Spring 2022

MS Environmental Biology Capstone Project

Dylan Brown
Regis University

MS ENVIRONMENTAL BIOLOGY
CAPSTONE PROJECT

by

Dylan C. Brown

A Project Presented in Partial Fulfillment
of the Requirements for the Degree
Masters of Science
in Environmental Biology

REGIS UNIVERSITY
May, 2022

MS ENVIRONMENTAL BIOLOGY
CAPSTONE PROJECT

by

Dylan C. Brown

has been approved

May, 2022

APPROVED:

______________________, Tyler Imfeld, Ph.D. (Faculty Advisor)

______________________, John Sakulich, Ph.D. (Chapters 1 & 2)

______________________, Tyler Imfeld, Ph.D. (Chapter 3)

______________________, Mike Ennis, Ph.D. (Chapter 4)

______________________, Kris Voss, Ph.D. (Exit Survey & Repository)

Table of Contents

FIGURE AND TABLE LIST

CHAPTER 2, LIST OF TABLES

CHAPTER 2, LIST OF FIGURES

FIGURE AND TABLE LIST

CHAPTER 3, LIST OF FIGURES

CHAPTER 1: LITERATURE REVIEW

Revisiting Tamarisk Invasion in Riparian Ecosystems: An Argument Against Single Species Management of the Southwestern Willow Flycatcher (Empidonax traillii extimus)

Introduction to the Taxa

Riparian environments are negatively impacted by anthropogenic activities which stymie the establishment of native riparian vegetation (Wiener et al., 2008). Additionally, presence of invasive species further degrades riparian areas and have a negative influence on avian biodiversity (Van Riper et al., 2018). Tamarisk is a human introduced invasive species that encroaches on critical habitat for the endangered southwestern willow flycatcher (*Empidonax traillii extimus*). The northern tamarisk beetle (*Diorhabda carinulata*) is used as a biocontrol for tamarisk to assist in remediation of riparian environments invaded by tamarisk (Deloach et al., 2000). The northern tamarisk beetle is selectively herbivorous of tamarisk, leading to defoliation and mortality of this invasive species (Dudley & Deloach, 2004). However, controversy embroils the continued implementation of the biocontrol because it reduces southwestern willow flycatcher habitat now dominated by tamarisk (Deloach et al., 2000; Dudley & Deloach, 2004; Wiener et al., 2008). This decrease in southwestern willow flycatcher populations is complicated by the species being protected under the Endangered Species Act. Management of tamarisk invasions with a narrow focus on southwestern willow flycatcher (single species management) is misguided. A better alternative would be removal of tamarisk through biocontrol release with a simultaneous natural revegetation effort.

Environmental Consequences of Tamarisk Invasion

Tamarisk was introduced into the United States to promote bank stabilization along riparian corridors in 1823 (Brock, 1994). Unbeknownst to ecologists of the time, this would create an ecological crisis that is projected to cost billions of dollars due to economic losses associated with decreased ecosystem services provided by riparian ecosystems (Harms & Hiebert, 2006). Tamarisk is encroaching upon swaths of stream tributaries in the southwestern United States and continues to spread at a rate of 20km annually (Brock, 1994). Tamarisk encroachment has effectively outcompeted native riparian vegetation, altered stream morphology, replaced critical habitat, increased risk for severe fires, and drastically changed soil and water chemistry (Deloach et al., 2000; Larson et al., 2019; Murray, 2019). The overwhelming success of tamarisk can be attributed to unique adaptations inherent to the species.

Tamarisk is a phreatophyte, meaning it uses a taproot (reportedly as deep as 6 meters) that penetrates deep into soils to access the water table (Hultine et al., 2020). Tamarisk also draws water from the surface if the taproot has not developed to the appropriate depth to contact the water table. This adaptation directly impacts native riparian phreatophytes, like cottonwoods (*Populus spp.)* and willows (*Salix spp.*), by reducing available water which halts their establishment and germination (Deloach et al., 2000; York et al., 2011). Additionally, tamarisk is xerophytic and halophytic, meaning it is adapted to both drought conditions and heavily salinized environments (Brock, 1994). Perhaps the most detrimental aspect of tamarisk invasion is the accumulation of concentrated salt within its foliage (Brock, 1994; Deloach et al., 2000; Murray, 2019). Tamarisk is deciduous, meaning it drops its foliage onto the topsoil annually, which fundamentally alters topsoil through increased saline concentrations. These innate characteristics give an extraordinary advantage to invading tamarisk and thwart many remediation efforts.

Remediation efforts are implemented in the interest of conserving native species. Remediation efforts include mowing or cutting aboveground biomass, controlled burning, or the introduction of a biocontrol to defoliate tamarisk stands (Harms & Hiebert, 2006). Controlled burning and removal of aboveground biomass are the most common type of remediation of tamarisk stands (Harms & Hiebert, 2006). After burning and removal of biomass, an herbicide is brushed on the remaining stems to kill the root system, which is expensive and ineffective for long-term removal goals (Brock, 1994; Dudley & Deloach, 2004; Harms & Hiebert, 2006; Hultine et al., 2014). The temporary nature of remediation can be attributed to the reproductive strategy implemented by tamarisk. Tamarisk seeds are dispersed by both wind and water and facilitate a wide range of potential spread (Deloach et al., 2000). Tamarisk also regenerates from fragments of its root system, stem, and crown area (Brock, 1994; Deloach et al., 2000).). When remediation is successful the absence of tamarisk does not guarantee the quick return of native flora to riparian ecosystems (Darrah & Van Riper, 2018; Paxton et al., 2011).

