

Tamarisk

BEST MANAGEMENT PRACTICES *in* COLORADO WATERSHEDS



COLORADO STATE UNIVERSITY
UNIVERSITY OF DENVER
COLORADO DEPARTMENT OF AGRICULTURE
DENVER BOTANIC GARDENS

Tamarisk Best Management Practices in Colorado Watersheds

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Part 1. INTRODUCTION



WHY IS TAMARISK A PROBLEM?
IDENTIFICATION, HABITAT, AND BIOLOGY

Why is Tamarisk a Problem?

ANNA SHER
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Tamarisk (*Tamarix* spp., a.k.a. saltcedar), is a non-native tree that was intentionally introduced in the United States in the late 1800s and promoted by nurseries and federal agencies alike for use as bank and roadside stabilization, wind-breaks, shade trees, and for ornamental purposes. By the 1950s, tamarisk occupied most western riparian areas along major rivers and streams. Today it occupies at least 1.6 million acres of prime riparian habitat from the central Great Plains to the Pacific Ocean and from southern Montana to northern Mexico, particularly in Arizona, New Mexico, California, Texas, Colorado, Utah, Nevada, Oklahoma and Wyoming (Zavaleta 2000). Tamarisk has been associated with increased flooding frequency due to channel narrowing (Blackburn et al. 1982), increased fire risk (Busch 1995, Busch and Smith 1995, Ellis et al. 1998), decreased or altered plant and/or animal diversity (Brotherson and Winkle 1986, Busch and Smith 1995, Ellis 1995, Bailey et al. 2001, Kennedy et al. 2005), salinization of soils (Brotherson and Field 1987, Busch and Smith 1995, Zamora-Arroyo et al. 2001), and increased evapotranspiration (Sala et al. 1996, Cleverly et al. 1997). Some controversy exists as to the degree to which tamarisk is actually the cause versus the consequence of many of these ecological changes (Stromberg et al. 2009). It

is clear that there are a number of interacting factors that have facilitated tamarisk's spread and persistence, most of which have been and continue to be facilitated by human activities (Everitt 1980). These factors include:

- Conversion of native riparian forests to agricultural and rangeland uses
- Damming of rivers fed by snowmelt which has shifted the time of peak discharge below the dams from spring to summer
- Creation of large areas of fine sediment that provide the ideal substrate for tamarisk colonization along the margins of reservoirs
- Increased salinity of rivers due to irrigation return flows and evaporation from reservoirs
- Reduced flood frequency downstream of reservoirs
- More stabilized base flows in rivers due to reservoir construction

Tamarisk seedlings are drought sensitive and not strong competitors (Sher et al. 2002); however, many human caused alterations of the ecosystem help to enhance its establishment and spread. Once established very little can grow in the understory of mature trees (Taylor 1998). Therefore, tamarisk removal is a necessary first



FIGURE 1. This photo from Dinosaur National Monument shows how tamarisk can prevent boating access and does not provide shade. (Photo by Michelle DePrenger-Levin)



FIGURE 2. Dense tamarisk understory is a poor environment for many native species and is difficult to navigate. (Photo by Michelle Ohrtman)

step when restoring habitat where it has established dense thickets. Tamarisk impacts include the following.

Tamarisk's Impacts

... To Agriculture

Like many riparian trees, tamarisk can be a water-intensive consumer. Therefore, water that would otherwise be available for ranching and agricultural uses in arid western states is reduced. In one often cited case study, tamarisk removal from around Spring Lake, New Mexico was rapidly followed by water reappearing in what was once a dry lake bed (Duncan 1997). It should be noted that the consensus opinion of a recent expert peer panel on tamarisk and evapotranspiration was that tamarisk water use rates are highly variable and thus control is only likely to yield water savings when replacement vegetation (if any) has very low water use (e.g., shrubs and grasses; Tamarisk Coalition 2009). In the absence of overbank flooding, tamarisk can also contribute to soil and groundwater salinity that are problematic in many western agricultural settings.

... To Recreation

In Colorado, dense stands of tamarisk occur up to the water's edge along major stretches of the Colorado, Green, and Arkansas Rivers. These stands can be so thick that river access for boating and fishing is completely eliminated. Camping and hiking is impossible due to these tamarisk thickets. Several studies have found bird diversity, particularly tropical migrants of interest to bird watchers, is restricted in areas dominated by tamarisk (Hunter et al. 1988, Ellis 1995).

... To Wildlife

Although tamarisk can provide habitat for some animal species including some birds (e.g., Brown and Trosset 1989) and crayfish (Kennedy et al. 2005), dense monocultures of tamarisk are a dramatic departure from the historic conditions to which native animals have adapted. Thus, the decline of tree diversity, forest structure and other changes associated with the presence of tamarisk are likely to affect native animals. Removal of tamarisk will often be necessary to promote or establish other plant species to support wildlife, such as cavity-nesting bird species (Ellis 1995). For example, tamarisk litter was found to have half the insect diversity and a quarter of the overall insect abundance when compared to litter of native Fremont cottonwoods (*Populus fremontii*) (Bailey et al. 2001), and areas cleared of tamarisk had significantly higher densities of an endemic pupfish (Kennedy et al. 2005). If native animals, such as cup-nesting bird species, are using tamarisk for habitat care must be taken to provide replacement vegetation.

... To Land Values

If you want to buy or sell property be aware that designated noxious weeds such as tamarisk affect land values. Weed management is required by state law, resulting in costs to both buyer and seller. Many prospective property buyers are now aware of the costs associated with purchasing weed-infested property. In some cases, the cost of managing large weed infestations may exceed the value of the land itself.

Because tamarisk can be an indicator of other problems, land managers seeking to improve land quality must consider overall ecosystem management. Even when tamarisk itself

is a problem, simply removing it may do little to improve land and habitat quality. Effective management strategies for tamarisk need to consider both the causes of invasion at a site and the desired outcome of management efforts. Hydrological changes are likely to be important, and therefore must be taken into account, both when diagnosing the source of land degradation and when planning for its restoration.

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Identification, Habitat, and Biology

ANNA SHER

Identification

Tamarisk (*Tamarix* spp.), also called saltcedar, is a deciduous, loosely branched shrub or small tree that has fine, gray-green cedar-like foliage (**Figure 1, 2**). It has a shrub-like growth pattern and ranges in height from 5 feet to greater than

30 feet, depending on environment. Bark can be reddish on younger stems, aging to orange, brown or grey on older trunks (**Figure 3**). Main stems can reach as tall as 8 meters. Tamarisk produces thousands of whitish or pinkish flowers at the tips of the branches each spring and summer (**Figure 4**). Seeds are very small with



FIGURE 1. Most of the tamarisk in North America is a hybrid between *Tamarix ramosissima*, which is native to Russia, and *Tamarix chinensis*, which is native to China. In Eurasia the native ranges of these two species do not overlap; however, after the intentional introduction of both species into North America these two species have hybridized to form the tamarisk or saltcedar populations we see today. (Photo by Stephanie Gieck)



FIGURE 2. Tamarisk seedlings shortly after germination. (Photo by Joe DiTomaso)



FIGURE 4. Close-up of tamarisk flowers. Blooms can be white to deep pink, with some variants with an orange hue. Flowering tends to occur in pulses; however, a tree can be flowering and have fruits at all stages of development simultaneously. (Photo by Tim Carlson)



FIGURE 3. Heights can reach greater than 30 feet and diameters greater than 12 inches at the base are common. (Photos by Anna Sher)

BOX 1. SIMILAR IN APPEARANCE: THE ATHEL TREE

There is an evergreen species of tamarisk, the athel tree (*Tamarix aphylla*), which occasionally escapes from ornamental plantings and becomes established in hot deserts and along lake edges and river and stream bottoms of the United States; however, it does not appear to be nearly as invasive as the deciduous tamarisk species (Figure 5).



FIGURE 5. The athel tree, *Tamarix aphylla*, shown on the left, and a direct comparison of athel tree leaf structure with saltcedar on the right. The athel tree is much more common in the desert southwest and has become invasive around Lake Mead, NV. It is also considered highly invasive in Australia. (Photos courtesy of Joe DiTomaso, UC-Davis)

a parachute-type plume of fine hairs. The athel tree (*Tamarix aphylla*) is similar to tamarisk in appearance (See **Box 1, Figure 5**).

Habitat

Tamarisk is found throughout North America, but dense stands are most common in the West and Southwest. Tamarisk is usually found in areas where there have been surface flows, as a result of flooding or receding water tables, such as on the edges of rivers, reservoirs or irrigation ditches (**Figure 6**). It can tolerate highly saline soils, and generally prefers fine textured soils. Good drainage and lower salinity is more likely to create conditions under which tamarisk would be outcompeted by other, faster growing species (Sher et al. 2000, Sher et al. 2002). Conditions that promote establishment from seed include alkaline soils, high moisture and shallow water tables for the first few weeks in a

high-light environment with little competition from other plants, and a gradually receding water table (Everitt 1980, Sher and Marshall 2003). Tamarisk has deep taproots and can use ground water but is not dependent upon it. For this reason, plants usually grow where the depth to groundwater does not exceed 10-15 feet; however, where groundwater is deeper than 20 feet, plants may form an open shrubland (Horton and Campbell 1974) (**Figure 7**).

Biology

Tamarisk has many adaptations that allow it to colonize and survive harsh environments. As a halophyte, it is known to tolerate soils with EC (electroconductivity) greater than 30 mmhos/centimeter. Most salt is excluded from the roots during uptake (Nagler et al. 2008), but salts that are absorbed are exuded on the leaves via specialized structures called salt glands. Although



FIGURE 6. *This infestation in Dinosaur National Monument shows the classic growth patterns in a riparian environment. (Photo by Michelle DePrenger-Levin)*



FIGURE 7. *Tamarisk can also occur as sparse shrubland in more xeric sites like this one, near Pueblo, CO. (Photo by Stephanie Gieck)*

seedlings require a moist environment, once established tamarisk can survive in areas with deep water tables and periods of extreme drought (Pockman and Sperry 2000). Tamarisk's ability to regulate evapotranspiration by shutting down when water is unavailable allows it to survive drought conditions (Horton et al. 2001, Devitt et al 1997). Tamarisk is a facultative phreatophyte, meaning that it can use both groundwater and shallow unsaturated zones (soil that is above the water table). Tamarisk is highly resistant of above ground disturbance, such as fire or mechanical damage, because the primary growing tip (apical meristem) is located on the root crown, below the surface of the soil (**Figure 8**). Tamarisk seedlings are vulnerable to scouring floods; however, mature trees are highly tolerant of flooding.

Tamarisk spreads primarily through seed; one tree can produce millions of seeds for several months of the year. Buried or submerged stems or stem fragments will root, while field experiments have shown that tamarisk does not resprout from root material (T. Naumann personal communication). Tamarisk does not spread vegetatively by runners (P. Shafroth, personal communication).

Ecology

It is likely that tamarisk currently occupies millions of acres in the western U.S., in monoculture and also as a part of both riparian and upland plant communities. As detailed in the introduction, tamarisk's establishment and spread are highly associated with drought, high salinity and increased fire frequency and intensity; however, there is some debate as to whether it is the cause (e.g., Cleverly et al. 1997) or symptom (e.g., Shafroth et al. 2002) of these conditions. Altering natural rivers systems with



FIGURE 8. *Tamarisk readily resprouts after fire.*
(Photo by Anna Sher)

dams and preventing natural overbank flooding have changed many riparian environments to favor high-density tamarisk populations. While research suggests that mixed stands of tamarisk and native vegetation have high habitat value, particularly with regard to birds (Sogge et al. 2008), tamarisk monocultures are dramatically different from native bosque communities (Bateman et al. 2008, Whitcraft et al. 2008, Brand et al. 2008, Nelson and Wydoski 2008). As a mature tree, tamarisk effectively excludes establishment of native plant species, but as a seedling is not highly competitive (Sher and Marshall 2003, Sher et al. 2002). Taken together, current knowledge about tamarisk ecology suggests that hydrology is a key component of riparian management, and that promotion of native vegetation can help prevent the establishment of tamarisk monocultures.

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Part 2. MANAGEMENT STRATEGIES AND TECHNIQUES



DEVELOPING A MANAGEMENT PLAN
INTEGRATED PEST MANAGEMENT
CHEMICAL AND MECHANICAL CONTROL
BIOLOGICAL CONTROL

Developing a Management Plan

ANDREW NORTON

A weed management plan is a site-specific document that will guide you in the process of managing tamarisk and restoring desired landscape services on your property. Before you begin management or restoration actions, it is essential that you take time to identify the problems on your property, set goals for your planned management activities, determine how you will determine success, and weigh the costs and benefits of alternative management and restoration approaches. An effective management plan provides a road map for your activities and will allow you to set reasonable goals and estimate the resources you will need to achieve them. Managing tamarisk (or other weeds) is a multi-year process. By defining your goals before you start you will be able to determine if your activities are leading you towards your ultimate goal(s), or if you need to re-evaluate your management strategies or the resources you need to achieve success. In this way a plan is not a static, fixed approach, but a method for you to learn from your activities and make adjustments, if needed. This is *adaptive management*, and is an essential approach for any weed management activity.

Where to start...

Shafroth et al (2008) suggest that there are seven steps in implementing a *Tamarix* management project: (1) defining overall project goals, (2) developing realistic project objectives

that will meet these goals based on assessments of potential sites, (3) prioritizing sites and creation of a site specific restoration plan, (4) create a site specific restoration plan, (5) plan implementation, (6) monitoring and evaluating project success, and (7) engage adaptive monitoring. Sher et al. (2010) provide details on managing tamarisk invaded sites, particularly with regard to planning for plantings or assessing the likelihood of passive revegetation. Of the seven steps, the first two usually take the most time and thought to complete. These are also the most important steps in the development of a successful management plan.

