Revegetation Strategies and Technologies for Restoration of Aridic Saltcedar (*Tamarix* spp.) Infestation Sites

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Abstract: Critical knowledge gaps exist regarding vegetative recovery in aridic, monotypic saltcedar (*Tamarix* spp.) stands with no desirable understory plants. Formulation of revegetation strategies that provide site stabilization, resistance to further saltcedar and secondary weed infestation, and acceptable habitat values for affected wildlife species becomes particularly problematic in monotypic saltcedar stands under biological, fire, and herbicidal (that is, nonmechanical) control scenarios. Amount and density of standing biomass (live and dead) remaining after control pose limitations in relation to seeding and outplanting techniques, seed interception in aerial (broadcast) applications, and seedbed preparation methods. Undisturbed soil surfaces impacted by saltcedar leaf litter accumulation, salinity, hummocky micro relief, and nutrient limitations restrict potential for successful revegetation. Long duration of saltcedar occupation may deplete desirable microbial communities, particularly arbuscular (endo)mycorrhizae symbiotic and host-specific to native revegetation species. Selected results of innovative revegetation strategies at study sites on the Rio Grande and the Colorado River are discussed. Technical approaches include: 1) soil surface and rhizosphere manipulation methods to facilitate removal of standing dead biomass, increase precipitation capture, improve soil moisture retention, and create microsites exhibiting lower salinity and increased protection from environmental extremes for improved seed germination; 2) salinity remediation using HydraHume ™; 3) seeding methodologies, including use of seed coating techniques; and 4) mycorrhizal inoculation methods.

Keywords: seedbed manipulation, mycorrhizal inoculation, triclopyr, mulching, *Atriplex*

Introduction

Executive Order 13112 (Invasive Species) mandates that Federal agencies control and monitor invasive species, provide restoration of native species and desirable habitat conditions in ecosystems that have been invaded, and conduct research to develop technologies to prevent introduction and provide environmentally sound control of invasive species. Unfortunately, research is often driven by evaluation of control measure effectiveness, with secondary emphasis on ability of sites to sufficiently recover vegetatively for site stabilization and habitat value enhancement (Anderson and Ohmart 1979; DeLoach and others 2000; Lair and Wynn 2002). On xeric, saline sites not subject to seasonal flooding, recovery of desirable vegetation may be the most limiting factor for site enhancement (Anderson 1995).

Tamarix L. spp. (saltcedar) is a highly invasive exotic shrub that has invaded thousands of acres along many major river systems (Crawford and others 1993; USBR 2000; McDaniel and others 2000). Throughout the Western United States, saltcedar infestation has been documented to produce adverse environmental effects in riverine and lacustrine systems. These effects include increased wildfire potential resulting from high densities of fine, woody fuel materials; significant reduction in biodiversity, wildlife habitat, and riparian ecosystem function and structure; and significant reduction of surface and groundwater return flows (Crawford and others 1993; Anderson 1995; DiTomaso and Bell 1996; CEPPC 1998; Zavaleta 2000a,b). Saltcedar spreads by seed dispersal and vigorous sprouting from lateral roots and decumbent stems (that is, prostrate stems with nodes in contact with the soil surface), competitively and rapidly displacing native stands of cottonwood (*Populus* L. spp.), willow (*Salix* L. spp.), and grasses that are more fire-resistant (Warren and Turner 1975; Anderson and Ohmart 1979; Lovich 1996; Wiesenborn 1996).

Saltcedar has been implicated in severe reduction of habitat value within the riparian corridors of major river systems (Anderson and Ohmart 1979; Crawford and others 1993; Anderson 1995). Minimum flow volumes within the middle Rio Grande River have recently been mandated as critical for maintenance of an endangered fish, the Rio Grande silvery minnow *(Hybognathus amarus* Girard). Saltcedar has also been suggested as a possible cause of habitat reduction along the Canadian River system for many native fish and wildlife species, including the endangered Arkansas River shiner *(Notropis girardi* Hubbs & Ortenburger) (Eberts 2000; Davin 2003). One implication of this requirement is that additional water (via surface and groundwater return flow contributions) will be needed to support improved habitat for this fish. Landscape-scale management of saltcedar could positively address this need because of saltcedar's phreatophytic growth regime, high consumptive use (evapotranspiration) rate, high stand densities, and increasing infestation extent. Similarly, adverse impacts of saltcedar infestation on habitat of the southwestern willow flycatcher *(Empidonax traillii* ssp. *extimus* Audubon) have been well documented (Anderson and Ohmart 1979; Carpenter 1998; DeLoach and others 2000; Dudley and others 2000; Zavaleta 2000a,b).

Fire prevention and management in natural areas is exacerbated in dense saltcedar stands (Friedman and Waisel 1966; Busch 1995; Scurlock 1995; Wiesenborn 1996; Zavaleta 2000a). Saltcedar is a multi-stemmed invasive (exotic) shrub, sprouting basally from the root crown and lateral roots (DiTomaso 1996; Carpenter 1998). It can produce near continuous cover, ladder fuel structure, and extremely high standing biomass of fine to medium, woody fuel material (Busch 1995; Wiesenborn 1996). In dense, monotypic stands, mean canopy height can exceed 12 m (39 ft), with canopy closure (aerial cover) often approaching 100 percent (Lair and Wynn 2002), resulting in high potential for canopy fire carry. Saltcedar stands are often characterized by dense understory and soil surface litter layers comprised of additional fine fuels consisting primarily of annual grasses, for example, Japanese brome *(Bromus japonicus* Thunb. ex Murr.), cheatgrass *(Bromus tectorum L.]),* and saltcedar leaf litter (Lair and Eberts 2002).

Background and Research Needs

Critical knowledge gaps exist regarding restoration of saltcedar infestations, for which limited research or field experience exists, especially on aridic/xeric sites. Specifically, primary information needs include strategies and techniques for vegetative recovery in aridic, mature, monotypic saltcedar stands with no (desirable) understory and sites where potential is limited for natural or artificial recovery of willow and/or cottonwood species because of unavailability of supplemental water (via seasonal flooding, shallow water table, or irrigation). Best management practices are needed that integrate multiple management tools and are capable of addressing both localized (small scale) and landscape-scale, mesic and xeric saltcedar infestations. These practices should result in implementation of control and revegetation measures that provide rapid initial reduction of saltcedar; maintenance of control over extended time periods; and establishment of desirable vegetation that is ecologically (successionally) sustainable, competitive, resilient to further disturbance, and that provides multiple habitat, site stability, and forage benefits.

Vegetative restoration of sites impacted by invasion (and subsequent control) of saltcedar presents technical and conceptual challenges, particularly within the context of biological, fire, or foliar herbicide control. For example, research funded through the Cooperative State Research, Extension and Education Service and Initiative for Future Agriculture and Farming Systems addresses biological control of saltcedar (using *Diorhabda elongata* Brulle) as an economically sound alternative to other measures, especially in relation to reducing physical site disturbance and use of herbicides. The research places priority on evaluation of revegetation techniques in relation to anticipated results of biological control alone (that is, as the initial or primary treatment, leaving high densities and biomass of defoliated or standing dead material), as opposed to follow-up, maintenance control subsequent to mechanical, fire, or herbicidal measures.

