

# Literature Review of Four Invasive Phreatophytes and One Invasive Grass within the Bosque Forest of the Middle Rio Grande

August 13, 2018



Prepared by  
Kyle ME Rose, Ph.D., Assistant Professor of Forestry  
New Mexico Highlands University  
for the Greater Rio Grande Watershed Alliance



New Mexico  
Forest and Watershed  
Restoration Institute

*New Mexico Highlands University*

## TABLE OF CONTENTS

<b>EXECUTIVE SUMMARY .....</b>	<b>3</b>
<b>ACKNOWLEDGMENTS .....</b>	<b>4</b>
<b>INTRODUCTION .....</b>	<b>5</b>
INVASIVE SPECIES CONTROL METHODS .....	5
AUXIN MIMICS .....	7
MITOSIS INHIBITORS .....	8
PHOTOSYNTHESIS INHIBITORS.....	8
LIPID BIOSYNTHESIS INHIBITORS.....	9
AMINO ACID SYNTHESIS INHIBITORS .....	9
SCOPE OF DOCUMENT.....	11
<b>SALT CEDAR (<i>TAMARIX</i> SPP).....</b>	<b>12</b>
INTRODUCTION .....	12
CONTROL .....	13
CONTROL CONSIDERATIONS.....	17
<b>RUSSIAN OLIVE (<i>ELAEAGNUS ANGUSTIFOLIA</i> L.).....</b>	<b>19</b>
INTRODUCTION .....	19
CONTROL .....	19
CONTROL CONSIDERATIONS.....	22
<b>SIBERIAN ELM (<i>ULMUS PUMILA</i> L.) .....</b>	<b>23</b>
INTRODUCTION .....	23
CONTROL .....	24
CONTROL CONSIDERATIONS.....	26
<b>TREE OF HEAVEN, AILANTHUS (<i>AILANTHUS ALTISSIMA</i> (MILL.) SWINGLE).....</b>	<b>26</b>
INTRODUCTION .....	26
CONTROL AND CONTROL CONSIDERATIONS .....	26
<b>RAVENNA GRASS (<i>SACCHARUM RAVENNAE</i> L.).....</b>	<b>28</b>
INTRODUCTION .....	28
CONTROL AND CONTROL CONSIDERATIONS .....	29
<b>RESEARCH GAPS AND FUTURE RESEARCH DIRECTIONS.....</b>	<b>30</b>
<b>REFERENCES.....</b>	<b>32</b>

## Executive Summary

Some of the many plant species moved from their native ranges to non-native ranges have become invasive, meaning they proliferate to the point that their presences causes negative economic or ecological impacts (Mack et al. 2000). Increased recognition of these impacts has led to increased efforts to either eradicate or control these non-native, invasive species. This document reviews biological, mechanical, and chemical control measures, and complications that accompany those control measures, of five invasive species of interest within the Middle Rio Grande River Bosque system: saltcedar (*Tamarix* spp), Russian olive (*Elaeagnus angustifolia*), Siberian elm (*Ulmus pumila*), tree of heaven or ailanthus (*Ailanthus altissima*), and Ravenna grass (*Saccharum ravennae*). In order to facilitate the reading of this document, the document begins with a short overview of invasive species, control measures, herbicide modes of action, and herbicides mentioned in the document. The specific measures taken to control the species covered in this document depend upon the social, economic, and ecological constraints of the project. In small-scale, recent invasions, it is sometimes possible to employ mechanical, or more commonly, chemical treatments alone and limit effects to desirable neighboring plants. In larger invasions, it is more common to employ the use of heavy machinery to remove the plants, taking care to remove as much of the roots as possible, and follow-up the mechanical control method with spot-treatments with herbicide. The number of reentries and monitoring period needed is species specific. In general, effective monitoring will require five to seven years to fully evaluate (Bay and Sher 2008). Because this review was not intended to provide specific recommendations based upon the goals of specific projects, it has been intentionally limited in providing those recommendations, favoring instead to review the scientific literature to provide the reader with quantitative estimates of results following the suite of control measures available to land managers. The goal is to aid the land manager in choosing treatments that suit the constraints of the project. Whenever possible, the literature reviewed pertains specifically to the Southwest, but in some cases (e.g. ailanthus and Siberian elm) this is not possible because the literature on the control of these species is scant, especially within the Southwest region. Finally, the document ends with a discussion of current research gaps and future research directions possible in order to further the effective management of the Bosque.

**Acknowledgments**

The author would like to thank the Greater Rio Grande Watershed Alliance and New Mexico Forest and Watershed Restoration Institute for financial support in writing this literature review. He would also like to thank Sandia Pueblo for graciously providing a tour of recent restoration projects.

## Introduction

Invasive species are those species that, once established in a region outside their traditional range, spread without human assistance and consequently change the composition or processes of their new environment (Mack et al. 2000). These changes to otherwise self-perpetuating systems can include extirpation of native species occupying the same niche and changes in disturbance (e.g. fire, flooding) regimes, in addition to potential economic losses felt by local and regional communities (Mack et al. 2000). Despite the fact some species, once thought to be invasive, are shown to be non-native (their original range is different from where individuals are found) but lacking invasive characteristics, invasive species still represent an important threat to biodiversity and functionality of ecosystems throughout the world (Russell and Blackburn 2017).

As a result of increased recognition of the capacity for invasive species to affect ecosystems, extensive time, money, and effort have been expended to identify and implement efficient eradication measures. In some cases, eradication has proven difficult or impossible and control measures are instead sought (Zavaleta et al. 2001). In still other cases, because of extenuating circumstances (e.g. changes in disturbance regimes from historic regimes; cost; social pressure), previously non-existent assemblages of species are accepted and managed. In this latter case, these new systems are called “novel ecosystems” (Hobbs et al. 2013).

### *Invasive species control methods*

Where control and/or eradication are possible for invasive plant species, options are usually broken down into three categories: mechanical, biological, and chemical. Mechanical methods can be as simple as methods involving hand-pulling or the use of a chainsaw, representing low soil disturbance and high specificity methods (where effects on non-target individuals and species is minimized), to methods employing heavy machinery, which cause more soil disturbance and affect the area more broadly (e.g. (González et al. 2017a)). Depending on the size of the area and the difficulty of accessing the site, among other factors, either low-disturbance or heavy-disturbance methods can be more cost effective (McDaniel and Taylor 2003).

Biological control or eradication methods employ the use of living organisms to either reduce fecundity (i.e. fertility and the production of offspring) or actively kill invasive species (Allendorf and Lundquist 2003). A successful example of biological control of an invasive cassava mealybug, which had been threatening 200 million people with food shortages and the control of which earned a World Food Prize and saved billions of dollars for Africa (Messing and Wright 2006). Some unsuccessful examples of this include the introduction and establishment of 210 species in Hawaii between 1890 and 1985, 20 of which were reported to prey on native species. Specifically, in 1883 and 1885, the mongoose (*Herpestes javanicus*), originally from India, was imported from Jamaica to control rats in sugarcane fields (Funasaki et al. 1988), but subsequently has been documented to prey on numerous native bird species (Hays and Conant 2007).

Chemical control methods involve the use of herbicides where the goal is to kill the sprayed individual. Methods of delivering the chemical are diverse. Some of the most common methods are the use of a paintbrush or spray bottle to apply directly to the stump of a small tree (e.g. (Belote et al. 2010)), the use of backpack sprayers to apply chemical in larger areas while maintaining control of its application in order to minimize non-target effects, the use of booms on ATVs or tractors when spraying in lines within plantation or fields, and the use of helicopters to spray in rare cases when stands of invasive species are homogeneous and large (e.g. (McDaniel and Taylor 2003)). In addition to a diversity of equipment used to apply herbicides, they can also be applied at different times of the year (e.g. before germination or during the growth period), depending on their “mode of action” and the biological characteristics of the target species.

Many herbicides, covering five “modes of action,” are available for use in restoration projects where control of invasive species is needed. These five modes of action include auxin mimics, mitosis inhibitors, photosynthesis inhibitors, amino acid synthesis inhibitors, and lipid biosynthesis inhibitors (Tu et al. 2001). The following sections will summarize the modes of action and principle herbicides that will be referenced within the literature review of control of phreatophytic (deep rooted) invasive plants.

### *Auxin mimics*

For those herbicides that are auxin mimics (e.g. 2,4-D, Triclopyr), the application of the herbicide results in uncontrolled growth (Tu et al. 2001). Increased cell growth is usually noticeable within the first hour following application because of increased cell wall elasticity. Additionally, because of the potential for stomatal guard cell swelling, application can lead to increased photosynthesis; with reduced control over guard cells, increased RNA and protein synthesis, uncontrolled photosynthesis, and disorganized growth, application usually leads to death of the individual, but the timing of mortality and the effectiveness of the application are dependent on the age, species, and health of the individual. In general, auxin mimics are not effective on monocots (e.g. grasses).