Goals

Tamarisk management projects need careful planning before initiation and an explicit statement of goals for your site is a necessary first step. In many cases, tamarisk may be a symptom of other historical alterations of your site (e.g., altered stream or river flow patterns, salinization) and tamarisk removal will not by itself change these situations (Glenn and Nagler 2005). In other areas tamarisk may be a driver of environmental problems, and removal of the weed may lead to improvement of the site and attainment of your goals. There is a great deal of scientific discussion about whether tamarisk is a symptom or a driver of problems (see Shafroth et al. 2005 or Poff and Zimmerman 2010), and part of the difficulty in evaluating this controversy has been a lack of well defined goals for tamarisk removal efforts. Your goals should be



FIGURE 1. *The appropriate management approach depends on site conditions and goals. A low water, low diversity site dominated by native grasses (top), a medium water site with a predominantly native understory (center), and a low water site with a predominantly weedy understory (Russian knapweed and cheatgrass) and a mature cottonwood overstory (bottom). In the top two sites, strategies that minimize soil disturbance and herbicide overspray will preserve the desirable vegetation at the site. In the bottom example, protection of the large cottonwoods is essential. (Photos by Andrew Norton)*

Take Photos!

tip

Take them during the inventory, while implementing control techniques, and when you are doing any followup assessments. Take them from a similar point each time – flag the location or you can add your photo point to your inventory map. Photo monitoring is an easy, qualitative assessment of your efforts over time and is useful in demonstrating before and after differences.

specific to your needs, but may include such factors as: increased surface water, increased access to riparian areas, increased native plant abundance or diversity, improved viewsheds, greater recreational value of the landscape, reduced fire risk, increased abundance of wildlife, etc.

Objectives

Your objective(s) are the specific and measurable ways that you will reach your goals. They can only be developed after having taken into account the environmental factors at your site and the resources available for project completion. For example, if your goal is to develop or improve wildlife habitat, you may determine after your site assessment that one of your objectives is to create more structural complexity by establishing a particular density of cottonwoods and willows. In many, if not most cases, you will not have sufficient resources to complete all of your objectives at the same time. A series of well-defined objectives that break down the project into manageable units is often a good idea. These “units” may comprise separate physical locations or separate portions within the project area that you have identified as needing different control techniques. For example, if your goal is the restoration of native plants, areas with significant

populations of other noxious weeds may require additional herbicide applications to meet project goals. At sites with few other problem species, ensuring that your control tactics minimize soil disturbance and/or herbicide drift will increase your success rate. At this stage in plan development it is essential that you assess the physical and ecological characteristics of your site, and identify similar sites with successful or unsuccessful management results. When developing your objectives it is important that you incorporate any active or passive restoration techniques you will be using. Including this information in creating your objectives, along with a realistic assessment of your budget and management costs will go a long way towards increasing the chance for success for your project.

Monitoring and Evaluation

Make sure that you include a monitoring plan as part of your project. Monitoring plans can be as simple as a series of photographs from the same set of points through time, and as complex as a large series of replicated plots with measurement protocols for many responses, such as hydrologic processes and plants and animals. In general, your monitoring efforts need to give you the information necessary to determine if you are on track to meet the goals of your project. This information will then allow you to adjust your management or restoration techniques as your project proceeds. A suitable monitoring plan will also allow you to evaluate your project's accomplishments, and will allow you to determine if you have met your goals. This *evaluation* is important both to you—were your efforts worth the time and expense?—and to other individuals and organizations. Other property managers can learn from your experience, and if you have received grant funds for your project your plan will enable you to report your success in meeting project goals.

Tamarisk Management Plan for Small Properties

MODIFIED FROM COLORADO NATURAL AREA'S PUBLICATION *Creating an Integrated Weed Management Plan: A Handbook for Owners and Managers of Lands with Natural Values*

Purpose:

This is a simplified weed management template that is specifically designed for tamarisk management on small properties/areas. It is designed to help landowners and managers clearly articulate and record management goals, objectives, location priorities, and proposed actions as well as to document management results and equipment and labor costs that will help direct future tamarisk management. It is intended more for landowner's personal use and is not designed to "market" or "justify" a weed management plan to a board or organization, although it may provide the basis for a technical assistance request from cooperative extension office and/or federal or state-funded private land conservation programs.

Date:

Name of Landowner or Property:

Approximate Size of Property:

1. Management Goals:

Management goals describe the purpose/use of the property and what you are trying to achieve.

Management goal examples:

- Restore water flow in spring-fed pond to support livestock operation.
- Restore an area with native vegetation and promote wildlife habitat.
- Provide access to creek for livestock and wildlife uses.

Management Goal(s):

2. Tamarisk Management Objectives:

Objectives are derived from your management goals and describe your desired condition, or EXACTLY what you want to happen as a result of your time and effort. You can have just one management objective or several, but writing any objective requires that you have a basic inventory of tamarisk on your property and have determined how its distribution affects your overall management goals that you just stated. A properly crafted objective can be a simple sentence, but must be specific and measurable. Good objectives contain most or all of the following components:

- Species (or other indicator)
- Location
- Attribute (the thing that gets measured...number of plants, % cover)
- Action (decrease, increase, maintain)
- Quantity or status (by a certain number or %)
- Time Frame (by next spring, in 5 years, over 20 years)

Tamarisk Management Objective examples:

- Eradicate the tamarisk in Jack Spring by August 2009.
- Remove tamarisk along ¼ mile of stream bank on Little Bird Creek from pumphouse to north property boundary over the next 5 years.
- Increase native willow cover around east stock pond by 50% within 10 years to help prevent tamarisk establishment.

Tamarisk Management Objective(s):

Defining Control...

These terms are commonly misused when talking about weed management. For example, when someone says she is going to eradicate cheatgrass from her ranch, she has quite a task ahead of her! Here is how many states and agencies define weed “control”:

Eradicate – Completely eliminating all weed plants, including live roots, rhizomes, and seeds. Eradicating a weed species within a defined management area is very difficult unless it is present in very small populations or numbers.

Suppress – To reduce abundance of a weed species, typically as measured or estimated in terms of canopy cover or plant density.

Contain – To confine an infestation so it does not expand, but it does not usually mean reducing the current infestation.

3. Prioritizing Infestations:

Determine the management priority of each tamarisk infestation or location on your property. Record the location and priority number you assign to that infestation in the management table below. Highest priority infestations should be related to your management objectives. Other factors that may influence how you prioritize infestations include: current extent of tamarisk on or near your property, current and potential impacts of tamarisk to the value of certain areas on your property, and difficulty of control with regard to size of and access to infestations.

4. Determine which methods are available or are most appropriate for the size, distribution, and location of tamarisk infestations on your property.

Review the management techniques section in this handbook and determine which technique or combination of techniques you are going to implement for each infestation or area and when, if possible. Record your selected technique(s) in the table.

5. Evaluating Implementation Results:

After you have completed the techniques you have implemented, it is time to assess if your current strategy is moving you towards your stated management goals in Step 1. This requires followup visits to the areas where weeds were controlled and a reassessment of the size and density of an infestation. For example, compare the size of the infestation after a growing season has elapsed to the size before control actions were initiated. In many cases, complete control of an infestation will take several years. Expect to have to treat resprouts for several years after the initial technique to ensure complete kill of an individual. Compare what you observe now to what the infestation or area looked like originally, using photos, or re-map the area using the same map you used for the initial inventory. Record your observations in the table.

6. Analyzing the Overall Effectiveness of Your Tamarisk Management Plan (the “adaptive” in adaptive management):

After you have analyzed the control results (in some cases over the course of several years), you can determine if you are meeting your tamarisk management objective(s) and therefore achieving your management goal(s) for your property. Make sure to consider the cost of control compared to the benefits realized from the weed control. If your management objectives are not being met, actions should be modified. If the benefits of control did not outweigh the cost, it might be better to create new objectives or try other control methods. For example, it may be more cost effective to use containment and prevention techniques to maintain the current level of tamarisk infestations and to prevent an increase in new or existing infestations.

Tamarisk Management Planning Worksheet

Date: _____ **Approximate Size of Property:** _____

Name of Landowner or Property: _____

Management Goal(s):

Tamarisk Management Objective(s):

Priority of sites/infestations:

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Integrated Pest Management: Maximizing Control Success

EXCERPTED FROM *Colorado Natural Areas Program's
Creating an Integrated Weed Management Plan: A
Handbook for Owners and Managers of Lands with
Natural Values.*

As you review the techniques effective for tamarisk management described in this section, it is important to remember that no single management technique is perfect for all weed control situations. Most of the time combinations of multiple types of treatments provide more effective and economical control of weeds with fewer detrimental overall impacts to people and the environment (Sheley et al. 1999, DiTomaso 2000). This practice is called Integrated Pest Management (IPM) and is the application of many kinds of techniques in a mutually supportive manner that utilizes the strengths of different treatments while minimizing the weaknesses. It involves the deliberate selection, integration, and implementation of effective weed control measures with due consideration to economic, ecological, and sociological consequences. Often, a combination of techniques (mechanical, chemical, cultural, biological) is chosen that together will control a particular weed species or infestation efficiently and effectively, with minimal adverse impacts to non-target plants and animals.

IPM differs from ordinary weed management in that it attempts to address the ultimate cause of weed infestation, rather than simply focusing on controlling weeds (typically by using only herbicides) by combining two or more control actions which will interact to provide better

control than any one of the actions might provide. Simply killing tamarisk will not remove the root causes of tamarisk invasion or prevent future invasions. It requires a thorough understanding of the biology and ecology of the weed species and the environment before selecting appropriate control techniques, as well as more persistence and time than simply addressing the symptoms of weed infestation. However, the long-term rewards are far greater and should lead to greater success in meeting management objectives.

IPM strategies are often species- and site-specific, tailored to exploit the weaknesses of a particular weed species, and designed to meet the desired level of control and to be practical with minimal risk to desirable organisms and their habitats.

BOX 1. CHARACTERISTICS OF APPROPRIATE CONTROL TECHNIQUES

Appropriate control techniques ideally are:

<i>Applied at the most effective time</i>	Most control actions are effective only during certain periods of the target species' life cycle. Treatments should be applied at the point in the life cycle when it is most vulnerable, and at a time when the least damage will be done to its natural predators and other non-target species.
<i>Least damaging to non-target organisms, including natural weed control organisms</i>	Land managers should carefully consider the likely effects of available control techniques on both target and non-target species before deciding which combination of control measures to use. Non-target organisms may include sensitive species, native plant communities, wildlife, areas revegetated to control weeds, insect pollinators, insects that feed on target weed species, and plant species that compete with the targeted weeds. The select control actions must not significantly damage these non-target organisms or lead to the creation of further problems over the long term.
<i>Least hazardous to human health</i>	Chemicals should be carefully chosen and applied correctly to minimize their potential toxicity to humans. In fact, the reduction of unnecessary pesticide use is one of the driving forces behind the development of IPM. Successful weed management involves more than spraying weeds. Similarly, mechanical tools such as mowers and chainsaws can be dangerous if not handled properly.
<i>Least damaging to the general environment</i>	Careful selection and judicious use of herbicides is important to avoid environmental contamination, especially around water. Certain formulations can be used in or around aquatic situations or where the ground water is close to the ground surface if the product label and best management practices are followed. In addition, timing of herbicide application is important to maximize the effectiveness of the chemical on the target weed, as well as to reduce the possibility of adverse side effects.
<i>Most likely to reduce the need for weed control actions over the long-term</i>	Control techniques fall into two general categories: those that seek to prevent weeds from establishing, and those that deal with weeds that are already present. Preventative and cultural measures to reduce soil disturbances or to reduce the input of weed seeds to an area, reseeding existing disturbed lands, and altering grazing practices to promote more vigorous stands of perennial plants are actions which work to prevent weed establishment. Actions which address existing weeds include pulling, mowing, applying herbicide, prescribed fire, grazing or releasing biological control insects. Any combination of these actions that address the underlying causes of weed infestation and spread is likely to be the most beneficial for controlling weeds over the long run.
<i>Most easily implemented</i>	Control techniques that are easier to apply are more likely to be completed and repeatable, and therefore most likely to have a beneficial effect.
<i>Most cost-effective in the short and long term</i>	Consider the benefits and costs (both in terms of risk and money) of the possible control actions. For example, is the potential for spreading weed seeds by driving a vehicle into an area infested by weeds outweighed by the increased ease of controlling weeds?

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Chemical and Mechanical Control

SCOTT NISSEN

Tamarisk has two attributes that make control difficult: 1) it rapidly becomes a perennial, meaning the plant will re-grow if the top growth is removed; and 2) it produces vigorous regrowth from below-ground buds following mechanical removal, burial or fire. These two characteristics make it necessary to treat plants with a systemic herbicide or to remove the trunk down to a depth where no lateral roots are produced. This could be a few inches or several feet below the surface. For example, in areas of frequent flooding where trees are often buried by sediment, a tamarisk trunk may have the capacity to

re-grow from several feet below the surface.

Two herbicides, available as six commercial products, are labeled for tamarisk management (**Table 1**). While both herbicides are systemic (the herbicide moves in the plant from shoot to the root and root to shoot) there are situations where one herbicide formulation is more appropriate. Selecting the appropriate herbicide depends on: 1) type of application; 2) age, size and density of the tamarisk infestation; 3) the amount of native vegetation remaining on site; 4) available funding; and 5) overall management objectives.

Table 1. Systemic herbicides used for tamarisk control.