Reducing the time for establishment of desired levels of cover, diversity, production, and habitat values is also important (Pinkney 1992; Anderson 1995; Lair and Wynn 2002). Natural recovery of saltcedar infestation sites following control measures, especially in less dense stands, needs to be evaluated in light of the definition of "recovery" and an acceptable time frame for it to occur. Natural recovery scenarios (that is, not artificially revegetated) often require 10 years or more for establishment of desirable, native vegetation, with the first 1 to 5 years typically dominated by ruderal weedy species. A prime objective should be to shorten or circumvent an extended ruderal and/or bare period by establishing diverse habitat characterized by predominance of early-, mid-, and late-seral perennial species. This also minimizes potential for capillary rise and salt accumulation at the soil surface following saltcedar reduction, and maintains lower wildfire hazard. Some sites may need initial establishment of earlier seral or transitional "ecobridge" species in order to cope with and adapt to harsh environmental conditions until the site stabilizes (from the standpoints of organic matter recovery, energy flow, and nutrient cycling). Other sites may facilitate later seral species and accelerated successional strategies.

Development and application of revegetation strategies also need to parallel recent technological developments in herbicidal and biological control of saltcedar, which hold great potential for rapid control of saltcedar on landscape scales. Valuable information can be derived from studies involving control of saltcedar by biological agents, fire, or herbicide application, especially in terms of the effect of growth medium manipulation (physically, biologically, chemically) on moisture capture and retention, restoration of a functional microbial community, species adaptation, and other management inputs. Amount and density of standing biomass (live and dead) remaining after control, seedbed preparation strategies, and time frame to achieve levels of control sufficient to favor vegetation establishment and site protection/stabilization are problematic in dense, mature saltcedar stands.

Effective techniques for seedbed preparation and seeding/outplanting in standing dead or defoliated material are needed that are more cost effective, require smaller equipment with less energy expenditure, and cause less environmental disturbance than conventional methods (for example, root plowing and raking). Presence of dense standing dead or defoliated saltcedar biomass poses limitations in relation to seeding techniques, seed interception in aerial applications, and shading impacts. After natural or prescribed fire treatment, undisturbed soil surfaces impacted by saltcedar leaf litter accumulation, salinity, hummocky microrelief, nitrogen limitations, and possible livestock trampling compaction may also restrict potential for successful revegetation. Absence of arbuscular mycorrhizae specifically symbiotic to native revegetation species (especially grasses and shrubs), because of the long duration of saltcedar occupation in dense, mature stands, may also be a significant constraint.

Saltcedar reduction may yield an interaction of both positive and negative impacts resulting from biological, fire, or herbicide application, requiring site-specific evaluation for restoration potential. Soil surface manipulation in the types and intensities needed for adequate soil surface manipulation (seedbed preparation) is absent following fire, biocontrol measures, and most herbicide applications (Szaro 1989; Pinkney 1992). Brief review to date of saltcedar revegetation literature, and communication with researchers and land managers experienced in saltcedar control and site restoration on xeric sites with dense, mature, monotypic infestations indicate that revegetation is difficult in the absence of soil surface manipulation (that is, some form of seedbed preparation) (Horton and others 1960; Lair and Wynn 2002). Different methods of achieving desirable growth medium conditions need testing through varied techniques of seedbed preparation to enhance microenvironmental conditions in the root zone of planted species, including saltcedar leaf litter dispersal or incorporation, improved contact of seeds with mineral soil, salinity reduction in surface soil layers, mycorrhizal fungi inoculation, and manipulation of soil nitrogen dynamics.

Stimulation of resprouting and increases in saltcedar density from remaining live root crowns and stems may occur as a result of saltcedar biomass reduction by mechanical measures or fire (wild or prescribed). The increased proportion of young, active growth increases competition for moisture, nutrients, and solar energy with planted vegetation. Use of mechanical methods or prescribed fire for biomass reduction needs sound planning and stringent controls as a viable tool, yielding an interaction of both positive and negative impacts. For example, rapid reduction of saltcedar canopy over large areas may be undesirable because of habitat sensitivity on sites occupied by endangered species such as the southwestern willow flycatcher (Busch 1995; Wiesenborn 1996). When applied on large (landscape) scales, reduction or elimination of biological control organism(s) may result, requiring reintroduction and subsequent redistribution (spread) over time of the biological agent(s) (Eberts 2002). Stimulation of resprouting from remaining live stems or root crowns resulting from mechanical or fire control measures, however, may promote higher rates of insect herbivory and increases in population size of biological agent(s) (Lair and Wynn 2002).

Current Research

Objectives

The USDI Bureau of Reclamation (USSR) is studying impacts of control measures (herbicidal, mechanical, and biological) and fire on site restoration/revegetation potential on aridic saltcedar infestation sites that are not candidates for revegetation with willow and cottonwood species. Development and evaluation of revegetation and habitat enhancement techniques are being conducted in historically dominant or monotypic saltcedar stands where potential for natural recovery of desirable native vegetation following control measures is limited or negligible. The studies address saltcedar control reflecting simulated biological control as the primary treatment (also applicable to foliar or basal bark herbicidal treatment) and mechanical control or fire where biological agents would be used as continuing maintenance (follow-up) control. The studies emphasize revegetation species response to mechanical techniques for saltcedar biomass reduction and seedbed preparation; manipulation of microbial (mycorrhizal) dynamics; and design and adaptation of selected species mixtures that are broadcast-applied (that is, simulation of aerial seeding), supported by companion single species trials.

Study Locations

Study sites for this research are San Marcial, New Mexico (approximately 30 mi [48 km] south of Socorro, New Mexico) and Cibola, Arizona (located approximately 45 mi [72 km] north of Yuma, Arizona).

San Marcial, NM—The San Marcial site is situated at an elevation of approximately 4,490 ft (1,369 m) on the immediate west side of the low flow conveyance channel along the Rio Grande River. Mean annual precipitation for the project area is 8.79 in (22.3 cm), with 5.47 in (13.9 cm) or 62 percent falling as rain during the summer monsoonal period of July through October (NOAA 2004). Soils of the project area are primarily fine sand and fine sandy loam, 0 to 2 percent mean slopes, typical of the braided channel floodplain zones adjacent to the middle Rio Grande River system (USDA NRCS 1988). All soils are moderately to strongly saline (electrical conductivity [EC,) 7 to 25 mmhos/cm), and may have clay loam to clay subsoil horizons with depths to bedrock typically exceeding 60 in (152 cm). The site is now instrumented for collection of localized climate and soil environment data, utilizing a HOBO™ remote weather station (Onset Computer Corporation, Pocasset, MA)

The general study site represents two distinct age classes of monotypic saltcedar *(Tamarix ramosissima* Ledeb.) infestation (no shrub understory and negligible herbaceous understory). Younger (aboveground) saltcedar are characterized by mean stem diameters less than 3 in (7.6 cm) and mean canopy cover less than 80 percent, resulting from prior prescribed burning conducted by the BLM in 1994. Older stands of saltcedar were protected from fire by means of a firebreak installed in 1993, and consisted of dense, old-growth populations characterized by mean stem diameters equal to or greater than 3 in (7.6 cm) (maximum diameters up to 16 in [40.6 cm]), and mean canopy cover approaching

100 percent. Lack of historical record or onsite evidence of natural or artificial reduction of saltcedar biomass in this latter population suggests an undisturbed stand age of at least 40 years.