The most common auxin mimic is 2,4-D, sold under the trade names Navigage®, Class®, Weed-Pro®, Justice®, Aqua-Kleen®, Barrage®, and Weedone® (Tu et al. 2001)<sup>1</sup>. Originally a component of agent orange, it has been used as an herbicide for decades. It is a relatively inexpensive herbicide that comes in two formulations, salt and ester, and targets dicots (e.g. deciduous trees and other broadleaf plants; not grasses). It degrades in the soil, primarily because of microbial activity, with a half-life of 10 days and has moderate to high soil mobility. In water, the half-life varies from hours to months. Toxicity is highest for birds and fish and lowest for mammals. Because of toxicity to fish, it is important to use the salt formulation in riparian zones. Both the salt and ester formulations can volatilize easily and should be applied using a coarse spray on days that are cool and calm (less than 5 mph wind). In general, the time to kill is between three and five weeks.

Another auxin mimic, picloram, is sold under the trade names of TordonK®, Grazon®, and Pathway® (Tu et al. 2001). It can be used to control perennial broadleaves, vines, and woody plants. It has a soil half-life of 90 days and water half-life of two to three days. Because of poor adsorption to soil (not tightly held by soil), it has moderate to high soil mobility and easily leaches and runs off the site, contaminating water where it is highly toxic to fish. As a result, it is not recommended for riparian areas.

---

<sup>1</sup> Note: always read the manufacturer's label before use. This summary is not comprehensive and does not substitute for the manufacturer's label.

Triclopyr, a commonly used auxin mimic, is a selective herbicide sold under the trade names of Garlon® and Remedy® (Tu et al. 2001), although Access® includes both triclopyr and picloram. It does not affect grasses; it is used to control woody annuals and broadleaf plants. It has a relatively short soil half-life of 30 days and is primarily degraded by microbial activity (Tu et al. 2001), but the half-life has been shown to be relatively slower in coarser texture soils and soils with higher organic matter content and cation exchange capacity (Douglass et al. 2016). In water, the half-life averages four days (Tu et al. 2001). Triclopyr adsorbs to soil at moderate levels, is moderately to highly mobile in soils, and is consequently susceptible to runoff into water bodies. It is of low toxicity to both mammals and birds, but moderately toxic to fish. The ester formulation (Garlon 4), however, is highly toxic to fish and other aquatic organisms and degrades slowly in water. In contrast, the salt formulation (Garlon 3a) can degrade within hours in water. It is best used when directly applied to target plants. Although the ester formulation is highly toxic to aquatic organisms, it is effective against root-sprouting species often the most cost-effective solution against *Tamarix* species. When used for these ends, it should be applied during the dry season to minimize runoff and effects to aquatic organisms.

#### *Mitosis inhibitors*

Mitosis inhibitors (e.g. fosamine), not as commonly used as other types of herbicides, enforce dormancy in plants (Tu et al. 2001). Many plants go through a period of dormancy during which metabolic processes are minimized and photosynthesis ceases. For example, many deciduous trees enter a period of dormancy during the winter season and leave dormancy only after experiencing a minimum number of chilling hours or when day length returns to a minimum length after winter. When dormancy is enforced, the plant cannot photosynthesize, but maintenance respiration continues, leading to a carbon shortage in the plant, eventually leading to plant death.

#### *Photosynthesis inhibitors*

Some herbicides directly target photosynthesis and inhibit it explicitly (Tu et al. 2001). Within this class of herbicides, Type I photosynthesis inhibitors (e.g. hexazinone) stop electron transport within Photosystem II, leading to the production of toxic compounds and eventually, the destruction of cells. More common herbicides, paraquat and diquat, are type II and allow for acceptance of electrons from Photosystem I, leading to the production of hydroxyl radicals which



reduce cell membrane integrity through the destruction of unsaturated lipids, such as chlorophyll and other cell wall membranes. With cell membranes damaged, they leak, which leads to cells drying out and the plant dying.

#### *Lipid biosynthesis inhibitors*

Lipid biosynthesis inhibitors (e.g. flauzifop-p-butyl) also affect cell membranes, but specifically block the growth and maintenance of them instead of explicitly targeting their immediate breakdown (Tu et al. 2001). In this case, with the inhibition of acetyl CoA carboxylase, fatty acid synthesis ceases and plant death occurs over time with failure of cell membranes. Importantly, because of differing enzymes binding sites for trees and grasses, this herbicide only affects grasses and can be used safely to control invasive grasses beneath a native tree canopy.

The most commonly used lipid biosynthesis inhibitor is flauzifop-p-butyl, sold under the trade names Fusilade DX®, Fusion®, and Tornado® (Tu et al. 2001). As is the case with all lipid biosynthesis inhibitors, it is grass-specific and can be used on all perennial grasses and nearly all annual grasses, with bluegrass (*Poa* spp) and fine fescues notable exceptions. It has a short half-life in the soil of 15 days. Although it is stable in water following rapid conversion to flauzifop acid, its soil adsorption is high, especially in clays, and soil mobility low and is unlikely to run off into water sources. Nevertheless, it is not labeled for aquatic use as a result of its toxicity to fish. An additional consideration is that it relies on moisture in the soil to be effective because it relies on plant uptake and plant growth for its mode of action. Consequently, it cannot be applied during droughts or when target plants are inactive. Finally, lipid biosynthesis inhibitors can lose effectiveness when applied at the same time as auxin mimics (e.g. triclopyr).

#### *Amino acid synthesis inhibitors*

Some the most commonly used herbicides (e.g. glyphosate, imazapyr, imazapic) are amino acid synthesis inhibitors (Tu et al. 2001). Without amino acids, plants cannot produce proteins and eventually die. In the case of glyphosate (Roundup®), carbohydrate translocation is also induced and may play a role in mortality. Not all herbicides within this class inhibit the production of the same amino acids (e.g. glyphosate vs. imazapyr), which means that the kill rate

can differ too. Importantly, this class of herbicides inhibit production of amino acids in plants, not animals.

Of the amino acid synthesis inhibitors, glyphosate, known most commonly as Roundup® and originally developed by Monsanto, is now sold generically and inexpensively under a host of trade names, including Rodeo®, GlyPro®, Accord®, Glyphomax®, and Touchdown® (Tu et al. 2001). It can be used to target both annuals and perennials. It has a relatively short half-life in soil (averaging 47 days) and a highly variable half-life in water. Glyphosate is not mobile in soils and breaks down primarily as a result of microbial activity. It is of slight toxicity to mammals, low toxicity to birds, and moderate toxicity to fish (variable depending on formulation).

Imazapyr is an expensive, non-selective (kills perennial grasses, broadleaf plants, vines, and woody plants) herbicide sold under the trade names of Arsenal®, Habitat®, Chopper®, and Stalker® (Tu et al. 2001). Acid forms of imazapyr (e.g. Arsenal®) are for terrestrial use, whereas salt forms (e.g. Habitat®) are labeled for control of aquatic plants in riparian zones and ditches not used for irrigation. This herbicide can be used as a pre-emergent (before germination) and post-emergent (on growing plants) in part because of its persistence in the soil. The half-life in soil generally ranges from 25-141 days (Tu et al. 2001), but this is heavily dependent on soils and ranged from 82-268 days in six upland soils in Colorado, degrading more quickly in soils of finer texture with higher organic matter and cation exchange capacity. Furthermore, sensitivity to herbicide residues can vary. For example, western wheatgrass (*Pascopyrum smithii* (Rydb.) Á. Löve) has been shown to be sensitive to imazapyr residues for 20-23 months following application in some soils (Douglass et al. 2016). It is of low to moderate mobility in soil (Tu et al. 2001). Importantly, non-target effects and kill can occur as a result of exudation from roots and movement of imazapyr through root grafts or the movement of soil to which it is adsorbed. In contrast to degradation in soil, the half-life is only two days in water and it is of only low toxicity to birds and fish with slight toxicity to mammals. In general, care should be taken to avoid broadcast spraying imazapyr to soil within twice the drip line of non-target plants.

Lastly, imazapic is a selective amino acid synthesis inhibitor sold under the trade names of Plateau®, Plateau Eco-Pak®, and Cadre® (Tu et al. 2001). It can be used for both annuals and perennials but is not effective on everything. As a result, it can be used in some settings to control non-desirable weeds or invasive species without damaging non-target, desirable species.

It has been used extensively to promote warm-season grasses during prairie restoration. It can be used as either a pre- or post-emergent herbicide, having a half-life in the soil of 120-140 days. Non-target effects are more limited than those incurred with imazapyr use in part because of low to moderate soil mobility, typically with movement limits of 6-12” horizontally and 18” depth. In water, it rapidly photodegrades within eight hours. It is of slight toxicity mammals, low toxicity to birds, and moderate toxicity to fish.