ACTIVE INGREDIENT	TRADE NAME (EPA Registration #)	FORMULATION lb ^{§ai} /gal	COMPANY
<i>Imazapyr</i> [‡] (signal word "Caution")	Habitat® (241-426)	amine salt 2 lb/gal	BASF
	Arsenal® PowerLine™ (241-431)	amine salt 2 lb/gal	
<i>Triclopyr</i> [‡] (signal word "Caution")	Garlon® 3A (62719-37)	amine salt 3 lb/gal	Dow AgroSciences
	Garlon 4 Ultra (62719-527)	EC [‡] 4 lb/gal	
	Remedy® Ultra (62719-522)	EC 4 lb/gal	
	Pathfinder II (62719-176)	EC 0.75 lb /gal	

[‡]Generic formulations of imazapyr and triclopyr are available.

^{§ai} stands for active ingredient

[‡]EC stands for emulsifiable concentrate. An emulsion is when one liquid is suspended in another liquid as small spheres. The Garlon 4 Ultra and Remedy Ultra formulations are the butoxyethyl ester of triclopyr, which have very low water solubility. These herbicides are applied as oil-in-water emulsion. These ester formulations are better at penetrating bark and that's why these formulations are used for basal bark applications.

Chemical and mechanical control are presented in the same section because they are often used together as the first step toward riparian restoration. The standard convention is to make the herbicide applications first and then use mechanical means to remove the resulting dead trees two years after treatment. For many large-scale applications this is probably the most economical option; however, for small areas with high aesthetic or recreational value removing the tree first and applying herbicides to the cut stump or subsequent re-growth is an alternative strategy. This strategy reduces herbicide use and limits herbicide residues to a much smaller percentage of the total area. In areas with desirable vegetation this could be particularly important. This strategy also allows immediate access to the site and works very well if there is still a cottonwood overstory.

Chemical Control

Imazapyr

Imazapyr is classified by the Herbicide Resistance Action Committee (HRAC) as a class B herbicide and by the Weed Science Society of America (WSSA) as a class 2 herbicide. These classifications relate to the herbicide's mode of action and are designed to help applicators and land managers rotate or combine herbicide modes of action. Rotating and/or combining herbicide modes of action reduces the risk of selecting for herbicide resistance.

Imazapyr kills plants by inhibiting an enzyme called acetolactate synthase (ALS) or acetohydroxyacid synthase (AHAS). This enzyme is the first step in the production of the branched chain amino acids; leucine, isoleucine and valine. Inhibiting amino acid production

results in the reduction or elimination of protein synthesis and this eventually stops plant growth. Shoot and root meristems (growing points) are sites where plant growth is the most rapid and herbicides like imazapyr move (translocate) from the site of absorption (leaves or roots) to these growing points. Imazapyr has nearly ideal chemical characteristics to move in the phloem to areas of rapid growth and this movement occurs with both root and shoot absorption. This is important because it means that spray droplets that are not intercepted by leaves can still contribute to long-term tamarisk control because the herbicide will be available for root absorption. There is a down side to imazapyr's excellent downward translocation. Imazapyr can translocate to tamarisk roots at high enough concentrations that the herbicide can be exuded from the root system. It can then be absorbed from the soil or via root grafts to cause injury to non-target species.

At the rates imazapyr is applied to control tamarisk it controls almost all grass and broad-leaf plants making it essentially non-selective. It provides limited control of thistles (Canada and musk thistle) and ALS-resistant kochia (*Kochia scoparia* L.). ALS-resistant kochia is very common in Colorado and is often the dominant annual weed species that invades tamarisk sites after imazapyr applications. The herbicide resistant biotypes were selected under annual cropping systems; however, the resistance gene is spread by pollen so resistant plants can be found miles from any crop fields.

Environmental Behavior

Imazapyr's residual soil activity has both positive and negative implications for tamarisk control and subsequent restoration efforts. Imazapyr's soil activity plays a part in achieving control;

however, imazapyr soil residues can delay restoration efforts. Sensitive restoration species can only tolerate a small amount of imazapyr in the soil. Therefore understanding imazapyr's environmental behavior is critical to developing restoration protocols with the greatest chance for success.

Imazapyr is water soluble and rapidly degraded by sunlight so imazapyr does not persist in water and the amount of time required

to reduce the imazapyr concentration by 50% (one half-life) in water is only 2-3 days (**Table 2**) (Mullipudi et al. 1991). Imazapyr on the soil surface is not degraded by sunlight, but is degraded primarily by microbial metabolism. Imazapyr's half-life in soil ranges from 25 to 142 days, while effective weed control can last from 3 months to 2 years depending on a number of factors (WSSA 2007). Any environmental parameter that influences soil microbial activ-

Table 2. Chemical characteristics that influence the environmental behavior and fate of imazapyr and triclopyr.

CHARACTERISTICS AND ENVIRONMENTAL BEHAVIOR	IMAZAPYR (Habitat®, Arsenal® Powerline™)	TRICLOPYR (Garlon Ultra™, Remedy Ultra™, Pathfinder II™)
Water solubility	11,272 ppm ¹	Free acid 430 ppm TEA ³ 234,000 ppm BEE ⁴ 6.8 ppm
Volatility	Very low; non-volatile 9.7×10^{-12} mmHg ²	The TEA formulation is essentially non-volatile; however, the BEE formulation is volatile above 80°F TEA 3.6×10^{-7} mmHg BEE 3.6×10^{-6} mmHg
Soil Adsorption	Weakly bound to soil, adsorption increases at soil pH below 6.5 and increases with high clay and organic matter content	Not tightly bound to soil, high organic matter and high clay soils can increase absorption and reduce biological availability, increasing persistence
Degradation and Persistence		
Half-life ⁵ in water	2-3 days, rapidly degraded by sunlight	1.3 days, rapidly degraded by sunlight
Half-life in soil	25-142 days (field studies); herbicide residues may injure vegetation for three months to two years depending on rate, soil type and environmental conditions.	30 days (average); ranges from 10-46 days depending on soil properties, moisture and temperature
Leaching Potential and Mobility	Remains in the upper 20 inches of soil. There is little evidence of lateral movement.	Vertical movement is very low. Lateral movement is also very limited.

¹ppm stands for parts per million

²mmHg stands for millimeters of mercury, which represents vapor pressure; vapor pressure indicates a herbicide's potential to become a vapor, the smaller the number the less volatility.

³TEA stands for Triethylamine salt; ⁴BEE stands for butoxyethyl ester

⁵Half-life refers to the amount of time required for the herbicide concentration to decrease by 50%

ity will affect imazapyr's half-life. Warm soil temperatures and good soil moisture will result in more rapid degradation and shorter residual activity, while cool, dry soil conditions would extend imazapyr's residual activity (Mangels 1991). In Colorado, soil degradation will not occur during the winter, and this will significantly extend imazapyr's residual activity. Imazapyr is weakly bound to soil; however, several factors can significantly influence its biological availability and vertical movement in the soil profile (Vizantinopoulos and Lolos 1994). Soils with high organic matter and low pH will bind more imazapyr than low organic matter and high pH soils. The more imazapyr that is bound to organic matter the longer the residual soil activity because the herbicide is not available for degradation by soil microorganisms.

Triclopyr

Triclopyr is classified by HRAC as a class O herbicide and by the WSSA as a class 4 herbicide. Triclopyr is a pyridine carboxylic acid herbicide, related structurally to picloram (Tordon), clopyralid (Transline) and aminopyralid (Milestone). All class O or class 4 herbicides are synthetic auxins. Plants contain a natural auxin called indole-3-acetic acid or IAA. At low concentrations these synthetic auxin herbicides can produce many of the same physiological responses as the naturally occurring IAA; however, at higher concentrations they cause many disruptions in normal plant growth and susceptible plants (dicots, a.k.a. broadleaf plants) eventually die. Plants treated with triclopyr or any synthetic auxin herbicide will show symptoms such as stems binding or twisting, abnormal leaf formation, shoot desiccation and wilting. Plant death can take several weeks or longer for a large plant like tamarisk. The plant functions

mediated by IAA are so varied and so fundamental to proper growth and development that even after using synthetic auxin herbicides for over 50 years there are very few examples of weeds that are resistant to this mode of action.

Triclopyr is more selective than imazapyr. Established grasses are generally very tolerant to triclopyr; however, cottonwoods and willows will be injured by inadvertent drift and potentially by herbicide exuded from the root system of treated plants. Triclopyr is rapidly absorbed by shoot and root tissue (especially the butoxyethyl ester) and plants rapidly convert the butoxyethyl ester to the free acid, which is the active form of the herbicide (Ganapathy 1997). Triclopyr translocates out the treated shoot and accumulates in the root system, but not to the same extent as imazapyr. While triclopyr does not have imazapyr's residual soil activity, triclopyr that is root absorbed will move (translocate) to the shoot.

Environmental behavior

The commercial formulations of triclopyr are the butoxyethyl ester (BEE) and the triethyl amine salt (TEA). Both the ester and salt forms are rapidly converted to the active form, triclopyr acid, by hydrolysis in soil and water. The acid form is readily degradable in water by UV light with a half-life of 1.3 days (**Table 2**) (Woodburn et al. 1993). As with imazapyr, soil degradation is microbial and the degradation rate is dependent on soil moisture and temperature. In warm, moist soils the degradation rate would be faster than under cool dry conditions. High organic matter soils bind more triclopyr making less biologically available, increasing persistence. Triclopyr's reported half-life in soil is between 10 to 46 days, but triclopyr can persist for 1 to 2 years in cold climates due to a lack



FIGURE 1. Helicopter making a 15 gallon/acre application and in this case avoiding a cottonwood tree. This helicopter carries about 70 gallons of spray solution. At 15 gallons/acre only 4 acres can be treated with a single load. The insert shows that the droplet size and spray pattern using water sensitive paper and an "artificial plant". This helicopter is operated by Olathe Spray Service, Inc., Olathe, CO. (Photos by J.R. Phillips)

of microbial activity (WSSA 2007).

In some systems that classify the mobility of organic compounds, triclopyr's mobility is considered to be very similar to 2,4-D (Hamaker 1975). This would characterize triclopyr as a mobile herbicide; however, triclopyr is subject to time dependent binding, this means that over time the herbicide binds more tightly to the soil (Butler et al. 1993). This significantly reduces triclopyr's vertical and lateral movement in soil. Several field studies indicate that even with high application rates triclopyr does not move below six inches even in bare ground plots (Butler et al. 1993).

Application Methods

Aerial application

Imazapyr is the only herbicide that provides consistent tamarisk control when applied by fixed wing aircraft or helicopter. In Colorado, fixed wing applications are generally not practical because there are very few large, contiguous, monotypic tamarisk infestations. Helicopter applications are very effective because higher application volumes can be used (10-15 gallons/acre) and this significantly reduces off-target spray drift to desirable vegetation. Helicopter applications are made at much slower air speed (30-50 miles per hour) compared to fixed wing aircraft. Native vegetation can be avoided during application due to the slow air speeds and very large spray droplets (**Figure 1**).



FIGURE 2. Tamarisk infestation found on an upland watershed near Florence, CO. A 30 ft swath of imazapyr was applied by helicopter at a rate of 64 ounces/acre with 1 % MSO in 15 gallons of water the previous fall. This picture was taken 12 months after treatment. Control was >95% when compared to the non-treated areas. This application method nearly eliminates off target drift due to the size of the spray droplets. (Photo by Stephanie Gieck)



FIGURE 3. This tamarisk is showing typical imazapyr injury symptoms the summer following aerial applications. This is an indication that herbicide is still active in the plant. When new shoots try to initiate growth in the spring enough herbicide is present in the plant that it moves to the new site of active growth and stops the new shoot from developing. Eventually these resprouts die, so by 12 months after treatment the entire plant appears dead. If you see new branches elongating that generally means that the plant will recover. (Photo by Scott Nissen)

The standard helicopter treatment is 64 ounces of imazapyr (1 pound of active ingredient) plus 1% (volume/volume) non-ionic surfactant (NIS) or methylated seed oil (MSO) applied in 10-15 gallons of water per acre. This method has proven to be the most consistent in New Mexico and in several Colorado locations (**Figure 2**). Across many different environments, this treatment has provided consistent tamarisk control, usually >90% when applications are made in August and early September. These applications should always be made to actively growing tamarisk.

In Colorado, very high populations of the tamarisk leafhopper (*Opsius stactogalus*) (see Figure 7, Biological Control section) tend to occur in early September to the point that the tamarisk begins to turn yellow and drop a significant amount of foliage. This can significantly reduce herbicide efficacy. Scheduling aerial

BOX 1. SOME ITEMS TO REMEMBER WHEN CONSIDERING HELICOPTER APPLICATIONS FOR TAMARISK MANAGEMENT

- **The more acres treated over the shortest time period will result in the lowest cost/acre;** however, it is difficult to suggest a minimum number of acres that make for a cost effective application. The Upper Arkansas Regional Weed Management Cooperative has organized cost effective tamarisk spray programs for as little as 300 acres. In 2007, it was possible to spend as little as \$150-180/acre for an aerial imazapyr application; however, with fluctuating fuel and chemical costs it is difficult to predict the cost of future applications.
 - **Aerial applicators will charge transportation costs and per diem for the pilot and the ground crew.** This provides an incentive to treat as many acres as possible so that these costs can be shared by the greatest number of landowners, spreading out the cost over the largest number of acres.
 - **The more contiguous the site the faster it can be treated.** Treating a number of small infestations is not as cost effective as treating a large contiguous area due the cost of moving support vehicles and transporting the helicopter between sites.
 - **Accessibility is very important in reducing costs.** Having the support vehicles stage close to the treatment area reduces the amount of time spent flying to and from the site (**Figure 4**).
 - **Applying 15 gallons of water per acre significantly increases application costs because most helicopters are only able to treat between 4 and 8 acres per load.** This means a significant amount of time flying to and from support vehicles rather than treating tamarisk. Several commercial applications have had excellent results using 10 gallons/acre. Reducing application volumes from 15-10 gallons/acre would reduce applications costs without compromising control.
 - **Habitat® should be used if there is any potential for inadvertent contact with water because Habitat® has an aquatic label.** Arsenal® Powerline™ should be used on upland sites.
-



FIGURE 4. Having good access near the tamarisk site is important in reducing application costs. This particular setup is operated by Front Range Helicopter, Johnstown, CO. A specially designed support vehicle carries water and aviation fuel, and mixes the herbicide for each load. It takes less than 5 minutes to reload the helicopter, and since application costs are charged by the amount of time the helicopter is actually in the air, the closer the helicopter support equipment can setup to the actual site of application the less expensive the application. (Photo by Scott Nissen)



FIGURE 5. Backpack sprayer properly labeled as a service container. The last line describing how the active ingredient was amended for application is not required by USEPA; however, it is useful information. (Photo by Joe Vassios, CSU)

applications for late August rather than early September would be one way to avoid this situation. Stress from leafhopper feeding reduces herbicide absorption by reducing retention of the spray solution.