Cibola, AZ—The Cibola site is located at an elevation of approximately 230 feet (70 m) in the Cibola Valley along the immediate east side of the Colorado River. Mean annual precipitation for the general project area is 3.83 in (9.73 cm) (NOAA 2004). Bimodal peaks in mean monthly precipitation occur in August through September and December through February, with all precipitation occurring as rainfall. Soils of the project area are primarily deep, well-drained silt loarns (USDA NRCS 1980) common to flood plain and alluvial sites (0 to 1 percent mean slopes) along this portion of the lower Colorado River. Soils are strongly saline, with salinity levels (as indicated by EC, measurements) extremely high (40 to 90 mmhos/cm) in the surface layer (top 6 in 115 cml), and low to moderate at 12-in (30-cm) soil depths (5 to 12.5 m mhos/cm).

The Cibola study site is comprised of mixed saltcedar and quailbush *[Atriplex lentiformis* (Torr.) S. Wats. ssp. *breweri (S.* Wats.) Hall & Clements) that was burned by wildfire on April 17, 2001. Saltcedar plants within the burn area are characterized by mean live stem diameters less than 2 in (5 cm) and mean, postfire canopy cover less than 25 percent.

Experimental Design and Statistical Analysis

Studies are replicated (4 blocks), split plot or split-split plot factorial designs suitable for ANOVA and multivariate analyses. These experimental designs incorporate evaluation of important response variables simultaneously within the same spatial and temporal context under a common error term. Univariate analysis was used to evaluate individual species responses, while multivariate techniques (for example, discriminant analysis, canonical correlation, multiple linear regression) assess treatment responses using combinations of plant community, climate, soil, and applied treatment variables. Studies incorporate control plots to reflect natural revegetation potential in the absence of treatment at all plot levels and within all replicates.

Seedbed Preparation, Mycorrhizal Inoculation, Seeding Mixture—Seedbed preparation (main plot) includes: 1) herbicide treatment only; 2) herbicide/shred/roller chop; 3) shred/roller chop; and 4) shred/roller chop/imprint.

Mycorrhizal inoculation (second level) includes: 1) broadcast granular; 2) pelleted seed coating; and 3) no treatment.

Seed mixtures (third level) include one of three grass/forb/shrub mixtures or no mixture, a "natural" recovery.

Treatments emphasize seeding without supplemental moisture (for example, seasonal flooding or irrigation) to reflect lower cost/lower maintenance vegetation establishment protocols and methodology. Specifically, treatments emphasize: 1) revegetation species response to mechanical techniques for saltcedar biomass reduction, seedbed preparation, and moisture capture/retention; 2) manipulation of microbial (mycorrhizal) regimes; and 3) design and adaptation of selected species mixtures that are broadcast-applied (that is, simulation of aerial seeding).

Project Term—Total project life is proposed for 5 years (2002 to 2006), involving baseline inventories, treatment applications, and posttreatment monitoring and weed management. Further, limited monitoring may continue for an additional 5 years following project completion, subject to research results, staff availability, and project funding. The intensive field data collection portion of the project is proposed for 3 years duration.

Baseline Inventories and Posttreatment Monitoring— Baseline and posttreatment inventories include soils (systematic core and electronic surface sampling), vegetation (fixed transects, using line intercept, line point, and systematic 1.0 m^2 110.8 $ft^2$1 quadrat sampling), and groundwater (monitoring wells). Posttreatment monitoring is conducted (at a minimum) once per year in late fall to early winter (October to December). Initial, measured field variables proposed for use in conducting baseline inventories and to evaluate treatment responses include soils, groundwater, vegetation, and wildlife management.

Using core sampling and surface electromagnetic techniques, soils are systematically sampled on an individual plot basis for surface (0 to 12 in 10 to 30 cml and subsoil (12 to 36 in 130 to 90 cml) texture, organic matter, fertility (macro- and micronutrients in the surface layer only), salinity (EC/SAR in the surface and subsoil), reaction (pH in the surface and subsoil), and moisture content/availability (surface and subsoil).

A minimum of one 2-in (5-cm) diameter, PVC-encased monitoring well per study was installed simultaneous with baseline inventories and prior to treatment applications for groundwater monitoring of ground water depth (baseline, pretreatment and monthly, posttreatment), conductivity, pH, alkalinity, major ions ($C1^-$, SOC, Ca", mg-, Na+, trace elements/metals, and NO3-/NO2-.

Vegetation monitoring included age class (baseline only), plant height, plant spacing, stem densities and diameters for saltcedar; species frequency; Vigor Index (function of culm and leaf height, seedhead production, and biomass); basal and canopy cover (total and by species) for both seeded and nonseeded; bare ground and litter; species diversity (Shannon-Weiner or modified Simpson's); and biomass (live standing crop + standing dead; total and by species) for both seeded and nonseeded species.

Modified Habitat Suitability Index evaluations for wildlife monitoring will be conducted on resultant small plot plant communities, with extrapolations to potential landscape-scale communities of the same character, to estimate general habitat values based on desired plant community composition and revegetation results.

Herbicide Application—Saltcedar was herbicidally treated at San Marcial to simulate injury and defoliation from biocontrol insects, using backpack applications of triclopyr in vegetable oil as a basal bark treatment (25 percent v/v). Seeded species competition for moisture and nutrients, and adjustment to altered soil microbial and organic matter regimes in affected *Tamarix* communities, should be evaluated in the presence of live saltcedar root growth while undergoing aboveground defoliation over time (chronic stress leading to root reserve depletion). Ongoing control of saltcedar sprouts following fire (Cibola) or mechanical treatment (both studies) is maintained herbicidally on treated plots over the duration of the study via spot treatment using backpack sprayers, or as situations indicate following revegetation treatments, carpet roller, or rope wick application (dependent upon plant densities, prevalence of nontarget vegetation, and cost effectiveness). Secondary invasive species will be similarly controlled using labeled herbicides appropriate for the target species and land use type.

