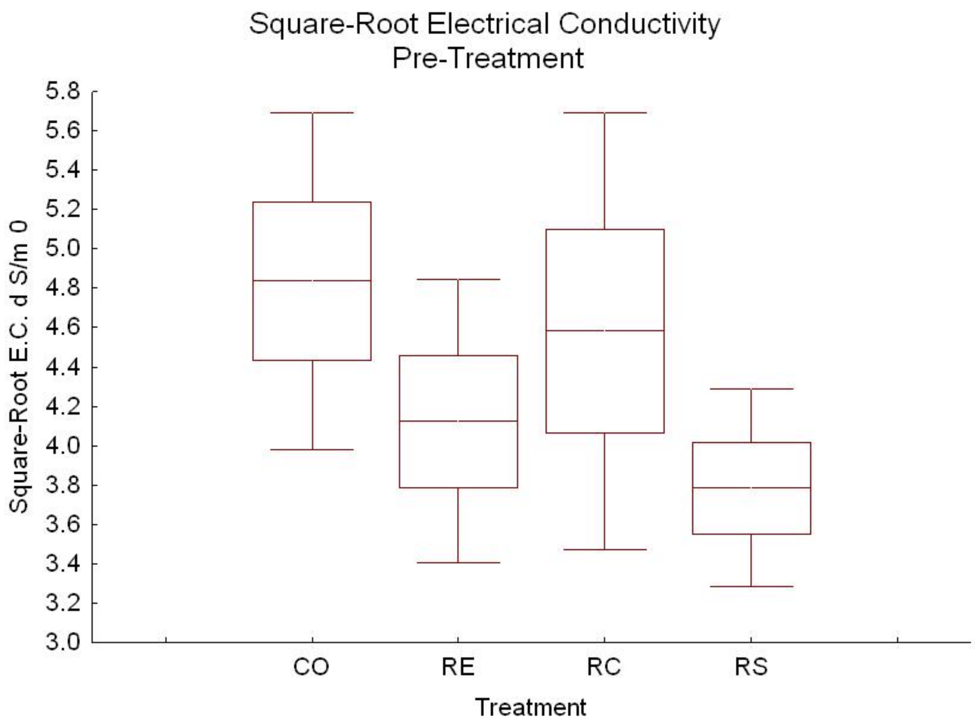

Figure 24. Electrical conductivity (E.C.) prior to application of tamarisk removal treatments. EC values were square-root transformed to homogenize variances. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

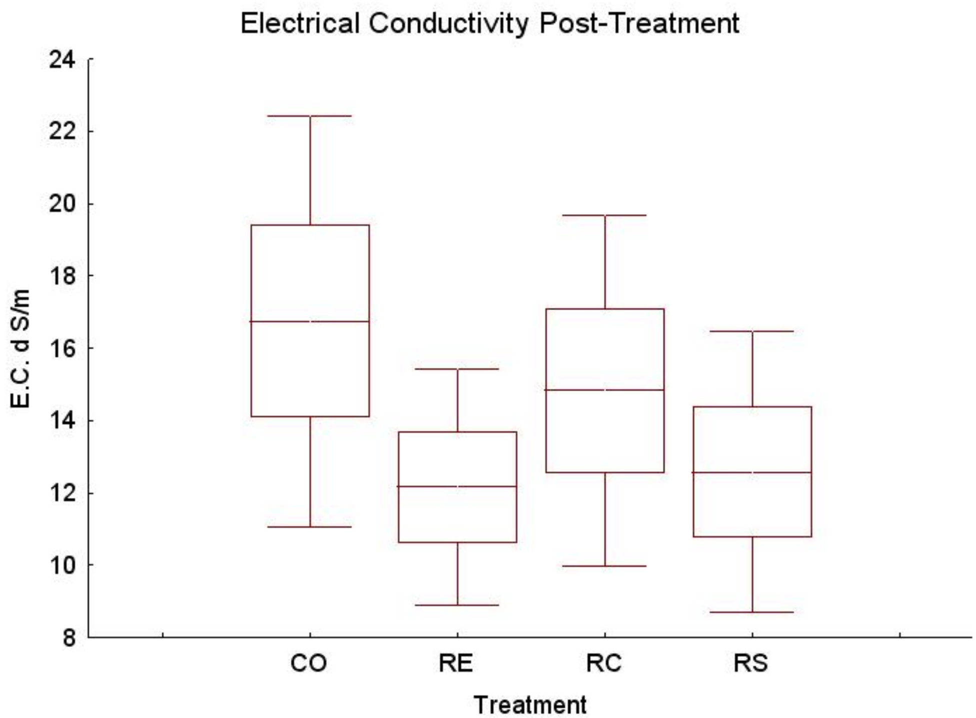

Figure 25. Effect of tamarisk removal treatments on electrical conductivity (E.C.). EC values were square-root transformed to homogenize variances. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

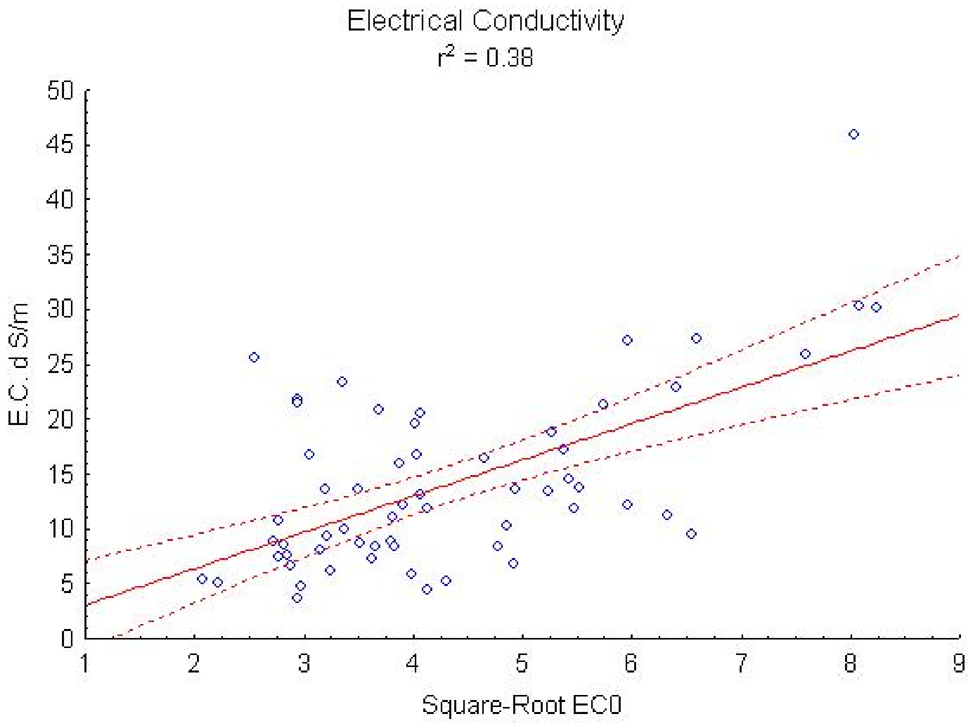

Figure 26. Electrical conductivity (E.C.) before and after implementation of tamarisk removal treatments. Pre-treatment EC values (EC0) were square-root transformed to homogenize variances. EC indicates post-treatment EC values. N = 15 blocks.

Boron concentrations were not explained by tamarisk removal treatments or pre-treatment boron values (Table 11, Figure 27, Figure 28). The pre-treatment boron concentration resembled those of EC with higher averages in control (CO) and *Removal* + *Chipping* (RC) plots (Figure 27). The main difference between EC and boron was an increase in boron in the traditional *Removal* treatment (RE) after treatment (Figure 29), thus causing the non-significant pre-treatment effect ($p = 0.174$) in Table 11 and an increased "bulge" at intermediate values of boron in the regression of pre- to post-treatment ($r^2 = 0.09$; Figure 29).

Table 11. ANCOVA of treatment and pre-treatment effects for B (ppm). Square-root of pre-treatment and post-treatment B values were used to homogenize variances.

	SS	DF	MS	F	p
Block	549.05	14	39.22		
Treatment	22.21	3	7.40	0.86	0.471
Sqrt(B0)	16.52	1	16.52	1.91	0.174
Error	354.35	41	8.64		

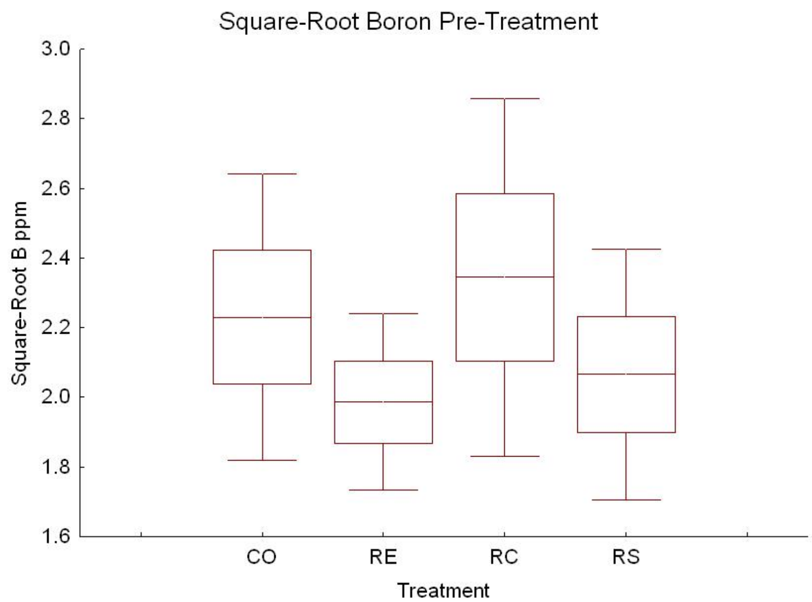

Figure 27. Boron (B) prior to application of tamarisk removal treatments. B values were square-root transformed to homogenize variances. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

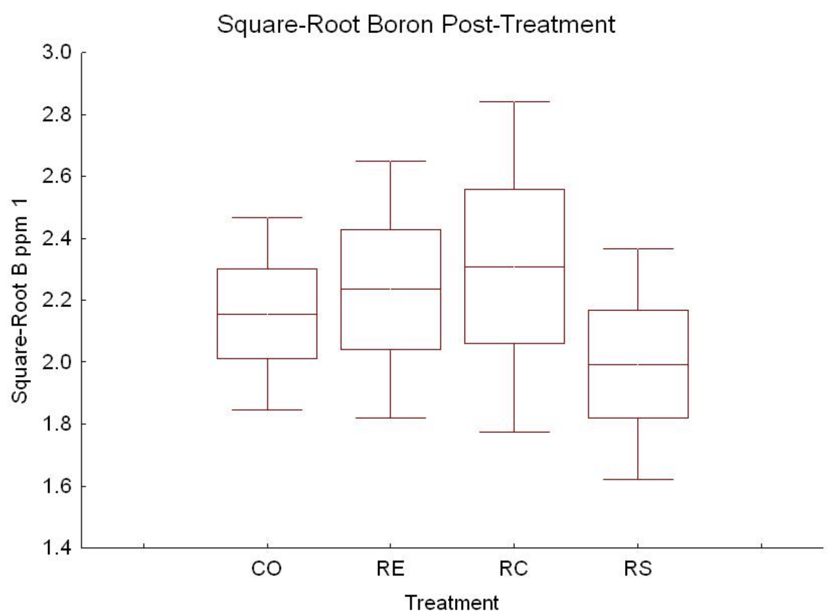

Figure 28. Effect of tamarisk removal treatments on B. B values were square-root transformed to homogenize variances. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

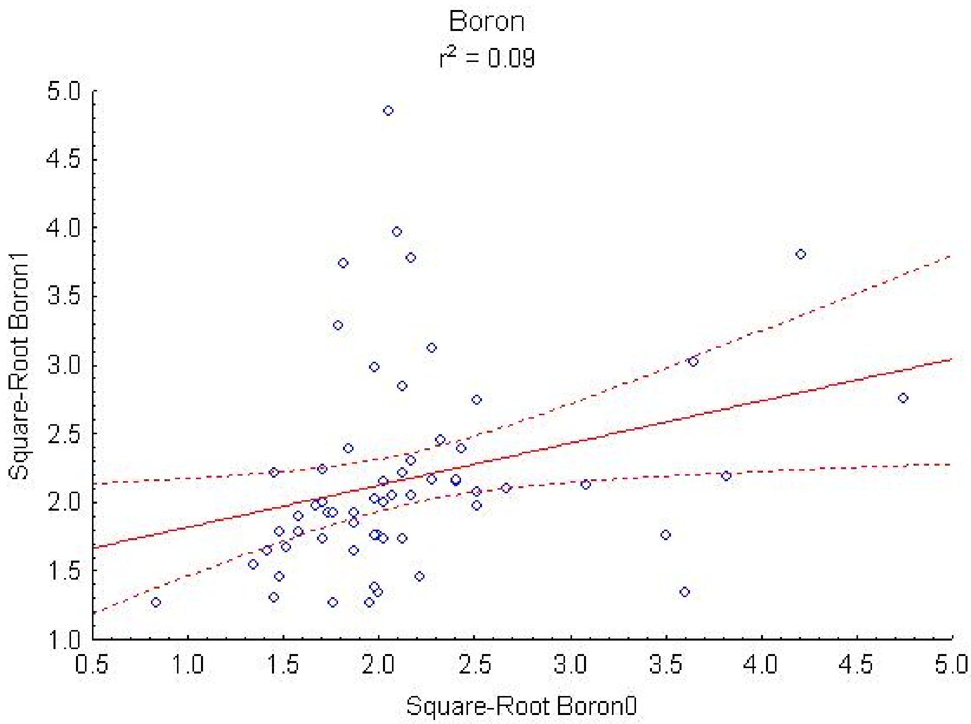

Figure 29. Boron before and after implementation of tamarisk removal treatments. Pre-treatment (Boron0) and post-treatment (Boron1) B values were square-root transformed to homogenize variances. N = 15 blocks.