Southwestern Willow Flycatcher

Avifauna depend on riparian areas for the ecosystem services they provide (Hinojosa-Huerta et al., 2013) including flycatcher species (Harms & Hiebert, 2006). There are four recognized taxa of flycatcher, and all are similarly considered a Neotropical migratory species (Paxton et al., 2007). One of the four subspecies of the flycatcher is the southwestern willow flycatcher which migrates between Mexico and the southwestern United States (Sogge et al., 1997). The southwestern willow flycatcher (hereafter referred to as flycatcher) can be observed in Arizona, California, Colorado, New Mexico, Nevada, and Utah over 5 months in the summer breeding season (Paxton et al., 2007). This subspecies is a riparian obligate, meaning it establishes only within environments of riparian vegetation (Sogge & Marshall, 2000). The flycatcher selects nesting habitat with midstory cover, abundant foliar cover, and dense stem structure among riparian areas typical of the southwestern United States (Friggens & Finch, 2015; Paxton et al., 2007; Sogge et al., 1997).

Rivers of the southwestern United States have continuing population declines of native riparian vegetation which decreases available habitat and populations of avifauna (Hinojosa-Huerta et al., 2013). Flycatcher populations decline from vegetation structure changes related to tamarisk invasion within riparian ecosystems (Bean & Dudley, 2018; Dudley & Deloach, 2004). The flycatcher was listed as an endangered species in 1995 by the US fish and Wildlife Service (Dudley et al., 2005; Friggens & Finch, 2015) because of continued habitat loss. A more robust response to combating the invasive species was needed to protect threatened riparian fauna.

Introduction of a Biocontrol

The northern tamarisk beetle (*Diorhabda carinulata*) was determined by Lloyd Andres and Robert Pemberton in the 1970's to be a frontrunner to combat the widespread invasion of tamarisk as a possible biocontrol (Dudley & Bean, 2012; Stenquist, 1999). After over two decades of studies were dedicated to understanding the potential risks, the biocontrol was approved to be released in 1996 (Dudley & Bean, 2012). This release was sanctioned by the Animal and Plant Health Inspection Program Plant Protection and Quarantine (APHIS). The intended role of the northern tamarisk beetle was as a defoliator that could easily move between stands of tamarisk and reduce evapotranspiration and photosynthesis of tamarisk, resulting in stand impermanence (Deloach et al., 2000). The northern tamarisk beetle was studied to ensure the beetle was host specific, easy to control and breed, and had a limited geographical range to ensure it would not spread throughout the United States (Bean & Dudley, 2018). If the northern tamarisk beetle had the ability to be implemented as a biocontrol, it would reduce the cost and effort that had been previously affiliated with tamarisk remediation (Bean et al., 2013).

Controversy over the release of the biocontrol measure has marred the progress of implementing the remediation. The flycatcher is observed to actively use tamarisk as a nesting substrate in invaded riparian habitats (Dudley et al., 2001). A coalition of experts that included stakeholders, local and state governments, federal agencies, and universities formed the Salt Cedar Biological Control Consortium (SBCC) in 1997 in response to concerns over flycatcher habitat reduction (Bean & Dudley, 2018). After careful consideration of the effective range of the northern tamarisk beetle, the U.S. Fish and Wildlife Service and Deloach stated that the geographic range of the beetle would not impact the habitat in question (Dudley & Deloach, 2004). As a preventative measure the U.S. Fish and Wildlife Service stipulated that the biocontrol's release would not be allowed within 200 miles of the protected flycatcher habitat (Bean & Dudley, 2018; Dudley & Deloach, 2004).

The northern tamarisk beetle was eventually released as a biocontrol in the western United States in 2001 to combat the invasion of tamarisk. After release, viable populations of northern tamarisk beetle were established in 5 of the 7 states where the biocontrol was implemented (Dudley & Deloach, 2004). Within two weeks following the release, tamarisk stands were observed to be defoliated and turned tamarisk stands brown (Bean et al., 2013; Bean & Dudley, 2018). Initial results suggested that tamarisk required multiple years of defoliation due to the resilience of the species, and replacement of the stand would occur gradually over a few years (Bean et al., 2013; Dickie et al., 2014; Dudley & Deloach, 2004). Over the course of the next few years, the biocontrol treatment was judged to be an overwhelming success and significantly reduced populations of tamarisk.

Expanding the Implementation of Biocontrol

The success of the implementation of the northern tamarisk beetle as a biocontrol emboldened managers to include other species of the northern tamarisk beetle in remediation efforts. The goal of including a wider spectrum of species was to promote viable populations of the biocontrol in areas where populations failed to establish (Dudley & Deloach, 2004). Three species were selected to be included in future remediations efforts, the subtropical tamarisk beetle (*Diorhabda sublineata*), the Mediterranean tamarisk beetle (*Diorhabda elongate*), and the larger tamarisk beetle (*Diorhabda carinata*) (Bean & Dudley, 2018; Dudley & Deloach, 2004). This larger implementation was released into 13 different states in the southwestern United States under the direction of APHIS. The three new species introductions were implemented in remediation between 2005 and 2009 with approximately 1.5 million beetles released into the 13 different states that were impacted by tamarisk (Bean & Dudley, 2018).

Despite the relative success of biocontrol releases, legal challenges mounted against the biocontrol to protect the flycatcher. Opponents of *Diorhabda spp*. release argue that the biocontrol has been observed to encroach on the protected habitat of the flycatcher, which could further decrease flycatcher populations. Bean & Dudley (2018) argue that there is little published literature suggesting that a reduction of tamarisk also reduces flycatcher populations. Regardless, in 2009 the APHIS released a memo to managers prohibiting the interstate movement of the beetles, citing concerns for the loss of habitat deemed critical for the endangered flycatcher. This essentially obstructed the continued use of *Diorhabda spp.* as a biocontrol for tamarisk encroachment. Shortly after the memo was circulated, the SBCC was disbanded, and funding was no longer allocated to the ongoing invasive removal projects. This decision will contribute to the continued spread of tamarisk, especially when considering future conditions of riparian environments.

