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Planning Riparian Restoration in the Context of *Tamarix* Control in Western North America

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Abstract

Throughout the world, the condition of many riparian ecosystems has declined due to numerous factors, including encroachment of non-native species. In the western United States, millions of dollars are spent annually to control invasions of *Tamarix* spp., introduced small trees or shrubs from Eurasia that have colonized bottomland ecosystems along many rivers. Resource managers seek to control *Tamarix* in attempts to meet various objectives, such as increasing water yield and improving wildlife habitat. Often, riparian restoration is an implicit goal, but there has been little emphasis on a process or principles to effectively plan restoration activities, and many *Tamarix* removal projects are unsuccessful at restoring native vegetation. We propose and summarize the key steps in a planning process aimed at developing effective restoration projects in *Tamarix*-dominated areas. We discuss in greater detail the biotic and abiotic factors central to the evaluation of potential restoration sites and summarize information about plant communities likely to replace *Tamarix* under various conditions. Although many projects begin with implementation, which includes the actual removal of *Tamarix*, we stress the importance of pre-project planning that includes: (1) clearly identifying project goals; (2) developing realistic project objectives based on a detailed evaluation of site conditions; (3) prioritizing and selecting *Tamarix* control sites with the best chance of ecological recovery; and (4) developing a detailed tactical plan before *Tamarix* is removed. After removal, monitoring and maintenance as part of an adaptive management approach are crucial for evaluating project success and determining the most effective methods for restoring these challenging sites.

Key words: **invasive species, passive restoration, revegetation, saltcedar, soil salinity, tamarisk.**

Introduction

Riparian ecosystems are recognized globally as important sources of numerous functions and services including havens of biodiversity, water quality enhancement, and sites for esthetic enjoyment and recreation (Brinson et al. 1981; Naiman et al. 2005). Throughout the world, the ecological condition of natural riparian systems has declined due to a number of sometimes interacting factors, including streamflow regulation, floodplain development, channelization, and the spread of non-native species (de Waal et al. 1994; Naiman et al. 2005). As a consequence, restoration of riparian vegetation has become a global resource management priority (Webb & Erskine 2003; Holmes et al. 2005; Hughes et al. 2005; Richardson et al. 2007).

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The spread of non-native plant species can be one of the causes of riparian ecosystem decline (Tickner et al. 2001; Richardson & van Wilgen 2004), and many restoration efforts in riparian and other ecosystems include the control or removal of invasive species (D'Antonio & Meyerson 2002; Holmes et al. 2005; Richardson et al. 2007). In western North America, shrub/small tree species and hybrids in the genus *Tamarix* (common names – tamarisk, saltcedar) have colonized several hundred thousand hectares of river bottomlands and reservoir margins (Zavaleta 2000; Gaskin & Schall 2002). The taxa that comprise the bulk of invasive *Tamarix* in western North America are *Tamarix ramosissima*, *T. chinensis*, and *T. ramosissima* x *T. chinensis* (Gaskin & Schaal 2002). In this manuscript, we use the genus name alone (*Tamarix*) to refer to this complex of species. *Tamarix* have been implicated in decreasing water yield, degrading wildlife habitat, displacing native vegetation, and increasing fire severity and frequency (Brock 1994; DiTomaso 1998; Dudley et al. 2000). Although there is disagreement in some cases about the degree to which these negative effects actually occur and the relative role of *Tamarix* invasion *per se* versus other impacts to riparian systems (Anderson 1998; Glenn & Nagler 2005), millions of dollars at federal, state, and local levels have been spent and are proposed to be spent on *Tamarix* control in western United

States (Hart et al. 2005; U.S. House of Representatives 2720 and U.S. Senate 177: Saltcedar and Russian-olive control and demonstration act, http://www.govtrack.us/congress/bill.xpd?bill = h109-2720).

Primary reasons stated for controlling *Tamarix* are to increase water yield, improve wildlife habitat, restore native vegetation, or decrease riparian forest fire frequency and severity (Shafroth et al. 2005). Central to all of these desired outcomes is the composition of the vegetation that occupies a site following control (hereafter referred to as "replacement vegetation"). For example, water yield changes depend largely on evapotranspiration differences between cleared vegetation and replacement vegetation, and wildlife habitat conditions depend largely on the composition of replacement vegetation versus *Tamarix*.

Many *Tamarix* control projects include riparian or bottomland restoration as a desired outcome, but there has been little emphasis placed on a process or principles to effectively plan associated restoration activities, including details that provide insights to the type of vegetation likely to replace *Tamarix*, with or without particular restoration actions. While there are gaps in knowledge of how to revegetate bottomland sites where *Tamarix* occurs, the existing literature on riparian restoration describes many effective approaches ranging from application of controlled water releases that closely mimic the natural flow regime (Hughes & Rood 2003; Rood et al. 2005) to intensive revegetation techniques (Pinkney 1992; Taylor & McDaniel 1998; Anderson et al. 2004), and hybrid approaches (Friedman et al. 1995; Bhattacharjee et al. 2006). Harms and Hiebert (2006) reported that in many cases, removal of *Tamarix* is not enough to restore native vegetation to a site. Other studies have shown that even active revegetation is likely to fail if there is no further maintenance and management (Briggs et al. 1994; Bay & Sher 2008). Further, the wholesale removal of *Tamarix* may have unintended negative consequences (Zavaleta et al. 2001; Sogge et al. 2008), or removal sites may be unsuitable for the desired replacement vegetation type if underlying factors facilitating or promoting *Tamarix* abundance (e.g., high soil salinity) are too severe or cannot be addressed (Briggs 1996; Glenn & Nagler 2005). We suggest that more careful and rigorous restoration planning can help lead to a higher probability of success and avert undesirable outcomes.

In this paper, we use the term "restoration" broadly to encompass projects that involve the conversion of *Tamarix* to a replacement vegetation type that achieves particular management goal(s) and help return at least parts of the system to a pre-existing dynamic or trajectory. We use the term "bottomland" to refer to the full set of fluvial surfaces within a river valley. Bottomlands include the subset of "riparian" sites, which have a fairly direct connection to the present flow regime or shallow alluvial groundwater and support mesic native riparian vegetation. Bottomlands also include areas of the historic floodplain which are now too dry to support mesic vegetation but can support a range of native xeric grass and shrub species. *Tamarix* removal efforts occur on both mesic and xeric sites.

The overarching goal of this paper was to present a planning process for restoration projects in the context of *Tamarix* control in the western United States. We hope to encourage resource managers, restoration practitioners and policy makers to plan riparian restoration upfront when planning *Tamarix* removal projects, and to provide them with sufficient rationale, guidance and detail to facilitate project implementation. This process is primarily intended to be applicable to restoration projects across a range of spatial scales and in a variety of regions within western North America. We suggest that it should also apply to a broader range of ecological contexts, and many of its key components have been suggested by others (Pastorok et al. 1997; Clewell et al. 2000). The primary objective of this paper was to summarize the principal steps of the process that are required to develop effective bottomland restoration projects in *Tamarix*-dominated areas. Further, we expand upon particular elements, particularly those associated with assessing potential restoration sites and developing an implementation plan. In these expanded discussions, we aim to provide a synthesis of many of the key details associated with restoration of *Tamarix* lands including the biotic and abiotic factors that are central to the evaluation of potential restoration sites, and information about plant communities likely to replace *Tamarix* under various conditions.