ANCOVA revealed no effect of tamarisk removal treatments (p = 0.593) and no pre-treatment dependencies on calcium (p= 0.337; Table 12, Figure 30, Figure 31). The highest average calcium concentration was found in the *Removal + Seeding* (RS) treatment and the lowest in the *Removal + Chipping* (RC) treatment before removal of tamarisk (Figure 30). These non-significant differences became even less pronounced after tamarisk removal (Figure 30).

The slope of the regression between pre- and post-treatment Ca was positive, therefore suggesting a pre-treatment dependency, but scattered data points at especially lower and higher pre-treatment Ca values weakened the relationship (Figure 32).

Table 12. ANCOVA of treatment and pre-treatment effects (Ca0) for Ca (meq/L)

	SS	DF	MS	F	p
Block	1388.87	14	99.20		
Treatment	50.96	3	16.99	0.64	0.593
Ca0	50.00	1	25.00	0.94	0.337
Error	1087.34	41	26.52		

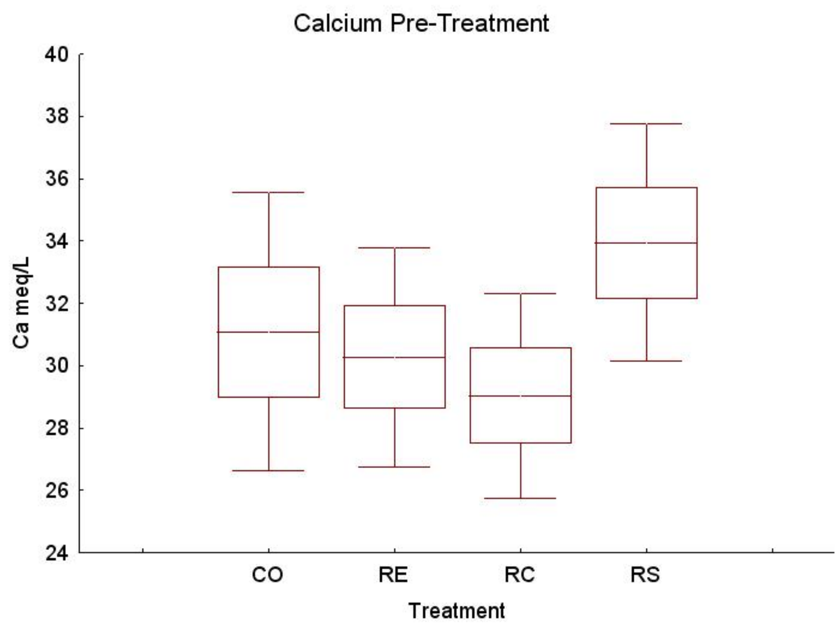

Figure 30. Calcium (Ca) prior to application of tamarisk removal treatments. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

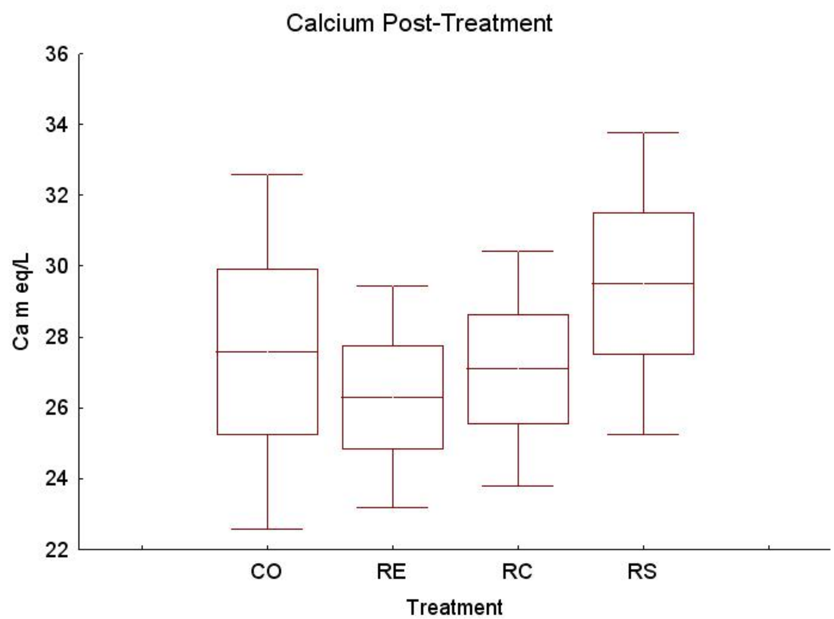

Figure 31. Effect of tamarisk removal treatments on Ca. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

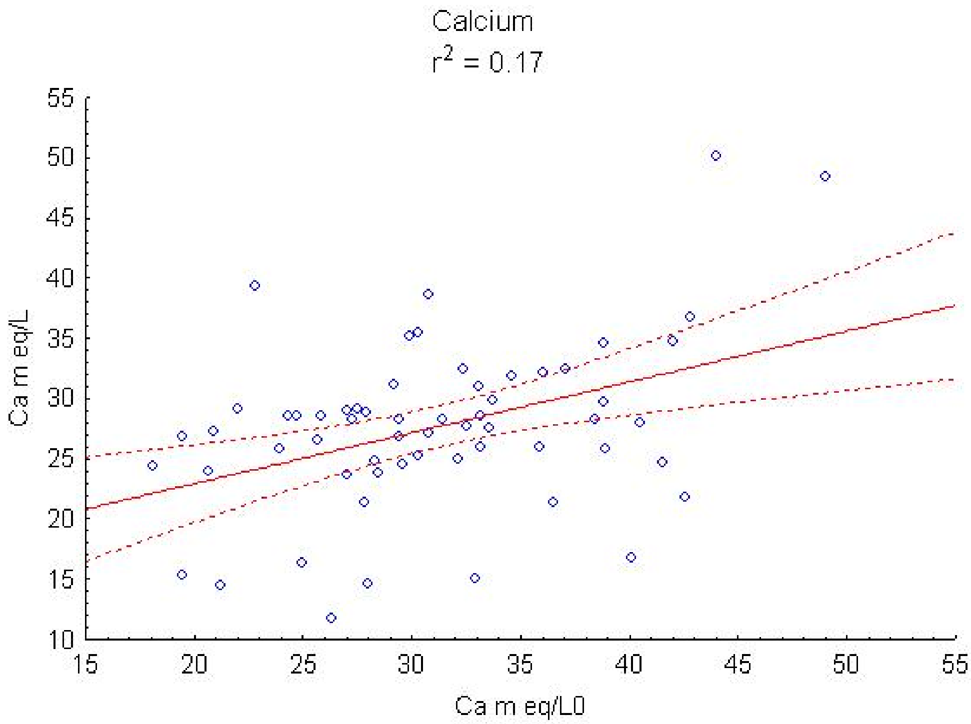

Figure 32. Calcium before (Ca meq/L0) and after (Ca meq/L) implementation of tamarisk removal treatments. N = 15 blocks.

Variation in HCO_3 was not explained by tamarisk removal treatments (p = 0.576) or pre-treatment values of HCO_3 (p = 0.302; Table 13, Figure 33, Figure 34). It was noteworthy that the post-treatment pattern of averages for HCO_3 (Figure 34) was nearly identical to that of Ca (Figure 31). The same comparison was not true for pre-treatment averages of HCO_3, which were highly similar and overlapping among treatments (Figure 33).

The regression of pre- to post-treatment plot averages was nearly flat with many points outside the 95% CI (r^2 = 0.03; Figure 35). In this case, the past did not explain current results.

Table 13. ANCOVA of treatment and pre-treatment effects for HCO_3 (meq/L)

	SS	DF	MS	F	p
Block	528.99	14	37.78		
Treatment	22.46	3	7.49	0.67	0.576
HCO3	12.21	1	12.20	1.09	0.302
Error	458.89	41	11.19		

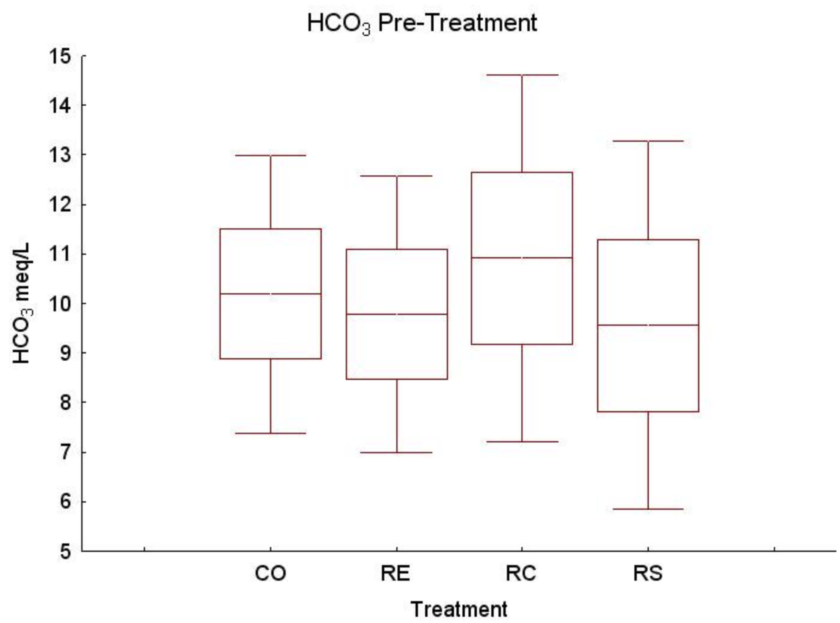

Figure 33. HCO_3 prior to application of tamarisk removal treatments. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

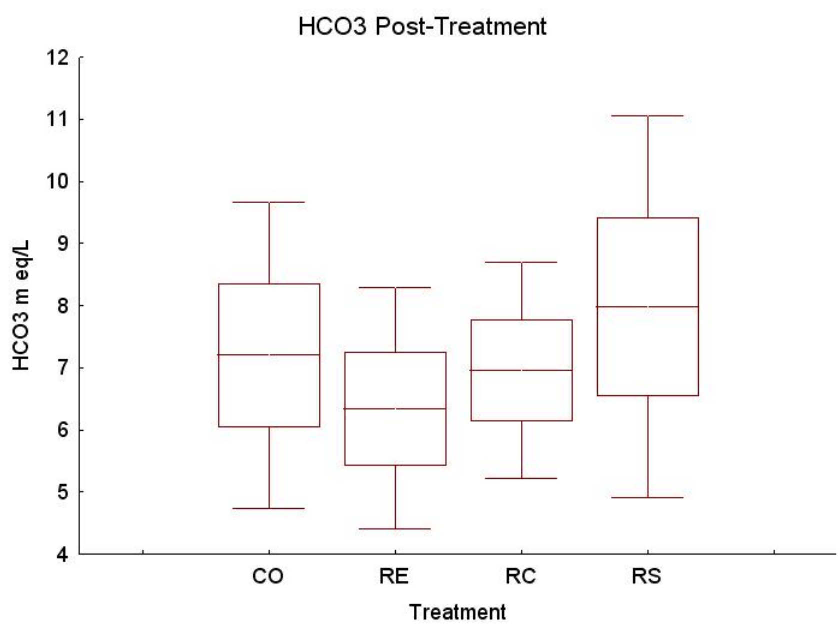

Figure 34. Effect of tamarisk removal treatments on HCO_3. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