Discussion of Future Conservation Goals

Managers that were involved in the implementation of the biocontrol for tamarisk effectively had no choice but to comply with the order from APHIS. The juxtaposition between an effective strategy for invasive management and the Endangered Species Act complicated the goal of tamarisk eradication. The potential consequences of tamarisk invasion are compounding the longer there is inaction. However, complying with the tenets of the Endangered Species Act is not inherently wrong. Protecting endangered species is the appropriate response when managing ecosystems, but this scenario does not provide an answer one way or another.

Furthermore, Paxton et al. (2011) argued that allowing the flycatcher to continue to inhabit riparian areas invaded by tamarisk is an example of an ecological trap. An ecological trap is when a species has a lower fitness due to constraints caused by living in a diminished habitat. The decision to declare tamarisk stands critical habitat is ostensibly offering protection to a species that is causing harm to the entire ecosystem. By removing water from an ecosystem through evapotranspiration, as in the case of tamarisk (Brock 1994), it impacts resources that affect aquatic species, mammals, and native vegetation. This creates a positive feedback loop where the environment continues to degrade and justification to preserve the habitat diminishes.

Drought conditions are expected to become more frequent in the arid southwest (Friggens & Finch, 2015; Hinojosa-Huerta et al., 2013). As previously discussed, tamarisk is a xerophytic species that is resistant to drought. Native cottonwood and willow species do not have this adaptation and can be expected to decline in their ability to establish (Diehl et al., 2020). Increased drought frequency favor tamarisk by the reduction of native biodiversity, enabling the spread of the invasive (Setshedi & Newete, 2020). These concerns are compounded by the fact that tamarisk is more prone to stand clearing fires (Busch and Smith 1993; Dudley & Bean,

2012) and resprouts after a fire disturbance, whereas native riparian flora does not possess this ability (Brock, 1994). Droughts will make ecosystems more arid through increasing temperatures and reduced availability of water (Hinojosa-Huerta et al., 2013), which in turn contribute to drier fuels and more frequent impacts of severe fire regimes (Dudley & Bean 2012).

Managers have made decisions predicated on the hope of returning to historic conditions of riparian ecosystems. After undergoing vegetation structure changes as drastic as tamarisk invasion, a return to historic conditions is likely impossible (Dudley & Deloach, 2004). Rather than rely on management based on historical conditions, managing for multiple successional stable states of an ecosystem is getting traction in current management considerations (Dickie et al., 2014). The idea of multiple stable states maintains that returning to historical species compositions fails to adapt to a changing environment.

Management using multiple stable states as a guide sets goals that can adapt to changing conditions. This may remove a triage mindset when deciding to protect riparian environments as a whole or adopt single species management of the flycatcher. By adopting this approach, it would be possible to slowly remove tamarisk with a biocontrol while simultaneously planting native species to preserve vegetation structure that is important to the flycatcher. This is the management recommendation that is suggested by Harms & Hiebert (2006).

When considering with the idea of multiple stable states, perhaps single species management with the goal of restoring historic distributions is also just as unlikely for the endangered flycatcher. Increased drought conditions will have a massive effect on species compositions worldwide, fighting to preserve historic conditions is a costly Sisyphean endeavor. This issue does not appear to be an example of environmental triage or choosing to let flycatcher populations decline, rather an appeal to set realistic expectations for future management goals.

References

Bean, D., & Dudley, T. (2018). A synoptic review of *Tamarix* biocontrol in North America: tracking success in the midst of controversy. *BioControl*, *63*(3), 361–376. https://doi.org/10.1007/s10526-018-9880-x

Bean DW, Dudley TL, Hultine K (2013) Bring on the beetles: the history and impact of tamarisk biological control. In: Sher A, Quigley M (eds) Tamarix: a case study of eco- logical change in the American West. Oxford Univ Press, New York, pp 377–403

Brock, J. H. (1994). Tamarix spp. (Salt Cedar), an invasive exotic woody plant in arid and semi-arid riparian habitats of western USA. *Ecology and Management of Invasive Riverside Plants*, *1982*, 27–44. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.208.6941&rep=rep1&type=pdf

Busch DE, Smith SD (1993) Effects of fire on water and salinity relations of riparian woody taxa. Oecologia 94:186–194

Darrah, A. J., & van Riper, C. (2018). Riparian bird density decline in response to biocontrol of *Tamarix* from riparian ecosystems along the Dolores River in SW Colorado, USA. *Biological Invasions*, *20*(3), 709–720. https://doi.org/10.1007/s10530-017-1569-z

Deloach, C. J., Carruthers, R. I., Lovich, J. E., Dudley, T. L., & Smith, S. D. (2000). Ecological interactions in the biological control of saltcedar (*Tamarix spp* .) in the United States : Toward a New Understanding. *Proceedings of the X International Symposium on Biological Control of Weeds.*, 69.