Restoration planning process

The process we propose for developing viable restoration projects for bottomland sites dominated by *Tamarix* consists of seven sequential steps and various feedbacks (Figure 1). These include: (1) goal identification; (2) development of objectives (including evaluation of important ecological and non-ecological site factors); (3) site prioritization; (4) development of a site-specific plan; (5) project implementation; (6) post-implementation monitoring and maintenance; and (7) adaptive management.

Step 1: Determine Overarching Goal(s)

Effective restoration of ecologically compromised bottomland sites is predicated on the development of goals that are both realistic and viable in the long term. In the context of controlling *Tamarix*, commonly stated restoration goals include: improving habitat for wildlife; reducing consumptive water use by vegetation; converting non-native vegetation to native vegetation; improving overall native biodiversity; and reducing the risk of fire. The goals that are ultimately selected and how they are prioritized will have profound consequences on how restoration is

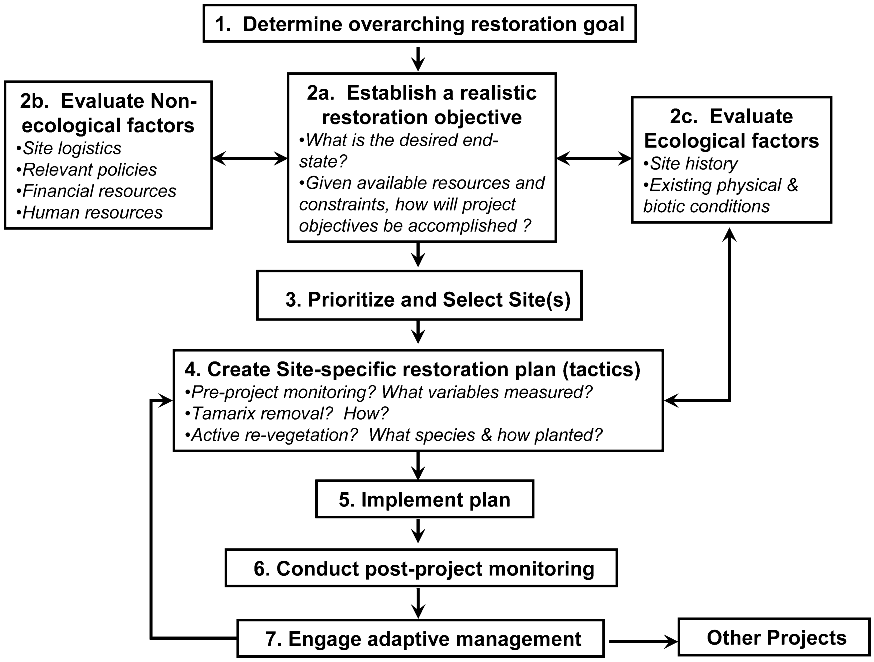

Figure 1. Diagram of process involved in restoration planning in the context of *Tamarix* removal. Boxes represent steps in the process. Arrows indicate the sequence of steps and feedbacks. Where multiple steps occur more or less simultaneously, they are placed parallel to each other.

planned and implemented, affecting critical considerations such as scale, location, and control method.

Clarifying project goals with one's funding agency or governing body is also important. In cases where the goal is vaguely described as *Tamarix* control, it is likely that assumptions have been made about project intent and expected outcomes. These expectations may be based, in part, on assumed impacts of *Tamarix*; thus, understanding and confirming the impacts is key to determining realistic goals. If assumptions are misplaced, then the project will often follow an incorrect trajectory that will likely be much more difficult to rectify than if the restoration goal had been discussed and agreed upon in the first place.

Step 2: Establish a Realistic Project Objective in the Context of Ecological and Non-Ecological Resources and Constraints

After the goal(s) have been articulated, the next step includes three components that should occur at about the same stage in the overall process: (a) setting a realistic project objective(s) in the context of evaluating both (b) ecological (i.e., site) and (c) non-ecological (e.g., financial) resources and constraints (Figure 1). These steps are linked by information feedback and, as such, tend to inform one another. For example, developing detailed, realistic restoration objectives is influenced both by the ecological characteristics of the sites and non-ecological factors. We suggest that taking the time to consider these three elements early in the planning process can significantly improve the success and cost-effectiveness of meeting the restoration goal.

Step 2a: Establish Realistic Project Objectives. A well-defined *goal* provides the overall purpose and approach to restoration. However, once stated, the restoration goal should be recast as achievable, specific, project objectives. For example, a project may have an overall goal of increasing water yield, with specific objectives that include what type of plant community is desired instead of *Tamarix*, the scale of the effort, number of sites, how stakeholders' needs will be met, etc. The more realistic the objectives, the more likely the stated goal will be achieved. This is, in essence, the strategic planning phase of the project, where clear objectives are defined in the context of all known institutional and ecological factors that may serve as assets or constraints to the effort.

Step 2b: Establish Ecological Factors. Evaluation of key ecological factors combines assessments of physical and biotic processes and the biological diversity they support (Holmes et al. 2005). Generally, the most effective restoration efforts are predicated on an understanding of ecological conditions at the watershed scale, along with more targeted data collection at the reach or site scale. It is important to develop a sense of the natural range of variation at a site, whether the current ecological condition may have changed in the recent past, and what has likely caused the changes. Assessment of reference sites, when they exist, can provide a key contribution to development of objectives, as well as help guide aspects of pre- and post-project monitoring (White & Walker 1997; Hughes et al. 2005).

Data collected at the watershed scale place the restoration project site within a broader context (Briggs 1996). The effect of perturbations upstream, downstream or in the uplands adjacent to a particular project site could lead to changes in water availability, channel morphology, soil chemistry, as well as other parameters that affect the current biologic makeup of the site and the site potential. Restoration practitioners should seek information on the primary land uses and human impacts in the watershed (e.g., farming, grazing, off-road vehicle use, groundwater pumping, flow impoundment or diversion structures, channelization), how uses and impacts are changing, and how these changes could affect restoration site conditions. Whereas there is greater reliance on gathering documented information at the watershed scale, new measurements will often need to be taken at site-specific scales.

At the site level, evaluation of a number of biotic and abiotic variables can greatly improve the probability of defining realistic objectives and ultimately completing a successful restoration effort. Bottomland morphology, surface and groundwater hydrology, and soil moisture availability, texture and salinity, are several of the key factors that should be evaluated in the context of restoration of *Tamarix*-dominated riparian sites. We discuss several of these factors in detail below.

Bottomland Morphology

Bottomlands are part of an alluvial valley formed of and underlain by alluvium that has been transported and deposited by the stream. Bottomlands may include the channel bed and banks, bars, and all other alluvial features resulting in one or more floodplains and terraces. These various morphologic surfaces can differ in their elevation above and lateral distance from the channel, which can result in substantial differences in variables such as surface inundation frequency, depth to shallow groundwater, and soil physical and chemical characteristics. Differences in these physical characteristics can, in turn, have a significant effect on the types of plant communities that can be supported. For example, surfaces only marginally above the elevation of the channel may be characterized by frequent inundation, shallow groundwater, and low soil salinity, making them suitable for mesic species, whereas terrace surfaces may no longer be inundated by surface flows and are generally characterized by lower water availability and higher salinity, making them suitable for xeric species. Given these considerations, a first critical step in the ecological assessment process is to identify the site's principal morphologic surfaces and describe the water availability, soil conditions, and relevant biological conditions on surfaces of interest (see details, below).