Ground Application

Ground applications are often made by an applicator carrying a backpack sprayer or a squirt bottle. Once an herbicide is transferred to a secondary container that can be carried by an individual it is considered a service container. The USEPA has specific requirements about how a service container is to be labeled (**Figure 5**).

FOLIAR APPLICATIONS

For individual plant foliar applications, imazapyr is the most effective herbicide (**Table 3**) (Duncan and McDaniel 1998). This treatment works well when applied to multi-stemmed tamarisk less than 10 feet tall. Plants should be sprayed to wet from several sides making sure to spray the terminal ends of branches, including blooms. This application works very well

BOX 2. EPA REQUIREMENTS FOR HERBICIDE LABELS

The EPA requires that herbicide containers be labeled in the following manner:

- **Name of the responsible party** (This could be the commercial applicator or person supervising the application or a private landowner.)
- **The herbicide's trade name**
- **The active ingredient** (imazapyr or triclopyr)
- **The signal word** (In the case of these two herbicides the signal word is "Caution" which is the lowest acute toxicity level)
- **The EPA registration number** (see **Table 1** of this section)
- An additional recommendation would be to indicate **how the original formulation has been altered**. Indicate the dilution and any surfactants, oils or dyes that may have been added to produce the treatment solution. Once the original herbicide has been mixed with carriers it cannot be returned to the original container. Pathfinder RTU and any undiluted herbicide can be returned to the original container.

for isolated plants, treating regrowth following mechanical removal, or treating the occasional resprout following aerial applications. The best time for these treatments is August or September. Imazapyr is applied as a 1% solution with 1% MSO. While a backpack sprayer works well for scattered plants, treating large numbers of plants per acre is more efficient with an ATV or truck mounted sprayer equipped with a retractable hose. In Colorado, >95% control has been achieved by treating tamarisk regrowth following mechanical removal using imazapyr and MSO. In field studies comparing applications to foliage from one versus two growing seasons,



FIGURE 6. An example of what happens following individual plant foliar treatments made to plants after one season versus two seasons of regrowth. Tamarisk regrowth on the right was treated with imazapyr one year after mechanical removal, while tamarisk regrowth on the left was treated two years after mechanical removal. The site is near Florence, CO and living trees were cleared mechanically in 2004. The top picture was taken in 2006 and bottom picture was taken in 2007. Both treatments provided 100% control 12 months after treatment and several cottonwoods in the background were unaffected by the treatment. (Photos by Scott Nissen)

Table 3. Foliar application methods for tamarisk control with imazapyr herbicides (*Habitat*[®] or *Arsenal*[®] *Powerline*[™]).

TREATMENT TYPE	RATE	TIMING	COMMENTS
<i>Aerial</i>	<ul style="list-style-type: none"> • 64 oz/ac imazapyr • 1% NIS or MSO • 10-15 gallons/acre application volume recommended 	Apply August or September	Across many environments this treatment has provided excellent control, provided trees are left undisturbed for two years.
<i>Individual plant foliar treatment</i>	<ul style="list-style-type: none"> • 1% imazapyr + 1% MSO • 1.3 oz product/1 gallon is approximately 1% 	Apply August and September	Spray foliage to wet from several sides, treatment works well treating regrowth following mechanical control or resprouts following aerial applications.

long-term control (greater than 24 months) was >95% for both treatments (**Figure 6**). The major advantage to this strategy is that it limits the amount of herbicide in the soil. With careful application desirable vegetation will not be affected and site restoration can begin immediately.

BASAL BARK TREATMENTS

Low volume basal bark treatments involve treating all sides of the tamarisk stems from the soil surface to a height of 12-18 inches with oil soluble formulations of triclopyr or compatible formulations of imazapyr (Parker and Williamson 2003). Basal bark treatments can be applied just about anytime of year; however, late fall and early spring applications are best because there is very little foliage to intercept the spray solution. Another advantage to late fall and early spring timing is that many desirable plants will be dormant, improving selectivity.

The oil soluble forms of triclopyr (*Remedy*[®] *Ultra*, *Garlon*[®] 4 *Ultra*) are mixed with a penetrating bark oil like *JLB Oil Plus* and applied to tamarisk stems (**Table 4**). In riparian sites the vegetable-based *JLB Oil* should be used instead

of petroleum-based penetrating oils. The recommended triclopyr concentration for low volume treatments is from 20-30% using oil to dilute the herbicide to the desired concentration; however, for larger stem diameters a 1:1 ratio of triclopyr to oil will improve control.

Another option is the oil compatible formulation of imazapyr, *Stalker*[®] (**Table 4**). While imazapyr is not generally considered to be soluble in oil, this formulation can be mixed with water or penetrating bark oil. Agitation is important to maintain *Stalker* as an emulsion and prevent phase separation. For low volume basal bark applications the oil compatible formulation of imazapyr can be applied at a concentration of 6-9% diluted with oil.

The smooth bark should be wetted from all sides. With young trees the smooth bark will start at the soil surface; however, basal bark applications can be successful on older tamarisk where the smooth bark could be 5-7 feet from the ground (Dr. Ken Lair, personal communication). As long as the application is made to smooth bark enough herbicide is absorbed to kill the tree. Bark that has become thick, corky and furrowed should not be treated. Basal bark

Table 4. *Herbicides used for low volume and thinline basal bark applications.*

APPLICATION PARAMETERS	*REMEDY ULTRA™ *GARLON®4 ULTRA™	PATHFINDER II™	STALKER®
Low Volume Treatment	<ul style="list-style-type: none"> Dilute 26-38 oz of herbicide (concentration 20%-30%) to one gallon with JBL bark oil or other oil carrier specified on the label. Treat a 12-18 inch band of smooth bark. In some situations a 1:1 ratio of herbicide to oil may provide more consistent results. 	<ul style="list-style-type: none"> Use undiluted product to treat a 12-15 inch band of smooth bark. 	<ul style="list-style-type: none"> Dilute 8-12 oz to one gallon with penetrating oil (concentration 6-9%). Spray to wet the lower 12-18 inches of smooth bark. Agitate frequently to maintain emulsion.
Thinline Treatment	<ul style="list-style-type: none"> Use undiluted product and apply as a narrow stream around the stem. Apply to smooth bark only. 	<ul style="list-style-type: none"> Use undiluted product and apply a narrow stream around the stem. Apply to smooth bark only. 	<ul style="list-style-type: none"> Dilute 24-48 oz in to one gallon using penetrating oil (concentration 19-37%). Make a zig-zag pattern rather than a straight line around the stem; this will increase the area of the treated surface. Agitate frequently.
Tamarisk Stem Diameter	<ul style="list-style-type: none"> ≤ 6 inches 	<ul style="list-style-type: none"> ≤ 2 inches 	<ul style="list-style-type: none"> ≤ 4 inches at breast height for low volume. ≤ 3 inches at breast height for thinline.
Volume Per Acre Per Year	<ul style="list-style-type: none"> Low volume concentrations of 30-20%, 7-10 gallons of diluted herbicide can be applied. Undiluted thinline application allows for 2 gallons. 	<ul style="list-style-type: none"> 10.7 gallons of the ready to use (RTU) formulation can be applied per acre. 	<ul style="list-style-type: none"> A total of 96 oz of Stalker® can be applied per acre. For low volume applications, 8-12 gallons of diluted herbicide can be applied per acre. For thinline applications 2-4 gallons of diluted herbicide can be applied per acre.
Use Pattern	<ul style="list-style-type: none"> Treat low to moderate stem density and undisturbed trees with stems up to 6 inches in diameter. Always make applications to smooth bark. This could be at ground level or at chest height or higher. 	<ul style="list-style-type: none"> Use to treat young plants with stem diameter of 2 inches or less. Common uses include re-growth following mechanical removal or the occasional re-sprout following aerial applications. 	<ul style="list-style-type: none"> Agitation is very important to maintain emulsion of Stalker® in penetrating oil. Treat low to moderate stem densities, do not treat sites with high densities of resprouts resulting from mowing operations.

*Remedy Ultra and Garlon 4 Ultra are new triclopyr formulations with vegetable oil-based carriers. The older formulations used petroleum-based carriers.

treatments generally work best on tamarisk trunks less than 6 inches in diameter.

Another application technique is called thinline basal bark. Thinline treatments are just as the name implies: rather than treating 12-18 inches of the lower trunk using a flat fan or cone nozzle, undiluted triclopyr is applied as a narrow stream around the trunk. Gravity then carries the treatment solution down the trunk until a band about 2-3 inches wide is created. The amount of triclopyr or imazapyr applied per stem is similar for both applications.

Pathfinder® II is a ready to use (RTU) triclopyr formulation developed specifically for basal bark and cut stump treatments. This formulation contains 13.6% triclopyr (0.75 pounds active ingredient triclopyr per gallon) so it is most appropriate for tamarisk stem diameters of 2 inches or less. Tamarisk resprouts after mechanical removal could be less than two inches in diameter even after two full growing seasons. Pathfinder's major advantages are: 1) there is less handling; 2) there is no mixing; and 3) unused product can be returned to the original container for storage.

Because applications are made to plant parts that will not be grazed, the maximum amount of triclopyr that can be applied per acre per year is 8 pounds active ingredient. At the recommended concentrations for low volume applications this allows for 7-10 gallons of dilute product (30-20%, respectively) to be applied as basal bark treatment per acre. Assuming an application rate of 6-8 ounces per plant, this enough spray volume to treat 100-200 plants per acre. For thinline applications the amount of Garlon® Ultra or Remedy® Ultra is 2 gallons per acre, since the product is undiluted. The amount of Pathfinder RTU that can be applied per acre is 10.7 gallons.

The total amount of Stalker that can be applied per acre is 3 quarts (1.5 pounds active ingredient of imazapyr). Using a concentration range of 6-9% for the low volume applications, 8-12 gallons of dilute herbicide can be applied per acre. For the thinline treatments the concentrations are much higher (19% to 37%), so the amount of diluted herbicide that can be applied per acre is much less, only 2-4 gallons per acre. One thing to remember with the oil-compatible formulations of imazapyr is that the product forms an emulsion, so agitation during the application process is important.

Basal bark treatments are less labor intensive than cut stump treatments because there is no requirement to cut and remove the tamarisk. The major disadvantage is that more chemical is used per acre compared to cut stump treatments because significantly more surface area is being treated.

A word of caution is warranted about using triclopyr ester formulations. While there is cautionary language on the Garlon®4 Ultra and Remedy® Ultra labels regarding the potential for herbicide volatility, it is worth mentioning that injury to non-target plants is possible due to off-target vapor drift when using these herbicides. Most herbicides formulated as esters will have some volatility and occasionally even an herbicide's free acid can be volatile. Dicamba is probably the best example of a volatile, free acid herbicide. The lipophilic (fat-loving/oil soluble) nature of triclopyr butoxyethyl ester is an important characteristic that allows this herbicide to penetrate tamarisk bark.

Triclopyr butoxyethyl ester does not have a particularly high vapor pressure compared to say 2,4-D esters (**Table 2** this section); however, under the right circumstances vapor drift can occur. Vapor drift is different from droplet drift

Table 5. *Herbicides used for cut stump applications.*

APPLICATION PARAMETERS	TRICLOPYR (Garlon®3A, *Garlon®4 Ultra, *Remedy® Ultra)	IMAZAPYR (Habitat®, Arsenal® Powerline™)
Concentration	<ul style="list-style-type: none"> Dilute Garlon®3A 1:1 with water or use undiluted Dilute 26-38 ounces of Garlon®4 Ultra to one gallon with penetrating oil (concentration 20-30%) 	<ul style="list-style-type: none"> Dilute 8-12 oz of Habitat® plus 1% MSO or penetrating bark oil to a volume of one gallon The concentration range will be 6% to approximately 10% For more consistent results use the 10% solution
Timing	<ul style="list-style-type: none"> Apply any time but avoid spring when tamarisk is actively growing 	<ul style="list-style-type: none"> Apply any time but avoid spring when tamarisk is actively growing
General Comments	<ul style="list-style-type: none"> For cut stump applications a total of 2.67 gallons of Garlon®3A can be applied per acre Diluted 1:1 with water means 5.3 gallons of diluted herbicide could be applied per acre For Garlon®4 Ultra and Remedy®Ultra 7 to 10 gallons of diluted herbicide can be applied per acre Treat the outer two inches of the trunk (cambium), sides of stump and root collar 	<ul style="list-style-type: none"> A total of 96 ounces of Habitat® can be applied per acre For cut stump applications, 8-12 gallons of diluted herbicide can be applied per acre Labor costs mean this treatment is probably better for smaller infestations or isolated trees in mixed stands (same as for triclopyr) Be careful not to over-apply; this will increase the potential for injury to non-target species (same as for triclopyr)

*Remedy® Ultra and Garlon® 4 Ultra are new triclopyr formulations with vegetable oil-based carriers. The older formulations used petroleum-based carriers.

and particle drift. Herbicide volatility and subsequent vapor drift occurs most often when herbicides are applied to non-absorbing surfaces; however, since absorption into bark is not 100% it is possible to have vapor drift from basal bark applications. Air temperatures above 80°F will cause an increase in volatility, but it is not just higher air temperatures that can increase vapor drift. The temperature of the sprayed surface can also increase volatility. It is possible that, even on days with air temperatures are below 80°F, the temperature of a dark surface in full sunlight could be significantly higher than 80°F. In addition, vapor drift can occur hours after the application was made, so that making basal bark applications during the coolest part of the day does not completely guard against vapor drift. As air and surface temperatures increase so does the possibility of vapor drift.