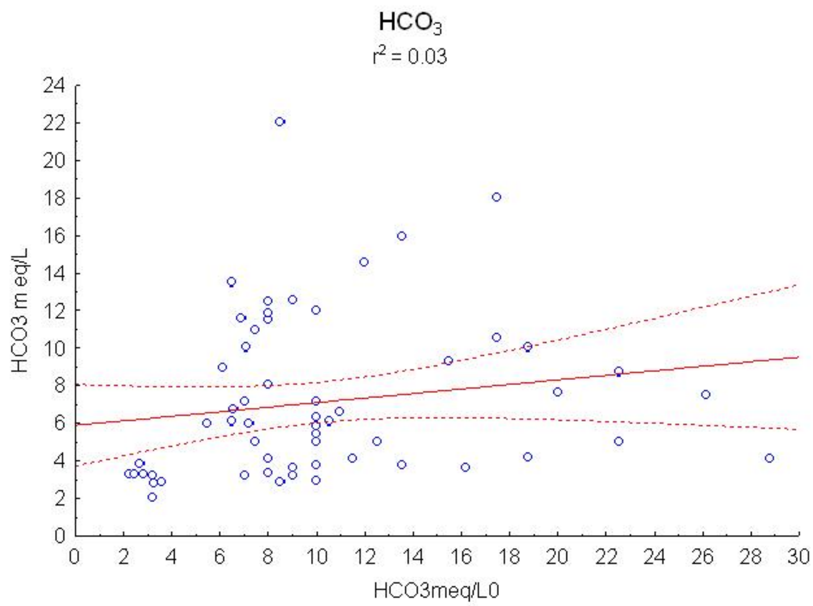

Figure 35. HCO_3 before (HCO_3. meq/L0) and after (HCO_3. meq/L) implementation of tamarisk removal treatments. N = 15 blocks.

Saturation % was not affected by tamarisk removal treatments (p = 0.41, Table 14; Figure 37) or pre-treatment saturation values (p = 0.87, Table 14; Figure 36). The highest pre-treatment saturation % average was observed in the *Removal + Chipping* (RC) treatment but, despite the square-transformation of data, the 95% CI on this average was very wide (Figure 36). Both the pre-treatment control (CO) and *Removal* (RE) treatments had equal and similar averages. Post-treatment averages changed somewhat, albeit non-significantly, with highest values observed in *Removal + Chipping* (RC) treatment and in the traditional *Removal* (RE) treatment.

Regression between pre-treatment and post-treatment saturation % was non-existent with nearly all plots lined up vertically at low pre-treatment values of saturation % (r^2= 0.02, Figure 38).

Table 14. ANCOVA of treatment and pre-treatment effects for Sat%. The square of sat% was used to transform pre-treatment values.

	SS	DF	MS	F	p
Block	4301.35	14	307.24		
Treatment	111.93	3	37.31	0.99	0.408
Square(Sat0%)	0.97	1	0.97	0.03	0.874
Error	1547.77	41	37.75		

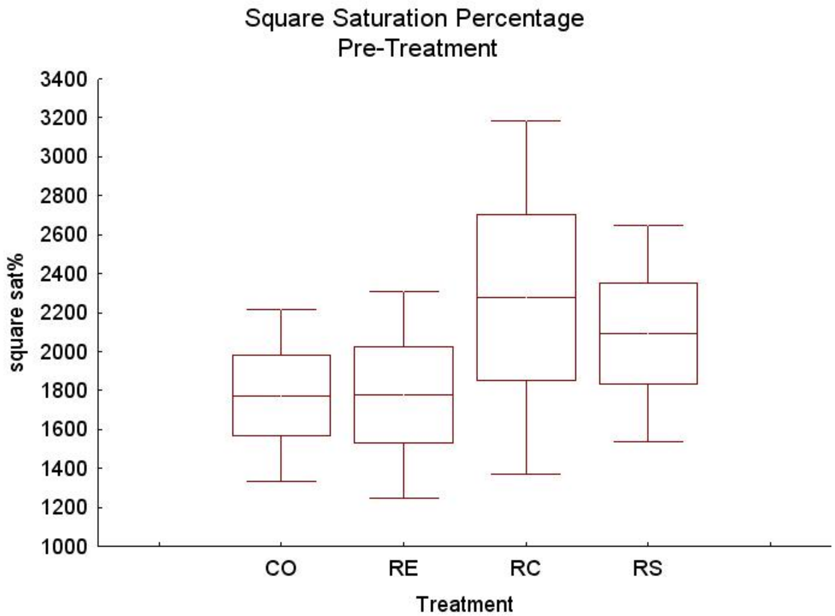

Figure 36. Saturation % prior to application of tamarisk removal treatments. The square of saturation was used to homogenize variance. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

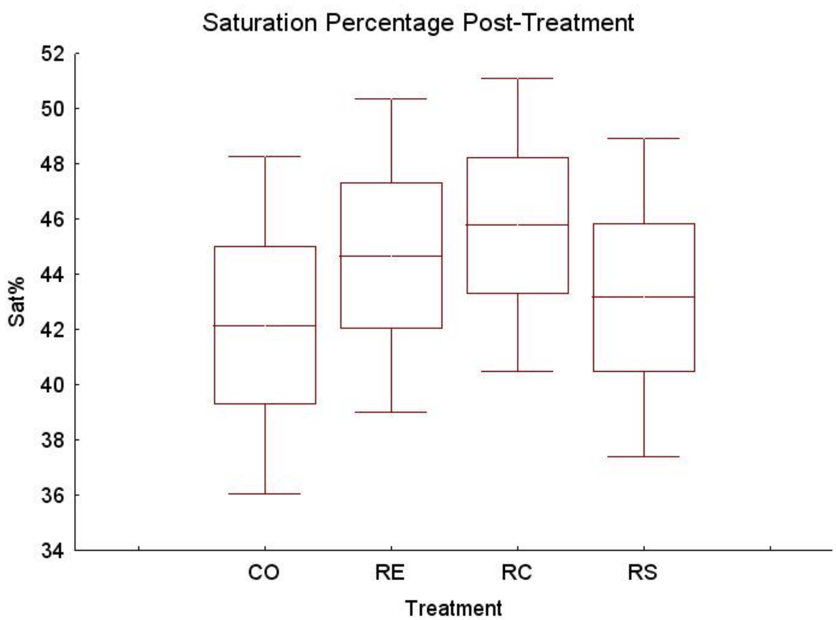

Figure 37. Effect of tamarisk removal treatments on Saturation %. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

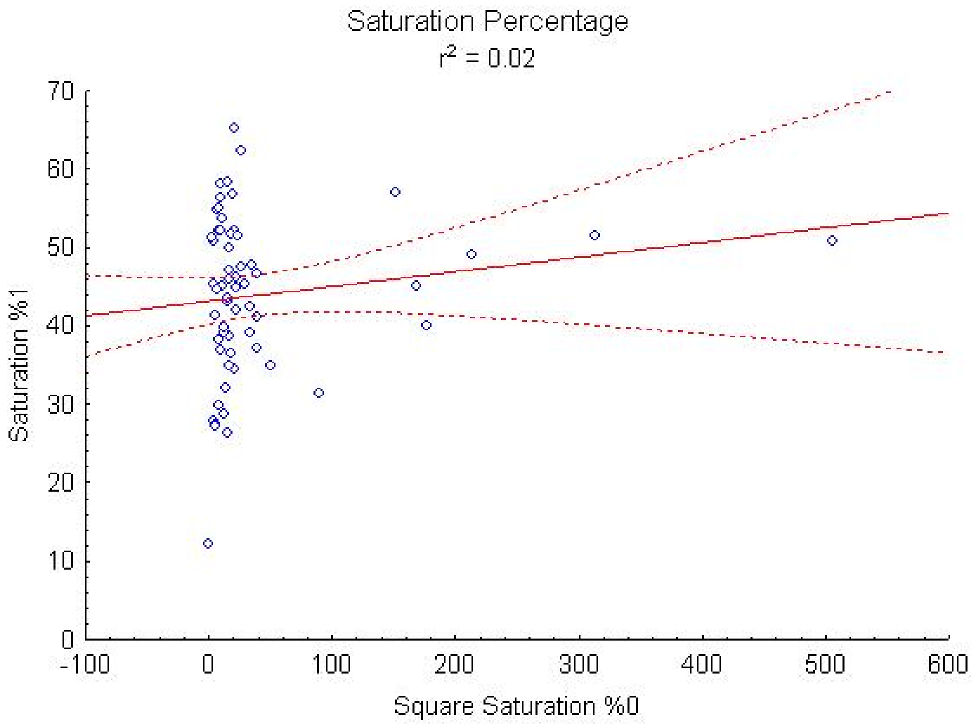

Figure 38. Saturation % before (Saturation% 0) and after (Saturation% 1) implementation of tamarisk removal treatments. The square of pre-treatment values was used to homogenize variance. N = 15 blocks.

The previous MANCOVA and ANCOVAs focused on soil chemistry. Here we focus next on cover variables. A multivariate (MANCOVA) tamarisk removal treatment effect was detected on post-treatment trees, shrubs, herbaceous cover, woody debris, soil, and litter cover values ($p < 0.001$, Table 15). Pre-treatment vegetation and cover variables had no effects on post-treatment values ($p > 0.42$, Table 15). We examined univariate results (ANCOVA) to identify the variables that responded to treatment effects.

Table 15. MANCOVA of treatment effects on post-treatment vegetation and cover variables. Pre-treatment vegetation and cover variables were used as covariates. Tree and shrub pre-treatment cover values were square-root (Sqrt) transformed.

	Wilk's λ	F	DF Effect	DF Error	p
Block	0.083	1.58	70	161.2	
Treatment	0.210	4.65	15	91.5	**<0.001**
Herbaceous Cover	0.943	0.40	5	33.0	0.844
Sqrt(Trees)	0.866	1.02	5	33.0	0.421
Woody Debris	0.969	0.21	5	33.0	0.954
Soil & Litter	0.959	0.28	5	33.0	0.918
Sqrt(Shrub)	0.915	0.61	5	33.0	0.693

Herbaceous cover was not explained by tamarisk removal treatments (p = 0.7; Table 16, Figure 39, Figure 40); however, pre-treatment values of herbaceous cover had a strong effects on post-treatment values (p < 0.001, Table 16). Pre-treatment averages of herbaceous cover were of comparable size between 4 and 6% with large 95% CIs (Figure 39). Post-treatment cover averages were all greater (>8%) than pre-treatment values with lowest values in the *Removal* + *Chipping* (RC) and *Removal* + *Seeding* (RS) treatments (Figure 40).

The significant regression between pre- and post-treatment herbaceous cover may be an aberration driven by a few extreme values at higher pre-treatment cover values (Figure 41). Moreover, data points were very scattered around the average at lower pre-treatment values.

Table 16. ANCOVA of treatment and pre-treatment effects for herbaceous cover.