Another important consideration is channel stability. Alluvial channels can fall out of dynamic equilibrium when there are significant differences between the quantity and type of sediment particle sizes that enter and exit a given stream reach. Significant changes in channel form can occur in such situations. Conducting restoration along reaches that are out of dynamic equilibrium and are undergoing rapid changes in channel form can be difficult, if not impossible. Therefore, resource managers should understand both when and where such channel changes are occurring and plan accordingly. Various methods to evaluate channel form and bottomland geomorphology are described in Kondolf and Piegay (2003).

Streamflow, Water Availability, and Disturbance Regimes

Within a given geomorphic surface under consideration for *Tamarix* removal, a few key physical and biological factors largely determine the suitability for different replacement vegetation types. The single greatest physical factor in arid and semi-arid western North America is water availability. Water availability at a site is a function of flooding regime, low flow levels, groundwater dynamics, and precipitation. Evaluation of stream flow regimes is commonly addressed through analysis of published stream gage records (e.g., http://waterdata.usgs.gov/nwis), using user-defined analyses or software designed to evaluate a number of flow variables (Richter et al. 1996; Henriksen et al. 2006). When no surface flow records exist, indirect methods can help to estimate the flow regime (Hedman & Osterkamp 1982).

The frequency and magnitude of flooding greatly influences the restoration potential of *Tamarix* removal sites. Natural flood regimes and associated fluvial processes are the drivers of structural and compositional diversity of riparian vegetation (Hughes 1997). In the western United States, aspects of flow regimes that may favor native pioneer trees (genera *Populus, Salix*) over *Tamarix* or allow a mix of native taxa and *Tamarix* include: flood magnitudes sufficiently large to create bare, moist germination sites; flood timing that is synchronized with the seed dispersal period of native pioneer trees; flood recession that is not too rapid for seedling root growth; base flows that provide continued high water availability; and a lack of subsequent floods until plants are of a sufficient size to withstand physical damage (Mahoney & Rood 1998; Hughes et al. 2001). Where these conditions have been met, native seedlings and saplings have been able to successfully establish in the presence of *Tamarix* (Shafroth et al. 1998; Sher et al. 2002; Nagler et al. 2005), ultimately dominating some river reaches (Stromberg et al. 2007*b*). Additionally, the frequency of suitable recruitment flows is an important driver of riparian forest patch heterogeneity and age class diversity. In natural systems in western North America, cohorts of pioneer trees are commonly separated by 3–10 years (Mahoney & Rood 1998).

Low flows or base flows are also critical to evaluate in a restoration context as they largely determine water availability during drier times of the year (Stromberg et al. 2007*a*). Low flows can be a direct source of moisture for riparian vegetation, and they also interact with alluvial groundwater. Understanding relations between the low flow regime and groundwater dynamics can provide an indication of site moisture availability, thus informing what plants might be most suitable for restoration. Different plant species and communities have been found to be associated with particular depth to groundwater ranges (Meinzer 1927; Stromberg et al. 1996). Although groundwater levels at some sites may be relatively stable, others may exhibit strong intra- and interannual variation (Scott et al. 2000; Shafroth et al. 2000). The best understanding of groundwater conditions comes from a long-term record of water level changes. If wells are not available at a site, information on groundwater depths could be inferred from the existing vegetation and known depth to groundwater tolerances. In areas with deeper groundwater and where overbank flooding is infrequent or absent, the dependence of vegetation on relatively low and highly variable annual precipitation severely constrains revegetation efforts, requiring selection of native species that can tolerate these low-moisture conditions (See Step 4, below).

Soil Chemistry and Texture

Soil salinity has become elevated in the bottomlands of many arid-region rivers where human activities (e.g., agriculture), and altered fluvial geomorphic processes have diminished water quality and reduced or eliminated inundation and associated leaching or flushing of salts (Jolly et al. 1993; Anderson 1995). As a result, soil salinity on many surfaces has increased to levels that no longer support many riparian plants. Floodplain soil salinity varies greatly across and within different river systems. Thus, salinity of floodplain soils is an important site factor to evaluate in a restoration context (Table 1). Understanding soil salinity at a site can allow development of lists of species that would be suitable for planting. Salinity tolerances have been examined for some common taxa, which are discussed further in Step 4, below. For many other species, research on salinity tolerance could benefit future restoration planning.

Soil texture is also important to consider in restoration planning because it can affect soil moisture, salinity, nutrient availability, aeration, the thickness of the capillary fringe above the water table, and competitive interactions between *Tamarix* and replacement species (Sher & Marshall 2003). The capillary fringe is thicker in fine-textured soils than in coarse-textured soils, which can provide more water to plants in areas with deeper groundwater. Clay soils have higher water holding capacity and are more nutrient rich than sandy soils. Often, though, the water held in clay soils is so tightly bound that it may be unavailable to plants. Salinity may be higher in clay soils because of the higher adsorptive (cation exchange) capacity. Sandy soils are quick to dry out after precipitation events and are often nutrient poor. Soils containing a mix of sand and clay may provide the most optimal combination of moisture and nutrient availability (Tables 1 and 2). Bottomland soils associated with *Tamarix* infestations exhibit extremely variable surface and subsurface textures and unconsolidated structures, ranging from fine sands to dense clays in variable depositional patterns. However, soil particle size often trends from coarse to fine with increasing distance from and height above the primary river channel.

Biotic Factors

In addition to the physical factors described above, several biotic factors are also critical in determining a site's restoration potential. These include availability of native plant and secondary weed propagules, and soil microbes.

Seeds or vegetative propagules of desirable native or undesirable exotic species may exist at the site or nearby in remnant patches, either as extant vegetation or in the soil seed bank (Goodson et al. 2001). Also, propagules may be able to be passively dispersed into the sites from

Table 1. General criteria for evaluating soil suitability for plant growth (modified from Hansen et al. 1991; Kotuby-Amacher et al. 2000).

	Suitability for Plant Growth			
Soil Property	*Good*	*Fair*	*Marginal to Poor*	*Very Poor*
pH	6.0–8.4	5.5–6.0 or 8.4–8.8	5.0–5.5 or 8.8–9.0	<5.0 or >9.0
EC	0–4 (growth of salt sensitive species may be limited)	4–8 (growth of many plants is limited)	8–16 (only salt tolerant plants grow satisfactorily)	>16 (only a few, very salt tolerant plants grow satisfactorily)
Texture	Sandy loam, silty loam, sandy clay loam	Clay loam, silty clay loam, sandy clay, loamy sand	Clay, silty clay, silt, sand	Bedrock
SAR	<6	6–10	10–15	>15
% Organic matter	>2	0.5–2	<0.5	Approximately 0

EC is electrical conductivity in dS/m; SAR is sodium adsorption ratio.

Table 2. Environmental factors, methods and measurements for site evaluation (adapted from Rhoades 1982; Cook & Stubbendieck 1986; Bonham 1989; Kotuby-Amacher et al. 2000; McWilliams 2003).