Dickie, I. A., Bennett, B. M., Burrows, L. E., Nuñez, M. A., Peltzer, D. A., Porté, A., Richardson, D. M., Rejmánek, M., Rundel, P. W., & van Wilgen, B. W. (2014). Conflicting values: Ecosystem services and invasive tree management. *Biological Invasions*, *16*(3), 705–719. https://doi.org/10.1007/s10530-013-0609-6

Diehl, R. M., Wilcox, A. C., & Stella, J. C. (2020). Evaluation of the integrated riparian ecosystem response to future flow regimes on semiarid rivers in Colorado, USA. *Journal of Environmental Management*, *271*(June), 111037. https://doi.org/10.1016/j.jenvman.2020.111037

Dudley T.L., DeLoach C.J., Lewis P.A., Carruthers RI (2001) Cage tests and field studies indicate leaf-eating beetle may control saltcedar. Ecol Restor 19:260–261

Dudley, T. L., & Deloach, C. J. (2004). Saltcedar (*Tamarix spp*.), Endangered species, and biological weed control—can they mix? 1 . *Weed Technology*, *18*(sp1), 1542–1551. https://doi.org/10.1614/0890-037x(2004)018[1542:stsesa]2.0.co;2

Dudley, T. L., & Bean, D. W. (2012). Tamarisk biocontrol, endangered species risk and resolution of conflict through riparian restoration. *BioControl*, *57*(2), 331–347. https://doi.org/10.1007/s10526-011-9436-9

Friggens, M. M., & Finch, D. M. (2015). Implications of climate change for bird conservation in the southwestern U.S. under three alternative futures. *PLoS ONE*, *10*(12), 1–23. https://doi.org/10.1371/journal.pone.0144089

Harms, R. S., & Hiebert, R. D. (2006). Vegetation response following invasive tamarisk (Tamarix spp.) removal and implications for riparian restoration. *Restoration Ecology*, *14*(3), 461–472. https://doi.org/10.1111/j.1526-100X.2006.00154.x

Hinojosa-Huerta, O., Nagler, P. L., Carrillo-Guererro, Y. K., & Glenn, E. P. (2013). Effects of drought on birds and riparian vegetation in the Colorado River Delta, Mexico. *Ecological Engineering*, *51*, 275–281. https://doi.org/10.1016/j.ecoleng.2012.12.082

Hultine, K. R., Froend, R., Blasini, D., Bush, S. E., Karlinski, M., & Koepke, D. F. (2020). Hydraulic traits that buffer deep-rooted plants from changes in hydrology and climate. *Hydrological Processes*, *34*(2), 209–222. https://doi.org/10.1002/hyp.13587

Hultine KR, Dudley TL, Koepke DF, Bean DW, Glenn EP, Lambert AM (2014) Patterns of herbivory-induced mortality of a dominant non-native tree/ shrub (Tamarix spp.) in a southwestern US watershed. Biol Invasions 17:1729–1742

Larson, D. M., Dodds, W. K., & Veach, A. M. (2019). Removal of woody riparian vegetation substantially altered a stream ecosystem in an otherwise undisturbed grassland watershed. *Ecosystems*, *22*(1), 64–76. https://doi.org/10.1007/s10021-018-0252-2

Murray, L., Schutte, B. J., Sutherland, C., Beck, L., Ganguli, A., & Lehnhoff, E. (2019). Integrating conventional management methods with biological control for enhanced Tamarix management. *Invasive Plant Science and Management*, *12*(3), 176–185. https://doi.org/10.1017/inp.2019.20

Paxton, E. H., Sogge, M. K., Durst, S. L., Theimer, T. C., & Hatten, J. R. (2007). The Ecology of the Southwestern Willow Flycatcher in Central Arizona — a 10-year Synthesis Report. *U.S. Geological Survey Open File Report 2007-1381*, 143.

Paxton, E. H., Theimer, T. C., & Sogge, M. K. (2011). Tamarisk biocontrol using tamarisk beetles: Potential consequences for riparian birds in the southwestern United States. *Condor*, *113*(2), 255–265. https://doi.org/10.1525/cond.2011.090226

Setshedi, K. T. A., & Newete, S. W. (2020). The impact of exotic tamarix species on riparian plant biodiversity. *Agriculture (Switzerland)*, *10*(9), 1–16. https://doi.org/10.3390/agriculture10090395

Sogge, M. K., Marshall, R. M., Sferra, S. J., & Tibbitts, T. J. (1997). A Southwestern Willow Flycatcher Natural History Summary and Survey Protocol. *Technical Report NPS/NAUCPRS/NRTR-97/12*, *May*, 34.

Sogge, M.K., and R.M. Marshall. 2000. A survey of current breeding habitats. Pages 43–56 in Status, Ecology, and Conservation of the Southwestern Willow Flycatcher. Finch, D.M. and S.H. Stoleson (eds). USDA Forest Service Rocky Mountain Research Station General Technical Report RMRS-GTR-60. 131 pp.

Stella, J.C., Bendix, J., 2019. Multiple stressors in riparian ecosystems. In: Multiple Stressors in River Ecosystems. Elsevier, pp. 81–110.

Stenquist S (1999) Saltcedar biological control and the Saltcedar Consortium. Aquat Nuis Species Digest 3:20–23

Van Riper, C., Puckett, S. L., & Darrah, A. J. (2018). Influences of the invasive tamarisk leaf beetle (*Diorhabda carinulata*) on avian diets along the Dolores River in Southwestern Colorado USA. *Biological Invasions*, *20*(11), 3145–3159. https://doi.org/10.1007/s10530-018-1764-6

Wiener, J. D., Dwire, K. A., Skagen, S. K., Crifasi, R. R., & Yates, D. (2008). Riparian ecosystem consequences of waater redistribution along the Colorado Front Range. *Journal Of The American Water Resources Association*, *10*(3), 18–21.