Mechanical Treatments—Mechanical treatments were used for saltcedar biomass reduction, seedbed preparation and mulching, salinity remediation, placement of seeds, and incorporation of soil microbial (mycorrhizal) amendments. These measures include saltcedar shredding/mulching by HydroAx^{T}" with WoodGator^{Tm} attachment, roller-chopping and land imprinting. These measures are evaluated for efficacy in creating soil surface microrelief(microcatchments) to enhance precipitation capture and retention in the rhizosphere of seeded/planted vegetation; reduction, redistribution, and/or dilution of salts in the upper soil profile and saltcedar leaf litter on the soil surface; creating more spatially uniform soil texture characteristics (in both depth and lateral extent) for improved planted vegetation adaptation; and proper depth placement and incorporation of mycorrhizal inoculum.

Growth Medium Amendments—Mycorrhizal inoculum (using host-specific species, as determined from baseline soil samples, current research, and pertinent literature) was obtained either commercially (for example, RTI, Incorporated, Salinas, CA; Bionet LLC, Marina, CA), or was provided via Cooperative Research and Development Agreement (CRADA) as donated research materials from Bionet LLC. Inoculum was placed and incorporated into the prepared seedbed either as a preplant granular broadcast application using a manual, rotary fertilizer or seed spreader at a prescribed rate of 60 lb/ac (67 kg/ha) product or as raw inoculum incorporated in commercially pelletized seed coatings (CelPril, Incorporated, Manteca, CA; Seed Systems, Incorporated, Gilroy, CA) and applied during broadcast seeding using prescribed seeding rates. Regardless of source, the inoculum contained one or more species of mycorrhizae that are host-specific to the native revegetation plant species, including *Glomus intraradices, G. mosseae, G. aggregatum,* and/or *G. fasciculatus.*

Planting Methodology—Revegetation was conducted in combination with mechanical and mycorrhizal inoculation treatments. At San Marcial, seeds were broadcast using manual (hand-held) and/or mechanized (tractor PTO-driven) rotary spreader(s).

Several methods were used at Cibola, including broadcast using manual (hand-held) and/or mechanized (tractor PTO-driven) rotary spreader(s); broadcast using a mechanized Brillion-type seed drill; drilled using a research plot drill with leading deep-furrow openers; and seedlings outplanted manually or mechanically depending upon species, container type, soil conditions, and equipment availability. Planting was done in conjunction with selected mechanical seedbed preparation treatments using the roller chopper and/or imprinter to facilitate desired seed depth placement and juxtaposition of seeds to incorporated mycorrhizal inoculum (subject to the experimental design).

Species Selection—Emphasis is placed on testing native species (in conjunction with associated seeding/planting methodology) as single species, seed mixtures, and seedling transplants that best reflect environmental site adaptation, practical field applications by agencies and private landowners, commercial availability, and cost-effectiveness. Evaluation of competition between species within designed mixtures under saltcedar control conditions is also performed. Evaluations are made on individual species as well as resultant plant communities. General design and number of mixture applications are amenable to site specific adjustment at other southwestern sites subject to individual site attributes.

Mixtures of native shrubs, forbs and grasses (tables 1 and 2) were seeded or planted following various experimental combinations of herbicide and/or mechanical treatments (San Marcial: 16 species, July 15 to 17, 2002; Cibola: 23 species, January 30 to 31, 2003). The Cibola study also incorporates a demonstration of irrigated and nonirrigated, single species trials, utilizing seeds and seedlings.

Seed coating for mycorrhizal inoculation was performed in cooperation with Bionet LLC (Marina, CA) and CelPril, Incorporated (Manteca, CA) at the San Marcial site and Reforestation Technologies, Incorporated (Salinas, CA) and Seed Systems, Incorporated, (Gilroy, CA) at the Cibola site.

All species, singly or in mixtures, were selected for optimum adaptation to interactions of climate, soil, salinity, competition from existing vegetation, and planned treatments, including preconditioning treatments as needed (for example, stratification and/or scarification for seeds; selection for salinity tolerance and mycorrhizal inoculation potential for seedlings). Both studies incorporate "transitional" or "ecobridging" species concepts within mixtures, using regional natives that exhibit greater establishment potential in terms of germination, seedling vigor, and reproductive capability under the harsh climatic and soil conditions on saltcedar revegetation sites.

Native revegetation species were obtained through cooperation with the USDA Natural Resources Conservation Service (NRCS) Plant Materials Centers plus acquisition of local native harvest or commercial source material, depending upon individual species availability. Species were of local (endemic) or regional origin where possible. Final species and cultivar selection, for both mixture and single species applications, were determined in consultation with local/regional cooperators (for example, USDI Bureau of Land Management, USDI Fish and Wildlife Service, USDA Forest Service, State fish and game departments, NRCS, local environmental organizations, and USBR).

Results and Discussion

Selected San Marcial results only are presented for the sake of brevity and to demonstrate the potential for the applied treatments. First-, second-, and third-year data collection (2002 to 2004) addressed frequency and density variables only. Subsequent monitoring years include canopy cover, biomass (live standing crop), plant diversity, and vigor parameters.

Treatment response indicates promising emergence, establishment, and vigor of seeded quailbush, four-wing saltbush

Table 1—Mixtures and seeding rates for San Marcial, NM, saltcedar revegetation study.