### *Scope of document*

Between 1960 and 2009, at least 355 peer-reviewed papers were published worldwide regarding the control of invasive plant species, including at least four published on saltcedar control in New Mexico (Kettenring and Adams 2011). During this time, the most common methods of control included herbicide (59%), cutting (34%), burning (24%), and hand pulling (20%), where herbicide control was generally the most effective across species and burning was usually counter-productive. It is important, however, to look at the species-specific results that can guide restoration prescriptions locally and regionally.

This document reviews peer-reviewed literature covering the control methods, both successful and unsuccessful, of four invasive, phreatophytic species and one invasive grass. An attempt has been made to select papers that are relevant to the Middle Rio Grande Bosque. For some species covered, the literature regarding control methods is sparse and a wider geographic net was cast in order to direct land managers to potential control methods that have not been documented in the scientific literature for the Middle Rio Grande Bosque at the time of writing.

In order, the four phreatophytes that will be covered are saltcedar (*Tamarix* spp), Russian olive (*Elaeagnus angustifolia* L.), Siberian elm (*Ulmus pumila* L.), and tree of heaven (*Ailanthus altissima* (Mill.) Swingle). The invasive grass that is covered by this review is Ravenna grass (*Saccharum ravennae* L.). Each discussion of control methods for each species will include a short introduction of the species of interest, a discussion of relevant research for control of the species using biological, chemical, and mechanical control methods, and a discussion of relevant research regarding complications controlling the species or the restoration of sites post-control. Depending on the amount of research available for each species, all or only some of these topics are covered.

Following the review of control methods, the document includes a short discussion of knowledge gaps, research needs, and future management considerations. The document ends with a bibliography that directs the reader to the primary sources cited in this document. In the event that the reader cannot access a paper and would like to get a copy of a paper cited in this document, please email the author at [kylrose@nmhu.edu](mailto:kylrose@nmhu.edu).

## **Saltcedar (*Tamarix spp*)**

### *Introduction*

Saltcedar (Figure 1) was introduced to the US in 1823 as an ornamental shrub in the east, with several saltcedar available for purchase at nurseries near Philadelphia, Pennsylvania in 1828 (Brotherson and Field 1987). Around 1870, it escaped from gardens in the western US, spreading



*Figure 1.* Saltcedar can stump sprout vigorously following removal treatments (photo by Kyle Rose).

slowly and unnoticed until the early 1900s. Before 1920, it was planted throughout the western US for erosion control but was soon thereafter recognized for its ability to spread rapidly on its own. As of 2011, it was the second most common tree along rivers of the western US (Glenn and Nagler 2005), despite decades of attempts to control and eradicate it.

### *Control*

Prior to 2001, when the saltcedar leaf beetle (*Diorhabda* spp.) was first released in ten sites within Texas, Colorado, Wyoming, Utah, Nevada, and California (DeLoach et al. 2003), saltcedar eradication efforts were at times successful to the point of total or near total eradication (McDaniel and Taylor 2003; González et al. 2017a), but were costly in both money and labor. Around this time, on the Bosque del Apache National Wildlife Refuge, for example, costs ranged from \$750 to \$1,300 per hectare to control saltcedar using techniques that combined chemical, fire, and mechanical control methods (Taylor and McDaniel 1998). The beetle was not released directly to the Middle Rio Grande River in New Mexico, but rather to the Rio Grande River in Texas, the San Juan River in Colorado, and the Pecos River in New Mexico. Despite this, it has been documented within the Middle Rio Grande portion of the Rio Grande (Dillon and Ahlers 2017). As a result, findings on impacts of the beetle are relevant to management of saltcedar within the GRGWA management area.

Following the introduction of the saltcedar leaf beetle, key questions posed by land managers now included whether the introduction of the biological control agent was effective enough on its own to eradicate saltcedar and, if it could not eradicate it altogether, if the control level it brought was enough to restore functionality and biodiversity to riparian areas heavily invaded by saltcedar without accompanying it with active removal and/or revegetation efforts.

Recent studies cite variable effects on mortality of saltcedar and recovery of native systems post-release. The most recent large-scale study that addresses the topic of biological control provides important guidance for projects where the goal is to reduce saltcedar cover and vigor while increasing understory native vegetation without active revegetation efforts included in the project (Sher et al. 2018). The study found that, in these conditions and in this region, 10% of saltcedar was still alive seven years post-release. This contrasts with another recent study monitoring mortality for six years post-release (Kennard et al. 2016), in which case no mortality occurred at three of ten sites monitored. In seven sites, mortality ranged from 15% to 56% during

that time. Impacts of the beetle on saltcedar mortality are clearly patchy and variable across the current range of the beetle.

Biological control, therefore, can be effective at reducing saltcedar cover but reduction of saltcedar cover is often an objective of a much larger goal to recover understory vegetative diversity. In this respect, perhaps the more important effect of the saltcedar leaf beetle is increased native understory cover and richness (the number of species present) following release (Sher et al. 2018). It is not the only control method in which native understory vegetation recovery has been noted, but it does require the least amount of labor to achieve that end.

Nevertheless, other methods, including chemical control using the cut-stump method and mechanical control by mastication, heavy machinery removal, or chainsaw followed by burning can increase the speed at which those results occur relative to biological control (Sher et al. 2018). In stands of homogenous saltcedar, even helicopter applications of imazapyr have been utilized to successful and cost-effective ends in comparison to mechanical methods (McDaniel and Taylor 2003). Following removal, the more saltcedar cover is reduced, the more the native understory community has responded in large-scale studies. Furthermore, Sher et al. (2018) found that low disturbance, chemical control combined with biological control increased understory plant community richness by 43% and 101% relative to biological control alone and high disturbance, mechanical control combined with biological control, respectively. This is a consistent finding across studies, as seen in González et al. (2017a), in which cut-stump treatments (mechanical + chemical control) resulted high in biodiversity relative to treatments that included burning or heavy machinery. Together, these results show the value of combining biological and chemical control methods when the goal is recovery of the native understory plant community. Not only can mechanical treatments limit recovery of the native understory community, they can facilitate invasion of non-native forbs, as found in a large study that included 244 treated sites and 172 untreated sites across six states, including New Mexico (González et al. 2017a).

Although mechanical control in combination with biological control can be less effective at increasing understory native plant richness than biological control alone, it can be more effective than biological control alone at reducing saltcedar cover. For example, when biological control alone was relied on to reduce saltcedar cover (Sher et al. 2018), saltcedar cover was six times

more abundant than in those sites where mechanical treatments were included. A final, important takeaway from Sher et al. (2018) is that if the goal of a project is to eradicate saltcedar as quickly as possible in a site where the saltcedar leaf beetle is present and active, the fastest way to achieve end is to employ a cut-stump treatment with a systemic herbicide (e.g. imazapyr). This method is costly and labor intensive, however, and in some cases, mastication combined with re-entries in the years following to apply a foliar herbicide can achieve similar results to cut-stump methods in these areas with biological control (Sher et al. 2018).

Despite the positive, additive effects of utilizing biological control methods in conjunction with other active methods, it is important to note beetle releases have slowed or stopped in many areas because of concern for the endangered Southwestern willow flycatchers, which utilizes stands of saltcedar for habitat (Hultine et al. 2010; Dudley and Bean 2012). Furthermore, when biological control alone is compared to methods that employ burning, mechanical control, or chemical control either alone, or more commonly, in conjunction, these methods can be better at controlling saltcedar (González et al. 2017a). Because of this, the tool chest of control methods for saltcedar should include more than biological control methods.

In studies looking at the effectiveness of mechanical control alone (no chemical control included), treatments are unlikely to eradicate saltcedar (Combs 2010), although repeated, costly entries with heavy equipment have realized successful removal of 97% of saltcedar (McDaniel and Taylor 2003). Use of heavy machinery, however, is unlikely to lead to increases in density or cover of native woody species (Ostojka et al. 2014). Fire has the potential to kill young (2-3 month) regenerating stands of saltcedar (Ohrtman et al. 2014). Prescribed fire has been as successfully used with follow-up cut-stump applications on both the Pecos and Middle Rio Grande rivers to reduce saltcedar cover (Harms and Hiebert 2006).

For chemical control of saltcedar, application as a basal bark or cut-stump treatment is recommended, although few studies have looked at chemical control alone as a saltcedar control method (González et al. 2017a). In occasionally flooded loamy fine sand in southwest Kansas, three treatments foliar applied ranged in effectiveness: 44% control using 10% triclopyr in diesel; 85% control using 1% imazapic + 1% methylated seed oil; and 92% control using 1% imazapyr + 1% methylated seed oil (Fick 2016). Although triclopyr did not perform well as a foliar application, both forms (salt and ester) are considered best practice in Montana in basal

bark applications (Garlon 3® vs Garlon 4® use depending on proximity to water) to small diameter trees (<3" diameter) at concentrations of 25-33% solution, avoiding times when the bark is wet (Combs 2010). When treating larger saltcedar, a cut-stump treatment, instead of a basal bark application, is recommended at concentrations of 50% solution for Garlon 3® or 25-30% solution mixed with basal oil, diesel, or kerosene for Garlon 4® (Combs 2010) applied from groundline to 18" height (Jacobs and Sing 2007).