Environmental Factor	*Methods*	*Measurements*
Geomorphology, flooding frequency	Examination of topographical maps, channel cross section surveys[a], stream gauge data[b], hydrological modeling[c,d,e]	Site elevation above and distance from river channel; channel stability; upstream flow regulation or diversions; flow regime; site flooding frequency
Groundwater	Monitoring well(s)	Groundwater depth; conductivity; pH; alkalinity; major ions (Cl^-, $SO_4^=$, Ca^{++}, Mg^{++}, Na^+, K^+); trace elements/metals; NO_3^-/NO_2^-
Soils and soil microbe availability	Core sampling[f] and/or surface electromagnetic techniques[g], bioassays[h,i], trap cultures [h,i,j]	Texture—surface (0–12 inches; 0–30 cm) and subsoil (12–36 inches; 30–90 cm); organic matter; fertility (macro- and micronutrients); salinity (EC/SAR; surface and subsoil); reaction (pH; surface and subsoil); moisture content/availability (surface and subsoil); inoculum potential and AMF species composition
Pre-treatment vegetation	Fixed transects, using line intercept, line point, and quadrat sampling[k,l]	Initial *Tamarix* infestation data: density, canopy cover; species richness (i.e., numbers of species) and/or diversity (e.g., Shannon-Weiner or Simpson's measures that incorporate abundance)[m] of native and exotic species; species frequency, density or cover of native and exotic species

[a] Harrelson et al. (1994); [b] http://waterdata.usgs.gov/nwis; [c] Hardy et al. (2005); [d] Brunner (2002); [e] Richter et al. (1996); [f] Robertson et al. (1999); [g] Sheets et al. (1994); [h] Brundrett et al. (1996); [i] Johnson et al. (1999); [j] Stutz and Morton (1996); [k] Elzinga et al. (1998); [l] Krebs (1999); [m] Magurran (1988).

upstream or upland environments (Merritt & Wohl 2002). In other instances, the site may lack the desired seeds and require active seeding as part of the management plan (see Step 4, below). The seed availability of exotic species may also be important. All sites under consideration will have been occupied by *Tamarix*, which, unless conditions have changed considerably since its initial colonization, could recolonize. Additionally, mature *Tamarix* stands are often characterized by non-native herbaceous understories dominated by, e.g., kochia (*Bassia scoparia*), various bromes (*Bromus arvensis*, *B. tectorum*, *B. rubens)*, perennial pepperweed (*Lepidium latifolium*), Russian knapweed (*Acroptilon repens*), Bermudagrass (*Cynodon dactylon*), pigweeds (*Amaranthus* spp.) and Russian thistles (*Salsola* spp.). Upon reduction of *Tamarix*, these weeds may rapidly colonize disturbed soils unless measures are taken to favor establishment of desirable plant communities, including active suppression of these secondary weeds (see Step 6, below).

The establishment and growth of species present at a site or planted can be influenced by the presence and composition of soil microbes and nitrogen availability. Sites dominated for many years by monotypic stands of *Tamarix* may have soils that lack arbuscular mycorrhizal fungi (AMF) (Beauchamp & Stutz 2005). AMF are soil fungi that associate with the roots of many plant species and help plants acquire relatively immobile soil nutrients, particularly phosphorus, in exchange for carbon produced in photosynthesis (Smith & Read 1997). Many native riparian species associate with AMF (but not most shrubs in the Chenopodiaceae); however, *Tamarix*, and many other invasive weed species are typically nonmycorrhizal (Allen 1991; Titus et al. 2002; Beauchamp & Stutz 2005). Competitive exotic species that are less dependent on mychorrhizal association may establish first and continue to dominate sites for extended periods (Allen & Allen 1984, 1986; Hanson 1991). Adding mycorrhizal inoculum to a site may increase the competitive ability of natives against nonmycorrhizal weeds.

Sites with long-term *Tamarix* occupation may also be nitrogen-limited (K. Lair, unpublished data). We discuss factors to consider when choosing inoculum and altering nitrogen availability in Step 4, below.

Ecological Evaluation Summary

Evaluation of ecological site characteristics during the project planning process should include an examination of bottomland geomorphology, flooding frequency, water availability, soil chemistry and texture, and structure and composition of native and non-native vegetation at the site (Stromberg et al. 2004). A summary of specific methods and measurements important in the site evaluation process is presented in Table 2. Many of these measurements can also be used in the context of baseline (pre-treatment) and post-treatment inventory and monitoring, which are discussed further in steps 4 and 6, below.

Step 2c: Evaluate Non-Ecological Factors. There are also a number of non-ecological factors that strongly influence selection of candidate restoration sites and what level of restoration realistically can be achieved. For example, resource mangers should take time to investigate the local, state, and federal permit requirements that may pertain to the site. Ignoring this crucial step may prevent a project from moving forward after precious time and money have been spent evaluating site conditions and developing the overall project design.

A project's budget should be sufficient not only for site assessments and project implementation but also for the inevitable and important maintenance and monitoring activities that occur after on-the-ground activities have been completed (see Step 6, below). One of the main reasons that many bottomland restoration efforts do not achieve their stated project objectives is the lack of attention to what happens after project implementation. A general rule of thumb is to have a budget where roughly 20% is allocated to post-project monitoring and maintenance (Briggs 1996), but this needs to be evaluated on a case-by-case basis.

Site access issues can greatly limit what can be accomplished at potential restoration sites. Remote sites or sites where access is legally restricted may limit access of machinery and personnel or lead to prohibitively high costs. However, ease of access has little relevance to the ecological site characteristics, and in some cases restoration of relatively inaccessible sites may provide desired ecological benefits. Thus, project managers should weigh the logistical and ecological costs and benefits to help fine-tune realistic restoration objectives.

Some sites are easily accessible, open to and frequently visited by the public, yet are not the most ecologically desirable choices for restoration. Project managers may still wish to consider these sites because they can provide opportunities for the public (including funding sources, politicians, federal and state officials, local landowners, etc.) to learn from the restoration experience, which can ultimately lead to broader support for other restoration activities. Similarly, involving community members and other stakeholders in bottomland restoration efforts can bring numerous benefits. Pride and the sense of inclusion that community involvement fosters can greatly increase the chance for long-term success. Community members can be involved in a wide range of activities, including revegetation, monitoring, irrigation, installing signs and fences, protecting the site from vandalism, and education and outreach activities (Briggs 1996; Briggs & Flores 2003). Finally, because stakeholders may have a range of interests and values, it is not uncommon for there to be opposition to particular elements of a project.

Step 3: Prioritize and Select Sites

The "best" site for restoration of *Tamarix*-dominated land will depend on factors discussed above including the overall goal and specific objectives of the project, the environmental conditions at potential project sites, and the non-ecological constraints that need to be considered for each site and project. Addressing these three factors in concert will help to ensure that planned activities are appropriate for the site, and that the site chosen will have the greatest chance for achieving the stated goal. In the common case where a practitioner is charged with restoring a specific site, a thorough evaluation of site conditions will help in formulating objectives that are appropriate for the site and have the greatest chance of being met.

Step 4: Create Site-Specific Plan (Tactics)

Site selection and prioritization are followed by the tactical step of creating a site-specific plan, the blueprint for the final three steps: *implementation*, *post-project monitoring and maintenance*, and *adaptive management*. This plan should be guided by the project's objectives, in order to reach the predetermined goals. The implementation plan should consider baseline monitoring, *Tamarix* removal approaches, and post-removal restoration approaches. Because *Tamarix* has such a broad ecological niche, removal and restoration activities may occur on bottomland sites ranging from regularly inundated floodplains to high terraces and historic floodplains that are largely isolated from the influences of river hydrology.