York, P., Evangelista, P., Kumar, S., Graham, J., Flather, C., & Stohlgren, T. (2011). A habitat overlap analysis derived from maxent for tamarisk and the south-western willow flycatcher. *Frontiers of Earth Science*, *5*(2), 1. https://doi.org/10.1007/s11707-011-0154-5

CHAPTER 2: GRANT PROPOSAL

Temporal Trends of Tamarisk Remediation to Native Vegetation Establishment

Abstract

Tamarisk (*Tamarix spp.)* invasion has negative cascading effects on both aquatic and terrestrial species populations. Tamarisk outcompetes native flora through chemical alteration of soil, rapid establishment, and an innate resistance to disturbances like drought and fire regimes, which results in a decrease of native flora through decreases in native habitat, water, and soil quality. Sampling after tamarisk removal will quantify impacts to the native riparian plant community, and underlying soil characteristics, and whether these impacts vary along a temporal gradient of time-since-removal within this study. Random quadrat sampling of vegetative communities and collection of soil samples at each sampling point will characterize the study site. An assessment of the vegetative community response after differing times since remediation will be quantified using an NMDS and PCA. Quantification of the residence time of tamarisk induced soil chemistry changes and vegetative community responses will guide continued removal efforts and contribute to the future management of riparian corridors.

Introduction

Anticipated Value

This study will quantify the effects of tamarisk removal and succession of native species over a temporal gradient within a riparian environment. Tamarisk threatens sensitive riparian areas and is projected to decrease native riparian vegetation in the southwestern United States (Dudley & Deloach, 2004). Additionally, tamarisk (*Tamarix spp.)* invasion decreases native species abundances in both terrestrial and aquatic components of riparian areas (Harms & Hiebert, 2006). This process is further bolstered by drought conditions expected under climate change (Harms & Hiebert, 2006; Dudley & Deloach, 2004). Since climate change and tamarisk invasion may create a positive feedback loop that deteriorates overall riparian ecology over time, a thorough examination of previous remediation efforts in riparian ecosystems is warranted to assess efforts to sustain viable riparian habitats. Sampling and comparing sites that historically implemented mastication removal 20, 10, and 5 years ago will identify the ability of native vegetation to establish after tamarisk removal. Measurement of species richness, evenness, and relative abundance after tamarisk removal efforts are pivotal to characterizing impacts and facilitating the return of a functional ecosystem and the resurgence of native flora. The results of this study will guide future management by assessing the impact of previous remediation efforts and the residence time of soil chemistry changes in response to tamarisk invasion.

Objectives

This study quantifies the difference in establishment of native species after differing lengths of time since tamarisk removal and will uncover any potentially lasting impacts from historic tamarisk presence, such as elevated saline concentrations in the soil in Colorado riparian ecosystems. A central question guiding this research asks how tamarisk removal impacts the native riparian plant community, and underlying soil characteristics, and whether these impacts vary along a temporal gradient of time-since-removal. Soil characteristics in areas previously invaded by tamarisk will be sampled for salinity, compaction, and pH to assess soil fertility and quantify the likelihood of natural native establishment after tamarisk removal.

Hypothesis

H1) Community responses will be negatively related to time-since-removal due to soil characteristics gradually returning to baseline through time.

H2) Community responses are consistent across time and are independent of tamarisk-altered soil characteristics.

Literature Review

Tamarisk was originally introduced to promote bank stabilization along riparian corridors in western North America in 1823 (Brock, 1994). Unbeknownst to anyone at the time, this would create an ecological crisis that is now projected to cost billions of dollars in economic losses from decreased ecosystem services provided by riparian ecosystems (Harms & Hiebert, 2006). Tamarisk has encroached on massive swaths of tributaries in the southwestern United States and continues to spread at the pace of 20km annually (Brock, 1994). Tamarisk encroachment has effectively outcompeted native riparian vegetation, altered stream morphology, replaced critical habitat, increased risk for severe fires, and drastically changed soil and water chemistry (Deloach et al., 2000; Dudley & Deloach, 2004; Larson et al., 2019; Murray, 2019). Unique adaptations inherent to tamarisk are attributed to the overwhelming success of the species

Tamarisk alters abiotic characteristic of the environment to stifle competition from native vegetation. Tamarisk is a phreatophyte, meaning it uses a taproot that penetrates deep into soils to access the water table, reportedly as deep as six meters (Hultine et al., 2020). Tamarisk also draws water from the surface if the taproot has not developed to the appropriate depth. This adaptation directly impacts native riparian phreatophytes, like cottonwoods (*Populus spp.)* and willows (*Salix spp.*), by reducing available water, which halts their establishment and germination (Deloach et al., 2000; York et al., 2011). Additionally, tamarisk is xerophytic and halophytic, meaning it is adapted to both drought conditions and heavily salinized environments (Brock, 1994). Perhaps the most detrimental aspect of tamarisk invasion is the accumulation of concentrated salt within its foliage (Brock, 1994; Deloach et al., 2000; Murray, 2019). Tamarisk is deciduous, meaning it drops its salty foliage onto the topsoil annually, which fundamentally alters topsoil by increasing salt concentrations. These characteristics give an extraordinary advantage to invading tamarisk and thwart many native revegetation and remediation efforts.

Removal of tamarisk is implemented in the interest of conserving native species. Current remediation efforts include controlled burning, mastication (mowing or cutting aboveground biomass), or the introduction of a biocontrol to defoliate tamarisk stands (Harms & Hiebert, 2006). Controlled burning and removal of aboveground biomass are the most common type of remediation of tamarisk stands (Harms & Hiebert, 2006). After burning and removal of biomass, an herbicide is brushed on the remaining stems to kill the root system, which is expensive and ineffective for long-term removal goals (Brock, 1994; Dudley & Deloach, 2004; Harms & Hiebert, 2006; Hultine et al., 2014). The temporary nature of remediation can be attributed to the reproductive strategy implemented by tamarisk. Tamarisk seeds are dispersed by both wind and water and facilitate a wide range of potential spread (Deloach et al., 2000). Tamarisk also regenerate from fragments of its root system, stem, and crown area (Brock, 1994; Deloach et al., 2000). These reproductive traits can change the vegetative composition of a riparian area which can have lasting implications for remediation efforts.