Cut-stump applications can result in high rates of mortality for saltcedar. Mortality at 15 months after treatment can be up to 90% when glyphosate + imazapyr (5% + 5% in water) or imazapyr alone (9.38% in water) are applied to cut individuals (Fick and Geyer 2010). Even more, one hundred percent mortality has been achieved using undiluted Pathfinder® (13.6% triclopyr). In both cases, these rates of mortality have been realized in operations that have taken up to 10 days to apply the herbicide. (Fick and Geyer 2010). These kill rates should be expected with greater probability when herbicide is applied within one hour after cutting, as recommended (Jacobs and Sing 2007). For all of these methods, it is possible that cut stems left on site can resprout. Therefore, it is recommended to burn, chip, or otherwise dispose of the slash to reduce risk of resprouting. Finally, where saltcedar is dominant or homogenous (the only species present), it can be effective to apply imazapyr as an aerial application (Jacobs and Sing 2007).

It should be noted that herbicides are, at times, mixed to increase effectiveness when treating saltcedar. Using nine herbicide treatments in southwestern Kansas, Fick & Geyer ( 2010) found that glyphosate alone, applied as a cut-stump application, had no effect on percent mortality, but that adding 2,4-D amine (30% mortality) or imazapyr (90% mortality) to glyphosate improved results. In the case of imazapyr being added to glyphosate at a rate of 5% + 5% in water, this achieved the same mortality rate as imazapyr alone at a rate of 9.38% in water, thus potentially reducing the cost of the operation relative to using imazapyr alone.

It is often advantageous to combine mechanical and chemical control methods. When controlling young saltcedar resprouts or natural regeneration, it is common that physical control (e.g. mowing) has no positive effect, but when it has been combined with fire or chemical control, it has been successfully employed to control both 2-3 month old plants (Ohrman et al. 2014) and established stands (Brotherson and Field 1987; Fox et al. 2001). For example, the use of a rollerchopper in 100 acres of recently burned areas dominated by saltcedar increased



mortality from 60.6% to 85.1% twelve months after burning (Fox et al. 2001). Alternatively, following up fire with cut-stump applications of 25% triclopyr (Garlon 4®) resulted in 89.9% and 94.5% when applied in February and March, respectively, after a summer fire the previous year. It should be noted that this directly contradicts a recent large-scale study (González et al. 2017a) that found following up burning with cut-stump applications were not effective. This could be because large studies that aggregate effects across disparate treatments can washout the effect of specific, successful methods within the larger category. The same study found saltcedar mortality occurred in only 38% of the 189 sites sampled, underlining the fact that these large-scale studies that lump treatment types into categories (e.g. cut-stump, mechanical) might miss the specific methods that lead to successful control of saltcedar.

It is not the purpose of this review to make recommendations regarding the best treatment because the control treatment selected will need to balance social, economic, and ecological constraints of the project. In some cases, chemical applications are not prohibited. In others, herbicides such as imazapyr are too costly. Or, the application of non-selective herbicides like imazapyr are likely to harm non-target neighbors. Finally, biological control may not be warranted because of the presence of the southwester willow flycatcher. It is up to the land manager to select the treatment, or combination of treatments, most appropriate to the project at hand.

### *Control considerations*

Some have argued that saltcedar is not as much of a problem as it has been thought of in the past (Stromberg et al. 2009). They argue that saltcedar's weak to inconclusive connection to falling water tables when using advanced methods (Shafroth et al. 2005; Cleverly et al. 2006; Hatler and Hart 2009) and mistaking correlation for causation (e.g. does saltcedar cause increased soil salinity or just tolerate it?) perpetuates much of the disdain for the species. It is thus argued that saltcedar is merely taking advantage of degraded ecosystems to establish and proliferate, a point supported by studies that demonstrate that native species are able to reestablish and self-perpetuate when flood regimes are restored or still present (Stromberg et al. 2007). Those that argue in favor of rethinking saltcedar's harmful impact on southwestern riparian areas promote using restoration goals that restore functionality and processes that are needed for the local ecosystem (Stromberg et al. 2009). Land managers can expect, moreover,

that where willows and, especially, cottonwoods are established, they will outcompete saltcedar (Sher et al. 2002). In this case and if saltcedar is utilized by the southwestern willow flycatcher (Shafroth et al. 2005; Dudley and Bean 2012; Bean and Dudley 2018) and can, therefore, be tolerated at low densities, efforts can be directed away from eradication to management.

Both chemical and mechanical control methods can result not only in reduced saltcedar cover but also increased native, understory herbaceous vegetation, although the species composition of that increase is not always riparian because of altered site conditions. In established stands of saltcedar, cut-stump applications of triclopyr (Garlon 4® at unknown rate) and whole-plant removal have resulted in reduced saltcedar and increased native plant cover two years post-treatment (Reynolds and Cooper 2011). Similar increases to native herbaceous cover and species richness can be achieved with mechanical control methods (Ostoja et al. 2014), but not all treatments are equally effective. The results of a large-scale (244 treated and 172 reference sites throughout six states, including New Mexico) suggest that no saltcedar control treatment is likely to directly contribute increases in native forbs, but both low-disturbance and heavy-disturbance mechanical control have been connected to small increases in native grass biodiversity (González et al. 2017a). Although burning reduced the need for follow-up herbicide applications, furthermore, it was associated with significantly fewer native species than in undesirable reference sites (the worst sites). It should be noted, however, increases in native cover do not always lead to increased species richness (Harms and Hiebert 2006). In fact, the community composition of previously riparian areas recovering from treatments can shift to upland species because of altered fluvial processes compared to historic norms. If the goal of a project in an area with altered flood regimes, therefore, is to restore riparian species communities, the project is unlikely to be successful unless those historic fluvial processes are restored (Stromberg 2001; González et al. 2017a). If, however, project goals involve eradication of non-native saltcedar in order to establish a self-perpetuating native community, a shift in community type from riparian to upland might be acceptable and considered successful.

Where the goal of a project is not eradication of saltcedar and, rather, includes restoration of native plant communities, follow-up control (González et al. 2017a), revegetation, and monitoring are of particular importance because of the potential for invasive plant species to take advantage of reduced cover to invade the understory (González et al. 2017b). Regarding

revegetation, it can be a part of a successful restoration project restoring native plant communities (González et al. 2017a). Research within the Middle Rio Grande shows that increased proximity to perennial water (best within 10 m), greater the precipitation (when great than 20.8 cm annual precipitation, no saltcedar regrowth present), more flooding, good drainage, lower soil pH, and coarse soil textures are connected to successful revegetation of native species, including increased species richness and abundance (Bay and Sher 2006). Importantly, using seed, rather than transplants, has been shown to be ineffective and should be avoided in most cases. These revegetation efforts have the potential to reduce microsites available to secondary invasions by understory vegetation. This has been documented in sites relying on both biological and mechanical control methods (González et al. 2017b). These invasions can become apparent during the first three years after mechanical control, as in the immediate impact found for both kochia (*Bassia scoparia*) and Russian thistle (*Salsola tragus*) following treatment, or delayed for up to five years in biological control areas, where both perennial forbs (e.g. *Acroptilon repens*) and annual grasses (e.g. *Bromus tectorum*) take advantage of reduced live canopy with increased saltcedar leaf beetle activity. Catching these invasions early is important, especially because both kochia and Russian thistle have shown resistance to imazapyr and glyphosate (Primiani et al. 1990; Chodova and Mikulka 2000). It is recommended, therefore, that follow-up activities commence in the immediate years following control efforts of saltcedar and continue, at least intermittently, for at least seven years following these activities (Bay and Sher 2008).

### **Russian olive (*Elaeagnus angustifolia* L.)**

#### *Introduction*

Russian olive (Figure 2) is a nitrogen fixer (Espeland et al. 2018), able to take advantage of marginally fertile sites, that produces seeds prolifically (Espeland et al. 2014). As a result, as recently as 2011, it was estimated to be the fifth most abundant tree species along the rivers of the western US (Glenn and Nagler 2005).

#### *Control*

Both chemical and mechanical control methods are linked to successful reductions in



*Figure 2.* Treatment prescriptions that retain Russian olive adjacent to standing cottonwood retain seed sources for repeated Russian olive invasions (photo by Kyle Rose).