Baseline Monitoring

Baseline monitoring is essential so that the efficacy of different methods and the overall success of the project can be evaluated objectively (Blossey 1999). When possible, an experimental design should be incorporated into the monitoring plan to more rigorously test different approaches. In cases where a tactic is not successful, monitoring can inform decisions early enough in the process so that different approaches can be attempted through adaptive management (step 7, below). The variables chosen in a monitoring plan should closely reflect the goals and objectives of a particular project. Sometimes, measurements taken to evaluate ecological factors (step 2, above) can also serve as important pre-treatment baseline information and can be used in subsequent monitoring of the restoration project (see step 6, below). In some cases, particular species may be used as indicators of broader system condition (Nelson & Wydoski 2008).

Control or Removal of *Tamarix*

As with most invasive plants, *Tamarix* may be controlled by mechanical (e.g., mowing, burning, and pulling), chemical (i.e., herbicide), and/or biological (e.g., goat or insect) means. The most effective or appropriate control strategy depends on (1) characteristics of the stand such as density and the presence of desirable vegetation, (2) site limitations such as accessibility, and (3) goals and constraints of the project itself. The economic costs associated with different approaches can vary considerably, which can be an important constraint when selecting a control method. Recent reviews of *Tamarix* control describe these approaches and past studies in more detail (Shafroth et al., 2005; Gieck 2006).

Following chemical, mechanical or biological control, there is still a need to decide how to handle the dead *Tamarix*. Standing dead trees (a possible product of chemical or biological control) may provide a resource for wildlife and help secure soils temporarily; however, they can impede revegetation efforts and control of secondary weeds, and may be a fire hazard. Trees may be shredded or mulched on site, but this may be constrained by site access. Controlled burns to remove dead *Tamarix* have been used in some areas, but must not be done before the death of the trees is assured because burning can stimulate regrowth from below-ground meristems.

Passive Restoration Approaches

The decision to use active or passive approaches to replace *Tamarix* following its removal will largely depend on characteristics identified in the site evaluation (step 2, above). Passive restoration or natural recovery, generally refers to facilitating the return of desirable system dynamics and species composition by removing some underlying stressor(s). Removal of invasive species in some cases may allow for the recovery of native vegetation. In riparian systems, other approaches to passive restoration include reduction or better management of livestock grazing pressure, removing or mitigating structures that control channels or floodplains, or restoring natural processes (Stromberg 2001).

Naturalizing flood regimes is often advocated as a key to restoring many elements of floodplain ecosystems (Poff et al. 1997; Stromberg 2001; Hughes & Rood 2003; Rood et al. 2005; Stromberg et al. 2007*a*). Advantages of incorporating natural flows or naturalized, managed flows are that they can result in sustainable restoration along a long segment of a river (Rood et al. 2003) and generate some of the spatial and temporal variability in riparian forest structure that typifies natural systems (Hughes et al. 2005). On rivers in western North America where *Tamarix* occurs, naturalized flows have been successfully implemented to promote native cottonwood and willow establishment (Shafroth et al. 1998; Taylor et al. 1999; Rood et al. 2003). Small-scale riparian restoration projects that typically target a single vegetation type are less dynamic and are rarely self-sustaining. Thus, restoration projects should seek to incorporate natural or naturalized flow regimes when feasible.

In many cases, naturalizing streamflow patterns and magnitudes is not possible, may not influence the restoration site (e.g., an isolated terrace), or may only be able to partially fulfill key functions. In these cases, a combination of passive and active approaches that seek to mimic natural processes has proven to be effective. For example, several projects have led to the successful establishment of desirable riparian vegetation by manipulating hydrology in off-channel settings, sometimes combined with *Tamarix* control or seed augmentation (Friedman et al. 1995; Bhattacharjee et al. 2006).

Natural recovery following *Tamarix* removal alone generally requires at least some healthy individuals of native species to remain on or near the site to provide a source of seed or vegetative propagules and to provide microsites favorable for other native species. Further, the presence of native taxa may indicate that underlying environmental conditions are still favorable; whereas the absence of native taxa suggests that natural revegetation of native species will likely be difficult. The amount of necessary remnant native cover for successful passive restoration varies depending on water availability. Xeric bottomland sites require at least 25%, whereas moist to mesic sites with intact hydrologic regimes may recover with as little as 10% cover of natives (K. Lair, Bureau of Reclamation, Denver, Colorado, personal communication). A survey of revegetated *Tamarix* restoration sites found that those with characteristics favorable for mesic native vegetation (e.g., low salinity and high precipitation) had a lower density and percent cover of *Tamarix* and other weeds (Bay & Sher 2008).

A second condition for successful natural recovery following *Tamarix* control alone is that soil, climatic, and hydrologic conditions during the recovery period (1–3 years following treatment) are suitable to maintain and promote expansion of the remnant native vegetation. Additionally, land use of the treatment site (e.g., livestock and/or wildlife herbivory, recreational use, and agronomic practices) must also be planned and managed to promote the native community. Finally, implementing passive approaches does not eliminate the need for maintenance and monitoring; any type of restoration effort will be more successful if monitored and maintained to promote survival of natives and prevent reinvasion of *Tamarix* or other weeds (see step 6, below).

Active Revegetation

When restoration sites are not good candidates for passive approaches, active revegetation measures should be considered. Harms and Hiebert (2006) noted increases in native plant cover on only a few of 33 passive restoration sites. Active revegetation, including species selection, can be strongly influenced by the *Tamarix* removal approaches used, and by site hydrology and soils characteristics. Active revegetation may use several methods including broadcast seeding, drilled seeding, and manual or mechanical transplanting of rooted plants or poles. On sites with shallow groundwater, low salinity, and regular overbank flooding, transplants are often more successful than seeding. Seeding is typically less expensive but is also susceptible to impacts from a wider range of environmental variables including drought and granivory. When project scope, soil and hydrologic resources (e.g., irrigation or shallow groundwater), and budget allow for use of transplant stock, determining appropriate containerized or bare-root stock attributes will be a key to successful establishment. A lower cost means of employing transplants is to develop dispersed seed source "islands" as a long-term source of propagules. Planning for transplant stock needs well in advance of implementation is required to obtain adapted seed and grow stock to needed size and maturity.

Revegetation following control of dense and/or mature stands of *Tamarix* is often difficult in the absence of some form of seedbed preparation; thus, revegetation is generally easiest after complete clearing of the *Tamarix* (Herbel et al. 1973; Pinkney 1992; Taylor et al. 1999; Anderson et al. 2004). After *Tamarix* is cleared, the material may be taken off site, or shredded and mulched on site and left as a groundcover (Dixon 1990; Lair & Wynn 2002*a*, 2002*b*). A sufficient quantity of surface mulch from *in situ Tamarix* can suppress annual secondary weed flushes, and buffer adverse environmental extremes (wind, temperature, evaporation, erosion processes). However, excessively deep mulch may prevent establishment of desirable species as well (David M. Merritt, U.S. Forest Service, Fort Collins, Colorado, personal communication).

In dense stands, removal or reduction of woody *Tamarix* biomass is typically needed to facilitate revegetation measures and equipment access. Root plowing of *Tamarix* has been shown to facilitate deep-furrow drill seeding into deeper soil horizons that may exhibit more favorable soil conditions (Lair & Wynn 2002*b*). However, on sites treated using a deep root rake (up to 100 cm), soil horizons are more likely to be mixed, which may change water holding capacity and salinity. Mulch (*Tamarix* chips or straw) can be added after seedbed preparation and planting to suppress weeds and increase the moisture holding capacity of the soil.