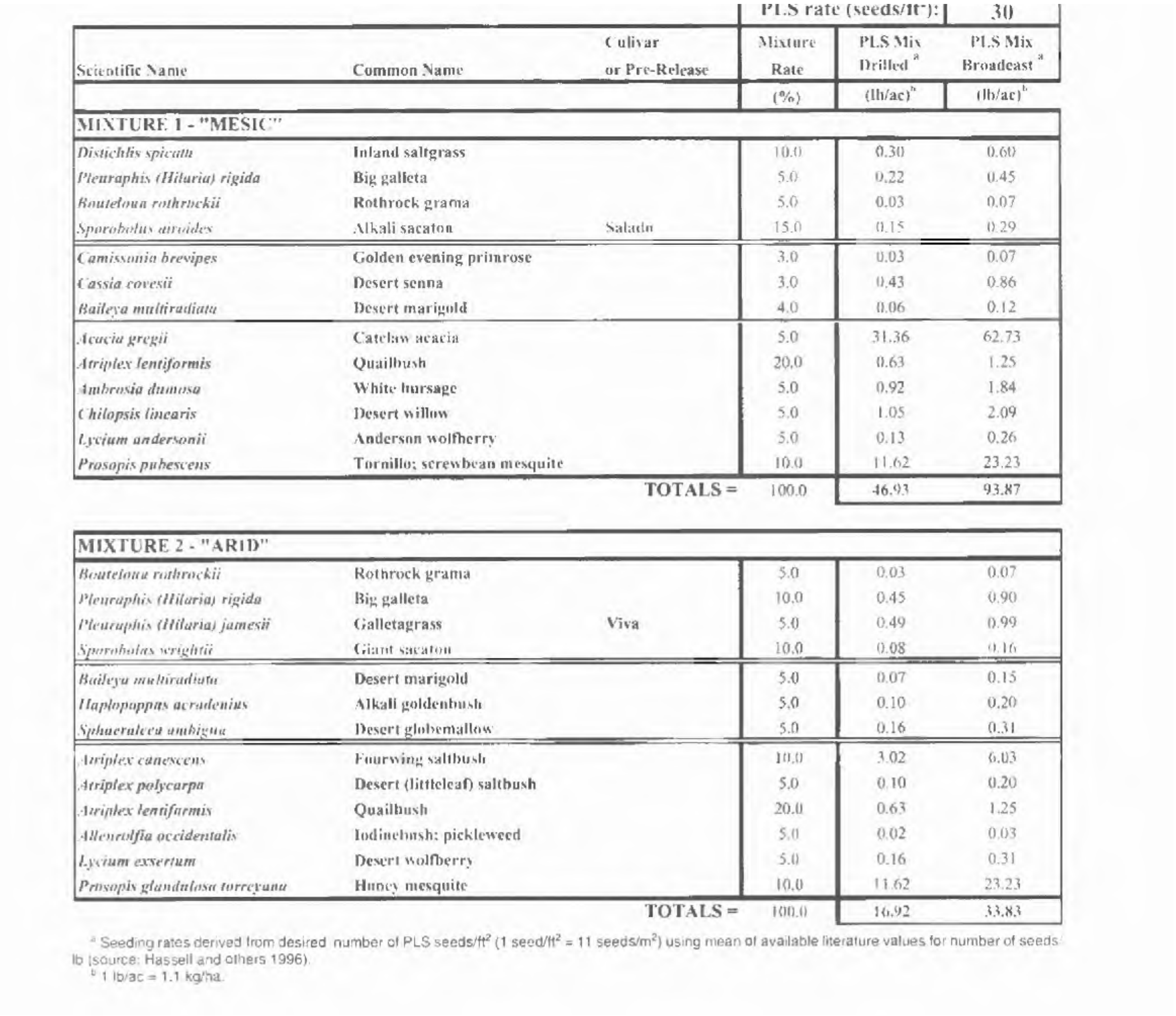
Scientific Name	Common Name	Cultivar or Pre-Release	PLS rate (seeds/ft^2): Mixture Rate (%)	20 PLS Mix Drilled [a] (lb/ac)[b]	PLS Mix Broadcast [a] (lb/ac)[b]
MIXTURE 1 - AGGRESSIVE					
Bouteloua curtipendula	Sideoats grama	Niner	10.0	0.50	1.01
Elymus elymoides	Bottlebrush squirreltail		10.0	0.55	1.09
Elymus trachycaulus	Slender wheatgrass	Pryor	10.0	0.68	1.35
Panicum virgatum	Switchgrass	Blackwell	15.0	0.43	0.87
Pascopyrum smithii	Western wheatgrass	Arriba	10.0	0.87	1.74
Sporobolus giganteus	Giant dropseed		5.0	0.03	0.06
Sporobolus wrightii	Giant sacaton		5.0	0.03	0.05
Plantago insularis	Wooly plaintain		2.0	0.06	0.13
Sphaeralcea coccinea	Scarlet globemallow		3.0	0.06	0.13
Heliotropium curassavicum	Quailplant; salt heliotrope		2.0	0.03	0.05
Atriplex canescens	Fourwing saltbush		12.7	2.55	5.11
Forestiera neomexicana	New Mexico olive	Jemez	0.30	0.07	0.15
Atriplex lentiformis	Quailbush		10.0	0.21	0.42
Shepherdia argentea	Silver buffaloberry		5.0	1.16	2.32
		TOTALS =	100.0	7.24	14.48
MIXTURE 3 - SANDY					
Achnatherum hymenoides	Indian ricegrass	Paloma	10.0	0.57	1.14
Elymus elymoides	Bottlebrush squirreltail		10.0	0.55	1.09
Elymus lanceolatus lanceolatus	Thickspike wheatgrass	Critana	5.0	0.34	0.68
Eragrostis trichodes	Sand lovegrass	Bend	5.0	0.03	0.07
Leptochloa dubia	Green sprangletop		5.0	0.10	0.19
Panicum virgatum	Switchgrass	Blackwell	15.0	0.43	0.87
Pleuraphis (Hilaria) mutica	Tobosagrass		10.0	0.23	0.46
Schizachyrium scoparium	Little bluestem	Pastura	10.0	0.42	0.85
Sporobolus cryptandrus	Sand dropseed		5.0	0.01	0.02
Oenothera deltoides	Dune evening primrose		2.0	0.06	0.13
Plantago insularis	Wooly plaintain		5.0	0.16	0.32
Sphaeralcea coccinea	Scarlet globemallow		5.0	0.10	0.21
Atriplex polycarpa	Desert saltbush		3.0	0.04	0.08
Lycium torreyi / L. andersonii	Torrey / Anderson's wolfberry		4.0	0.07	0.14
Ephedra viridis	Green ephedra		4.0	2.06	4.12
Ephedra nevadensis	Nevada ephedra		2.0	1.03	2.06
		TOTALS =	100.0	6.22	12.43

Scientific Name	Common Name	Cultivar or Pre-Release	PLS rate (seeds/ft^2): Mixture Rate (%)	20 PLS Mix Drilled [a] (lb/ac)[b]	PLS Mix Broadcast [a] (lb/ac)[b]
MIXTURE 2 - MESIC					
Bothriochloa barbinodis	Cane bluestem	Grant	15.0	0.21	0.42
Elymus canadensis	Canada wildrye		9.0	0.83	1.65
Elymus lanceolatus	Streambank wheatgrass	Sodar	5.0	0.32	0.64
Pascopyrum smithii	Western wheatgrass	Arriba	15.0	1.31	2.62
Puccinellia airoides	Nuttall's alkaligrass		5.0	0.02	0.04
Sporobolus airoides	Alkali sacaton	Salado	16.0	0.10	0.21
Anemopsis californica	Yerba mansa		5.0	0.04	0.08
Sphaeralcea coccinea	Scarlet globemallow		5.0	0.10	0.21
Baccharis glutinosa	Seep willow		5.0	0.00	0.01
Lycium andersonii	Anderson's wolfberry		6.0	0.11	0.21
Chilopsis linearis	Desert willow		5.0	0.70	1.39
Chrysothamnus nauseosus graveolens	Rubber rabbitbrush		4.0	0.08	0.17
Sarcobatus vermiculatus	Greasewood		5.0	0.20	0.41
		TOTALS =	100.0	4.03	8.06
STANDARD MIXTURE					
Bouteloua curtipendula	Sideoats grama	Niner	10.0	0.50	1.01
Elymus trachycaulus	Slender wheatgrass	Pryor	11.0	0.74	1.49
Panicum virgatum	Switchgrass	Blackwell	15.0	0.43	0.87
Pascopyrum smithii	Western wheatgrass	Arriba	10.0	0.87	1.74
Sporobolus airoides	Alkali sacaton	Salado	15.0	0.12	0.23
Sporobolus giganteus	Giant dropseed		5.0	0.03	0.05
Anemopsis californica	Yerba mansa		2.0	0.02	0.03
Plantago insularis	Wooly plaintain		2.0	0.06	0.13
Sphaeralcea coccinea	Scarlet globemallow		2.0	0.04	0.08
Atriplex canescens	Fourwing saltbush		12.0	2.41	4.83
Baccharis glutinosa	Seep willow		3.0	0.00	0.00
Atriplex lentiformis	Quailbrush		4.0	0.08	0.17
Lycium andersonii	Anderson's wolfberry		7.0	0.12	0.25
Chrysothamnus nauseosus graveolens	Rubber rabbitbrush		2.0	0.04	0.08
		TOTALS =	100.0	5.48	10.96