Russian olive cover and reproductive capacity (Reynolds and Cooper 2011; Espeland et al. 2018). In both cut-stump (Garlon 4® at unknown concentration) and whole-plant removal operations in Chelly National Monument in Arizona, Russian olive cover was reduced to near zero and seed rain was reduced to  $0.5 \pm 0.3$  and  $0.3 \pm 0.2$  seeds/m<sup>2</sup>, respectively, representing significant reductions in seed rain relative to control plots in which seed rain was  $27.8 \pm 11.3$  seeds/m<sup>2</sup> (Reynolds and Cooper 2011). In Montana, a 96% kill rate was achieved by cutting Russian olive to ground level with a John Deere 326D skid steer with tree shear, followed by an application of 25% triclopyr (Element 4®) applied with an herbicide emitter attached to the tractor (Espeland et al. 2018), a method that would likely be most appropriate in stands that are dominated by Russian olive, rather than stands it has recently invaded. Using this method, 2,500 Russian olives were treated per hectare, costing 17.7 person-hours, 39.5 L fuel, and \$427 in herbicide (7.9 L triclopyr) per hectare (Espeland et al. 2017). Successful treatment of resprouts

occurred using a foliar application, applied for two years following the initial treatment, using a mixture of Element 4® (2.59 g ai L<sup>-1</sup>; 0.135%) and Milestone® (1.29 g ai L<sup>-1</sup>; 0.22%) with 2.6 g surfactant mixed in water. A light application of glyphosate (0.54 g ai ha<sup>-1</sup>) was used with good success to control Russian olive regenerated through seed in the seedbank. Follow-up activities are of particular importance with Russian olive because the seedbank can be extensive and germination prolific, potentially increasing exponentially through years four and five post-removal (Espeland et al. 2017).

In treatments of scattered, large Russian olive, frill cut applications have been successful (Patterson and Worwood 2010; Patterson 2011). This type of herbicide application utilizes an application of a small quantity (1-2 ml) of herbicide to cuts made in the trunk of a tree using an ax or hatchet, with generally one downward cut through the bark to the sapwood for each inch of trunk diameter (Patterson and Worwood 2010). Experiments comparing the effectiveness of application timing, herbicides, and application rates suggests that the most cost-effective results can be realized when applying low rates (1-1.5 ml) of glyphosate (41%) or 2,4-D (47.3%) herbicide to frill-cuts during the growing season (Patterson and Worwood 2010; Patterson 2011).

In some cases, significant reductions in Russian olive cover can be realized with limited chemical applications when the treatment aims to reintroduce natural processes, flooding, that favor native species (Muldavin et al. 2017). For example, the Albuquerque Overbank Project began in the winter of 1997-98, treating an area where invasive species represented 72% of the canopy. To begin, the project removed a large stand of Russian olive via root plowing. Following this, the floodplain was expanded by lowering the bar and installing side channels with small islands constructed to slow the flow of flood waters and increase sediment deposition. The first flood, in 1998, was associated with over 10,000 cottonwood per hectare establishing on site and demonstrated the effectiveness of lowering the bar to encourage flooding. In 2003 and 2005, a 25% mixture of triclopyr (e.g. Garlon 4®) in vegetable oil was applied as a spot treatment to Russian olive sprouts. Concurrently, a 50% mixture of triclopyr in water (e.g. using Garlon 3®) was applied to larger trunks using a cut-stump method. Despite increased beaver activity affecting cottonwood density on site after fifteen years and the incursion of the invasive grass, *Saccharum ravennae*, the project represents a successful integration of mechanical and chemical methods with installation of structural changes to the riparian system. The authors, nevertheless,

suggest targeting areas that are not highly channelized when implementing these strategies. Their project overview also includes a discussion of costs associated with these activities but is outside the scope of this review. The treatment combination of this project, finally, not only helps to discourage Russian olive establishment and growth but can likewise aid in control of other invasive species, including saltcedar, Siberian elm, and red mulberry (*Morus rubra* L.) (Muldavin et al. 2017).

### *Control considerations*

As with saltcedar removal in areas where historic fluvial processes have been altered, areas where successful eradication of Russian olive has occurred may be promote establishment of upland, rather than riparian understory species (Reynolds and Cooper 2011). The importance of restoring these processes is further highlighted because of the reductions in Russian olive germination land managers can expect when Russian olive seed is buried at least three inches belowground (Hybner and Espeland 2014). Similarly to saltcedar, nevertheless, increases of groundwater levels should not be expected with removal of Russian olive (Reynolds and Cooper 2011).

Following reductions in, or eradication of, Russian olive, revegetation can be a key component of projects including restoration of native plant communities as a goal. In order to accomplish this, site preparation in the fall before planting has been successfully employed using a light application of glyphosate ( $0.54 \text{ g ai ha}^{-1}$ ) in Montana (Espeland et al. 2017). In this case, 22 species were planted and only two failed to establish. Planting with broadcast seed resulted, for example, in a reduction of non-native perennial grasses from 25.7% cover in the control plots to 7.7% cover in revegetated plots. Despite planting activities, both native and non-native forb cover was reduced with Russian olive control treatments. Importantly, successful revegetation activities may have been tied to fencing the area and keeping revegetated areas clear of ungulates (Espeland et al. 2017).

## Siberian elm (*Ulmus pumila* L.)

### *Introduction*

Siberian elm (Figure 3) is an invasive phreatophyte in the southwest (Long et al. 2003) with little utilization by native birds (Smith and Finch 2014). It is invasive because the fast-growing tree can not only take advantage of productive conditions within riparian areas, but can also tolerate wind, low soil fertility, and the periodic, unpredictable droughts characteristic of the region (USFS USDA Southwestern Region 2014a). When considering how to control Siberian elm



*Figure 3.* Siberian elm trees have resprouted intensively in the understory following mechanical removal (photo by Kyle Rose)

within riparian areas of the Middle Rio Grande, it is important to recognize that, as with other invasive phreatophytes of the region, it does not typically invade areas that are regularly flooded. Although its seeds can be dispersed by water, they are generally dispersed by wind. This means that restoration of historic flooding regimes can, by itself, limit its occurrence with the important

Bosque ecosystem. Secondly, it is limited to invasion of areas with direct sunlight, whether in areas of scattered cottonwood or open grassland. Because of shade intolerance, it will not usually be found in interior forest without direct sunlight to the forest floor (USFS USDA Southwestern Region 2014a). Despite awareness in the region that this species represents a difficult species to control on a landscape level, comparatively fewer peer-reviewed studies on controlling Siberian elm have been published.

### *Control*

Once established on a site, control methods of Siberian elm must contain a chemical component. Using mechanical or physical control methods alone (e.g. girdling or heavy machinery) will result in extensive production of root sprouts (USFS USDA Southwestern Region 2014a). In fact, Siberian elm has been shown to be a high performing biomass production species able to survive at a high rate (76%) when coppiced annually for six years (Geyer 2006). The US Forest Service, furthermore, does not recommend the use of prescribed fire for control of Siberian elm (USFS USDA Southwestern Region 2014a). The lack of an approved biological control agent, furthermore, underlines the importance of including a chemical control method to the overall Siberian elm control plan.

The US Forest Service has provided recommendations for chemical control of Siberian elm for using foliar, basal bark, cut-stump, and girdle+herbicide methods (USFS USDA Southwestern Region 2014a). For foliar applications to trees less than six feet in height, it is recommended that all foliage is covered as much as possible without herbicide dripping to the ground. The chemical used can be triclopyr (1.5% v/v), in which case non-target effects to grasses will not occur, glyphosate (0.75-1.5% Rodeo® or 1-1.5% Roundup®), in which case non-target effects should be expected for any neighboring plants wetted by the solution, imazapyr (1-5% Arsenal® or 5% Chopper®), which can kill neighboring non-target plants through roots grafts, or a mix of aminocyclopyrachlor, imazapyr, and metsulfuron methyl (Viewpoint® at 13-20 ounces per acre), which can kill non-target grasses in addition to Siberian elm (USFS USDA Southwestern Region 2014a).

For larger Siberian elm, basal bark, cut-stump, and girdling plus herbicide have been recommended by the Forest Service (USFS USDA Southwestern Region 2014a). For basal bark applications to trees less than 8' tall and 2-3" in diameter, it is recommended to employ an



application from ground level to 12” height using a 20% triclopyr plus 80% penetrating oil mixture applied in January/February or from June to September. For cut-stump applications Siberian elm, 20% glyphosate can be applied using a paintbrush, wick applicator, or low-volume hand-held sprayer within five to fifteen minutes after cutting the tree. Finally, for even larger trees and to limit labor costs, 50-100% glyphosate or triclopyr can be sprayed or painted onto the cut surface of the girdling site. This method relies on active growth for effectiveness and should be employed during the growing season (USFS USDA Southwestern Region 2014a). Despite detailed recommendations within the *Field Guide for Managing Siberian Elm in the Southwest* (USFS USDA Southwestern Region 2014a), the sources for these recommendations are not peer-reviewed studies.