Effect	SS	DF	MS	F	p
Block	5044.17	14	360.30		
Treatment	253.56	3	84.52	0.47	0.701
Herbaceous Cover	3577.36	1	3577.36	20.10	**<0.000**
Error	7296.81	41	177.97		

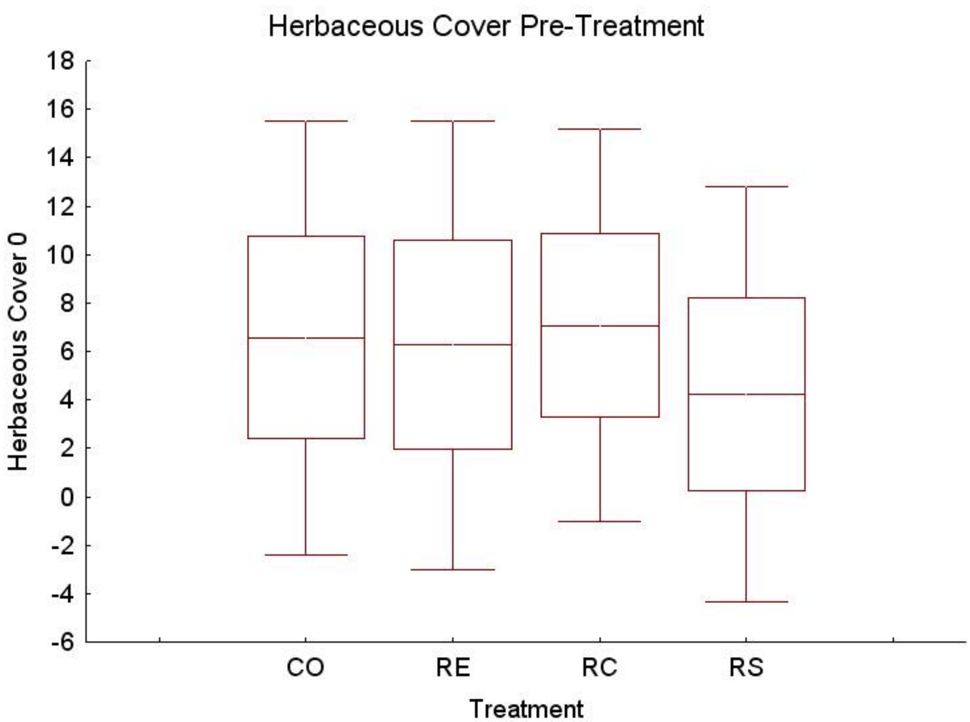

Figure 39. Herbaceous cover prior to application of tamarisk removal treatments. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

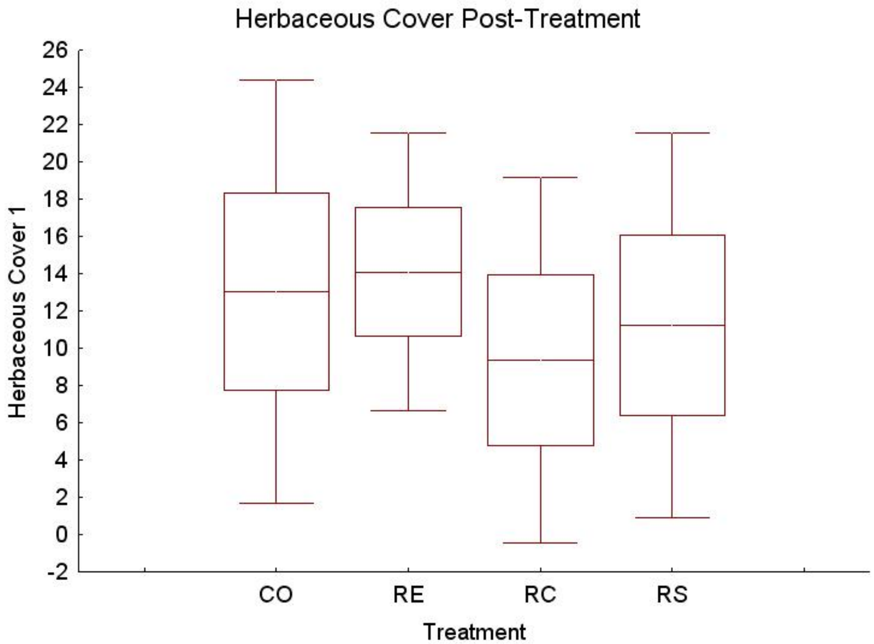

Figure 40. Effect of tamarisk removal treatments on herbaceous cover. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

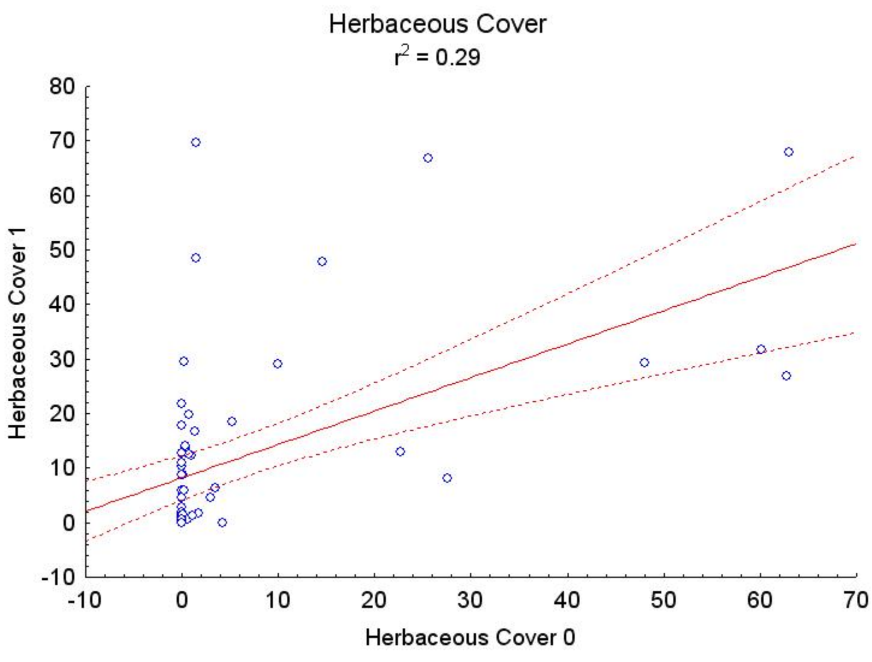

Figure 41. Herbaceous cover before (Herbaceous Cover 0) and after (Herbaceous Cover 1) implementation of tamarisk removal treatments. N = 15 blocks.

Tamarisk removal treatments had no significant effect on shrub cover (p = 0.14; Table 17, Figure 42, Figure 43). Post-treatment averages were similar (Figure 42). The square-root of pre-treatment shrub cover significantly explained the variation in post-treatment shrub cover (p < 0.001; Table 17), although this was not apparent. Pre-treatment data transformations failed to homogenize variances among treatment; however we did choose the square-root as the best transformation (r^2 = 0.49, Figure 44). As a result, the 95% CI for the pre-treatment control (CO) average was >2× that of the narrowest CI for traditional *Removal* (RE). The control average also had the highest average. The unequal variances among pre-treatment data might explain the high r^2 of 0.49 by causing extreme and high values of pre-treatment shrub cover to push the regression towards high significance (Figure 44).

Table 17. ANCOVA of treatment and pre-treatment effects for shrub cover. Pre-treatment values were square-root transformed to homogenize variances.

Effect	SS	DF	MS	F	P
Block	614.75	14	43.91		
Treatment	160.23	3	53.41	1.94	0.139
Sqrt(Shrub)	1361.64	1	1361.64	49.39	**<0.001**
Error	1130.33	41	27.57		

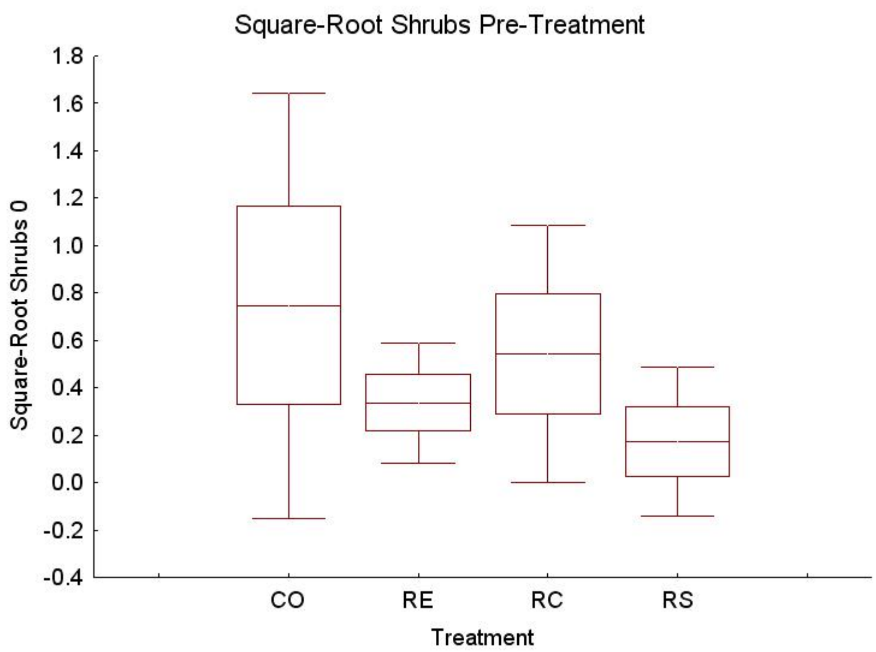

Figure 42. Shrub cover prior to application of tamarisk removal treatments. Values were square-root transformed to homogenize variances. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

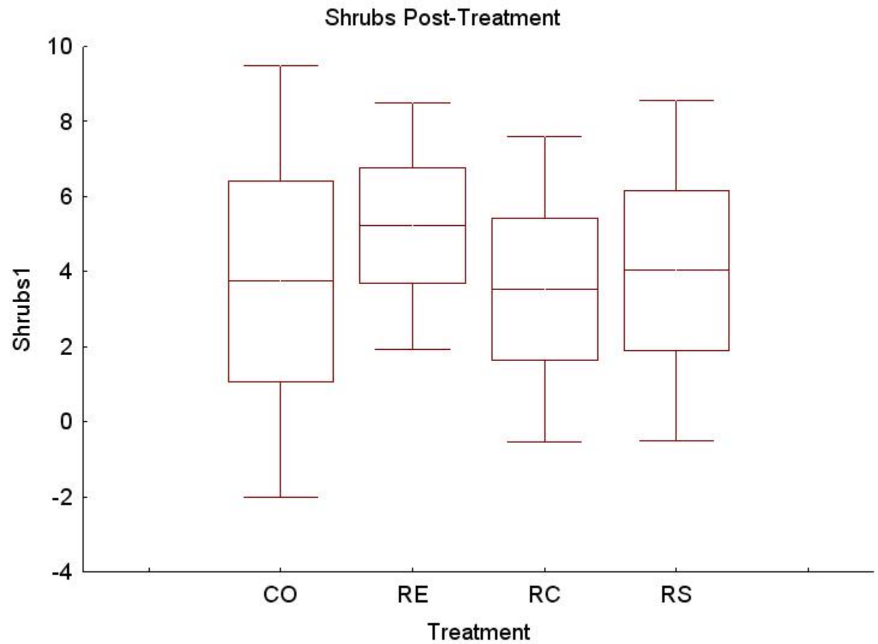

Figure 43. Effect of tamarisk removal treatments on shrub cover. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

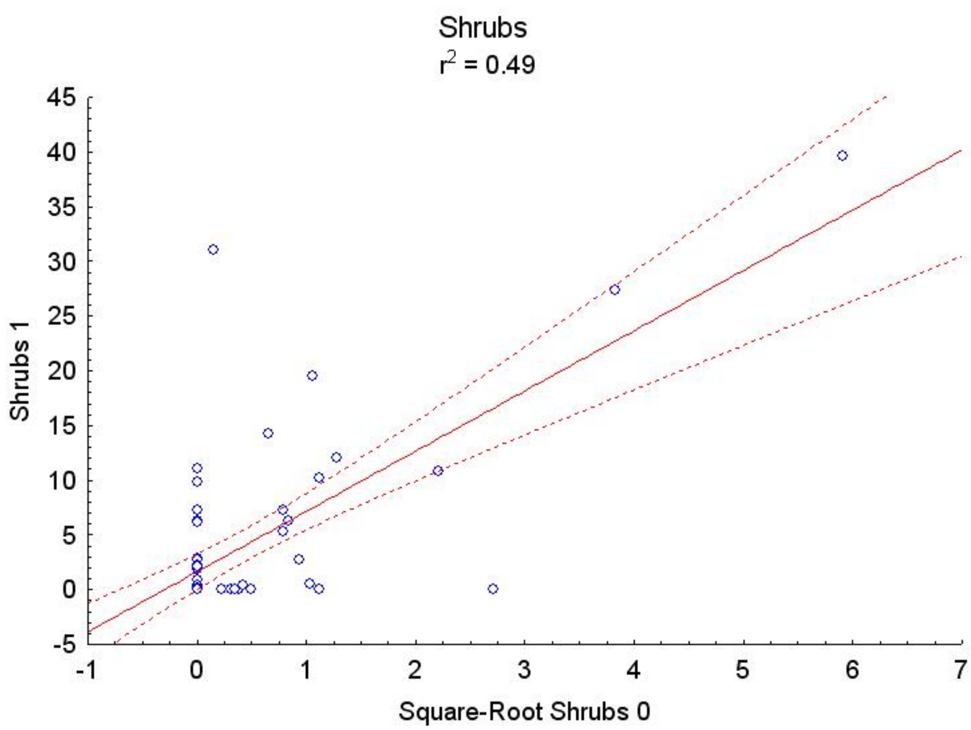

Figure 44. Shrub cover before (Square-Root Shrubs 0) and after (Shrubs 1) implementation of tamarisk removal treatments. N = 15 blocks.