[a] Seeding rates derived from desired number of PLS seeds/ft^2 (1 seed/ft^2 = 11 seeds/m^2) using mean of available literature values for number of seeds/lb (source: Hassell and others 1996).

[b] 1 lb/ac = 1.1 kg/ha.

Table 2-Mixtures and seeding rates for Cibola, AZ. saltcedar revegetation study.



PLS rate (seeds/ft²): 30

Scientific Name	Common Name	Culivar or Pre-Release	Mixture Rate (%)	PLS Mix Drilled [a] (lb/ac)[b]	PLS Mix Broadcast [a] (lb/ac)[b]
MIXTURE 1 - "MESIC"					
Distichlis spicata	Inland saltgrass		10.0	0.30	0.60
Pleuraphis (Hilaria) rigida	Big galleta		5.0	0.22	0.45
Bouteloua rothrockii	Rothrock grama		5.0	0.03	0.07
Sporobolus airoides	Alkali sacaton	Salado	15.0	0.15	0.29
Camissonia brevipes	Golden evening primrose		3.0	0.03	0.07
Cassia covesii	Desert senna		3.0	0.43	0.86
Baileya multiradiata	Desert marigold		4.0	0.06	0.12
Acacia gregii	Catclaw acacia		5.0	31.36	62.73
Atriplex lentiformis	Quailbush		20.0	0.63	1.25
Ambrosia dumosa	White bursage		5.0	0.92	1.84
Chilopsis linearis	Desert willow		5.0	1.05	2.09
Lycium andersonii	Anderson wolfberry		5.0	0.13	0.26
Prosopis pubescens	Tornillo; screwbean mesquite		10.0	11.62	23.23
		TOTALS =	100.0	46.93	93.87
MIXTURE 2 - "ARID"					
Bouteloua rothrockii	Rothrock grama		5.0	0.03	0.07
Pleuraphis (Hilaria) rigida	Big galleta		10.0	0.45	0.90
Pleuraphis (Hilaria) jamesii	Galletagrass	Viva	5.0	0.49	0.99
Sporobolus wrightii	Giant sacaton		10.0	0.08	0.16
Baileya multiradiata	Desert marigold		5.0	0.07	0.15
Haplopappus acradenius	Alkali goldenbush		5.0	0.10	0.20
Sphaeralcea ambigua	Desert globemallow		5.0	0.16	0.31
Atriplex canescens	Fourwing saltbush		10.0	3.02	6.03
Atriplex polycarpa	Desert (littleleaf) saltbush		5.0	0.10	0.20
Atriplex lentiformis	Quailbush		20.0	0.63	1.25
Allenrolfia occidentalis	Iodinebush; pickleweed		5.0	0.02	0.03
Lycium exsertum	Desert wolfberry		5.0	0.16	0.31
Prosopis glandulosa torreyana	Honey mesquite		10.0	11.62	23.23
		TOTALS =	100.0	16.92	33.83

[a] Seeding rates derived from desired number of PLS seeds/ft² (1 seed/ft² = 11 seeds/m²) using mean of available literature values for number of seeds/lb (source: Hassell and others 1996).

[b] 1 lb/ac = 1.1 kg/ha.

[Atriplex canescens (Pursh) Nutt.], and slender wheatgrass *[Elynzus trachycaulus* (Link) Gould ex Shinners Alkali sacaton *[Sporobolus airoides* (Torr.) Torr. I, sideoats grama [Bouteloua *curtipendula* (Michx.) Torr.], Anderson wolfberry *(Lycium andersonii* Gray), and giant dropseed *(Sporobolus giganteus* Nash) are also establishing in lesser quantities. Minor occurrences of native species exhibiting natural recovery (nonseeded) following saltcedar reduction include vine mesquite *(Panicum obtusum Kunth),* salt heliotrope *(Heliotropium curassauicum L.),* buffalo gourd *(Cucurbita foetidissima* Kunth), and jimson weed *(Datura stramonium L.).*

Initial frequency and density of seeded plant materials were highest in plots treated with herbicide only (no mechanical treatment), achieving frequencies of 16 to 47 percent and densities of 0.25 to 3.0 plants/m^2 (0.023 to 0.28 plants/ft^2) (figures 1 and 2). However, all plants in the herbicide-only plots were extremely stunted (less than 5 cm (2 in) in height), weak, and highly stressed. The saltcedar stands were 75 percent defoliated from the herbicide treatment. The remaining canopy of dense saltccdar, however, still provided ample cover such that shading and protection from wind maintained higher humidity levels than those in plots where mechanical biomass reduction had occurred- It is hypothesized that this shading and higher humidity promoted greater initial germination of seeded materials. However, as the growing season progressed, factors of continued shading, high salinity in exposed (bare) surface soil, and undisturbed, highly saline saltcedar leaflitter du ffseverely inhibited growth following germination.