Soil surface treatments are also used to: (1) create soil surface microrelief to enhance precipitation capture and infiltration; (2) reduce, redistribute, and/or dilute salts in the *Tamarix* leaf litter and upper soil profile; (3) create more spatially uniform soil texture characteristics for improved seed germination and establishment; and (4) assure proper depth placement and incorporation of broadcast seed and/or mycorrhizal inoculum. Where root plowing or raking is not indicated, seedbed preparation may be possible with other implements such as roller choppers, land imprinters, and pitter-seeders. These mechanical methods are potentially less costly and cause less environmental disturbance than traditional root plowing or root raking.

When removal of only aboveground biomass of *Tamarix* is possible or desired, planting will be influenced by stand structure prior to control. Where *Tamarix* is sparse enough to permit equipment access, broadcast seeding and other soil treatments may precede subsequent mechanical biomass reduction or removal measures. Where density of *Tamarix* prevents such access, seeding or planting must typically follow control activities. Finally, in those cases, where standing biomass is not likely to be removed, active revegetation may only be possible in patchy areas where space exists to allow seedbed preparation, and/or light to reach plantings. Presence of dense, standing-dead or defoliated *Tamarix* limits seeding and transplanting techniques and can cause shading impacts.

Species Selection

The majority of sites requiring active restoration will likely contain one or more of a complex of environmental constraints including deep groundwater, infrequent (or absent) flooding, high soil salinity or alkalinity, and low and variable precipitation. The environmental constraints occur predominantly within four general salinity-moisture regimes, which are listed in Table 3, along with associated plant communities and representative genera from southwestern United States. Salinity tolerances of some representative species are listed in Table 4.

Plant material selection requires consideration of plant adaptations to site conditions as well as the plant or seed availability and cost-effectiveness (Burton & Burton 2002; McKay et al. 2005). When selecting plant materials for restoration projects, usually the best approach is to choose container stock or seed that is endemic to the local reach of the river system. However, a survey of plant material providers in western United States suggests that use of pure local ecotypes and wild collected seed may often be logistically infeasible or even undesirable (Smith et al. 2007). At a minimum, plant material should be adapted to similar soils, elevation, and climate as the project site. Other things to consider when selecting plants are: germination rates, seedling vigor, seedbed preparation needs, seeding methods for field establishment, and the sustainability of planted species (e.g., ability to reproduce without further management).

Native species that have the ability to tolerate or suppress weed competition, high reproductive success, favorable pollination requirements, and high insect and disease resistance also increase chances of project success. When seed is not commercially available, mechanized or seed industry standard methods should be utilized wherever possible in seed collection, cleaning, conditioning, viability testing and storage. Seed mixtures that rely more heavily on species that (1) are not commercially available; (2) are characterized by small or dispersed field populations; and/or (3) require manual seed collection and processing will inflate revegetation costs significantly.

Many species have specific pre-conditioning requirements to break seed dormancy. For example, mesquite species (*Prosopis* spp.) need mechanical scarification or acid treatment, and many forb and grass species require pre-chilling (Young & Young 1986). Whereas these treatments may not be feasible for large lots of seed intended for extensive acreages, they should be considered in smaller applications requiring reduced seed quantities. The presence of some dormant seed, however, may prove advantageous by allowing a fraction of the seed to persist in the soil seed bank, thereby allowing for germination to occur over a broader range of conditions and times.

Ecology of Seeded Species and Seeding Approaches

Following *Tamarix* removal, ruderal, weedy species may come to dominate the site for the first 1–5 years. A prime

Table 3. Generalized site and plant community type descriptions with representative genera (adapted from synthesis of: Bernstein 1958, FWPCA 1968, Dick-Peddie 1993, Ogle 1994, NRCS 1996, FAO 2000, Lair & Wynn 2002*a*, 2002*b*, Stannard et al. 2002, Swift 2003).

Salinity-Moisture Regime	*Vegetation Community*	*Salinity Range*	*Representative Genera*	
Mesic, lower salinity sites with seasonally shallow water tables or surface flows	High proportion of non-chenopod shrubs, grasses and annual and perennial forbs	<4 dS/m	Trees, shrubs	*Populus, Salix, Celtis, Prunus, Forestiera, Juglans, Robinial; Salix, Amorpha, Baccharis, Pluchea, Ephedra, Lycium, Shepherdia, Rhus, Eracameria/Chrysothamnus*
			Grasses	*Distichlis, Sporobolus, Paspalum, Leymus, Spartina, Panicum*
			Forbs	*Anemopsis, Sphaeralcea, Corydalis, Eriogonum*
Ephemerally mesic, highly saline sites receiving periodic groundwater and/or surface flow (e.g., alkali sinks)	High proportion of halophytic chenopod species, few grasses	>12 dS/m	Shrubs	*Suaeda, Atriplex, Allenrolfea, Sarcobatus*
			Grasses	*Distichlis, Puccinellia, Sporobolus, Muhlenbergia*
			Forbs	*Salicornia, Heliotropium, Atriplex (herbaceous)*
Xeric, moderately to highly saline sites	Mixture of shrubs, forbs and grasses; dominated by halophytic species within Chenopodiaceae	>8 dS/m	Trees, shrubs	*Acacia, Prosopis, Parkinsonia/Cercidium; Atriplex, Allenrolfea, Suaeda, Isocoma, Sarcobatus*
			Grasses	*Sporobolus, Elymus, Pascopyrum, Leptochloa, Pleuraphis, Panicum*
			Forbs	*Sphaeralcea, Heliotropium, Frankenia*
Xeric, less saline sites	Mixture of shrubs, forbs (including legumes) and grasses; higher proportion of forbs and grasses	<8 dS/m	Trees, shrubs	*Chilopsis, ForestieraLycium, Ephedra, Krascheninnikovia, Rhus, Prosopis, Fallugia, Lesquerella*
			Grasses	*Achnatherum, Bothriochloa, Bouteloua, Elymus, Eragrostis, Pleuraphis, Panicum*
			Forbs	*Oenothera, Sphaeralcea, Anemopsis, Ambrosia, Baileya, Frankenia, Chrysopsis/Haplopappus*

For each salinity-moisture regime, we recommend using local, native species from the genera listed.

objective should be to shorten an extended weed-dominated or bare ground phase by establishing diverse habitat characterized by predominance of early-, mid-, and late-seral perennial species, in concert with sound, integrated weed management measures. This also reduces potential for capillary rise and salt accumulation at the soil surface, and can reduce wildfire potential. Some sites may require initial establishment of earlier seral species that are better adapted to harsh environmental conditions until the site stabilizes.

Concepts like "initial floristics" (Egler 1954; Gilpin 1987) provide important insights into the effects of the initial species composition on subsequent plant establishment and successional dynamics (Kline & Howell 1987; Allen 1995). For example, inclusion of vigorously reproducing species like quailbush (*Atriplex lentiformis*) in initial seedings of xeric *Tamarix* control sites commonly results in dominance of quailbush for extended periods, inhibiting establishment of other desirable natives that were concurrently seeded (Pinkney 1992; Bay & Sher 2008; K. Lair, Bureau of Reclamation, Denver, CO, unpublished data). Similarly, initial establishment of cottonwoods (*Populus* spp.) can effectively suppress co-establishing *Tamarix* (Sher et al. 2002).