Tamarisk removal treatments had no significant effect on native tree cover (p = 0.16; Table 18, Figure 45, Figure 46), whereas the pre-treatment native tree cover effect was significant (p = 0.002, Table 18). Because native trees were not targeted for removal, we did not expect *a priori* differences. However, before and after cover values differed; indeed, differences emerged post-treatment, perhaps as visibility increased without tamarisk cover in the traditional *Removal* (RE) and *Removal + Chipping* (RC) treatments.

The regression between pre- and post-treatment values was moderately strong, but dependent on a single value at highest tree cover pre- and post-treatment (r^2 = 0.26, Figure 47). Furthermore, many tree cover values post-treatment were zero. Again, the strength of the regression might be an artifact of this pair of high cover values.

Table 18. ANCOVA of treatment and pre-treatment effects for tree cover. Pre-treatment and post-treatment values were square-root transformed to homogenize variances.

Effect	SS	DF	MS	F	p
Block	5.80	14	0.41		
Treatment	1.47	3	0.49	1.83	0.157
Sqrt(Trees)	2.86	1	2.86	10.67	**0.002**
Error	10.99	41	0.27		

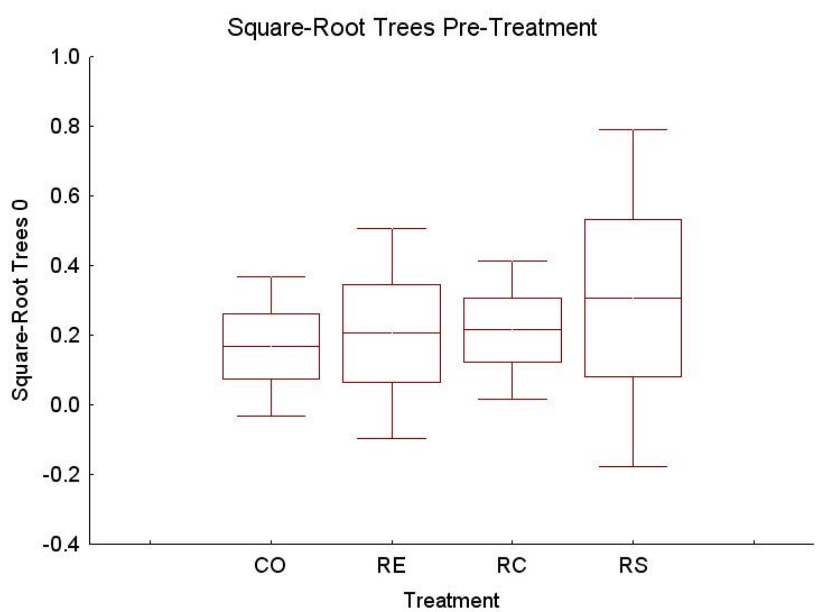

Figure 45. Tree cover prior to application of tamarisk removal treatments. Values were square-root transformed to homogenize variances. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

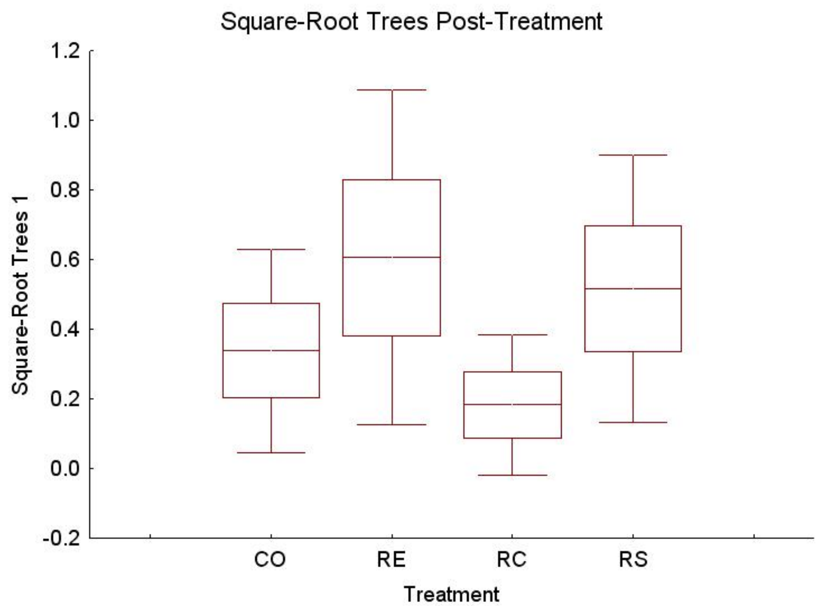

Figure 46. Effect of tamarisk removal treatments on tree cover. Values were square-root transformed to homogenize variances. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

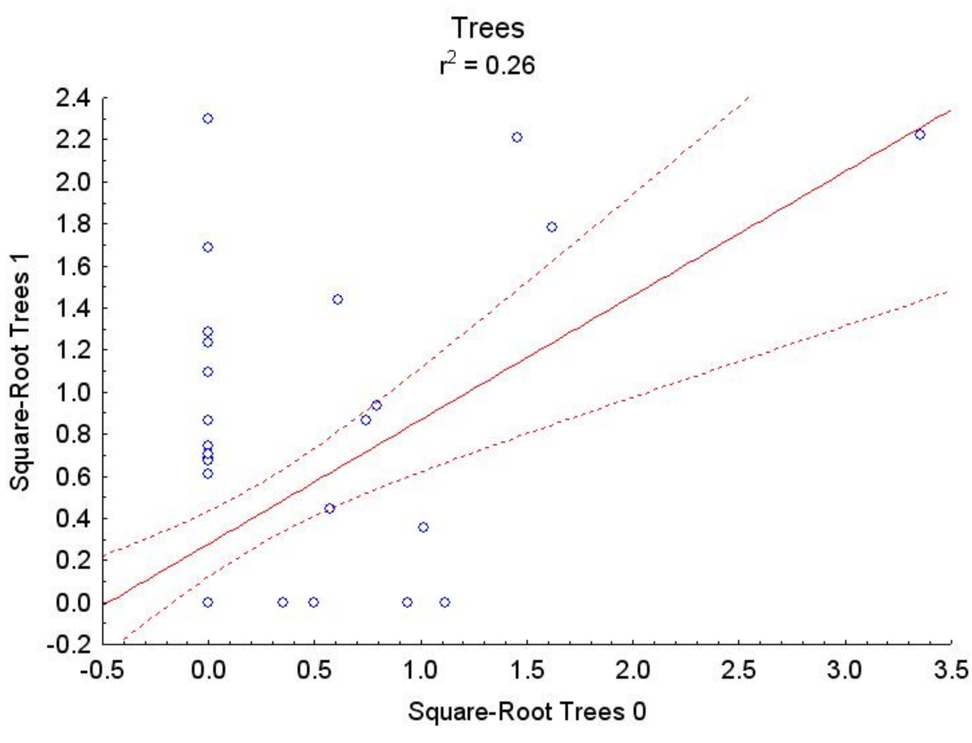

Figure 47. Tree cover before (Square-Root Trees 0) and after (Square-Root Trees 1) implementation of tamarisk removal treatments. N = 15 blocks.

Woody debris cover was significantly reduced in all tamarisk removal treatments except the control ($p < 0.001$, Table 19). Pre-treatment averages ranged from 26 to 27%. Reduction was at least fourfold on an untransformed scale (Figure 48, Figure 49). Differences among non-control plots were minor. Pre-treatment woody debris cover had a significant effect on post-treatment values ($p = 0.02$, Table 19), although the effect was moderate ($r^2 = 0.03$, Figure 50). The slope of the pre- to post-treatment regression was positive and shallow with a large number of data points outside the 95% CI.

Table 19. ANCOVA of treatment and pre-treatment effects for woody debris cover. Post-treatment values were square-root transformed to homogenize variances.

Effect	SS	DF	MS	F	p
Block	48.38	14	3.45		
Treatment	120.39	3	40.13	36.29	**<0.001**
Woody Debris0	6.47	1	6.47	5.85	**0.020**
Error	45.33	41	1.11		

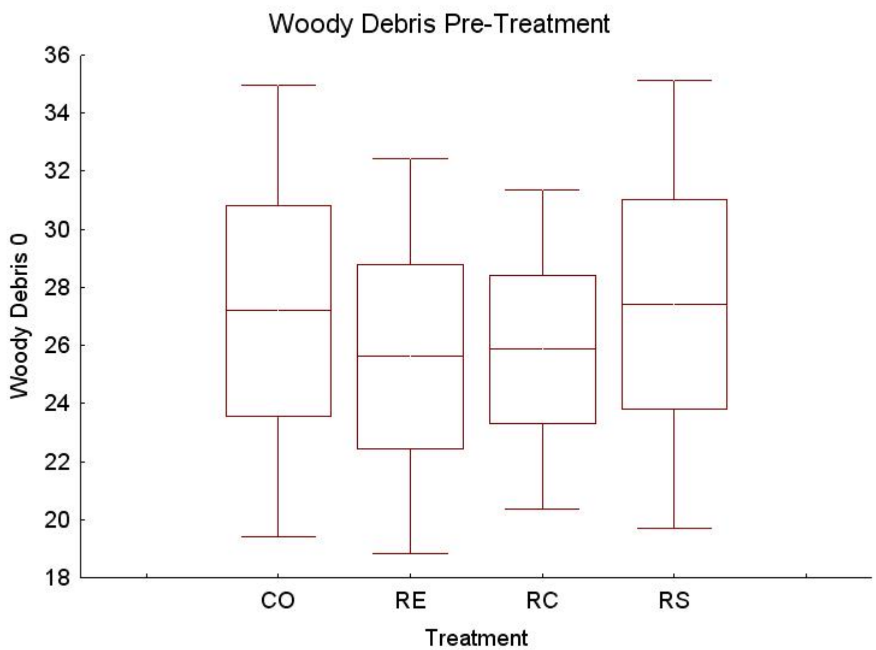

Figure 48. Woody debris cover prior to application of tamarisk removal treatments. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

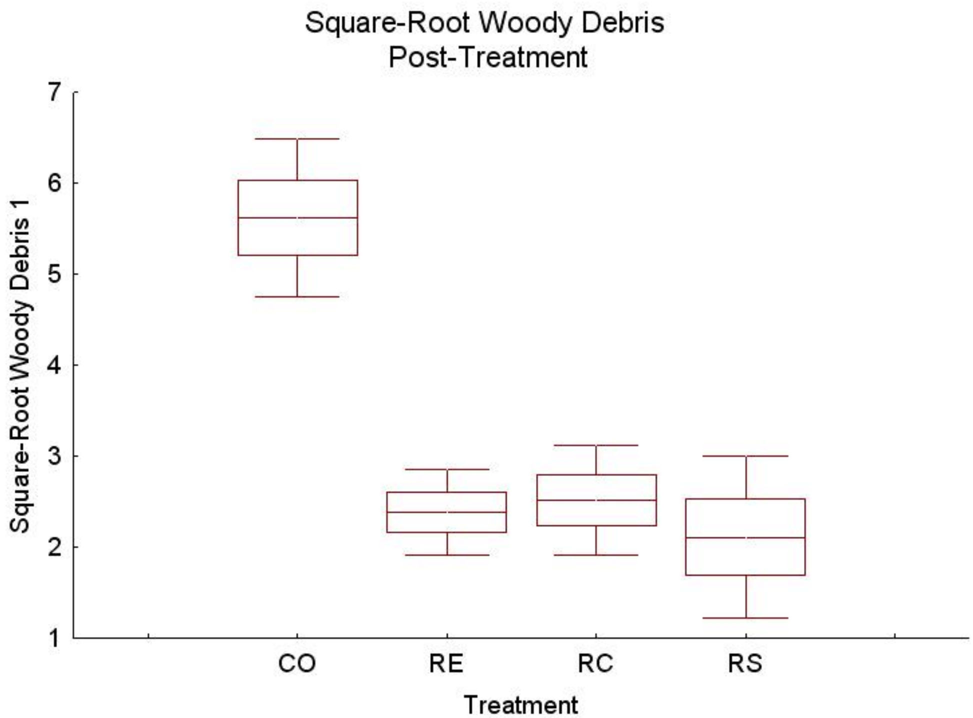

Figure 49. Effect of tamarisk removal treatments on woody debris cover. Values were square-root transformed to homogenize variances. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