Even when remediation is successful, the absence of tamarisk does not guarantee the return of native flora to riparian ecosystems (Darrah & Van Riper, 2018; Paxton et al., 2011). This study will detail the impacts of remediation after removal of tamarisk and assess if a return to historical conditions is feasible. Quantifying the temporal abundance of native species between three sampling strata will add to the understanding of riparian ecology after invasive removal. Additionally, assessing the residence time associated with soil chemistry changes will guide future revegetation efforts and determine when soil fertility is conducive for natural reestablishment.

Methods

Study Site

This study will be conducted in Grand Junction, Colorado at Connected Lakes, which is a section of James M. Robb Colorado River State Park. The Connected Lakes area consists of 48 acres and is one of five sections of James M. Robb Colorado River State Park. This site is managed by Colorado Parks and Wildlife. The areas of interest are the northwestern shore where tamarisk was removed 20 years ago, the southwestern shore where tamarisk was removed 10 years ago, and the eastern shore where tamarisk was removed 5 years ago (Appendix 1). A non-remediated site along the Colorado River adjacent to Connected Lakes will serve as a control. The fact that these sites all occur in the same lake network is ideal because this spatial proximity should reduce impacts of confounding differences in environmental variables.

Vegetation Sampling

Community responses to tamarisk invasion over time will be randomly sampled using 100 sampling locations. At Connected Lakes, 75 sampling points will be randomly selected around the shore of the lake using ArcGIS. Points will be within 0.5 to 6 meters of the shoreline and extend the length of the previous remediation effort. Additionally, 25 sampling points will be randomly selected at an adjacent riparian area along the Colorado River as a control. At each point a 1x1m quadrat will centered and, within which, I will record the percent cover of each individual plant species. I will also document the percent of bare ground within the site and the percent of ground cover by litter or duff.

Soil Sampling

To quantify soil characteristics within the differing time gradients, 100 soil samples will be collected. A soil sample will be collected from the top 10cm of soil at each sample point and stored in a 4oz glass sampling container after homogenization. Samples will be immediately labeled and placed on ice with an accompanying chain of custody form. Samples will be shipped to and analyzed by Weld Laboratories in Greely, Colorado for pH, potassium, phosphorous, organic matter, salinity, zinc, calcium, sulfur, and nitrate-nitrite concentrations.

Data Analysis

Species richness, abundance, and evenness will be quantified from the precent cover of each quadrat. Data will be assessed for normality and undergo transformations as necessary. For A non-metric multidimensional scaling (NMDS) will be fit to ordinate community-level data for interpretation. The NMDS will be fit using the Brey-Curtis distance matrix with the dependent variables of species richness, evenness, and relative abundance. Fitting an NMDS will establish gradients of the community vegetation. Along each NMDS axis differences between the length of time since removal and the control site can be compared for differences in community compositions. Using this output will determine if the time-points differ from each other and the effectiveness of tamarisk removal based on community responses.

I will use principal component analysis (PCA) to analyze collected soil data. Variables will be assessed for normality and transformed as necessary then fit into a PCA model. I will retain all PC axes that collectively explain 80% of the variance within the data. The result will answer if these time-points differ from the control or each other along each PC axis.

Potential Negative Effects

Negative effects of this study will be marginal to nonexistent. Vegetation sampling using quadrats is a passive sampling method which has no perceived negative impacts. The volume of soil collected for analysis will also have negligible impacts on the environment. Accessing areas for sampling may introduce minimal wildlife disturbance and vegetation trampling. These impacts will be minimized by staying on established trails when possible and avoiding stepping on vegetation when leaving the trail.

Project Timeline

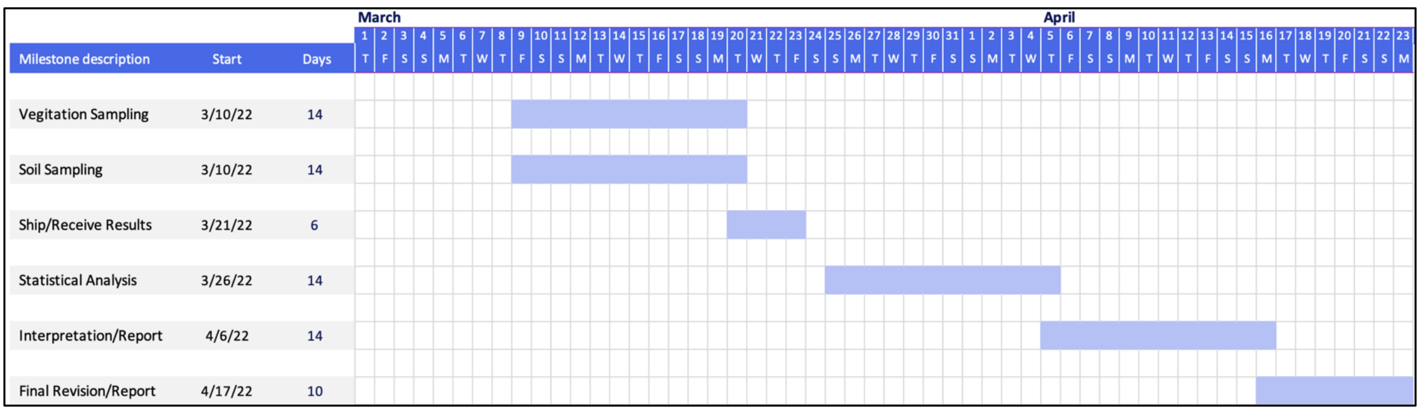

Figure 1: The proposed timeline for the sampling effort is displayed in a Gantt chart