CUT STUMP TREATMENTS

The idea is to cut the tamarisk trunk as close to the soil surface as possible using a chain saw followed by treating the outer 2 inches of the trunk with a systemic herbicide containing imazapyr or triclopyr. There is no need to treat the entire surface. The stump should be cleaned of sawdust before herbicide applications are made and the treatments should be applied within an hour (treating the stump within minutes is preferred). If stumps are not treated quickly the herbicide will be less effective.

Chain saw operations should be conducted by trained individuals, using proper safety equipment. A trained and experienced chain saw operator will be more efficient and the more horizontal the cut the more thoroughly the herbicide can soak in and the less likely it is to run off.

Like basal bark applications, cut stump treatments can be made just about any time of year;

however, it is best to avoid spring applications when tamarisk is growing rapidly (**Table 5**). Cut stump treatments are significantly more costly than basal bark applications because of the labor associated with tamarisk removal.

Any type of herbicide application made under the dripline of sensitive species like cottonwoods has the potential to cause injury. Applicators need to be very careful not to over-treat the target species. Inadvertent spray drift, root exudation and root grafting are three major pathways that can expose non-target plants to these herbicides. Spray drift is probably the most obvious way these herbicides will kill sensitive non-target plants and injury resulting from spray drift will develop soon after application. Root exudation, root grafting or excessive soil residues can injure or kill willows and cottonwood, but the symptoms will take much longer to develop.

Mechanical Control

Removing tamarisk stumps by first cutting the root crown several feet below the soil surface (root plowing) and then raking the cut stumps (root raking) into large slash piles is very costly and destructive. Mechanical operations provide an opportunity for secondary invaders such as cheatgrass, Russian knapweed and perennial pepperweed to become established because the site is heavily disturbed. In Colorado, there are very few situations where this expense could be justified; however, removal of tamarisk biomass will probably be necessary at some point during the restoration process, except in the case of very scattered infestations (**Table 6**).

The most appropriate mechanical control options in Colorado are the use of what are called site preparation tractors or skid steers equipped with forestry mulching attachments. One example is the Prentice™ Hydro-Ax which



FIGURE 7. A site preparation tractor equipped with a forestry mulching head clears tamarisk on the upper Arkansas. In the foreground is a mulched tamarisk next to a cottonwood. This management tool can be highly selective, but is expensive. When mulching live trees resprouts should be treated the following year. (Photo by Stephanie Gieck)



FIGURE 8. Example of coarse mulch produced with mulching equipment. (Photo by Stephanie Gieck)

is a large, articulated tractor designed for the logging industry and adapted for brush and tree clearing when equipped with a mulching attachment (**Figure 7**). This hydraulic driven, rotating drum attachment is equipped with replaceable carbide-tipped blades or teeth that can clear a swath from 6-10 feet wide. These articulated tractors range in horsepower from 185-260 and have the hydraulic power necessary to mulch any tamarisk on site (**Figure 8**). The Hydro-Ax can mow or chip living or dead tamarisk at the rate of about one acre per hour on level terrain.

Table 6. General information and relative cost associated with mechanical mulching and individual tree extraction equipment used for tamarisk biomass removal.

EQUIPMENT	SIZE	APPLICATION	APPROXIMATE COST
Skid steer with TimberAx™, Fecon™ or some other forestry mulching attachment	<ul style="list-style-type: none"> Weight is 6K-10K lbs with 60-90 hp Mulching attachment is about 2K lbs Cutting width is around 6 ft. 	<ul style="list-style-type: none"> Hydraulic power limits this size unit to continuous use on tamarisk up to 3.5 in. diameter and occasional use of trunks to 8 in. diameter. 	<ul style="list-style-type: none"> Costs range from \$100-\$150 per hour with the cost per acre ranging from \$200-\$600. Cost per acre depends on terrain, tamarisk density and size. Transportation costs generally charged at lower rate per hour.
Site preparation tractor like a Prentice™ Hydro-Ax with a Fecon™, Woodgator™ or some other forestry mulching attachment	<ul style="list-style-type: none"> These machines can be massive. Weight range from 26K-32K lbs with 185-260 hp Mulching attachments ranges from 3K-8K lbs Cutting width from 6-10 ft 	<ul style="list-style-type: none"> Hydraulic power is generally not a limiting factor for these machines. Large trees can be mulched on site and they can work continuously on any sized tamarisk. 	<ul style="list-style-type: none"> Cost approximately \$350 per hour with the cost per acre ranging from \$350-\$1000. Cost per acre depends on terrain, tamarisk density and size. These large units are more expensive per hour, but can move faster so may actually cost less per acre. Transportation costs can be much higher for this type of equipment.
Track hoe, crawler excavator or hydraulic excavator equipped with a modified bucket adapted for whole tree extraction (Examples: Komatsu PC228, Caterpillar 320D series or Deere 200D)	<ul style="list-style-type: none"> Medium sized excavators weighing 44K-80K lbs with 149 to 268 hp Effectively extracting trees in a 50-ft swath 	<ul style="list-style-type: none"> Removes most size trees with the crown intact Trees are piled or windrowed for future mulching or burning. Works well in mixed stands since individual plants are easily removed Can extract trees inside irrigation ditches or from river and stream banks 	<ul style="list-style-type: none"> Cost per acre depends on terrain conditions and stand density Extraction and piling can range from \$350-\$750 per acre Combinations of extraction and mulching range from \$1250-\$2000 per acre These costs do not include followup herbicide treatments for regrowth^A

^A All mechanical removal procedures will require followup herbicide treatments to control resprouts from roots and buried stems.

On difficult terrain it can take much longer to mulch large tamarisk so the cost per acre can be much higher.

For small areas or scattered stands of tamarisk with average stem diameters of 3.5 inches or less the smaller skid steer equipped with a TimberAx™ mulching head is another option. These units have limited hydraulic power that

limits their ability to take down large trees; however, they are highly maneuverable, cost less per hour than the larger Hydro-Ax, and are less expensive to transport. Remember that cost per hour is not necessarily a good indicator of the cost per acre. In rough terrain or with large diameter trees a smaller skid steer could take much longer to do the same job. Make sure you



FIGURE 9. One main advantage of this type of equipment is the ability to remove a tamarisk understory from a cottonwood gallery forest. This helps to reduce fire danger and allows for the establishment of more desirable understory species. The pile of coarse mulch in the foreground was a tamarisk. (Photo by Scott Nissen)

match the equipment to the task for the best results. Mechanical removal can be very desirable if there is significant cottonwood overstory (**Figure 9**).

Individual tree extraction is an alternative to using a forestry mulching attachment for removal to tamarisk biomass (**Figure 10**). This technique has been used successfully all over the southwest for tamarisk, Russian olive, pinyon pine, and mesquite removal. The excavator boom can reach places that are inaccessible to other equipment. Extracted trees are placed in large piles or windrows to be burned (**Figure**



FIGURE 10. An example of individual tamarisk extraction using a track hoe. Notice that most of the crown has been removed. (Photo by Charlie Hart, Texas A&M)



FIGURE 11. Stream bank following tamarisk removal using a track hoe. This windrow will eventually be burned or mulched. The amount of biomass from a heavy tamarisk infestation could be as high as 100 tons to the acre. (Photo by Charlie Hart, Texas A&M)

11). If burning is not feasible then trees can be extracted and mulched in separate operations. The combined cost of extracting and mulching is over \$1000 per acre and there is still the additional cost of treating tamarisk sprouting from broken roots and buried stems. There is



FIGURE 12. *This is why follow up herbicide treatments are necessary for sites where the tamarisk has been removed by extraction. Root pieces and buried stems can easily re-sprout and re-infest cleared areas. (Photo by Charlie Hart, Texas A&M)*

more soil disturbance using the individual tree extraction technique and large divots need to be backfilled following tree removal.

The main advantages to this technique are that less herbicide is needed per acre as followup treatments and it works well in mixed stands of cottonwoods and willows. Extraction is even more surgical than mulching. Removing the entire tamarisk crown limits regrowth to smaller diameter root pieces and buried stems (**Figure 12**), which are easier to control than resprouts growing from large crowns.

Tamarisk, Fire, and Secondary Invaders

Tamarisk is well adapted to survive frequent fires. In fact, the interval between fires in a tamarisk dominated plant community is significantly shorter than for a cottonwood gallery forest (DiTomaso 1998). While tamarisk is not as competitive as cottonwoods and willows (Sher et al. 2000), this increase in fire frequency gives tamarisk a significant advantage.

A tamarisk understory can provide a significant amount of fine to medium, woody fuels of sufficient biomass to allow a fire to bridge to the tops of large cottonwoods. These are sometimes called ladder fuels. In addition to the fuel provided by the tamarisk, fine fuels consisting primarily of weedy annual grasses and leaf litter may also be present.

Fire would appear to be an ideal tool to remove tamarisk biomass followed by individual plant treatments of resprouts or to remove tamarisk biomass after aerial herbicide applications. Large areas could be cleared using a prescribed burn at lower cost per acre than mechanical removal. The problem is that tamarisk's response to fire can be unpredictable. There are reports that fire has caused what appeared to be dead tamarisk to re-sprout, while the same scenario in a different location had no effect (K. McDaniel, personal communication). There are also reports from the field that tamarisk regrowth resulting after a fire can be more difficult to control with herbicides than regrowth resulting from mechanical removal (K. Lair and S. Simmons, personal communication). To date there are no definitive studies to explain the impact of fire on tamarisk physiology; however, the high frequency of an unusual growth form called fasciation (the fusing of stems) is one indication that the plant's physiology has been affected (**Figure 13**). The take-home message is that tamarisk resprouts vigorously after fire (**Figure 14**) and the best role for fire in the management of tamarisk biomass may still need to be identified.

Another common problem when a tamarisk site burns is the fact that fire-hardened stumps can sometimes puncture standard tractor tires (**Figure 15**). To avoid this problem special solid tires and track vehicles are often used when working a tamarisk site following a fire.

Even an intense fire may not eliminate stand-



FIGURE 13. The unusual growth form called fasciation that often occurs after a tamarisk stand is burned. The physiological cause is unknown, but plants tend to be inherently more tolerant to herbicides following a fire. (Photo by Kenneth Lair)



FIGURE 15. Tamarisk re-growing within weeks of a very hot fire that removed nearly all the above ground biomass. The remaining wood has been fire hardened and is strong enough and sharp enough to puncture a standard tractor tire. (Photo by Cameron Douglass, CSU)



FIGURE 14. This tamarisk has vigorous regrowth following a fire. This photo provides a good indication of how well tamarisk is adapted to fire. The fire occurred in April of 2008 and this picture was taken in August of the same year. (Photo by Scott Nissen)

ing biomass. Tamarisk is considered a highly volatile vegetation type which means that the foliage contains high amounts of fats, waxes and oils that will readily burn. Without leaf material, getting a fire to burn hot enough and long enough to remove standing dead material would be very unlikely. **Figure 14** shows the results of a very intense fire that started in the spring when the tamarisk had leafed out. Weather conditions were very dry and fire was pushed by high winds. Even with nearly ideal conditions, this fire was not intense enough to completely burn 2-3 inch stems.

Before attempting any kind of prescribed burn to remove tamarisk biomass, you should contact

one of the 17 district foresters of the Colorado State Forest Service. You can find the district office in your area at <http://csfs.colostate.edu>. Your local district forester can provide important information about site preparation, preparing a burn plan, air quality impacts, fuel characteristics and how to gather resources to contain the fire within the desired area.

Fire can have other unintended consequences such as facilitating the establishment of other invasive weeds, also referred to as secondary invaders. Fire can create a short-term increase in water and nutrient availability and, when combined with the loss of competing vegetation, this creates an ideal environment for these secondary invaders. Some common secondary invaders are perennial pepperweed (*Lepidium latifolium*), Russian knapweed (*Acroptilon repens*), downy brome (*Bromus tectorum*) and kochia (*Kochia scoparia*). There can be a multitude of weedy and desirable seeds in the soil seed bank. A fire, whether intentional or accidental, can often provide the disturbance necessary for secondary invaders to become established (**Figure 16**).

It is vital that landowners and land managers consider the possibility that other invasive species can take advantage of the disturbance caused by fire, mechanical removal, herbicide applications and even biological control. You should have some idea what the common invasive species are in your county, be able to identify them (preferably in the seedling stage) and have some strategy to deal with these secondary invaders. There is no benefit to replacing one invasive species with others, and the establishment of these secondary invaders will further increase the cost and time required to replace a tamarisk-dominated plant community with one composed of more desirable native species.