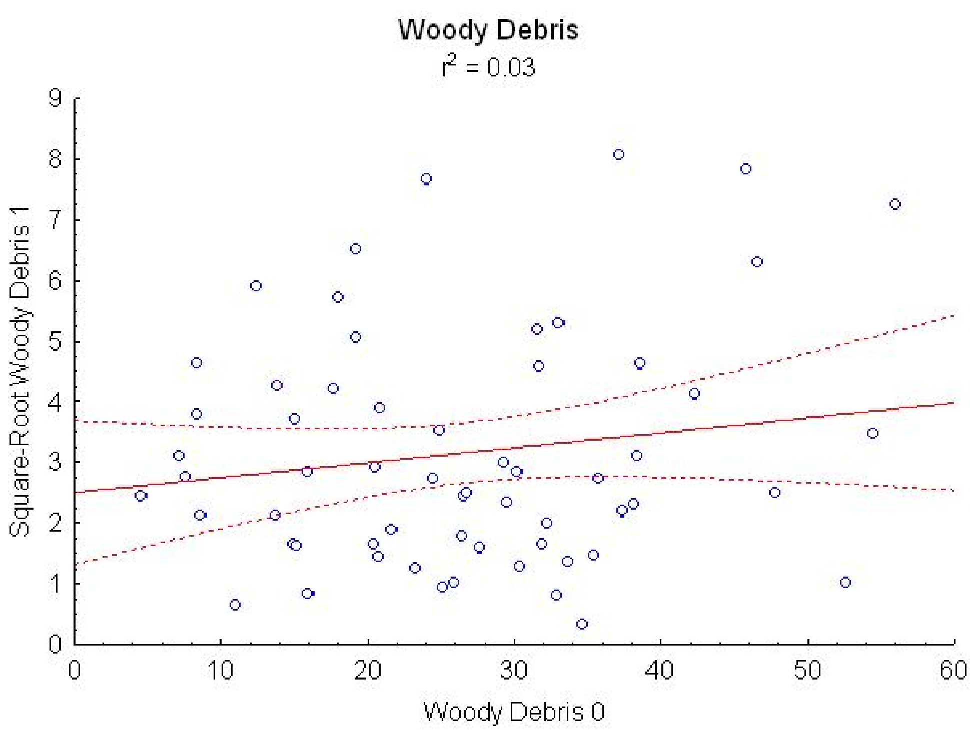

Figure 50. Woody debris cover before (Woody debris 0) and after (Square-Root Woody Debris 1) implementation of tamarisk removal treatments. N = 15 blocks.

Both tamarisk removal treatments ($P < 0.001$) and pre-treatment soil and litter cover ($p = 0.005$) had significant effects on post-treatment soil and litter cover (Table 20). Although pre-treatment 95% CIs overlapped greatly, the control plots (CO) showed the lowest soil and litter cover at about 63%, whereas other treatments were similar in magnitude between 66-67% (Figure 51). The highest soil and litter post-treatment cover values were achieved in the *Removal + Chipping* (RC) and *Removal + Seeding* (RS) treatments at >79%, followed by slightly lower cover values in the traditional *Removal* treatment (RE) (Figure 52). Lowest soil and litter cover were found in the control plots (CO; about 48%) as during the pre-treatment phase.

The slope of the regression between pre- and post-treatment values was positive ($r^2 = 0.11$, Figure 53) thus suggesting that past results somewhat explained current results. The low r^2 explained by the presence of many data points outside the 95% CI, however, indicated that treatments might have disrupted the pre-treatment effect.

Table 20. ANCOVA of treatment and pre-treatment effects for soil and litter cover.

Effect	SS	DF	MS	F	p
Block	7636.86	14	545.49		
Treatment	7777.11	3	2592.37	7.88	**<0.001**
Soil & Litter	2847.32	1	2847.32	8.66	**0.005**
Error	13479.62	41	328.771		

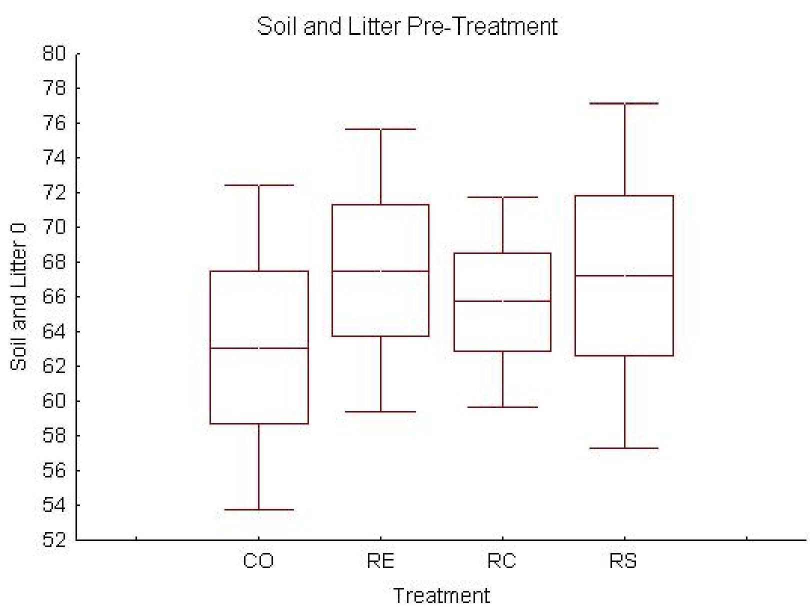

Figure 51. Soil and litter cover prior to application of tamarisk removal treatments. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS =

removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

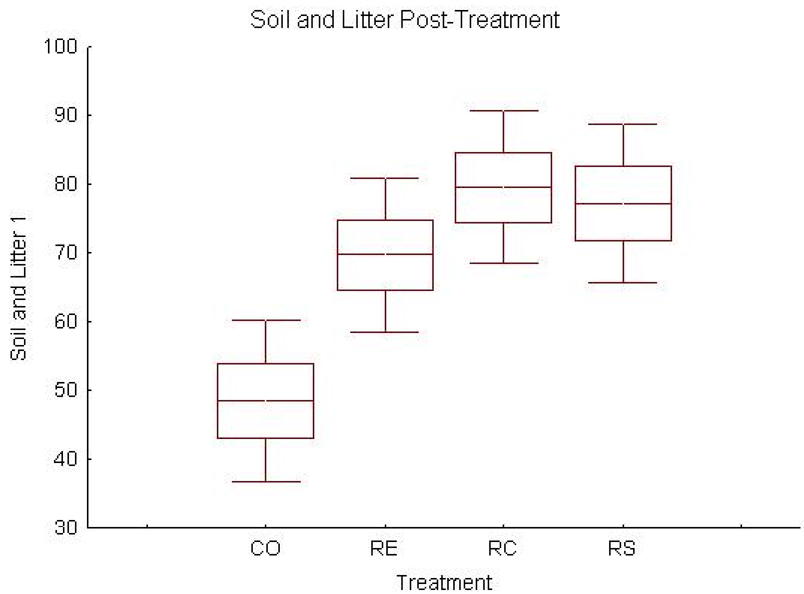

Figure 52. Effect of tamarisk removal treatments on soil and litter cover. Legend: CO = no-removal control; RE = *Removal*; RC = Removal + Chipping; and RS = removal + Seeding. Line represents the mean, edges of box are ±1 STE, and the error bars are the 95% confidence intervals. N = 15 blocks.

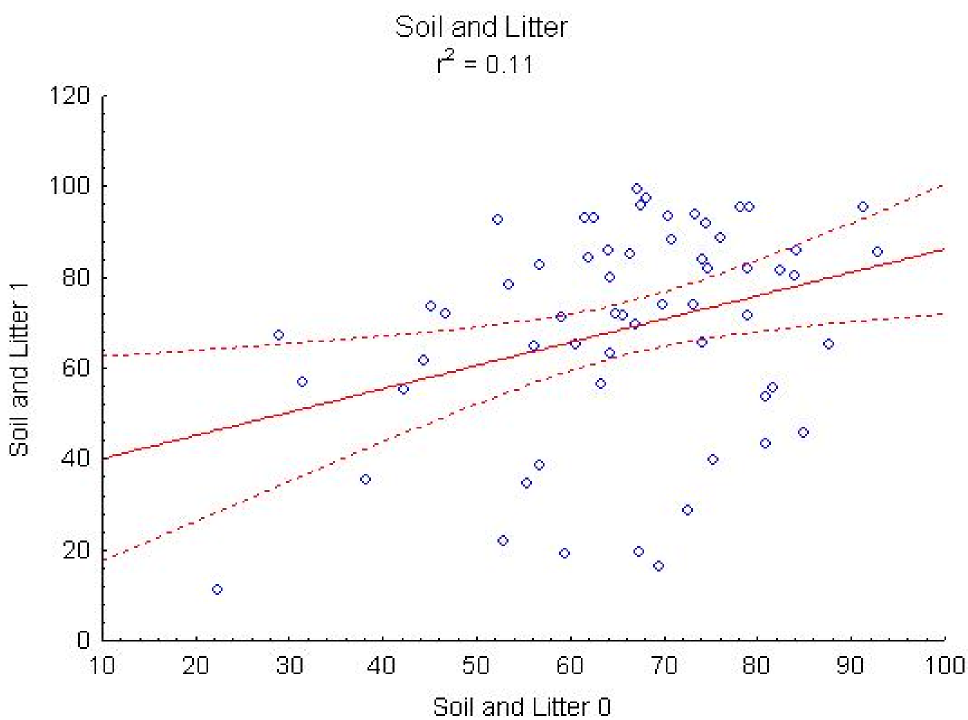

Figure 53. Soil and litter cover before (Soil and litter 0) and after (Soil and litter 1) implementation of tamarisk removal treatments. N = 15 blocks.

REMOTE SENSING

Analyses of imagery totaled approximately 160 hours. A formal accuracy assessment was not performed as part of this study due to the substantial increase in costs associated with this task. However, three separate ground-truthing field visits were conducted in order to refine the final map. In addition, the results of the field visits gave the analyst a better estimate of how accurate the final product was. Since a formal accuracy assessment was not produced, the estimates provide the user of the map an idea of how well each of the weeds was able to be extracted from the imagery.

The three noxious weed species, tall whitetop, tamarisk, and Russian knapweed, were detected in the UMR's 500-year floodplain using 6-inch spatial resolution aerial imagery (Figure 54). Each of the three species was detected. Tamarisk was detected in the greatest amounts with 202 acres (82 ha), 8 acres (3 ha) of Russian knapweed were detected, and 0.03 acres (.01 ha) of tall whitetop were detected.

Greatest areas of infestation for tamarisk were on and around the SNWA's Warm Spring Ranch, the BLM's Perkins Ranch and White Narrows area, and downstream of tribal land. Russian knapweed was mostly found about 2/3 mi upstream of the Highway 168 Bridge, on tribal land, and two areas on the SNWA's Warm Spring Ranch. Tall whitetop was only detected on the SNWA parcel south of Warm Spring Road (north/east side of the river) and about ½ mile upstream of the Highway 168 Bridge.

The tamarisk was estimated to be accurate to 75-85%. Tamarisk presented the most consistent and distinguishable spectral characteristics. An aggressive approach to identifying and mapping tamarisk was employed that attempted to ensure capture of most of the tamarisk present in the study area. This aggressive approach could have resulted in increased errors of commission. The most likely confusion for tamarisk in the study area was with willow.

The Russian knapweed was estimated to be within 65-80% accuracy. The greatest challenge associated with identification and mapping of knapweed were due to two different spectral signatures within the same imagery. In addition, density of knapweed had a strong influence over whether knapweed would be extracted. Very dense areas generally resulted in consistent positive detection, while scattered plants, particularly surrounded with bare soil were not consistently detected. Due to these factors, errors of commission were unlikely, but errors of omission may have increased.

The tall whitetop was estimated to be 60-70% accurate. Tall whitetop presented many challenges for identification and mapping using remotely sensed imagery in the study area. Similarly to knapweed, it had a varied spectral signature and detection varied with density of weed infestation. Due to these factors, errors of omission of this species were more likely than errors of commission.