In contrast, "facilitation" models (Grime 1979; Kline & Howell 1987) emphasize plant dominance resulting from competitive displacement of pioneering species by later establishing, stress-tolerant plants that take advantage of the site amelioration provided by the pioneers. On highly disturbed substrates, native species establishment may be delayed or favorable successional trajectories adversely altered when attempts are made to greatly accelerate successional processes through exclusive planting of late seral species (Gilpin 1987; Allen 1995). Strategies allowing for initial seeding and establishment of less competitive species followed by subsequent inter- or over-seeding of more aggressive species may be preferable where rapid site stabilization is not critical (Romney et al. 1987; Redente & Depuit 1988).

The need to suppress competition from *Tamarix* and/or secondary weeds following seeding may also dictate the composition and sequence of initial and subsequent seedings. For example, along the upper Pecos River in southeastern New Mexico, long-term (50–60 years) chemical and mechanical *Tamarix* control have converted riparian sites to monotypic kochia (*Bassia scoparia*), including some genotypes that are apparently imazapyr-resistant (Tranel & Wright 2002; K. Lair & S. Nissen 2006, Bureau of Reclamation, Denver, CO, and Colorado State University, Fort Collins, CO, unpublished data). Native grasses were seeded on these sites, and once established

Table 4. Salt tolerances of selected plants frequently used in revegetation projets.

Salinity	*Very High (>12 dS/m)*		*High (8–12 dS/m)*		*Moderate (4–8 dS/m)*		*Low (<4 dS/m)*	
Species	*Common Name*	*Scientific Name*	*Common Name*	*Scientific Name*	*Common Name*	*Scientific Name*	*Common Name*	*Scientific Name*
Grasses	Inland saltgrass	*Distichlis spicata*[a,b]	Vine mesquite	*Panicum obtusum*	Cane bluestem	*Bothriochloa barbinodes*	Sand dropseed	*Sporobolus cryptandrus*
	Canada wildrye	*Elymus canadensis*[c,d]	Knotgrass	*Paspalum distichum*[d]	Switchgrass	*Panicum virgatum*	Giant dropseed	*Sporobolus giganteus*
	Slender wheatgrass	*Elymus trachycaulus*[a,e]	Giant sacaton	*Sporobolus wrightii*	Big Galleta	*Pleuraphis rigida*	Cane bluestem	*Bothriochloa barbinodis*
	Altai wildrye	*Leymus angustus*[a,f]					Indian ricegrass	*Achnatherum hymenoides*
	Beardless wildrye	*Leymus triticoides*[b,c]					Sideoats grama	*Bouteloua curtipendula*
	Alkali muhly	*Muhlenbergia asperifolia*					Blue grama	*Bouteloua gracilis*
	Western wheatgrass	*Pascopyrum smithii*[a,b]					Bottlebrush squirreltail	*Elymus elymoides*
	Nuttall's alkaligrass	*Puccinellia nuttaliana*[a,b]					Thickspike wheatgrass	*Elymus lanceolatus*
	Alkali cordgrass	*Spartina gracilis*[a]					Sand lovegrass	*Eragrostis trichodes*
	Alkali sacaton	*Sporobolus airoides*[a,b]					Needlegrasses	*Achnatherum/Nasella/Stipa/Hesperostipa* spp.
							Knotgrass	*Paspalum distichum*
							Little bluestem	*Schizachyrium scoparium*
Forbs	Alkali goldenbush	*Isocoma acradenia*			Evening primrose	*Oenothera* spp.[b]	Buckwheat	*Eriogonum* spp.
	Salt heliotrope	*Heliotropium curassavicum*			Globemallow	*Sphaeralcea* spp.[b]	Plantain	*Plantago* spp.
	Glasswort	*Salicornia* spp.[a]					Evening primrose	*Oenothera* spp.
	Heath	*Frankenia* spp.[g]					Goldenaster	*Chrysopsis/Haplopappus* spp.
							Blazing star	*Mentzelia* spp.
							Blanketflower	*Gallardia* spp.
Shrubs	Acacia	*Acacia spp.*[g]	Baccharis	*Baccharis* spp.[b]	Mormon tea	*Ephedra* spp.[b]	Rabbitbrush	*Chrysothamnus/Eracameria* spp.
	Iodinebush	*Allenrolfea occidentalis*	Desert willow	*Chilopsis linearis*	Wolfberry	*Lycium* spp.	Currant	*Ribes* spp.
	Fourwing saltbush	*Atriplex canescens*[b,g]	Alkali heath	*Frankenia* spp.			Sumac	*Rhus* spp.
	Shadscale	*Atriplex confertifolia*[b,g]	Arrowweed	*Pluchea sericea*			Winterfat	*Krascheninnikovia lanata*
	Mat saltbush	*Atriplex corrugata*[b,g]					Sagebrush	*Artemisia* spp.
	Quailbush	*Atriplex lentiformis*,[g]						
	Nuttall's saltbush	*Atriplex nuttallii*[a,e]						
	Desert saltbush	*Atriplex polycarpa*[g]						
	Greasewood	*Sarcobatus vermiculatus*[a,b]						
	Seepweed	*Suaeda* spp.[a]						
Trees			Screwbean mesquite	*Prosopis pubescens*	Honey mesquite	*Prosopis* spp.	Hackberry	*Celtis occidentalis*
							Ash	*Fraxinus* spp.
							Walnut	*Juglans microcarpa*
							New Mexico locust	*Robinia neomexicana*
							Willow	*Salix* spp.
							Cottonwood	*Populus* spp.
							Desert willow	*Chilopsis linearis*

Ratings represent upper limits of plant survival; productivity and vigor of plants are initially affected typically at salinity values approximately 40-50% of the survival rating (adapted from synthesis of: Bernstein 1958, FWPCA 1968, Dick-Peddie 1993, Ogle 1994, NRCS 1996, FAO 2000, Lair & Wynn 2002a, b, Stannard et al. 2002, Swift 2003). Scientific names follow the USDA Plants Database.
[a] NRCS 1996, [b] Swift 2003, [c] FWPCA 1968, [d] Bernstein 1958, [e] Stannard et al. 2002, [f] Ogle 1994, [g] FAO 2000.

sufficiently to suppress kochia (in concert with herbicidal kochia control measures), the seeded grass community will be augmented by interseeding of desirable forbs and shrubs.

Growth Medium Manipulation

Mycorrhizal Inoculation. In areas with extended and extensive occupation of nonmycorrhizal weeds including *Tamarix*, mycorrhizal inoculum potential may be low, and amending the soil may improve the performance of natives over nonmycorrhizal exotics (Allen & Allen 1984, 1986; Hanson 1991). Mycorrhizal inoculum can be obtained either commercially, or by harvest and incorporation of raw soil inoculum from adjacent native stands. Mechanical treatments previously described can be used to incorporate or improve depth placement of the inoculum.