Budget

Table 1: A breakdown of anticipated costs associated with the sampling effort

Expense	Explanation of Cost	Justification	Cost
Soil Analysis	$20 X 100 samples	75 soil samples within the park and 25 samples of control plot	$2,000
Vegitation Analysis	$20 for PVC (quadrat)	PVC used for construction of quadrat for sampling effort	$20
Travel Expenses	500 mi/roundtrip X $0.58/mi	1 roundtrip expense for sampling effort at park	$290
Lodging Expenses	$96/Day X 14 Days	Two weeks of lodging expenses for sampling effort at park	$1,344
Food/Incidentals	$19/Day X 14 Days	Two weeks of food/incidentals for sampling effort at park	$266
GPS	Garmen eTrex GPS unit	GPS unit used for locating random sampling points	$100
Sampling Supplies	Miscellaneous equipment	Sharpies, clipboard, disposable gloves, water, and sunscreen	$50
Total			$4,070

References

Brock, J. H. (1994). Tamarix spp. (Salt Cedar), an invasive exotic woody plant in arid and semi-arid riparian habitats of western USA. *Ecology and Management of Invasive Riverside Plants*, *1982*, 27–44. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.208.6941&rep=rep1&type=pdf

Darrah, A. J., & van Riper, C. (2018). Riparian bird density decline in response to biocontrol of *Tamarix* from riparian ecosystems along the Dolores River in SW Colorado, USA. *Biological Invasions*, *20*(3), 709–720. https://doi.org/10.1007/s10530-017-1569-z

Deloach, C. J., Carruthers, R. I., Lovich, J. E., Dudley, T. L., & Smith, S. D. (2000). Ecological interactions in the biological control of saltcedar (*Tamarix spp* .) in the United States : Toward a New Understanding. *Proceedings of the X International Symposium on Biological Control of Weeds.*, 69.

Dudley, T. L., & Deloach, C. J. (2004). Saltcedar (*Tamarix spp*.), Endangered species, and biological weed control—can they mix? 1 . *Weed Technology*, *18*(sp1), 1542–1551. https://doi.org/10.1614/0890-037x(2004)018[1542:stsesa]2.0.co;2

Harms, R. S., & Hiebert, R. D. (2006). Vegetation response following invasive tamarisk (Tamarix spp.) removal and implications for riparian restoration. *Restoration Ecology*, *14*(3), 461–472. https://doi.org/10.1111/j.1526-100X.2006.00154.x

Hultine, K. R., Froend, R., Blasini, D., Bush, S. E., Karlinski, M., & Koepke, D. F. (2020). Hydraulic traits that buffer deep-rooted plants from changes in hydrology and climate. *Hydrological Processes*, *34*(2), 209–222. https://doi.org/10.1002/hyp.13587

Hultine KR, Dudley TL, Koepke DF, Bean DW, Glenn EP, Lambert AM (2014) Patterns of herbivory-induced mortality of a dominant non-native tree/ shrub (Tamarix spp.) in a southwestern US watershed. Biol Invasions 17:1729–1742

Larson, D. M., Dodds, W. K., & Veach, A. M. (2019). Removal of woody riparian vegetation substantially altered a stream ecosystem in an otherwise undisturbed grassland watershed. *Ecosystems*, *22*(1), 64–76. https://doi.org/10.1007/s10021-018-0252-2

Murray, L., Schutte, B. J., Sutherland, C., Beck, L., Ganguli, A., & Lehnhoff, E. (2019). Integrating conventional management methods with biological control for enhanced Tamarix management. *Invasive Plant Science and Management*, *12*(3), 176–185. https://doi.org/10.1017/inp.2019.20

Paxton, E. H., Theimer, T. C., & Sogge, M. K. (2011). Tamarisk biocontrol using tamarisk beetles: Potential consequences for riparian birds in the southwestern United States. *Condor*, *113*(2), 255–265. https://doi.org/10.1525/cond.2011.090226

York, P., Evangelista, P., Kumar, S., Graham, J., Flather, C., & Stohlgren, T. (2011). A habitat overlap analysis derived from maxent for tamarisk and the south-western willow flycatcher. *Frontiers of Earth Science*, *5*(2), 1. https://doi.org/10.1007/s11707-011-0154-5