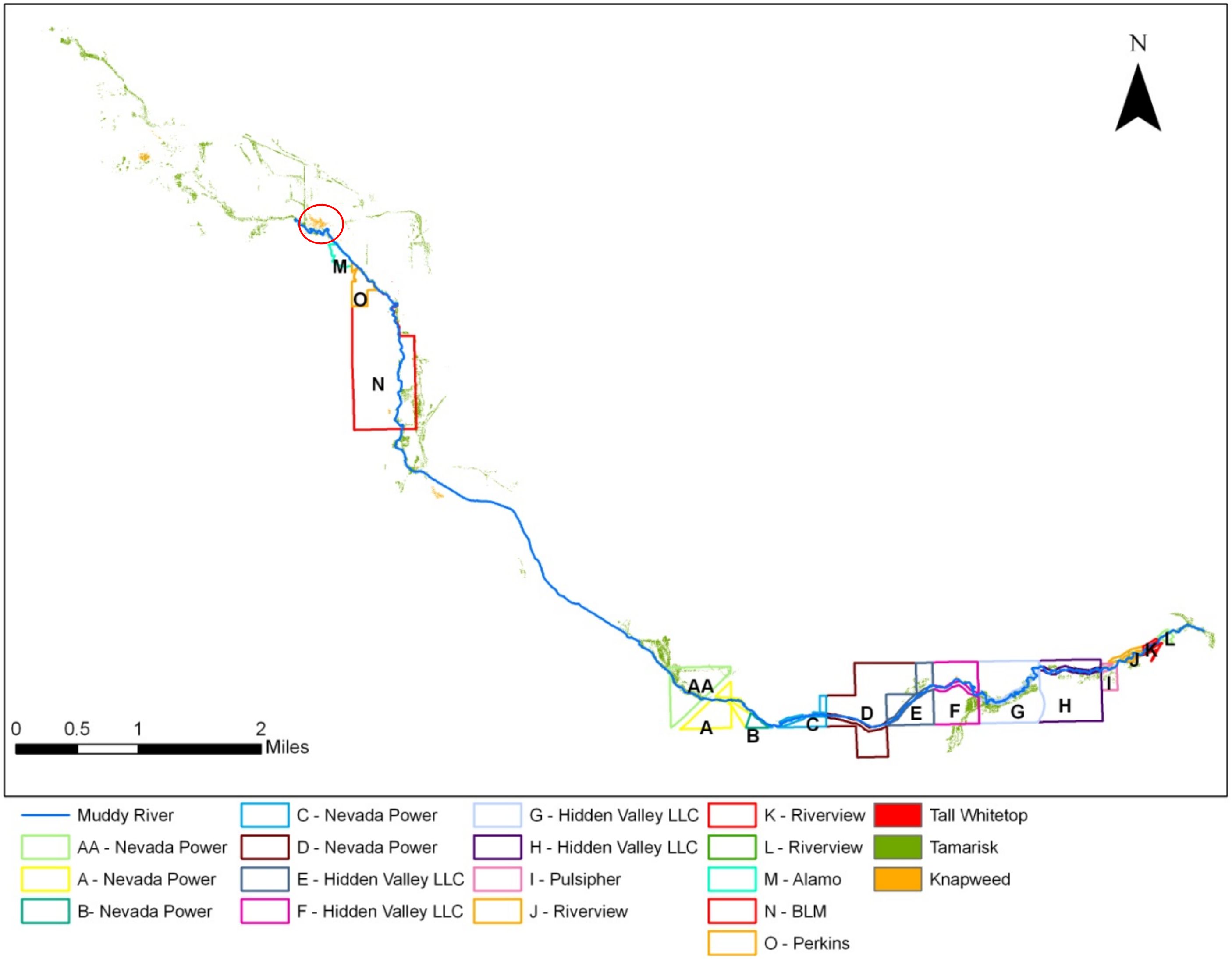

Figure 54. Tamarisk, tall whitetop, and Russian knapweed mapped in the Muddy River floodplain. Oval indicates tall whitetop area.

DISCUSSION AND MANAGEMENT IMPLICATIONS

RETROSPECTIVE STUDY

The retrospective study counter-intuitively revealed that soil salinity steadily increased for 10 years after removal of tamarisk. We had assumed that removal of the tamarisk canopy would allow successive storms to wash away accumulated salts, especially boron, in the soil and allow succession to proceed and native trees to grow. In turn, breeding birds would find more suitable habitat. Exactly the opposite occurred; indeed, older treated areas have more inland salt grass and forbs, lower bird counts, and more saline soils. Because these plot's canopies remained open, the early successional quailbush also dominated or persisted for at least a decade. In addition to breeding birds, fish counts did not seem to consistently respond to restoration. It appears that a coupled effect is causing salinity levels to increase near the surface. Previously tamarisk trees were pulling water down to the root level and without them capillary action is allowing the water to be pulled toward the surface where it evaporates leaving the salts behind. Moreover, soils in treated areas receive more sun exposure than their untreated, shaded counterparts; as a result increased solar radiation further evaporates soil moisture while leaving salts to concentrate at the surface. The limited 10+ cm (4 inch) precipitation of this area appears too little for flushing away salts. Except for the area downstream of California Wash that floods periodically, the Muddy River is very unlikely to flood from its deeply incised channel and wash away salts (Provencher and Andress 2004). Bhattacharjee et al. (2008) reviewed soil characteristics that contributed to success of cottonwood seedlings on the Rio Grande after removal of non-natives such as tamarisk and found that the most important variable across different soil types was the rate of moisture decline. Unlike the floodplain of the Rio Grande, the incised banks of the Muddy River are not appropriate for cottonwood and willow establishment because they are too high, dry, and saline. It is only at the very narrow edge of the water that cottonwood and willow can establish; indeed, recent willow wattles plantings at the water's edge by MRRIEAC have been successful.

More importantly, these results show that removal of tamarisk is not sufficient to achieve restoration characterized by late-succession riparian species that breeding birds may use. We expected that all Clark County bird species of special concern would prefer denser vegetation composed of native riparian tree and shrub species (i.e., ash, mesquite, arborescent willow, and shrubby willows). In the case of Phainopepla, mesquite woodlands either dense or open would be preferred. Of Clark County's priority bird species we noted Arizona Bell's Vireo, Blue grosbeak, and Phainopepla during our breeding bird surveys. Only Arizona Bell's Vireo was more consistently observed in areas of dense tamarisk. Both the Phainopepla and the blue grosbeak were more evenly observed in areas of varying levels of restoration and areas of dense tamarisk. No other similar bird surveys results were found for the Muddy River. Van Riper et al. (2008) observed that breeding bird densities were highest along the lower Colorado River where densities of tamarisk with vertical structure ranged from 40-60% and the remainder in native vegetation, which supports our observations of breeding birds on the UMR. Van Riper et al. (2008) also noted that birds continued to respond positively with increasing amounts of native vegetation up to about 60%, but did not increase in numbers beyond this point. No measurements of age of stands or how the natives or non-natives were dispersed on the landscape were addressed within the scope of the van Riper et al. (2008) study. Additionally, Fleishman et al. (2003) conducted an assessment of the effect of non-native plant species on breeding birds and noted that species abundance, richness or dominance of non-native plants were not of significance so long as the community retained structural diversity. These studies lend further support to our hypotheses and focus on finding factors that may prevent native riparian woody species (late-successional species) from recruiting.

The hypothesized relationship between the removal of tamarisk and fish abundance was different than the one with breeding bird abundance. Greater solar insolation in the water column would stimulate primary and secondary productivity, and therefore benefit fish growth and reproduction. The opposite was hypothesized for breeding birds and reduced tamarisk cover. The Virgin River chub did not appear to respond to varying vegetation restoration levels. In fact, the chub were captured on nearly all river reaches in the study. We believe that a more powerful sampling method is needed to correlate vegetation cover to fish abundance. Increased fish sampling, or a method that could more accurately reflect fish using a river reach would need to occur in order to have adequate numbers for a true statistical comparison of fish use in reaches where years since removal of tamarisk vary.

EXPERIMENTAL STUDY

The objective of the experimental study was to examine the short-term effectiveness results of tamarisk removal treatments. At most one year after implementation, it became clear that no soil chemical variables and no vegetation cover showed any response. For soil chemical variables, pre-treatment values explained well post-treatment patterns, therefore effects of wood chip effects on soil salinity, weed response, and recruitment of seeded materials could not be assessed yet. We expect, however, that quailbush, a highly aggressive early succession species, may be more successful to recruit in the chipping plots based on observations of its recruitment success through rip-rap and heavy gravel around a recent weir on the BLM-Perkins property.

Variables tracking physical changes caused by removal, namely woody debris cover and soil and litter cover, strongly changed after treatment implementation. These two variables responded in opposite fashion; indeed, removal of tamarisk and its associated heavy woody debris exposed mineral soil and created fine litter. Moreover, native revegetation was accomplished by spreading bales of native hay on the plots, thus increasing litter.

The ecological differences among the three active removal treatments could be important, albeit not yet expressed, because they can differently affect the beginning of plant succession. However, in all treatments we expect the same need for post-treatment touchups to eliminate resprouting of tamarisk over a five year period. As an example, MRRIEAC continues to periodically spot-spray tamarisk saplings emerging in plots treated in 1996. At the time of post-treatment sampling, the success rate for tamarisk and Russian knapweed treatment was not measurable, and will need to be reassessed in future sampling. The traditional *Removal* plots should probably most resemble the pathway followed by retrospective study plots. Therefore, we would expect quailbush dominance. The *Removal + Chipping* treatment could conceivably limit future establishment of naturally dispersed seeds by simply hiding mineral soil, but may favor seeds that established due to wood chips acting as mulch or providing shade. No effects of chipping on the soil salinity of plots or whether chipping may actually serve as mulch for invasive weeds were assessable at one-year post-treatment. The *Removal + Seeding* treatment was meant to jumpstart succession with willow cuttings and herbaceous seeds and in theory should yield desirable results.

REMOTE SENSING OF WEEDS

Of great concern to managers are known and previously undetected areas of infestations where noxious weed control needs to be continued. When remote sensing was proposed as part of this study, we were especially interested in detecting weeds on private lands where we did not have access and from where sources of noxious seeds could escape. Remote sensing results indicate areas where non-native weed eradications could make the most impact. Estimated accuracy of the classified imagery indicates the analyses were moderately successful. Tall whitetop and knapweed were detected in relatively small areas thus it may be reasonable to dedicate resources to eradicate those areas immediately before they spread. These two species have the ability to make soil chemistry inhospitable to other species for several years (Stevens 1986, Renz and Blank 2004); therefore their removal is time sensitive. Moreover, eradication of knapweed and tall whitetop is difficult and requires follow up application of herbicides.

As stated before the estimated accuracy of the remote sensing analyses indicates it was moderately successful at detecting tamarisk, Russian knapweed and tall whitetop. The analyses fulfilled the objective of detecting patches of the three non-natives throughout the floodplain regardless of property boundaries, which would not easily be achieved by on-the-ground field crews. As a point of comparison, consider that potentially a field technician could sample 700 random locations or approximately 1 point location per 5 acres. This process would take at least two to three weeks to attempt access for these locations, and an additional month or more to compile the results into a comparable map of invasive weeds. This approach might result in savings of 80%, however, you wouldn't have any confidence in areas that weren't sampled, and it is likely that this process would require more time than our analysis required.

A limitation of our analysis was that a formal accuracy assessment was not conducted. In addition, success of detection of Russian knapweed and tall whitetop that were difficult to see from a distance were not estimated to be as successful in identifying distinct spectral signatures to be extracted from the imagery.

RECOMMENDATIONS

Retrospective study

Different stakeholders have different visions for the UMR floodplain. If the management objective is to increase the quality of habitat suitable for riparian breeding birds and native fish species, then it appears that there is a threshold of native riparian vegetation to tamarisk that is optimal to emulate (van Riper et al. 2008). Using this narrow view, one could argue for maintaining tamarisk to an acceptable level to satisfy the structural and thermal needs of birds. Because current levels of tamarisk are already above that level suggested by van Riper et al. (2008), a lower intensity of tamarisk removal with active restoration of native species may be achievable. However, our bird count results show that Clark County's priority species used both treated and untreated areas; therefore there is no obvious reason to maintain tamarisk. A different objective for the UMR would be to restore the floodplain and keep removing all non-native species while greater regulatory constraints are not implemented (for example, regulations caused by the presence of breeding southwestern willow flycatcher). We recommend this approach. An added benefit would be to reduce hazardous fuel levels of tamarisk in proximity to many human structures (Everitt 1980, Di Tomaso 1998).

Greater removal of tamarisk, however, may not bring greater amounts of bird usage for at least a decade because the potential of the floodplain soils cannot support recruitment of native trees except at the very edge of the river. If managers desire an accelerated colonization of woody species with high levels of vertical structure and thermally buffered habitat to support riparian bird species and other species, then elevating the river and the surrounding water table will be key to the success of native tree and tall shrub revegetation. Allowing the river to periodically flood and the water table adjacent to the river channel to wet the floodplain could reduce soil salinity by allowing salts to be flushed away. There are no other hydrological options to accomplish this process with 10+ cm of precipitation. Accumulation of salts under the canopy is not unique to tamarisk; Merritt and Cooper (2000) found that soils under old stands of cottonwood and tamarisk had comparable salt levels.