FIGURE 16. This tamarisk was recently burned by a wildfire. In addition to the vigorous tamarisk regrowth, there are now two secondary invaders at this site, perennial pepperweed and Russian knapweed. (Photo by Cameron Douglass, CSU)

Unintended Consequences of Large Scale Tamarisk Removal

Tamarisk was introduced and planted to establish windbreaks, provide protection for livestock and people (shade) and to stabilize highly erodible stream banks in arid western regions. As agriculture pushed west, rainfall was no longer sufficient for crop production so large irrigation projects were developed which included storage reservoirs and irrigation systems. It was not long before people realized that streams feeding these storage reservoirs could be highly erodible and flood events often carried large sediment loads that threatened to reduce reservoir storage capacities. Tamarisk came to the rescue, so to speak. In many areas it stabilized stream banks and significantly reduced sediment loads carried into reservoirs.

It was not until the 1920s that the invasive nature of tamarisk first began to raise concerns (Brotherson and Winkel, 1986). Fast-forward another 90 years: state and federal agencies across the western US are now attempting to remove

tamarisk from many western river systems. Whether for water salvage or habitat improvement, the large-scale removal of tamarisk by biological, mechanical or chemical means could have unintended consequences. The primary concern of many hydrologists is erosion.

Erosion is a natural process, but the large-scale removal of tamarisk could lead to significant erosion that has been rare since tamarisk stabilized numerous highly erodible stream banks across the west. In the absence of flexible woody stems to reduce the shear forces of flowing water, bank undercutting and eventual bank failures are likely. This is especially true when stream banks are composed mostly of sand. Sand is more easily dislodged than gravel and cobbles because it has less mass, and it is also more easily dislodged than silt and clay because it does not have the capacity to stick together.

An excellent example of the erosion that could occur with large-scale tamarisk removal was documented on the Rio Puerco, New Mexico, in 2006. A six-mile stretch of the river was sprayed by helicopter in 2003. No attempt was made to avoid native vegetation, like the sandbar willow (*Salix exigua*), so both tamarisk and native willow populations were controlled (**Figure 17**). In 2006, summer thunderstorms caused flooding that eroded 24 million cubic feet of sediment from this stretch of the river and increased the width of the river channel in the sprayed river section by 84% (Vincent et al. 2009) (**Figure 18**). The eroded material traveled three miles downstream before depositing on the floodplain.

It is possible to identify areas where the likelihood of erosion is high. The following are some characteristics of highly erodible river and stream banks:

- Limited regulation that leaves the river susceptible to large floods.



FIGURE 17. Rio Puerco channel in January 2007 downstream from the sprayed stretch. Average channel width did not change during the flood of 2006. (Photo by Julie Roth, USGS)



FIGURE 18. Rio Puerco channel in January 2007 in the section sprayed with imazapyr to control tamarisk in 2003. This section experienced a large flood in August 2006. Lateral erosion of the banks widened the channel by an average of 84% through the sprayed section. In this photo the left bank is intact, the right bank has eroded away except for a fragment next to the standing person. (Photo by Kirk Vincent, USGS)

- A river channel that is straight or steep.
- Banks that have no vegetation to reduce the shear forces of flowing water.
- River banks composed primarily of sand.

To minimize erosion of river and stream banks, strategies need to focus on protecting the bank. Tamarisk's success at stabilizing stream banks clearly demonstrates that woody stems can protect the bank by creating drag and reducing the velocity and shear forces of flowing water (Vincent et al. 2009). The stream bank is also protected because tree roots help to reinforce the soil (Pollen-Bankhead et al. 2009).

Strategies to minimize erosion include, but are not limited to the following:

- Avoid killing native vegetation growing along the bank. Helicopter applications applied in 10-15 gallons per acre will have very little off-target drift. GPS guidance systems allow pilots to identify sensitive areas before treatment and onboard computers can automatically shut off the spray boom to avoid treating desirable species.
- Carry out control projects in stages over several years so that only short stretches of the river bank are destabilized at one time.
- Begin site restoration as soon as possible after tamarisk control. In some areas passive restoration can be quite rapid; however, actively replacing vegetation will be necessary in some areas.
- Focus active restoration efforts on the stream bank first.

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Biological Control

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Biological control is the use of living organisms to manage pest populations. In biological control of weed pests, these living organisms are herbivorous (plant feeding) insects and, occasionally, plant pathogenic organisms.

When tamarisk was introduced into North America from Asia many of the insects that feed on this plant in its native range were left behind. In Russia and China there are more than 200 species of herbivorous insects that feed on tamarisk. One of the reasons that tamarisk has been so successful in taking over habitats in North America is that the tree is able to grow larger, faster, and produce more seeds because it lacks the herbivores that feed on the plant. Biological control seeks to use host-specific insects to reduce tamarisk's growth rate, seed output and survival so that the tree is no longer able

to dominate North American plant communities. In contrast to other control strategies (such as the use of herbicides or mechanical removal), biological control does not kill tamarisk quickly, and successful biological control does not mean that tamarisk will be eradicated from a site. Instead, biological control is expected to reduce the ability of tamarisk to out-compete native, desirable vegetation and greatly reduce the density of the weed. Once established at a site, biological control is self-perpetuating and permanently reduces tamarisk's competitive ability.

As of 2008, only one species of biological control agent for tamarisk has been approved for release in Colorado. This insect, *Diorhabda carinulata* (formerly *D. elongata*), appears to have substantial impact on tamarisk growth, seed

BOX 1. HOST SPECIFICITY

To be effective, biological control agents must feed on the target weed but leave desirable vegetation unharmed. Prior to permitting and introduction, candidate biological control agents are put through a series of tests to determine which plants they are able to feed and reproduce upon. Unlike many larger animals, most insects are very host specific and feed on only one or a few closely related plants. *Diorhabda elongata* was screened against 59 species of plants, and was found to feed on *Tamarix* spp. and on three species in the genus *Frankenia*. However, larval survivorship is very low on this plant (Deloach et al. 2003). and under field conditions adults will not lay eggs on *Frankenia* (Dudley and Kazmer 2005).

output, and survival. In addition to *Diorhabda* there are 3 other species of non-native insects that feed on tamarisk. However, these 3 species probably have little impact on tamarisk health.

Diorhabda carinulata

Diorhabda carinulata, the tamarisk leaf beetle, was first released into North America in 2001. Following these initial, experimental, releases, the USDA-APHIS, Colorado Department of Agriculture and Colorado State University initiated a program to develop insectary sites and a redistribution program for the beetle in Colorado. As of spring, 2008, these agencies have released the tamarisk beetle at 9 separate sites within Colorado, and have documented that the beetles have established at 5 of these sites.

Diorhabda spends the winter in the adult stage underneath leaf litter and loose soil. In spring these overwintered adults leave the soil and begin laying eggs on tamarisk foliage as the plants leaf out. *Diorhabda* eggs are small, tan and are deposited in clusters of 3 – 20 or so eggs. These eggs then hatch into small back larvae that feed on tamarisk leaves. These immature beetles

go through three larval instars before dropping off the plant to pupate in leaf litter or soil.

Depending on temperature, these pupae become adults and emerge from the soil after 7-14 days. Adults are 0.5-0.6 centimeters (slightly less than ¼ inch) long, yellow or yellow-brown with two dark stripes down the back.

In Colorado, *Diorhabda* may go through between 1 and 2 generations per year. The number of generations is determined by a combination of temperature and day length. *Diorhabda* will develop more quickly as temperatures increase up to 35°C. At temperatures common in tamarisk-infested areas of Colorado, it takes *Diorhabda* 5-8 weeks to complete a generation. However, when day lengths are less than 14 hours and 39 minutes, the beetles will begin to enter their overwintering, diapause stage. Thirteen days after this “critical day length” *Diorhabda* adults will stop laying eggs and will leave the plants in preparation for winter. Any larvae on the plants at this time will continue to develop into adults, but will not emerge from the soil until the following year. Because day length varies with latitude, at latitudes south of 36° 20’, day lengths never exceed 14 hours



FIGURE 1. *Diorhabda* adults.
(Photos by Andrew Norton)



FIGURE 2. *Diorhabda* egg cluster.



FIGURE 3. *Diorhabda* second instar larvae.

39 minutes, and *Diorhabda* has only one generation per year. Beetles that emerge after the critical day length has passed may still lay a few eggs but they are more likely to quickly enter diapause than beetles that have already been reproductive. At the border between Colorado and New Mexico, egg laying will stop around July 14th, in Pueblo around July 23rd, in Grand Junction July 28th and in Fort Collins August 3rd. The extra time available for egg laying in northern Colorado allows for at least a partial second generation and increases the rate of population growth for the beetles. *Diorhabda* adults prefer to aggregate on host trees. Large numbers of adults will feed and then mate on a tree and the females will lay numerous egg clusters. It appears that, after a tree has a large enough number of egg clusters such that the resulting larvae might run out of food, the adults will then move to another nearby tree to mate and lay eggs. Longer distance dispersal also occurs, probably soon after the beetles first become adults. In Dinosaur National Monument, *Diorhabda* have been found more than 6 miles downriver from release locations.



FIGURE 4. Feeding by *Diorhabda* results in shriveled, brown foliage. Larvae and adults scrape off the tissue from the leaves and shoots, resulting in dry, dead tissue. (Photo by Andrew Norton)



FIGURE 5. High populations of *Diorhabda* completely defoliate tamarisk trees. This picture was taken in Dinosaur National Monument in September 2007, 15 months after a nearby *Diorhabda* introduction. (Photo by Andrew Norton)

Impact on Tamarisk

Feeding by *Diorhabda* adults and larvae results in the death of leaves and young shoots. In portions of the state where *Diorhabda* can complete two generations per year (see above) tamarisk trees may be defoliated in June, re-sprout in July and undergo a second round of defoliation in August. Feeding damage results in reduced water use by tamarisk, and after 1 or 2 years of defoliation tamarisk trees will begin to die back



FIGURE 6. A 1-quart ice cream container used to transport *Diorhabda* adults. The containers may be fastened to the tree in the early morning; *Diorhabda* adults will leave the containers as temperatures begin to rise. (Photo by Andrew Norton)

with many brown, apparently dead, branches. After 4 or 5 years of repeated defoliation tamarisk trees will begin to die.

Releases in Colorado

The first releases of *Diorhabda* in Colorado were made in 2001 along the Arkansas River in Pueblo. This release was performed to collect important basic information about beetle establishment, spread, and impact on tamarisk. In late 2005 the first “implementation” releases of *Diorhabda* were made in Colorado. The intent of these releases was to collect more information about *Diorhabda*’s impact on tamarisk in different parts of the state, and as populations grow to provide a source for additional releases into tamarisk stands in Colorado.

The results have varied from no establishment (4 sites), establishment but slow growth of beetle populations (2 sites), to rapid and even explosive population growth (3 sites). For example, in Dinosaur National Monument *Diorhabda* populations had expanded to occupy more than 40 miles of the river corridor and had defoliated or partially defoliated thousands

of trees by the end of the third growing season after release. While we do not fully understand the reasons behind this varied success, successful sites have:

- Large tamarisk populations with at least some trees widely separated from their neighbors
- Healthy, growing trees not under drought stress
- Low densities of predatory insects such as ants
- Low densities of the tamarisk leafhopper, *Opsius stactogalus* (see below).
- Larger initial release size (at least 5,000 adults).

Obtaining *Diorhabda*

The USDA’s Animal Plant Health Inspection Service (USDA-APHIS) regulates transportation of biological control agents across state lines. It is against the law to transport *Diorhabda* into or out of Colorado without a permit. Different *Diorhabda* species are suitable for different latitudes and climates, and it is possible that the “wrong” species of *Diorhabda* will interfere with the success of the species that we have. Please do not transfer *Diorhabda* (or other biological control agents) into or out of Colorado without first checking with the Colorado Department of Agriculture and then obtaining the necessary permits from USDA-APHIS

Beginning in the summer of 2008 *Diorhabda* populations in Colorado will have reached sufficient size for collection and redistribution to other sites within the state. The Colorado Department of Agriculture’s Palisade Biological Control insectary is coordinating these efforts, and you can call or email them to request a release on your property. All releases made in 2008 must be accompanied by a simple moni-

toring program to measure success of beetle establishment and impact on tamarisk plants. This will help the Colorado Department of Agriculture better assess the impact of beetles at varied locations across the state and make recommendations regarding future releases.

BOX 2. UPDATE

As this manual was going to press in June 2009, USDA-APHIS had recently re-initiated consultation with the US Fish and Wildlife Service over concerns that *Diorhabda* may impact populations of a federally listed endangered bird subspecies, the Southwestern Willow Flycatcher, which may breed in tamarisk. At present, releases of *Diorhabda* must be at least 200 miles from such populations. As of summer, 2009, this “200 mile limit” prevents releases into the Rio Grande, San Juan and upper Dolores watersheds. At present no interstate movement of the beetles is permitted, and we strongly encourage you to contact the Colorado Department of Agriculture, Palisade Insectary for the latest information before releasing or redistributing *Diorhabda* in Colorado.

As populations of *Diorhabda* become abundant on your own property, you may be able to collect from these for release into other sites. The best time to collect adults is in spring soon after they emerge from overwintering. *Diorhabda* adults will be most numerous in spring in the areas that larvae were most abundant the previous August. Use a sweep net to collect the adults and then transfer them into cardboard containers along with a small amount of green tamarisk foliage for transport. It is important to sort these adults as they are put into the container to make sure that you are transferring only *Diorhabda* and not other, potentially harmful, insects. A 1-quart cardboard container can hold 1,000 – 2,000 adults. When full, place these in an ice chest with some blue ice to keep the insects cool until they reach their destination. If kept cool, *Diorhabda* can be held for 2 or 3 days before release, but shorter storage durations will increase your chances of success.