Peer-reviewed sources for the control of Siberian elm are few and largely center on control through surface (cut-stump) and basal bark application to stumps. Specifically, two studies (Geyer 2003; Geyer and Iriarte 2014) have investigated methods for control of Siberian elm using these methods. Similar methods were employed in both Geyer (2003) and Geyer and Iriarte (2014), but only Geyer and Iriarte (2014) provided quantitative results. Despite a delayed application (90 days during the dormant season) of herbicide to cut stumps, application of 3% imazapyr in oil (Chopper®) and 5% triclopyr in oil (Garlon 4®) resulted in 0.5 and 0.7 sprouts per stump, respectively (Geyer and Iriarte 2014). For basal bark applications, all methods reduced stump sprouts to fewer than one per stump, a significant reduction relative to the control treatment (over 40 sprouts per stump) where trees were cut to 18” height using a chainsaw. The lowest performing basal bark applications (to 3-4” band near ground level of each tree) to cut trees included Garlon 4® (triclopyr; 5% in oil; 0.1 sprouts per stump with 80% of stumps without sprouts) and Vista® (fluroxypyr; 10% in oil; one sprout per stump with 80% of stumps without sprouts). The highest performing basal bark applications included Crossbow® (2,4-D + triclopyr; 5% in oil; zero sprouts per stump with 100% of stumps without sprouts) and Chopper® (imazapyr; 3% in oil; 0.8 sprouts per stump with 90% of stumps without sprouts). As always application of imazapyr-based herbicides risk non-target mortality, but this was not discussed in the study (Geyer and Iriarte 2014).

### *Control considerations*

The US Forest Service has recommended control efforts work upstream to downstream because seed source is of primary concern when considering the potential for Siberian elm to reinvade areas of where eradication efforts have occurred (USFS USDA Southwestern Region 2014a). As with other invasive phreatophytes discussed in this review, restoration of historic flooding regimes and establishment of native species following control efforts are likely to increase the likelihood of successful restoration programs.

## **Tree of heaven, ailanthus (*Ailanthus altissima* (Mill.) Swingle)**

### *Introduction*

This fast-growing, invasive phreatophyte (Figure 4) has been spreading within the Middle Rio Grande River region. Able to spread rapidly through root sprouts, its seeds spread primarily through wind-blown dispersal (Landenberger et al. 2007), but the seeds can float and be dispersed along riparian corridors (Kowarik and Säumel 2008).

### *Control and control considerations*

The most exciting developments in the control of ailanthus come from Pennsylvania, where a fungus (*Verticillium albo-atrum* (PSU Isolate 140)) was found (Schall and Davis 2009a, 2009b) to kill ailanthus at a rate of 100% in both greenhouse and field studies. Not only did inoculation with *V. albo-atrum* result in eradication of ailanthus, assessments of the sites 5-6 years after inoculation showed no difference in understory plant communities (Harris et al. 2013). The fungus has subsequently been found in Virginia (Snyder et al. 2013), Ohio (Rebeck et al. 2013), and a close relative has been found in Europe (Maschek and Halmschlager 2016) to be similarly pathogenic to ailanthus. Nevertheless, this fungus has not been found in New Mexico and is not currently listed for use in the state (USFS USDA Southwestern Region 2014b).

Elsewhere, in Ohio, California, Canada, and the Mediterranean region of Europe (Meloche and Murphy 2006; DiTomaso and Kyser 2007; Lewis and McCarthy 2008; Constán-Nava et al. 2010), studies on the potential to use chemical and mechanical control methods for



*Figure 4. Ailanthus seedlings present a difficult challenge for removal (photo by Kyle Rose).*

ailanthus have yielded potentially useful protocols for control of ailanthus in the Middle Rio Grande River of New Mexico. As with Siberian elm, control methods that only employ mechanical or physical methods for control of ailanthus are unlikely to be successful (DiTomaso and Kyser 2007). Comparing four treatments, including 1) hand-pulling + mulching, 2) cut-stump + glyphosate, 3) cut-stump alone, and 4) injection using the EZJect Capsule Injection System®, Meloche and Murphy (2006) found that the cut-stump + glyphosate method reduced juvenile shoot production by 90% relative to the control and was the best treatment after two years, a finding similar to that found in another study (Constán-Nava et al. 2010). The EZJect system was only used on large trees (>60m height and >5cm diameter at 1m height), but was effective when used. The stem injection technique has been used effectively elsewhere, with a 95-100% reduction in ailanthus when using imazapyr, but because imazapyr use can result in non-target mortality up to 17.5% up to 3 m from the targeted individual (DiTomaso and Kyser 2007; Lewis and McCarthy 2008), a 92% reduction in ailanthus using stem-injected glyphosate

might represent a better option (DiTomaso and Kyser 2007). Stump injections have been shown to be ineffective across common herbicides (DiTomaso and Kyser 2007).

Despite the effectiveness of stem-injection techniques, they tend to be expensive (Meloche and Murphy 2006) and are only useful for large trees. In contrast, basal bark applications have been used to control at nearly 100% both vigor and resprouting of ailanthus using both 20% v/v triclopyr- and 20% v/v imazapyr-based solutions in oil (DiTomaso and Kyser 2007). Because of the potential for non-target mortality using imazapyr, achieving nearly complete control using triclopyr suggests that a basal bark application of triclopyr could be a successfully employed method on a large-scale in the future.

**Ravenna grass (*Saccharum ravennae* L.; synonym *Erianthus ravennae* (Jackson and Henry 2011))**

*Introduction*

Ravenna grass (Figure 5) is a grass with the following weediness characteristics: indeterminate growth, long-distance seed dispersal, deep root system, seed dormancy, and plastic growth (Jessup 2013). This means that it grows while conditions are favorable, adjusts growth and/or physiology to environmental conditions, accesses water when more shallow-rooted competitors cannot, and can



*Figure 5. Ravenna grass established beside the Rio Grande River (photo by Kyle Rose).*

build up seed in the soil until conditions are favorable for germination. Does not produce as many seeds as other grasses, but each panicle still can produce over 10,000 seeds with 80% germination rates (Springer and Goldman 2016). This combination of characteristics can make control difficult. Unfortunately, its presence has been noted within the Middle Rio Grande River region (Muldavin et al. 2017), but research is scarce regarding control measures for Ravenna grass.

#### *Control and control considerations*

Physical control methods, including mowing and burning, are unlikely to effectively control Ravenna grass, because the roots must be removed to stop resprouting (Ashigh et al. 2010). Although grass-specific herbicides exist (e.g. lipid biosynthesis inhibitors such as flauzifop-p-butyl), application of these herbicides can lead to non-target mortality of other annual and perennial grasses. If conditions are favorable, including low wind speeds and the

absence of nearby native grasses in need of protection, the employment of flauzifop-p-butyl (e.g. Fusilade DX®) is likely to successfully control Ravenna grass when applied during the growing season.

### **Research gaps and future research directions**

Although recent large-scale studies have included plots in New Mexico, long-term monitoring of sites in New Mexico have not been translated into papers that make specific recommendations for management of invasive phreatophytes in New Mexico. This limits this author's ability to make confident recommendations about the potential to control these species long-term and the intervals and frequency of follow-up activities needed to achieve optimal results. Furthermore, the social and economic constraints of the Middle Rio Grande River region, and their interaction with restoration efforts, have not been studied. For example, how can a project best blend traditional Bosque grazing with restoration of the functionality of the Bosque system? Translating the wealth of knowledge from decades of restoration efforts within the Middle Rio Grande River region into quantifiable dataset capable of being analyzed to better characterize successful and unsuccessful control efforts could increase the speed of our understanding of control methods specifically applicable to this region.

The dearth of current research on the control of Siberian elm, ailanthus, and Ravenna grass is of note. Although studies have found methods that can successfully control some of these species, they have not always been verified in this region. The climate (both in extremes of temperature and amount of rainfall) and timing of climate patterns are both different in the Southwest relative to other parts of the country. As a result, recommendations to apply a treatment in April may be appropriate in one region, but inappropriate in New Mexico if conditions are favorable for growth in riparian areas sooner in the Southwest relative to other regions. Hence, controlled studies to both verify methods and optimize the timing of application for the southwest are needed.

Finally, throughout the document, the successful restoration of riparian communities has been tied to not only the eradication of undesirable, non-native species, but also to the restoration of processes (e.g. historic flooding regimes) and functionality to these areas. The author

understands that land managers are unable bring processes back to these systems, whether for lack of power, money, or even political concerns where widening the river might mean a reduction in land owned. For this reason, in many cases, it might be desirable to define novel (new) Bosque, or even non-Bosque, structures and plant assemblages that would be considered successful if established in such a way that they can be sustainably perpetuated (either through natural or cost-effective artificial regeneration). In some cases, the new, targeted structure and assemblage might be upland. In all cases, research is needed to test the methods of conversion to desired systems, the sustainability of those systems, and the modeled or predicted cumulative effects if implemented on a landscape scale.