Provencher et al. (2005) recommended reconnecting the river to its floodplain for the third and more expensive option for restoring the UMR. There are only three areas with wide enough floodplains and few human structures in the UMR where this approach could be implemented: Warm Spring Ranch, between White Narrows and Warm Springs Road, and from the old Hidden Valley Dairy to the Highway 168 Bridge in Moapa. All three areas have recovering or high quality remnant communities; however, size of the floodplain and a low number of human structures are more critical features as revegetation would follow restoration activities. In these segments of the river, banks are highly entrenched and restoration would require significant resources described in Provencher et al. (2005). Private ownership in the downstream old Hidden Valley Dairy to the Highway 168 Bridge would likely prevent reconnecting the river to the floodplain. Realizing that a detailed restoration study would be required to determine restoration options and feasibility (Provencher et al. 2005), two approaches can be used to reconnect the river to the floodplain: (i) elevate the river by stepping it down using weirs in the current channel (as done with one weir on the BLM-Perkins Ranch) or (ii) reconstruct parts of the river channel by excavating new meanders (thus increasing sinuosity) and plug the old channel to create backwater wetlands. The first option is cheaper and simpler than the second one, but it is not cheap. Introducing a series of weirs has the advantage of providing barriers to crayfish and upstream tilapia invasion should reach-specific eradication of these organisms be undertaken. The second option requires heavier excavation equipment working in fine sediment that may be easily erodible and more planning, but it allows a greater opportunity for the river to overflow its bank on a greater proportion of the floodplain.

In the absence of reconnecting the river to its floodplain, our retrospective results would indicate that the best time to seed restored plots with native species is immediately after removal of tamarisk when soils are least saline. In the past, however, MRREIAC's seeding of plots immediately after removal rarely succeeded despite expert advice on native seed composition and use of dry water polymers. At the time in 2004, MRREIAC hypothesized that high salt content caused by tamarisk was the reason for seed failure; indeed, the hypothesis was the impetus for this project. MRREIAC tried planting cottonwoods and mesquite on Nevada Power D and grass seed on Hidden Valley E, however neither approaches were successful likely as a result of a lowered water table, patchy and limited rainfall, or lack of adequate water. More recently, planting willows as wattles at the river's edge, as done on the Riverview K property, was successful by taking advantage of water readily present. Mesquite equipped with slow-drip watering systems were more successful because it avoided seeding and incorporated a temporary watering system, however, watering columns need to be refilled periodically. Seeding with inland saltgrass and alkali sacaton (*Sporobolis airoides*) under a future mesquite canopy would also be considered desirable.

Experimental study

The post-treatment sampling period of the experimental was woefully too short. We highly recommend that all experimental plots be periodically resampled following a similar protocol as conducted in the experimental part of this study. Sampling could be completed in two to three weeks by two people; however, soil analyses would require delays and greater expense. If control plots become unavailable due to tamarisk removal, then all treated plots should still be resampled because we expect patchy responses from the vegetation, the loss of one degree of freedom (the control plot), and a need for all the replication possible to maintain statistical power. Sampling could probably be conducted every three to five years to allow for adequate vegetative growth. Based on our

Great Basin experience in fire surrogate studies, the response of herbaceous vegetation takes a minimum of 3-5 years to respond to treatments on soils receiving 2 to 3 times the annual precipitation reported in the lower Mojave Desert. Plants, especially on entrenched river banks, may take decades to establish and proceed through succession in arid environments. We also recommended that treated plots be revisited to spot-spray tamarisk suckers; however, minimal funding needs to be provided to maintain this effort.

Remote Sensing of Weeds

The new weed map generated by remote sensing conducted here should be distributed to UMR stakeholders. TNC is prepared to distribute it to MRREIAC, Bureau of Land Management, SNWA, U.S. Fish and Wildlife Service, Nevada Power, the Moapa River Indian Reservation, and the town of Moapa. We recommend that MRRIEAC should assume a leadership role to (i) approach private owners and public land managers for eradication of Russian knapweed and tall whitetop where we detected these species and (ii) resume or maintain on-going UMR tamarisk and Russian knapweed removal efforts (i.e., continue the effort that started the retrospective study). Tamarisk removal is still needed downstream of the confluence of the Muddy River and California Wash, between the Nevada Power plant and tribal land, throughout the BLM-Perkins Ranch, and across small locations of the Warm Spring Ranch and upstream of it. Without significant funding resources, MRRIEAC will not be able to complete this work. While MRRIEAC has been pursuing alternative sources of funding, Clark County should consider directly contracting with MRRIEAC for targeted weed control on the UMR. No other organization is as effective, accepted by local stakeholders, and efficient on the UMR.

ACKNOWLEDGEMENTS

The Nature Conservancy is grateful to the Clark County's Desert Conservation Program and Southern Nevada Public Land Management Act for funding and support for this project. We thank Bureau of Land Management field office, MRREIAC, Southern Nevada Water Authority, Nevada Department of Wildlife, Nevada Division of Forestry, and Nevada Power for their support and assistance. We thank Ann Shreiber, Liz Bickmore, Mauricia Baca, Carl Lundblad, Brian Hobbs, Mark Beckstrand, Bruce Lund, Jeanne Tinsman, Kevin DesRoberts, John Hiatt, Caroline Titus, Rita Schlageter, Angela Klapperich, and Chandra Copplin.

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Appendix A. Bird species detected during breeding bird surveys along the Muddy River in 2008 and 2009.

Scientific Name	Common Name	Breeding (Y/N)	Parcels Observed	Year Detected
Pipilo aberti	Abert's Towhee	Y	B,C,D,E,F,G,H,I,K,L	2008 & 2009
Fulica americana	American Coot	Y	C,D,E	2009
Falco sparverius	American Kestrel	Y	C,D,F	2008 & 2009
Turdus migratorius	American Robin	Y	F	2009
Myiarchus cinerascens	Ash-Throated Flycatcher	Y	G,H	2008
Hirundo rustica	Barn Swallow	Y	A	2008
Vireo bellii	Bells Vireo	Y	F,H,I,L	2009
Thyromanes bewikii	Bewicks Wren	Y	D,E,F,G,H,I,L,K,A,B	2008 & 2009
Sayornis nigricans	Black Phoebe	Y	A,B,C,D,E,G,H,I,K,L	2008 & 2009
Archilochus alexandri	Black-chinned Hummingbird		G,H	2008
Polioptila melanura	Black-tailed Gnatcatcher	Y	D,E,F,G,H,I,L,K	2008 & 2009
Amphispiza bilineata	Black-throated Sparrow	Y	G	2009
Passerina caerulea	Blue Grosbeak	Y	C,D,E,F,H,K,L	2008 & 2009
Anas discors	Blue-winged teal		K	2008
Spizella breweri	Brewer's Sparrow	Y	F	2009
Molothrus ater	Brownheaded Cowbird	Y	D,F,G,H,I,K,L	2008 & 2009
Icterus bullocki	Bulloch's Oriole	Y	E,H,I,L,K	2008 & 2009
Vireo cassinii	Cassin's Vireo	Y	G	2009
Bombycilla cedrorum	Cedar Waxwing		G	2008
Petrochelidon pyrrohonota	Cliff swallow	Y	C,D,E,F,H,I,K,L	2008 & 2009
Corvus corax	Common Raven	Y	D,E	2008 & 2009
Geothlypis trichas	Common Yellothroat	Y	D,F,G,H,I,L,K	2008 & 2009
Toxostoma crissale	Crissal Thrasher	Y	C,D,E,F,G,H,I,K,L	2008 & 2009
Streptopelia decaocto	Eurasian Collared Dove	Y	E,G,H,I,L,K	2008 & 2009
Tyrannidae	Flycatcher Spp	Y	D	2008
Callipepla gambelii	Gambel's Quail	Y	C,D,E,F,G,H,I,K,L	2008 & 2009

Ardea herodias	Great Blue Heron	Y	D	2008 & 2009
Geococcyx californianus	Great Roadrunner	Y	C,D,E,G,H,I,L	2008 & 2009
Quiscalus mexicanus	Great-Tailed Grackel	Y	C,D,A,B	2008 & 2009
Carpodacus mexicanus	House Finch	Y	A,B,D,G,H,I,L	2008 & 2009
Passer domesticus	House Sparrow	Y	H,I,K,L	2008 & 2009
Passerina cyanea	Indigo Bunting	Y	F,G,H,I,L,K	2008 & 2009
Picoides scalaris	Ladder-backed Woodpecker	Y	G,H,I,L	2008 & 2009
Passerina amoena	Lazuli Bunting	Y	E,F,K,L	2008 & 2009
Carduelis psaltria	Lesser Goldfinch	Y	H,I,L,G	2008 & 2009
Chordeiles acutipennis	Lesser Nighthawk	Y	G	2008 & 2009
Vermivora luciae	Lucy's Warbler	Y	E,F,G,H,I,L,K	2008 & 2009
Anas platyrhynchos	Mallard	Y	A,B,C,D,E,H,I,L,K	2008 & 2009
Cistothorus palustris	Marsh Wren	Y	C,D,E,F,H,I,L,A,B	2008 & 2009
Mimus polyglottos	Mockingbird		H	2008
Zenaida macroura	Mourning Dove	Y	C,D,E,F,G,H,I,L,K,A, B	2008 & 2009
Mimus polyglottos	Northern Mockingbird	Y	D,F,H,I,L,G	2008 & 2009
Stelgidopteryx serripennis	Northern Roughwinged Swallow	Y	C,D,E,F,G,H,I,L,K,A, B	2008 & 2009
Vermivora celata	Orange-crowned Warbler	Y	C	2009
Phainopepla nitens	Phainopepla		A,E,F,H,I,L,K	2008 & 2009
Vireo plumbeus	Plumbeous Vireo	Y	G	2009
Agelaius phoeniceus	Red-winged blackbird	Y	C,D,A,B	2008 & 2009
Regulus calendula	Ruby-crowned Kinglet	Y	C,H,I,L,A,B	2009
Sayornis saya	Say's Phoebe	Y	C,D,E,F,G,H,I,L,K	2008 & 2009
Melospiza melodia	Song Sparrow	Y	C,D,E,F,G,H,I,L,K,A, B	2008 & 2009
Spizella	Sparrow Sp		C	2008
Actitis macularia	Spotted Sandpiper	Y	A,B	2009
Cathartes aura	Turkey Vulture		F,H	2008
Passeriformes	Unknown	Y	C,F,G	2008

	Passerine			
Auriparus flaviceps	Verdin	Y	C,D,E,F,G,H,I,L,K,A, B	2008 & 2009
Tachycineta thalassina	Violet-green Swallow		D	2008
Vireo gilvus	Warbling Vireo	Y	G	2008
Aphelocoma californica	Western Scrub-jay	Y	H,I,L	2009
Tyrannus verticalis	Western Kingbird	Y	D	2008
Sturnella neglecta	Western Meadowlark		D	2008
Piranga ludoviciana	Western Tanager	Y	H,I,L	2009
Wilsonia pusilla	Wilson's Warbler	Y	H,I,L	2009
Zonotrichia leucophrys	White-crowned Sparrow	Y	CDKAB	2009
Zenaida asiatica	White-winged Dove	Y	H,I,L,K	2009
Aix sponsa	Wood Duck		K	2008
Dendroica petechia	Yellow warbler	Y	K,H,I,L	2008 & 2009
Icteria virens	Yellow-breasted Chat	Y	G,H,I,L	2008 & 2009
Xanthocephalus xanthocephalus	Yellow-headed Blackbird	Y	K,D	2008 & 2009
Dendroica coronata	Yellow-rumped Warbler	Y	A,B,G	2009

Appendix B. Fish species detected during fish surveys along the Muddy River in 2008 and 2009

Scientific Name	Common Name	Parcels Observed	Year Detected
Cyprinella lutrensis	Red Shiner	G,A,B,E,C,F,L	2008
Gambusia affinis	Mosquito fish	A,B,C	2008
Gila seminuda	Virgin River Chub	A,B,C,D,E,F,I,K,L	2008 & 2009
Rhinichthys osculus	Speckled Dace	A,B,K	2008
Cyprinus carpio	Common Carp	A,B	2008
Ictalurus punctatus	Channel Catfish	G,A,B,E,F	2008
Micropterus salmoides	Largemouth Bass	A,B	2008
Oreochromis aureus	Blue Tilapia	E,C	2008 & 2009
Poecilia mexicana	Shortfin Molly	A,B,C	2008 & 2009
Ameiurus nebulosus	Bullhead Catfish	D,K	2009
Ameiurus melas	Black Bullhead	C	2009
Orconectes virilis	Virile Crayfish	F	2009