Make sure that you have received permission from the landowner or management agency prior to collecting *Diorhabda*.

Releasing *Diorhabda*

The best time to release *Diorhabda* is in the early morning or late evening after temperatures cool down. In the heat of the day *Diorhabda* may disperse immediately following release and this decreases the likelihood of establishment. Pick a large, healthy tree and gently transfer the adults to the foliage. Release all of the adults in the same location – *Diorhabda* prefer to aggregate and when in a large group the beetles will be better able to find mates and withstand any predatory insects that may be on the tree.

Within a week you should see egg masses at your release site, and larvae should appear after 2 ½ to 3 weeks. However, at several release sites



FIGURE 7. *Opsius stactogalus* adult and late instar nymph. (Photo by Andrew Norton)



FIGURE 8. Damage from *Opsius* feeding. Tamarisk foliage turns a yellow or orange color following feeding by *Opsius*. (Photo by Andrew Norton)

Diorhabda dispersed immediately after release and colonized other trees 200 m or more away. If *Diorhabda* is not apparent at your release tree they may be nearby—but it will be difficult to locate them until their population has become large enough to cause noticeable damage to tamarisk.

Other Insects Associated with Tamarisk

Opsius stactogalus, the tamarisk leafhopper, was unintentionally introduced into North America several years ago. This species is common on tamarisk throughout its range in North America and may become very abundant at times. This species has not undergone host specificity testing or the approval process for biological



FIGURE 9. The armored scale *Chionaspis etrusca* on tamarisk. (Image courtesy of The United States National Collection of Scale Insects Photographs Archive, USDA Agricultural Research Service, Bugwood.org)

control agents, but it apparently only feeds on tamarisk. When abundant, *Opsius* infestations may produce a significant amount of sticky honeydew that attracts aphids, wasps, lady beetles and other predatory insects. These insects may, in turn, feed on *Diorhabda* eggs and larvae. At high *Opsius* densities tamarisk foliage may prematurely yellow in late summer, but this damage probably has little impact on tamarisk growth and reproduction.

Less common than the tamarisk leafhopper are two species of scale insect (*Chionaspis etrusca* and *C. gilli*). These were probably unintentionally introduced as well. These insects rarely reach high population densities and probably have no significant impact on tamarisk growth and reproduction.

BOX 3. DOCUMENTING YOUR RELEASES

Biological control will likely take longer to achieve results than other management strategies. Because of this, it is critical that you document the locations and dates of your releases. This will reduce the chance that your releases will fail because other management strategies were initiated at your release site, and will provide you with useful information on project successes and failures.

- **Record the date, location and number released for each *Diorhabda* release you perform.** For location, a description of the site (nearest street address along with a map showing the release point) is suitable. Another option is to use a handheld GPS to record the coordinates for the release, or a computer application such as Google Earth to locate and record site data. The Colorado State Insectary in Palisade keeps a database of all biological control releases made in the state. These data are used to help researchers and policy makers evaluate the success of biological control activities in Colorado and elsewhere. You can send your release information to:

Dan Bean
Colorado Department of Agriculture
Palisade Insectary
750 37.8 Rd.
Palisade, CO 81526
(970) 464-7916
dan.bean@ag.state.co.us

- In addition to documenting the date, location and number released, it is a good idea to **take photographs of your release site at the time of release**. Comparison of photographs taken before and after *Diorhabda* establishment will allow you to determine what impact *Diorhabda* has had on your tamarisk stand and will help you strategize for future management efforts.
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Part 3. RESTORATION



RESTORATION AFTER TAMARISK CONTROL

Restoration After Tamarisk Control

ANNA SHER
KENNETH LAIR

The ultimate goal of most tamarisk removal projects is to facilitate restoration or replacement of the tamarisk by more desirable species, thereby proactively filling the vacant ecological niche created by tamarisk removal. We strongly recommend that all projects have a well-defined goal in mind before tamarisk removal (see *Developing a Management Strategy*). Even if a specific plant community is not a part of a management objective, promoting native reestablishment should be considered for the following important benefits:

- Site stabilization and erosion control
- Restoring or enhancing desirable wildlife habitat
- Reducing reinvasion by tamarisk and other secondary weeds
- Potential use for forage or recreation
- Aesthetics

Whether revegetation will occur naturally (“passive”), will require seeding or planting (“active”), or is even necessary at all will be a function of site characteristics and conditions discussed below. Here we provide a synthesis of some of the current research and experience regarding revegetation after tamarisk control. We must emphasize the importance of water availability, in the form of precipitation, presence of regular seasonal river flows and flood-

plain inundation, and/or relatively shallow water tables. **Simply put, plants will not establish without moisture.** Naturalizing stream flows is the ideal, and will be most likely to create a sustainable native plant community, but restoration has been successful in regulated waterways. If no natural sources are available in a given location or year, irrigation or other forms of moisture conservation and/or augmentation (e.g., water harvesting/spreading, mulching, groundwater wicking) can be effective.

Tamarisk control methods can also affect revegetation. Application of soil-active herbicides (such as imazapyr) may result in soil residues that can inhibit or reduce establishment years after application **Figure 1** (Gieck 2007). Fire can affect soil chemistry, and heavy machinery can damage desirable plants and adversely alter soil texture and structure. Moist conditions (through flooding, irrigation or precipitation) will help mitigate all of the above, but generally the least disruptive approaches are best. Managers will need to weigh benefits of the lowest impact tamarisk control (e.g., cut stump, biological) against site access needs (i.e., that require removal of standing biomass) in choosing site treatments before revegetation. What follows is not intended to be an exhaustive guide for revegetation, but should rather serve as an overview of considerations and a starting point for planning restoration efforts.



FIGURE 1. Careful foliar application of imazapyr at this site near Pueblo, Colorado minimizes the size of the herbicide affected area; however revegetation in these spots will be more difficult than surrounding areas for at least a year. (Photo by Stephanie Gieck)



FIGURE 2. Above: before tamarisk control. Below: after control. This somewhat xeric site in the lower Arkansas was a good candidate for passive revegetation, given the native cover was over 25%. Aesthetics, use for forage, and native herbaceous cover improved with effective tamarisk removal alone. (Photos by Rick Enstrom)

Passive Revegetation

Natural recovery (i.e., “passive” revegetation) of the native plant community over time is probable without requiring supplemental (i.e., “active revegetation”) activities under several, specific conditions. This natural recovery assumes that:

1. **SOME DESIRABLE SPECIES ARE ALREADY PRESENT (Figure 2).** There appear to be minimum thresholds of pre-treatment (remnant) plant community composition (above ground biomass and/or canopy cover basis). Suggested thresholds for remnant natives are:
 - Moist to mesic riparian sites exhibiting favorable hydrology: 10%
 - Arid to xeric riparian sites: 25%
2. **CONDITIONS WILL PROMOTE DESIRABLE SPECIES (Figure 3).** Soil, climatic and hydrologic conditions during the recovery period (1-3 years following treatment) must be favorable to maintain and promote expansion of the remnant native vegetation. The following should be considered:
 - **Hydrology.** Close proximity (<50 feet) to a permanent, actively flooding water source. Natural recruitment will be minimal in drought years, even with close proximity to water.
 - **Control method and intensity.** Chemical residues can impede establishment, and mechanical control can significantly alter physical and chemical attributes of the soil.
 - **Use of the treatment site.** Livestock and/or wildlife grazing, recreational use, agronomic practices, etc. must be planned and managed to promote health, vigor and expansion of the remnant native community.



FIGURE 3. *Passive revegetation of desirable grasses was achieved at this southern Colorado site due to a strong remnant population and the presence of water (inset is same site prior to restoration. (Photos by Rick Enstrom)*

3. **MONITORING IS CONDUCTED.** Any type of revegetation effort will be more successful if monitored for survival of natives and reinvasion of tamarisk or other weeds. Treating secondary invasions will be necessary if the underlying land management issues that led to the initial invasion are not addressed. See section below for recommendations.

Very few sites, in fact, do fit these criteria. In a survey of 33 “passive” restoration sites, very few showed increases in native plant richness or cover over time, particularly in the Colorado Plateau (Harms and Heibert 2006). Natural recovery scenarios can require 10 years or more for establishment of desirable, native vegetation, with the first 1-5 years often dominated by ruderal species. An evaluation of riparian restoration projects in Arizona found natural

regrowth was most likely if there was significant flooding and the underlying causes of degradation were addressed (Briggs et al. 1994). In Colorado, passive revegetation has been successful in areas where there was a substantial remnant plant population and where active flows were present.

Active Revegetation

Recommendations for active revegetation methods, including species selection, will be strongly influenced by the tamarisk control and removal measures and by site conditions, including equipment access. Active revegetation after tamarisk removal has been the most successful under the following conditions (from Bay and Sher 2008):



FIGURE 4. Active revegetation was successful at this site in Mesa County due to careful species selection. (Photo by Michelle DePrenger-Levin)

1. CONDITIONS ARE FAVORABLE TO SPECIES SELECTED (**Figure 4**). See **Table 2** for recommended species and their environmental tolerances. In general, sites that have had the most successful active revegetation are those with higher percent sand (>40%), low to moderately high salinity (<20 mmhos/centimeter), and are close to permanent flows (<65 feet). It is important that underlying issues that may have caused initial invasion be addressed as much as possible (e.g., hydrologic).
2. MONITORING IS CONDUCTED. See section below for recommendations.
1. POLE/WHIP PLANTINGS OR ROOTED TRANSPLANTS. This technique will lead to fastest recovery and may promote passive increases in overall plant community diversity over time, but is more expensive. These must be planted such that roots will have access to the capillary fringe (i.e., region with both water and oxygen) or in the water table itself (for poles); given standard auguring equipment, this generally means <8 feet at time of planting. Appears to work best when water is always within 10 feet below surface, plantings are within 40 feet of active flows, and there is good drainage (e.g., >3% gravel).
2. SEEDING. Generally, this technique works best for greatest vegetative cover and more immediate species diversity, and can be used with more saline and alkaline soils; however it can be more risky because of vulner-

Active revegetation may be conducted following removal of tamarisk using one or more of the following methods:

Table 1. General overview of conditions that are suitable for each of three revegetation approaches. Recommendations taken from surveys of tamarisk restoration and land manager experience for revegetation method (e.g., Bay and Sher 2008, Shafroth et al. 2008).

SITE CONDITIONS	POLE PLANTINGS AND/OR TRANSPLANTS	SEEDING	PASSIVE REVEGETATION
1) Remnant plant community	Not required	Not required	Present (see text for minimum % by type)
2) Hydrology			
Water table	Within reach of pole, never deeper than 10 ft during the year	NA	Base on health of remnant plant community
Distance to active flows	<40 ft best	Dependent on species	<50 ft or subject to overbank flooding
3) Soils			
	Good drainage (>3% gravel) Salinity is species-dependent	Good drainage (>25% sand) <20 mmhos/cm, pH 5.5-8.8	Based on health of remnant plant community
4) Tamarisk control and removal			
	Cut-stump, removal of standing dead for site access	Mechanical control, removal of standing dead for soil seedbed preparation	Cut stump, spot treatments, biological control

ability to environmental stressors including drought and predation. Time must be given for establishment, with success not quantifiable for sometimes 5 years or more. Techniques for planting include:

- **Broadcast** using aerial or ground-based seeders (for large projects), or manually (for small projects).
- **Disk drill** (typically with leading coulters or furrow openers) for large projects where site access and seedbed conditions permit

Active Revegetation: Relationship to Tamarisk Removal Methods

Tamarisk removal may occur before or after soil treatments; where tamarisk stands are sufficiently open to permit equipment access, broadcast seed-

ing, soil amendment and/or mycorrhizal inoculation may precede removal or mulching of the standing trees. However, in dense stands dead trees impede site access and soil preparation. It is imperative to note, that of the following, only root raking will reduce or minimize re-growth of live trees; burning and/or mulching alone will not kill mature trees and will promote resprouting.

Root Raking/Plowing

Root raking and plowing are effective means of control, and yields a seedbed amendable to any type of plantings, irrigation, and use of agronomic implements for seedbed preparation and incorporation of soil amendments. However, its applicability to watersheds in Colorado is minimal; it is most appropriate for riparian zones within

broad alluvial floodplains, as is more commonly found in neighboring states such as New Mexico.

Mulching

Leaving shredded or mulched woody material on site can promote native species and/or reduce weed encroachment (e.g., Jodaugiene et al. 2006). Little published data exist that are specific to tamarisk; however, at a site near Pueblo, secondary invasion by cheatgrass was reduced in areas where tamarisk had been hydroaxed (Sher et al. 2008). Our experience suggests that in arid sites mulch also significantly reduces surface moisture evaporation and associated salt deposition, and further ameliorates (buffers) environmental extremes of moisture, temperature and wind. Mulching can aid both passive and active revegetation; however, mulch layers can restrict site access and/or types of equipment used, suppress desirable species that may be present in the seedbank, and require broadcast seeding in lieu of drilled seedings. To improve contact with soil, other implements can subsequently be employed to mechanically incorporate seed, amendments and/or inoculum, including roller choppers, land imprinters, and/or heavy tandem (offset) disking.

Burning

Burning standing dead material must be done with caution, as tamarisk burns can adversely alter soil chemistry, making establishment of desirable species difficult, and favoring tamarisk (Busch 1995). Low intensity fires can increase nutrient availability to reestablishing plants; however, dense tamarisk can burn very hot, and thus, fires are more likely to decrease the fertility of the soil. Burning can also increase soil salinity, particularly in dense, younger (e.g., stems

less than 15 years old above ground) tamarisk stands.