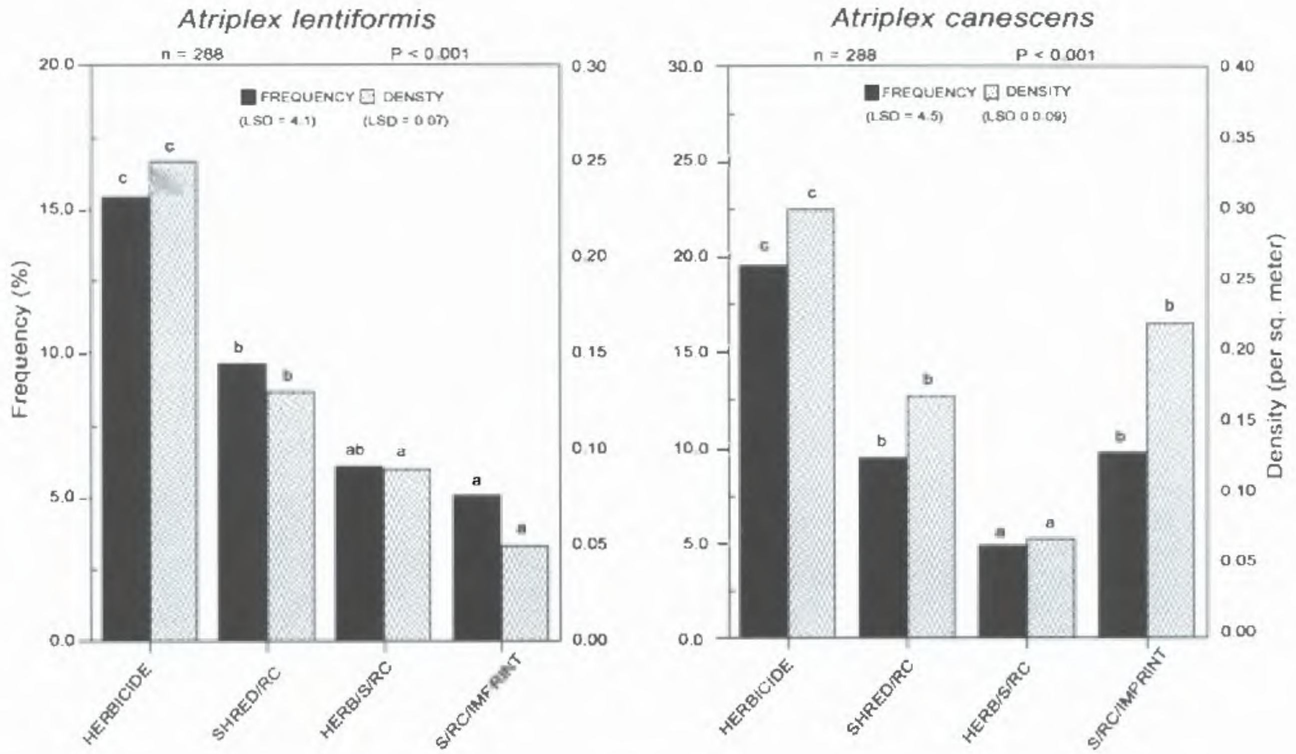


Figure 1—Response to herbicidal and mechanical treatment by *Atriplex lentiformis* and *A. canescens*. First year (2002) data for San Marcial, NM, saltcedar revegetation study. Dark bars are frequency (left Y-axis); light bars are density (right Y-axis). HERB = herbicide, SHRED or S = Woodgator shredded; RC = roller chopped. Bars within a parameter (of like color) with different letters are significantly different at $P < 0.001$.

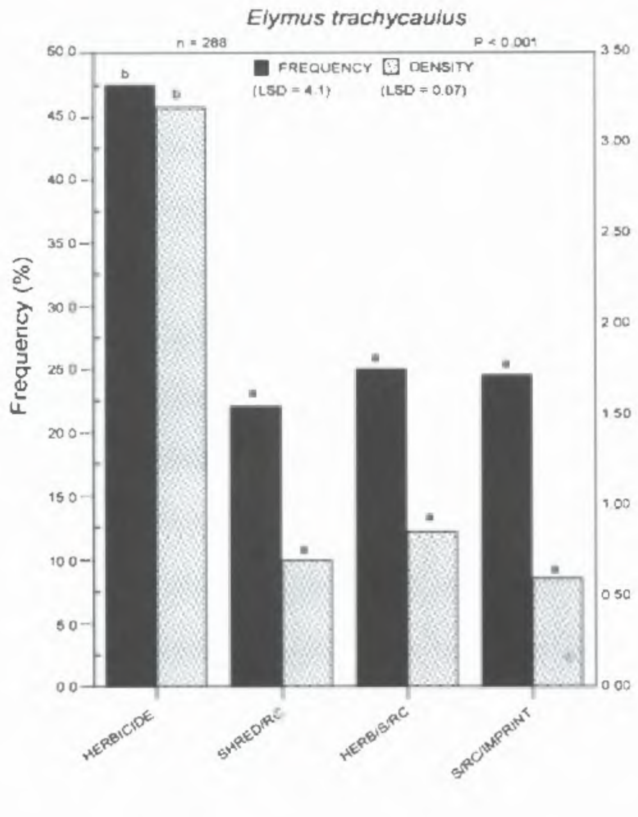


Figure 2—Response to herbicidal and mechanical treatment by *Elymus trachycaulus*. First year (2002) data for San Marcial, NM, saltcedar revegetation study. Dark bars are frequency (left Y-axis); light bars are density (right Y-axis). HERB = herbicide; SHRED or S = Woodgator shredded; RC = roller chopped. Bars within a parameter (of like color) with different letters are significantly different at $P < 0.001$.

While mechanically treated plots exhibited less initial germination and emergence of the seeded species (figures 1 and 2), frequency and density ranging from 5 to 25 percent and 0.05 to 0.8 plants/m^2 (0.005 to 0.007 plants/ft^2) respectively, indicate desirable emergence of several of the key seeded species in light of the severe site environmental constraints. Precipitation received at the site strongly reflected the southwestern regional drought status, with 7.69 in (19.5 cm; 87 percent of mean annual precipitation) and 5.89 in (15.0 cm; 67 percent of mean annual precipitation) received during the 2002 to 2003 initial establishment years, respectively. Of greater importance, essentially all of the emerged species exhibited greater productivity (high growth rates, vigor, and biomass production). Canopy heights ranged from 0.5 to 2.0 m (1.6 to 6.6 ft), 0.3 to 1.5 m (1.0 to 4.9 ft), and up to 45 cm (17.7 in) for quailbush, fourwing saltbush, and the two dominant grasses (slender wheatgrass, sideoats grama), respectively. Many of the plants were already sexually reproductive after one growing season, particularly sideoats grama.

Essentially 100 percent of the species that emerged under standing saltcedar (herbicide treatment only) in 2002 are dead and decomposed. In contrast, the dominant shrub species in mechanically treated plots have greatly increased in frequency and density, doubled in canopy height and volume, and most are sexually reproductive. It is anticipated that continued germination, emergence and establishment will occur in mechanically treated plots as seed dormancy mechanisms are broken and seedling recruitment from established plants increases. Increased germination and emergence for the dominant species may also be a function of the roller chopping treatments, which provide depressions for increased moisture capture and retention, and salinity reduction in the depression bottoms, providing microsites for enhanced seed germination.

Few differences were noted between mechanical treatments for saltcedar biomass reduction and seedbed preparation (figures 1 and 2), particularly for the seeded grasses. Herbicidal defoliation of saltcedar prior to mechanical shredding and mulching of the saltcedar, however, reduced frequency and density of the saltbushes (figure 1), perhaps suggesting potential adverse impacts on amount and/or characteristics (chip size, amount of fine stems, recalcitrance of larger stems) of the resultant mulch material. While the data suggest that there are negligible differences between mechanical treatments, all such treatments resulted in saltcedar mulch material uniformly covering the soil surface. With apparent greater establishment of seeded species on mulched areas than in standing (herbicidally treated) saltcedar, potentially positive aspects of in situ, saltcedar-derived mulch cover are evident. These potential benefits include weed suppression resulting from the following:

- Minimized soil disturbance (in comparison with traditional root plowing and root raking);
- Reduction of exposed bare soil;
- Increased soil C:N ratios, providing establishment advantage to later seral (non ruderal), perennial species;
- Moisture conservation;
- Moderation (buffering) of temperature and wind extremes;
- Salinity remediation through reduction of evaporation and capillary rise of salts to the soil surface;
- Microsite environment and protection for seedlings;
- Cost savings (in comparison with traditional root plowing and root raking);
- Younger (aboveground) stands of saltcedar (5 cm 12 in1 mean stem diameter or less) amenable to biomass mulching by roller chopper alone.