## References

- Allendorf, F. W., and L. L. Lundquist. 2003. Introduction: population biology, evolution, and control of invasive species. *Conserv. Biol.* 17(1):24–30.
- Ashigh, J., J. Wanstall, and F. Sholedice. 2010. *Troublesome Weeds of New Mexico*. New Mexico State University, College of Agricultural, Consumer and Environmental Sciences, Cooperative Extension Service.
- Bay, R. F., and A. Sher. 2008. Success of active revegetation after *Tamarix* removal in riparian ecosystems of the southwestern United States: a quantitative assessment of past restoration projects. *Restor. Ecol.* 16(1):113–128.
- Bay, R. F., and A. A. Sher. 2006. Success of active revegetation after *Tamarix* spp. removal in southwestern riparian ecosystems: A quantitative assessment of past restoration projects.
- Bean, D., and T. Dudley. 2018. A synoptic review of *Tamarix* biocontrol in North America: tracking success in the midst of controversy. *BioControl*.
- Belote, R. T., L. J. Makarick, M. J. C. Kearsley, and C. L. Lauver. 2010. Tamarisk removal in Grand Canyon National Park: Changing the native–non-native relationship as a restoration goal. *Ecol. Restor.* 28(4):449–459.
- Brotherson, J. D., and D. Field. 1987. *Tamarix*: impacts of a successful weed. *Rangelands*. 9(3):110–112.
- Chodova, D., and J. Mikulka. 2000. Identification of resistance to imazapyr and cross resistance to selected sulfonylurea herbicides in *Kochia scoparia*. *Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz*. (Sonderh. 17):383–388.
- Cleverly, J. R., C. N. Dahm, J. R. Thibault, D. E. McDonnell, and J. E. Allred Coonrod. 2006. Riparian ecohydrology: regulation of water flux from the ground to the atmosphere in the Middle Rio Grande, New Mexico. *Hydrol. Process.* 20(15):3207–3225.
- Combs, J. 2010. *Best Management Practices for Montana, Biology, Ecology, and Management of Russian Olive (Elaeagnus Angustifolia L.) and Saltcedar (Tamarix Ramosissima, T. Chinensis, and Their Hybrids)*. United States Department of Agriculture, Natural Resources Conservation Service.



- Constán-Nava, S., A. Bonet, E. Pastor, and M. J. Lledó. 2010. Long-term control of the invasive tree *Ailanthus altissima*: Insights from Mediterranean protected forests. *For. Ecol. Manage.* 260(6):1058–1064.
- DeLoach, C. J., P. A. Lewis, J. C. Herr, R. I. Carruthers, J. L. Tracy, and J. Johnson. 2003. Host specificity of the leaf beetle, *Diorhabda elongata* deserticola (Coleoptera: Chrysomelidae) from Asia, a biological control agent for saltcedars (Tamarix: Tamaricaceae) in the Western United States. *Biol. Control.* 27(2):117–147.
- Dillon, K. G., and D. Ahlers. 2017. *Photographic Monitoring of Defoliation by the Tamarisk Beetle*. Albuquerque, NM.
- DiTomaso, J. M., and G. B. Kyser. 2007. Control of *Ailanthus altissima* using stem herbicide application techniques. *Arboric. Urban For.* 33(1):55.
- Douglass, C. H., S. J. Nissen, P. J. Meiman, and A. R. Kniss. 2016. Impacts of imazapyr and triclopyr soil residues on the growth of several restoration species. *Rangel. Ecol. Manag.* 69(3):199–205.
- Dudley, T. L., and D. W. Bean. 2012. Tamarisk biocontrol, endangered species risk and resolution of conflict through riparian restoration. *BioControl.* 57(2):331–347.
- Espeland, E. K., J. M. Muscha, J. Scianna, R. Kilian, N. M. West, and M. K. Petersen. 2018. Secondary Invasion and Reinvasion after Russian-Olive Removal and Revegetation—CORRIGENDUM. *Invasive Plant Sci. Manag.* :1.
- Espeland, E. K., J. M. Muscha, J. Scianna, R. Kilian, N. M. West, and M. K. Petersen. 2017. Secondary Invasion and Reinvasion after Russian-Olive Removal and Revegetation. *Invasive Plant Sci. Manag.* 10(4):340–349 Available online at: <https://www.cambridge.org/core/article/secondary-invasion-and-reinvasion-after-russianolive-removal-and-revegetation/DCED967E78476E8AA9A2FC62CA4937E6>.
- Espeland, E. K., T. A. Rand, and K. J. Delaney. 2014. Russian olive fruit production in shelterbelt and riparian populations in Montana. *Ecol. Restor.* 32(4):354–357.
- Fick, W. H. 2016. Ecology and Management of Saltcedar. P. 744 in *10th International Rangeland Congress*.

- Fick, W. H., and W. A. Geyer. 2010. Cut-stump treatment of saltcedar (*Tamarix ramosissima*) on the Cimarron National Grasslands. *Trans. Kansas Acad. Sci.* 113(3/4):223–226.
- Fox, R., R. Mitchell, and M. Davin. 2001. Managing saltcedar after a summer wildfire in the Texas Rolling Plains. *McArthur, E. Durant; Fairbanks, Daniel J., comps. Shrubl. Ecosyst. Genet. Biodivers. proceedings; 2000 June 13-15; Provo, UT. Proc. RMRS-P-21. Ogden, UT US Dep. Agric. For. Serv. Rocky Mt. Res. Station. p. 236. 21:236–237.*
- Funasaki, G. Y., P.-Y. Lai, L. M. Nakahara, J. W. Beardsley, and A. K. Ota. 1988. A review of biological control introductions in Hawaii: 1890 to 1985.
- Geyer, W. A. 2006. Biomass production in the central great plains USA under various coppice regimes. *Biomass and Bioenergy.* 30(8–9):778–783.
- Geyer, W. A. 2003. *Cut surface (top) and basal application of herbicides on high Siberian elm stumps.* Research Report 2001. North Central Weed Science Society. SAS Institute Inc. 2002-2003. Version 9.1. Cary NC: SAS Institute Inc.
- Geyer, W. A., and L. Iriarte. 2014. Stump-sprout control on selected tree species in Kansas. *Trans. Kansas Acad. Sci.* 117(3–4):295–298.
- Glenn, E. P., and P. L. Nagler. 2005. Comparative ecophysiology of *Tamarix ramosissima* and native trees in western U.S. riparian zones. *J. Arid Environ.* 61(3):419–446 Available online at: <http://linkinghub.elsevier.com/retrieve/pii/S0140196304002101>; last accessed June 15, 2018.
- González, E., A. A. Sher, R. M. Anderson, R. F. Bay, D. W. Bean, G. J. Bissonete, B. Bourgeois, et al. 2017a. Vegetation response to invasive *Tamarix* control in southwestern U.S. rivers: A collaborative study including 416 sites. *Ecol. Appl.* 27(6).
- González, E., A. A. Sher, R. M. Anderson, R. F. Bay, D. W. Bean, G. J. Bissonete, D. J. Cooper, et al. 2017b. Secondary invasions of noxious weeds associated with control of invasive *Tamarix* are frequent, idiosyncratic and persistent. *Biol. Conserv.* 213.
- Harms, R. S., and R. D. Hiebert. 2006. Vegetation response following invasive tamarisk (*Tamarix* spp.) removal and implications for riparian restoration. *Restor. Ecol.* 14(3):461–472.

- Harris, P. T., G. H. Cannon, N. E. Smith, and N. Z. Muth. 2013. Assessment of plant community restoration following Tree-of-Heaven (*Ailanthus altissima*) control by *Verticillium albo-atrum*. *Biol. Invasions*. 15(9):1887–1893.
- Hatler, W. L., and C. R. Hart. 2009. Water loss and salvage in saltcedar (*Tamarix* spp.) stands on the Pecos River, Texas. *Invasive Plant Sci. Manag.* 2(4):309–317.
- Hays, W. S. T., and S. Conant. 2007. Biology and impacts of Pacific Island invasive species. 1. A worldwide review of effects of the small Indian mongoose, *Herpestes javanicus* (Carnivora: Herpestidae). *Pacific Sci.* 61(1):3–16.
- Hobbs, R. J., E. S. Higgs, and C. M. Hall. 2013. Defining novel ecosystems. *Nov. Ecosyst. Interv. new Ecol. world order.* :58–60.
- Hultine, K. R., J. Belnap, C. Van Riper Iii, J. R. Ehleringer, P. E. Dennison, M. E. Lee, P. L. Nagler, K. A. Snyder, S. M. Uselman, and J. B. West. 2010. Tamarisk biocontrol in the western United States: ecological and societal implications. *Front. Ecol. Environ.* 8(9):467–474.
- Hybner, R., and E. Espeland. 2014. Russian Olive *Elaeagnus angustifolia* L. Effect of Seed Burial Depth on Seedling Emergence and Seed Viability. USDA Natural Resources Conservation Service Plant Materials Technical Note No. MT-107. 6 pg.
- Jackson, P., and R. J. Henry. 2011. *Erianthus*. P. 97–107 in *Wild Crop Relatives: Genomic and Breeding Resources*, Springer.
- Jacobs, J., and S. Sing. 2007. *Ecology and Management of Saltcedar (Tamarix ramosissima, T. chinensis and T. ramosissima x T. chinensis hybrids)*. US Department of Agriculture, Natural Resources Conservation Service.
- Jessup, R. W. 2013. Perennialism and Weediness in the Saccharinae. P. 503–515 in *Genomics of the Saccharinae*, Springer.
- Kennard, D., N. Louden, D. Gemoets, S. Ortega, E. González, D. Bean, P. Cunningham, T. Johnson, K. Rosen, and A. Stahlke. 2016. Tamarix dieback and vegetation patterns following release of the northern tamarisk beetle (*Diorhabda carinulata*) in western Colorado. *Biol. Control*. 101.