Soil Preparation

Previous work in tamarisk control and site restoration on xeric sites with dense, mature infestations indicates that revegetation of disturbed sites (natural or anthropogenic) is difficult in the absence of seedbed preparation, including soil manipulation (Taylor et al. 1999; Szaro 1989), and/or restoration of soil microbial communities (Lair and Wynn 2002). Seedbed preparation may include the following:

1. **TILLING.** Disturbing the soil surface, even to a shallow degree, can increase seed contact with soil, penetration of precipitation, and ease of other planting methods.
2. **SOIL SALINITY.** Saline soil is often a problem in these ecosystems, and will usually require choosing salt-tolerant species for revegetation (see **Table 2**). The primary means of remediation for salt in soil is leaching through flooding, which moves the salts beyond the rooting zone of establishing plants. Sprinkler irrigation is unlikely to provide enough water to leach salts, but if there is access to furrow irrigation, this and other agronomic approaches to remediate salts will be possible. Naturally flooded sites are less likely to have a soil salinity problem.
3. **SOIL NITROGEN.** Although tamarisk-invaded soils are often lacking in nitrogen and other nutrients, native species often do very well under such conditions (e.g., Sher et al. 2002). Increases in nutrient availability are likely to promote exotic weeds; thus, amendments should be used with caution (Shafroth et al. 2008).

4. **MICROBIAL COMMUNITY.** Soils of tamarisk-invaded areas are often lacking in important microflora and fauna, including beneficial fungi called mycorrhizae. In some cases, the addition of arbuscular mycorrhizae (AMF) have been shown to increase establishment and/or growth of common restoration species (Sher 2007). These may be reintroduced through incorporation of soils from nearby reference sites, or use of salvaged topsoil or transplanted native plants, where feasible. When these are not available, commercial inoculants of arbuscular mycorrhizae may be used, typically containing spores of *Glomus intraradices* and/or related species within the *Glomus* and/or *Gigaspora* genera.

Species Selection

If active revegetation is chosen, species must be carefully selected based on project objectives, and both site and resource limitations. Identifying “reference sites” where desirable plant communities occur in similar soils and moisture regimes may be particularly useful in this regard. Using seed or propagated material from local sources is the ideal, as these would be best adapted to the environment; however, fewer nurseries carry “local genotypes” and will generally charge more for it (Smith et al. 2007). Environmental constraints affecting riparian and floodplain sites infested with tamarisk are anticipated to occur predominantly within four generalized plant habitat types or edaphic/hydrologic regimes, driven primarily by soil moisture and salinity limitations (See **Box 1**).

BOX 1. GENERALIZED PLANT COMMUNITIES IN WHICH ENVIRONMENTAL CONSTRAINTS ARE LIKELY TO OCCUR, AND EXAMPLE REVEGETATION COMPOSITIONS

Predominantly mesic, less saline / sodic sites receiving subirrigation from seasonally shallow water tables

EXAMPLE: grasses and annual / perennial forbs; pole plantings of cottonwood and/or willow.

Ephemeral mesic, highly saline / sodic sites receiving periodic groundwater and/or surface flow contributions (e.g., alkali “scalds”, “slicks”, “sinks”)

EXAMPLE: higher proportion of halophytic (salt loving) shrubs and forbs (e.g., shadscale, plantain); fewer grasses (alkali sacaton, western wheatgrass in fringe zones)

Arid, less saline / sodic sites

EXAMPLE: mixture of shrubs, forbs and grasses; broader spectrum of adapted species (including legumes); higher proportion of forbs and grasses

Arid, moderately to highly saline / sodic sites

EXAMPLE: mixture of shrubs, forbs and grasses; emphasis on more halophytic species, particularly shrubs

Examples of adaptation of selected species (non-exhaustive) in relation to these regimes and ecological / environmental constraints are provided in Table 2

Table 2. Suggested native species used in revegetation after tamarisk removal with environmental constraints. This should not be considered a complete list, but rather as candidate species guidelines. All species are appropriate for use in Colorado, where specialization to Western versus Eastern slope is relevant, it is noted under “Zone of Adaptability.”

COMMON NAME	SCIENTIFIC NAME ADAPTED CULTIVAR	ZONE OF ADAPTABILITY	HIGHER MOISTURE REQUIREMENT	THRESHOLD SALINITY ^b (mmhos/cm)	MAXIMUM SALINITY ^b (mmhos/cm)	SOURCE ^a
Grasses (seeded or transplanted)						
Galleta grass	<i>Pleuraphis jamesii</i> Viva	alkaline flats, saline swales, Eastern Plains		8	12	6
Alkali sacaton	<i>Sporobolus airoides</i> Salado, Saltalk	alkaline flats, saline swales, riparian, salt meadow ^c		14	26	2
Altai wildrye	<i>Leymus angustus</i> PrairieLand, Pearle, Eejay	riparian, West Slope		10	20	2, 3
Beardless wildrye	<i>Leymus multicaulis</i> Shoshone	riparian, saline swales, West Slope	√	12	26	1, 2, 3
Blue grama	<i>Bouteloua gracilis</i> Hachita, Lovington, Alma	riparian, East Slope		3	6	4
Canada wildrye	<i>Elymus canadensis</i> Mandan	riparian	√	6	12	4
Inland saltgrass	<i>Distichlis spicata</i>	riparian, saline swales, salt meadow	√	6	12	4
Alkaligrass	<i>Puccinellia</i> spp.	riparian	√	14	30	2
Slender wheatgrass	<i>Elymus trachycaulus</i> Pryor, San Luis	riparian, saline swales		10	22	1, 2, 3
Western wheatgrass	<i>Pascopyrum smithii</i> Rosana, Rodan, Arriba, Walsh, Barton	alkaline flats, saline swales, riparian, salt meadows		6	16	1, 2, 3
Forbs (seeded or transplanted)						
Pennsylvania smartweed	<i>Polygonum pennsylvanicum</i>	riparian, East Slope		4	8	6
Globemallow	<i>Sphaeralcea</i> spp.	riparian, saline swales		4	8	6
Plantain	<i>Plantago</i> spp.	riparian, saline swales, alkaline flats		2	6	6
Evening primrose	<i>Oenothera</i> spp.	riparian, saline swales		2	6	6

^a Adapted and synthesized from Stannard et al. 2002 (1), Majerus 1996 (2), Ogle 1994 (3), Bernstein 1958 (4), Shafroth et al 2008 (5), K Lair, Bureau of Reclamation, Personal Communication (6)

^b Threshold salinity indicates the level of soil salt concentration at which plant performance begins to be observably or measurably reduced. Maximum salinity indicates that level at which plant viability, growth and/or performance are severely or permanently curtailed.

^c Salt meadows: meadow and pasture areas in riparian zones typified by clay to clay-loam soils and typically dominated by halophytic grass species.

Table 2 (continued)

COMMON NAME	SCIENTIFIC NAME ADAPTED CULTIVAR	ZONE OF ADAPTABILITY	HIGHER MOISTURE REQUIREMENT	THRESHOLD SALINITY ^b (mmhos/cm)	MAXIMUM SALINITY ^b (mmhos/cm)	SOURCE ^a
Shrubs (seeded or transplanted)						
Fourwing saltbush	<i>Atriplex canescens</i> Wytana, Rincon	riparian, saline swales, alkaline flats Wytana, Rincon	√	6	1.0	1
Green ash	<i>Fraxinus pennsylvanica</i>	Cardan		8	1.0	1
Greasewood	<i>Sarcobatus vermiculatus</i>	alkaline flats, East Slope		8	16	6
Silverberry	<i>Elaeagnus commutata</i>	Dupuyer, Pondera		5	8	1
Shadscale	<i>Atriplex confertifolia</i>	alkaline flats, West Slope		12	20	6
Winterfat	<i>Krascheninnikovia lanata</i> Hatch	riparian, alkaline flats Hatch		6	1.0	1
Trees (poles or transplanted)						
Cottonwood	<i>Populus</i> spp.	riparian	√	2	4	5
Willow	<i>Salix</i> spp.	riparian	√	2	4	5
Hackberry	<i>Celtis occidentalis</i>	saline swales		4	6	5
New Mexico olive	<i>Forestiera pubescens</i> Jemez	riparian, West Slope		4	6	6

^a Adapted and synthesized from Stannard et al. 2002 (1), Majerus 1996 (2), Ogle 1994 (3), Bernstein 1958 (4), Shafroth et al 2008 (5), K Lair, Bureau of Reclamation, Personal Communication (6)

^b Threshold salinity indicates the level of soil salt concentration at which plant performance begins to be observably or measurably reduced. Maximum salinity indicates that level at which plant viability, growth and/or performance are severely or permanently curtailed.

Finally, revegetation species selection and mixture formulation should preferably be determined in cooperation and consultation, as appropriate, with other potential stakeholders, including the Natural Resources Conservation Service (NRCS) and associated Plant Materials Centers (NRCS-PMC), Bureau of Land Management (BLM), Fish and Wildlife Service (FWS), U.S. Forest

Service (FS), National Park Service (NPS), State Fish and Game Departments (F&G), Bureau of Reclamation (BOR), landowners and managers, and local environmental organizations.

Monitoring and Maintenance

The purpose of monitoring is to be able to evaluate progress toward the project goal - a step often neglected in the planning and budgeting process. Conducting pilot projects with thorough monitoring is highly recommended to avoid wasting resources. Restoration takes time; thus, determination of “success,” however defined, is usually not possible immediately after implementation. This is an important consideration when establishing specific project objectives and stakeholder expectations. Baseline (pre-treatment) and post-treatment inventories should include soils (systematic core and/or electronic surface sampling), vegetation (fixed transects, using line intercept, line point, and quadrat sampling), and groundwater (monitoring wells). Post-treatment monitoring should be conducted (as a minimum) once per year. A general list of measurement variables to consider for baseline, pre- and post-monitoring are included in **Box 3**.

Selection of monitoring variables should be decided based on project goals. Some measurements such as initial tamarisk invasion may be valuable to researchers in the future, even if they are not critical to measuring restoration success. Thus, where resources permit, we strongly encourage land managers to consult with researchers or local conservation service offices wherever possible to maximize the value of any restoration project. Collaborations could also reduce labor costs associated with monitoring (e.g., when students are used).

BOX 2. SOME RESOURCES FOR REVEGETATION

Sher AA, Lair K, Deprenger-Levin M, Dohrenwend K. 2010. Best management practices for revegetation in the upper Colorado River basin. Denver Botanic Gardens, Denver, CO.

A Guide for Planning Riparian Treatments in New Mexico, United States Department of Agriculture, September 2007

—a printed guide from the experiences of staff from NRCS and Soil and Water Conservation Districts in New Mexico, including many useful links to detailed guides available online, such as planting depths for poles and whips.

PLANTS Database (<http://plants.usda.gov>)

—an online database that provides detailed information on thousands of species, including native status, distribution and uses.

Federal Interagency Stream Restoration Working Group (FISRWG). 1998. Stream Corridor Restoration: Principles, Processes and Practices. Available at http://www.nrcs.usda.gov/technical/stream_restoration/.

—a detailed document describing a wide range of restoration options and methods for use in riparian areas.

BOX 3. GENERAL LIST OF MEASUREMENT VARIABLES TO CONSIDER FOR BASELINE, PRE- AND POST-MONITORING

(adapted from Shafroth et al. 2008)

Using core sampling, soils are systematically sampled for parameters of:

- Texture

Surface (0-12 in; 0-30 cm) and subsoil (12-36 in; 30-90 cm).

Note: In highly xeric / thermic locales like the Lower Colorado River system, the intensive salt accumulation lies within the top 4-6 in silt to silt-loam horizon because of the extreme evaporative demand. This is true for ambient soil salinity, and for deposition from dense tamarisk. In these cases, soil sampling should occur at increments of 0-6 in, 6-12 in, and 12-36.

Soils

- Organic matter
- Fertility (macro- and micro-nutrients)
- Salinity (EC/SAR, surface and subsoil)
- Reaction (pH, surface and subsoil)
- Moisture content / availability (surface and subsoil)

Soil moisture is highly variable over time and space; thus, analysis of results must be considered as a relative measure (e.g., when comparing sites sampled on the same day). The most meaningful measures are those conducted on a regular basis throughout the growing season.

Monitoring well(s) installed simultaneous with baseline inventories and prior to treatment applications for assessment and tracking of:

- Groundwater depth
- Conductivity
- pH
- Alkalinity
- Major ions (Cl⁻, SO₄⁼, Ca⁺⁺, Mg⁺⁺, Na⁺, K⁺)
- Trace elements/metals
- NO₃⁻/NO₂⁻

Groundwater

- Initial tamarisk infestation data
- Stand/individual age (age class, plant height, or stem diameters)
- Species frequency/density
- Vigor (function of, for example, culm and leaf height, seedhead production, and biomass)
- Basal and canopy cover (total and by species)
- Bare ground and litter
- Species richness (i.e., numbers of species) and/or diversity (e.g., Shannon-Weiner or Simpson's measures that incorporate abundance)
- Biomass (live standing crop, total and by species)

Vegetation

(both desirable and undesirable species)



FIGURE 5. *Tamarisk* removal at this site in Dinosaur National Monument was halted when post-removal monitoring revealed extensive re-invasion by whitetop (*Lepidium draba*) (Photo by Michelle DePrenger-Levin).

Final Note

Restoration after tamarisk removal is an art as much as it is a science, and requires careful planning and monitoring based on project needs and conditions. It may be necessary to delay revegetation efforts under drought conditions or when broadcast herbicide applications have been made. It is also advisable to conduct smaller-scale trials before commitment to particular species or approaches, so as to avoid wasted resources (**Figure 5**). Ultimately, successful revegetation after tamarisk removal will be the best investment of your time and resources, giving you the maximum benefit for your restoration effort.

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