Sideoats grama exhibited positive response to mycorrhizal inoculation (figure 31, with frequency and density values 2.5 to 4.5 times greater than under no inoculation. This finding suggests that mycorrhizal colonization and association with seeded native, mycorrhizal species can occur on highly saline/sodic sites characteristic of mature, monotypic saltcedar infestations. Given the high salinity (mean EC, of 16 mmhos/cm) of the seeded soils, these findings also suggest that reintroduction of mycorrhizal populations into saltcedar infestation sites is more dependent on co-introduced presence of native host plant species than on soil salinity levels. This capability is critical in enabling and accelerating establishment of desirable, mycorrhizae-dependent native species on these sites. This is particularly important for more rapid establishment and spread of competitive, transitional ("eco-bridging") native

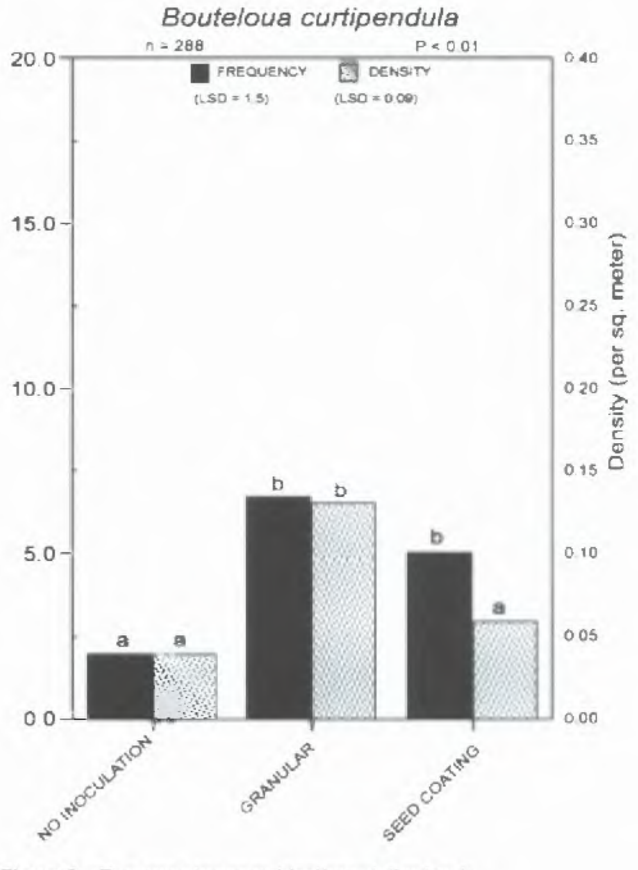


Figure 3—Response to mycorrhizal inoculation treatment by *Bouteloua curtipendula*. First year (2002) data for San Marcial, NM, saltcedar revegetation study. Dark bars are frequency (left Y-axis); light bars are density (right Y-axis). Bars within a parameter (of like color) with different letters are significantly different at $P < 0.01$.

species that help suppress encroachment of secondary invasive species following saltcedar control. The saltbushes and slender wheatgrass exhibited no positive response to mycorrhizal inoculation, consistent with the literature and the author's experience that these species are only mildly- to non-mycorrhizal, and thus are not dependent on mycorrhizal associations for initial establishment.

While there were no differences in sideoats grama frequency between mycorrhizal inoculation methods (figure 3), sideoats grama density (abundance) was reduced under seed coating inoculum incorporation. This result may be reflective of the seed coating process enclosing and binding mycorrhizal spore material more tightly to the immediate floret or seed coat envelope, rather than being distributed more uniformly through the potential rhizosphere of the germinating and growing plant. This latter state is considered more desirable than mycorrhizal inoculum material being more tightly bound to the seed during early growth and establishment (St. John 2003). Trends for inoculation efficacy will continue to be monitored in subsequent years.

There was poor correlation ($r^2 < 0.10$) of dominant seeded species frequency or density with soil salinity/sodicity across plots and treatments. At the San Marcial site, soil ECe ranged from 7 to 25 mmhos/cm. The majority of the dominant seeded species that have emerged are highly saline tolerant (by design), and thus may minimize any correlation to soil salinity because of their high tolerance levels.

Summary

Formulation of revegetation strategies that provide site stabilization, resistance to further saltcedar and secondary weed infestation, and acceptable habitat values for affected wildlife species becomes particularly problematic in monotypic saltcedar stands under biological, fire, and herbicidal (that is, nonmechanical) control scenarios. Amount and density of standing biomass (live and dead) remaining after control poses limitations in relation to seeding and planting techniques, seed interception in aerial (broadcast) applications, and seedbed preparation methods. Undisturbed soil surfaces impacted by saltcedar leaf litter accumulation, salinity, hummocky microrelief, and nutrient limitations restrict potential for successful revegetation. Long duration of saltcedar occupation may deplete needed microbial communities, particularly arbuscular mycorrhizae symbiotic and host-specific to native revegetation species.

Sixteen species of native shrubs, forbs, and grasses were seeded following various experimental combinations of simulated biocontrol treatment. Establishment results from the San Marcial study site indicate promising emergence, establishment and vigor of seeded quailbush, four-wing saltbush, and slender wheatgrass, alkali sacaton, sideoats grama, Anderson wolfberry, and giant dropseed.

While few differences were noted between mechanical treatments for saltcedar biomass reduction and seedbed preparation, these treatments resulted in saltcedar mulch material uniformly covering the soil surface. Positive aspects of in situ, saltcedar-derived mulch cover include weed suppression, moisture conservation, moderation (buffering) of temperature and wind extremes, salinity remediation through reduction of evaporation and capillary rise of salts to the soil surface, microsite environment and protection for seedlings, cost savings, and younger (aboveground) stands of saltcedar following control that are amenable to biomass mulching by roller chopper alone.

Sideoats grama (a mycorrhizal "indicator" species) exhibited positive response to mycorrhizal inoculation, suggesting that mycorrhizal colonization and association with seeded native species can occur on highly saline/sodic sites characteristic of mature, monotypic saltcedar infestations. This finding also suggests that absence (depletion) of desirable mycorrhizal populations in mature saltcedar stands is a function of native species displacement and loss (native host-dependent) rather than a direct response to increasing soil salinity/sodicity.

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