- Kettenring, K. M., and C. R. Adams. 2011. Lessons learned from invasive plant control experiments: a systematic review and meta-analysis. *J. Appl. Ecol.* 48(4):970–979.
- Kowarik, I., and I. Säumel. 2008. Water dispersal as an additional pathway to invasions by the primarily wind-dispersed tree *Ailanthus altissima*. *Plant Ecol.* 198(2):241–252.
- Landenberger, R. E., N. L. Kota, and J. B. McGraw. 2007. Seed dispersal of the non-native invasive tree *Ailanthus altissima* into contrasting environments. *Plant Ecol.* 192(1):55–70.
- Lewis, K., and B. McCarthy. 2008. Nontarget tree mortality after tree-of-heaven (*Ailanthus altissima*) injection with imazapyr. *North. J. Appl. For.* 25(2):66–72.
- Long, J., A. Teclé, and B. Burnette. 2003. Cultural foundations for ecological restoration on the White Mountain Apache Reservation. *Conserv. Ecol.* 8(1).
- Mack, R. N., D. Simberloff, W. Mark Lonsdale, H. Evans, M. Clout, and F. A. Bazzaz. 2000. Biotic invasions: causes, epidemiology, global consequences, and control. *Ecol. Appl.* 10(3):689–710.
- Maschek, O., and E. Halmschlager. 2016. First report of *Verticillium* wilt on *Ailanthus altissima* in Europe caused by *Verticillium nonalfalfae*. *Plant Dis.* 100(2):529.
- McDaniel, K. C., and J. P. Taylor. 2003. Saltcedar recovery after herbicide-burn and mechanical clearing practices. *J. Range Manag.* :439–445.
- Meloche, C., and S. D. Murphy. 2006. Managing tree-of-heaven (*Ailanthus altissima*) in parks and protected areas: a case study of Rondeau Provincial Park (Ontario, Canada). *Environ. Manage.* 37(6):764–772.
- Messing, R. H., and M. G. Wright. 2006. Biological control of invasive species: solution or pollution? *Front. Ecol. Environ.* 4(3):132–140.
- Muldavin, E. H., E. R. Milford, N. E. Umbreit, and Y. D. Chauvin. 2017. Long-term Outcomes of Natural-process Riparian Restoration on a Regulated River Site: The Rio Grande Albuquerque Overbank Project after 16 Years. *Ecol. Restor.* 35(4):341–353.

- Ohrman, M. K., S. A. Clay, S. Waughtel, and J. Moriles. 2014. Effectiveness of Control Treatments on Young Saltcedar (*Tamarix* spp.) Plants. *Invasive Plant Sci. Manag.* 7(1):25–31.
- Ostojka, S. M., M. L. Brooks, T. Dudley, and S. R. Lee. 2014. Short-term vegetation response following mechanical control of saltcedar (*Tamarix* spp.) on the Virgin River, Nevada, USA. *Invasive Plant Sci. Manag.* 7(2):310–319.
- Patterson, R. K., and D. R. Worwood. 2010. Russian olive control: Herbicide rates and timing. *J. NACAA.* 3(1) Available online at: <https://www.nacaa.com/journal/index.php?jid=49>.
- Patterson, R., and Dr. R. Worwood. 2011. Russian Olive Control-Frill Cut Treatment. Utah State University Cooperative Extension.
- Primiani, M. M., J. C. Cotterman, and L. L. Saari. 1990. Resistance of kochia (*Kochia scoparia*) to sulfonylurea and imidazolinone herbicides. *Weed Technol.* 4(1):169–172.
- Rebeck, J., M. A. Malone, D. P. G. Short, M. T. Kasson, E. S. O’Neal, and D. D. Davis. 2013. First report of Verticillium wilt caused by *Verticillium nonalfalfae* on tree-of-heaven (*Ailanthus altissima*) in Ohio. *Plant Dis.* 97(7):999.
- Reynolds, L. V., and D. J. Cooper. 2011. Ecosystem response to removal of exotic riparian shrubs and a transition to upland vegetation. *Plant Ecol.* 212(8):1243–1261.
- Russell, J. C., and T. M. Blackburn. 2017. The rise of invasive species denialism. *Trends Ecol. Evol.* 32(1):3–6.
- Schall, M. J., and D. D. Davis. 2009a. *Ailanthus altissima* wilt and mortality: etiology. *Plant Dis.* 93(7):747–751.
- Schall, M. J., and D. D. Davis. 2009b. Verticillium Wilt of *Ailanthus altissima*: Susceptibility of Associated Tree Species. *Plant Dis.* 93(11):1158–1162 Available online at: <https://doi.org/10.1094/PDIS-93-11-1158>.
- Shafroth, P. B., J. R. Cleverly, T. L. Dudley, J. P. Taylor, C. Van Riper, E. P. Weeks, and J. N. Stuart. 2005. Control of Tamarix in the western United States: Implications for water salvage, wildlife use, and riparian restoration. *Environ. Manage.*

- Sher, A. A., D. L. Marshall, and J. P. Taylor. 2002. Establishment patterns of native *Populus* and *Salix* in the presence of invasive nonnative *Tamarix*. *Ecol. Appl.* 12(3):760–772.
- Sher, A. A., H. El Waer, E. González, R. Anderson, A. L. Henry, R. Biedron, and P. Yue. 2018. Native species recovery after reduction of an invasive tree by biological control with and without active removal. *Ecol. Eng.* 111:167–175 Available online at: <http://linkinghub.elsevier.com/retrieve/pii/S0925857417306018>; last accessed June 15, 2018.
- Smith, D. M., and D. M. Finch. 2014. Use of native and nonnative nest plants by riparian-nesting birds along two streams in New Mexico. *River Res. Appl.* 30(9):1134–1145.
- Snyder, A. L., M. T. Kasson, S. M. Salom, D. D. Davis, G. J. Griffin, and L. T. Kok. 2013. First report of *Verticillium* wilt of *Ailanthus altissima* in Virginia caused by *Verticillium nonalfalfae*. *Plant Dis.* 97(6):837.
- Springer, T. L., and J. J. Goldman. 2016. Germination of *Saccharum ravennae* (L.) L.(Poaceae) Caryopses and Intact Spikelets. *Crop Sci.* 56(2):682–688.
- Stromberg, J. C. 2001. Restoration of riparian vegetation in the south-western United States: importance of flow regimes and fluvial dynamism. *J. Arid Environ.* 49(1):17–34.
- Stromberg, J. C., M. K. Chew, P. L. Nagler, and E. P. Glenn. 2009. Changing perceptions of change: the role of scientists in *Tamarix* and river management. *Restor. Ecol.* 17(2):177–186.
- Stromberg, J. C., S. J. Lite, R. Marler, C. Paradzick, P. B. Shafroth, D. Shorrocks, J. M. White, and M. S. White. 2007. Altered stream-flow regimes and invasive plant species: The *Tamarix* case. *Glob. Ecol. Biogeogr.*
- Taylor, J. P., and K. C. McDaniel. 1998. Restoration of saltcedar (*Tamarix* sp.)-infested floodplains on the Bosque del Apache National Wildlife Refuge. *Weed Technol.* :345–352.
- Tu, M., C. Hurd, and J. M. Randall. 2001. Weed control methods handbook: tools & techniques for use in natural areas.
- USFS USDA Southwestern Region. 2014a. *Field Guide for Managing Siberian Elm in the*

*Southwest*. TP-R3-16-1. US Department of Agriculture, Forest Service, Southwest Station. 1-12 p. Available online at:  
[https://www.fs.usda.gov/Internet/FSE\\_DOCUMENTS/stelprdb5410128.pdf](https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5410128.pdf).

USFS USDA Southwestern Region. 2014b. *Field Guide for Managing Tree-of-heaven in the Southwest*. Available online at:  
[https://www.fs.usda.gov/Internet/FSE\\_DOCUMENTS/stelprdb5410131.pdf](https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5410131.pdf).

Zavaleta, E. S., R. J. Hobbs, and H. A. Mooney. 2001. Viewing invasive species removal in a whole-ecosystem context. *Trends Ecol. Evol.* 16(8):454–459.