Mycorrhizal inoculum should be selected carefully, as distribution of non-native species or ecotypes of fungi may have detrimental environmental consequences similar to the distribution of non-native plant species (Schwartz et al. 2006). Isolates chosen for inoculation should have a high specificity and benefit to the target host plants, rapid colonization ability, low dispersal ability, and poor long-term competitive ability which would allow eventual extirpation of the introduced fungi by native fungi (Schwartz et al. 2006). In general, inoculum should be generated from on or near-site donor soil whenever possible or, when obtained from commercial sources, the isolate most local to the site should be chosen. The majority of commercial AMF inoculum contains spores of *Glomus intraradices, G. mosseae, G. aggregatum,* and/or *G. fasciculatus*.

Salinity Remediation. In addition to salinity reduction afforded by mechanical creation of micro-relief on the soil surface, commercial soil amendments are available that reduce salt impacts. Products most commonly used involve a chemical reaction where soluble salts are converted to neutral or acidic compounds; or physical adsorption of sodium (Na^{++}) via colloidal attachment and sequestration. Although these products may reduce salinity or sodicity, their effectiveness is limited by the cost of the higher application rates required in soils with high electrical conductivity and the need to incorporate these products via tillage or irrigation for maximum efficacy, which is often infeasible.

Nitrogen Dynamics. Similar to scenarios where mycorrhizal inoculation may be needed, soils with a history of long-term monotypic *Tamarix* domination may be nitrogen-limited. Nitrogen (N) augmentation may be counterproductive; however, often shifting successional advantage and duration to ruderal, often exotic species that can respond to and assimilate N more rapidly (Brooks 2003). Sequestration of N in microbial biomass through application of organic, high carbon:nitrogen ratio materials (such as sawdust or sugar) may prove more beneficial to establishment and vigor of native perennial species that rely more heavily on longer-term assimilation and storage of N in persistent biomass, though study results have been mixed (Alpert & Maron 2000; Corbin & D'Antonio 2004).

Site-Specific Plan Summary

In summary, the step of developing a site-specific plan can be very complex and include a wide range of components. Key aspects include planning for baseline monitoring, deciding on the most appropriate *Tamarix* removal approach, considering both passive and active restoration approaches, and, if an active approach is chosen, exploring such detailed factors as species selection, seed ecology and seeding approaches, use of transplants, and growth medium manipulations.

Step 5: Implement Plan

This is the step where the site-specific plan (step 4) is put into action. Incorporation of the previously presented steps: identifying goals, developing project objectives while considering ecological and non-ecological factors, site prioritization selection and development of a site specific plan can help to focus efforts on sites with the best chance of success for a particular goal and ensure that funds are spent responsibly and effectively. Continued monitoring and maintenance of restoration sites will further increase chances of project success and inform other practitioners as to the techniques that are most effective in restoring *Tamarix*-dominated areas.

Under some circumstances, it may be helpful to begin restoration implementation on "pilot" sites or as small-scale experiments before expansion to larger areas. Pilot efforts may be particularly useful when there are still significant uncertainties following site evaluation. The outcomes of pilot studies may be used to inform future, expanded restoration activities. In many cases, however, restoration projects and funding are on a strict timeline and therefore do not have the luxury of including a pilot phase.

Step 6: Conduct Post-Project Monitoring and Maintenance

The purpose of monitoring is to evaluate progress toward the project goal and to inform adaptive management (step 7, below). Monitoring and maintenance are often neglected because required resources are often omitted in the budgeting process (Holmes et al. 2005). Restoration takes time; thus, determination of "success," however defined, is usually not possible immediately after implementation (Palmer et al. 2005). This is an important consideration when establishing specific project objectives and stakeholder expectations.

Selection of monitoring methods and the scope and frequency of monitoring efforts should be decided based on project goals and objectives. Where resources permit, we strongly encourage land managers to consult with researchers to maximize the value of any restoration project. Partnerships with local universities can result in reduced costs of monitoring through use of students. Such partnerships will also facilitate proper evaluation of monitoring methods, scientific soundness, and comparability to other projects.

Maintenance

Having the budget and personnel to conduct site maintenance activities can significantly affect whether or not a bottomland restoration effort meets its stated objectives (Briggs 1996; Briggs & Flores 2003). In the absence of maintenance activities, bottomland restoration projects commonly fail (Briggs & Cornelius 1998). The extent and type of maintenance that occurs depends on a variety of activities that are designed to help desirable vegetation become established, including irrigation, reducing competition from undesirable species, repairing irrigation systems, and maintaining livestock fences.

In arid southwestern United States, diligent maintenance of the seeded or planted vegetation for at least the first two growing seasons is critical, as desirable species often struggle to establish in the face of climatic extremes and secondary weed competition. Weed suppression is paramount for conserving limited water and nutrient resources and reducing the build-up of a weed seed bank. Stringent management of livestock in the revegetated area will also be needed to assure minimal herbivory or trampling damage to the young seedlings or saplings, including potential livestock exclusion during the establishment period (typically 2–5 years).

Step 7: Conduct Post-Project Monitoring and Maintenance

Adaptive management, in a broad sense, is an approach to natural resource management that integrates social and political demands for restoration with scientific understanding, in order to restore or rehabilitate ecological functions and services. Ideally, such an approach includes (1) identification of uncertainties in understanding of the natural system of interest; (2) use of conceptual and predictive models along with scientific understanding to design restoration approaches and anticipate system response; (3) implementation of well-designed management actions; (4) careful monitoring of the results of those actions; and 5) iteratively adapting management approaches based on new scientific understanding and an understanding of social and political needs driving the restoration. In a narrower sense, adaptive management emphasizes the scientific method of hypothesis testing and experimentation as a way of adapting and refining management actions (Holling 1978; Walters 1986). An iterative process of learning from previous actions is the essence of an adaptive management approach and is a key element in any restoration planning process (Fig. 1; Pastorok et al. 1997). In the context of the planning process we present in this paper, adaptive management is largely dependent upon rigorous monitoring to identify aspects of *Tamarix* removal and associated restoration actions that could be improved. Recommendations for improvement may be incorporated into later implementation activities of a given project, or, if results are made broadly available to the appropriate natural resource and scientific personnel, then recommendations may benefit other, similar projects that have yet to be undertaken.

Conclusions

Throughout the world, control of invasive species and associated restoration will continue to receive substantial attention and funding. The case of *Tamarix* in western United States presents an opportunity for resource managers and the scientific community to work together to elucidate the types of activities that are effective in attaining restoration goals, and, just as importantly, those that are ineffective. We suggest that projects will be more successful over the long term by engaging in the process that we have described. Further, clear and accessible reporting and documentation of approaches used, successes, failures, etc., can greatly improve future efforts. These sorts of actions can ensure that past restoration experiences in the context of *Tamarix* control benefit similar future projects as well as projects involving restoration and invasive species in different settings.

Implications for Practice

- Restoration projects that include controlling or removing *Tamarix* will benefit from a comprehensive planning and implementation process that involves setting clear goals and objectives, evaluating ecological and non-ecological site conditions, developing a detailed project plan, pre- and post-project monitoring and maintenance, and adaptive management.
- Key ecological site factors to evaluate include surface and groundwater regimes, soil salinity and texture, soil microbes, and the current vegetation and propagule availability.
- Important non-ecological factors relate to permitting, site access, budgeting, and stakeholder involvement.
- Project planning involves consideration of baseline monitoring, *Tamarix* removal approaches, passive and active restoration approaches, species selection, and growth medium manipulation.
- Results of post-project monitoring should be used to evaluate success and to inform adjustments to future restoration actions in an adaptive management framework.

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