APPENDIX

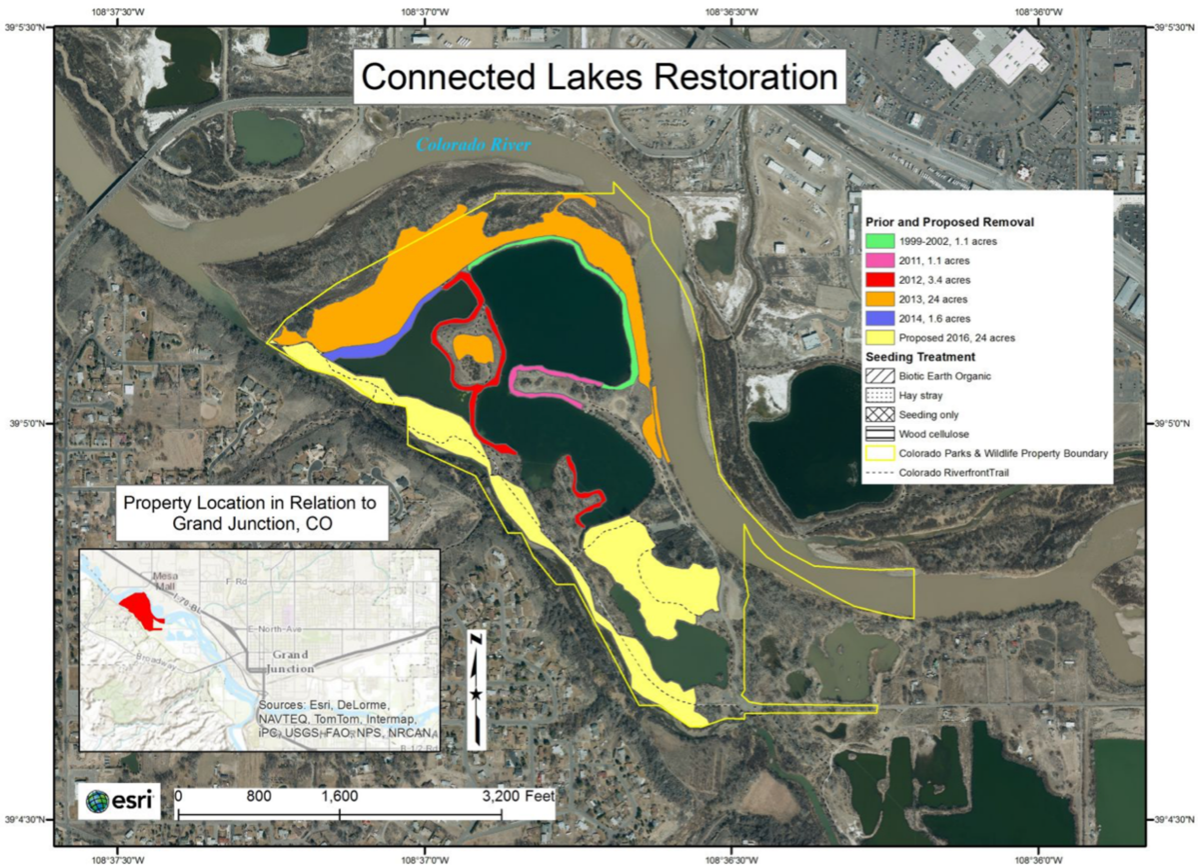

Figure A-1: Map of sampling area for this study. Colors on map represent differing times since removal of tamarisk at Connected Lakes. Map reproduced from the Tamarisk Coalition.

Researcher Qualifications

Dylan Christopher Brown
Curriculum Vitae

510 Xenon Ct.
Lakewood, CO 80228

303.868.3610
Dylanbrown46@gmail.com

EDUCATION

Regis University 2020-Present

- Master of Science in Environmental Biology
    - Degree anticipated May of 2022

Colorado Mesa University 2012-2017

- Bachelor of Science in Environmental Science and Technology
  - Concentration in Pollution Monitoring and Control
- Minor in Geographic Information Systems and Technology (GIS)
- 40 Hour OSHA certification in Hazardous Waste Operations and Emergency Response (HAZWOPER)

PROFESSIONAL EXPERIENCE

Alpine Remediation - Golden, CO 07/2019 – 08/2020
Environmental Field Technician

Conducted environmental sampling and in situ remediation for Phase II and Phase III Environmental Site Assessments. Frequently collected soil, vapor, and groundwater samples to be used for management considerations. Sampling is typically used to determine hydrocarbon concentrations, chlorinated solvent concentrations, or geotechnical data.

- Implemented remediating techniques to treat contaminated soil and groundwater with in-situ applications with a variety of media including ORC, HRC, Fenton's Reagent, microbes, permanganate, and iron.
- Operated direct push drill rigs (Geoprobe 54LT; AMS 9500 VTR) and truck mounted auger drills (CME-85); for sampling, groundwater injections, or installing monitoring wells.
- Experienced with transporting drilling equipment as a CMV in compliance with DOT regulations and weigh station requirements.
- Frequently travel to surrounding states for extended periods of time; and adapt to changing scope of work, or site safety requirements.

United States Forest Service - Grand Junction, CO 05/2019 – 06/2019
OHV Crew

Operated and maintained ATVs used for traveling to remote sites in the Uncompahgre and Grand Mesa National Forests which included camping on site. Responsible for maintaining access for recreational trails and fire suppression operations.

- Certified through the Forest Service in use of OHV equipment, 4-wheel drive vehicles, hauling of trailers, chainsaws, first aid/CPR, and defensive driving.
- Extensive use of GPS devices, mapping/orienteering, SPOT, and Intouch devices in order to locate work site and emergency evacuation areas.

Capco Inc. - Grand Junction, CO 7/2018 – 05/2019

QA Inspector

Worked with government contracts ensuring conformance of ordered parts before acceptance and shipment of military equipment. Involved frequently interpreting CAD files and confirming measurements fall into acceptable tolerances using various measuring instruments.

- Maintained stringent documentation of lot integrity and comforting material of each component as required by Department of Defense regulations.

Allosource - Centennial, CO 12/2017 – 06/2018

Operations Processing Lab Technician

Produced allografts for transplant by medical professionals into patients with tendon, muscle structure, and bone defects or damage. Quality assurance and quality control measures are constantly implemented as well as, and extensive documentation.

- Use of QA/QC practices in a sterile laboratory environment, with settle plates involved with every process to monitor microbial activity in an ISO level 5 environment. This includes collection, labeling, and preparation of samples for the microbiological testing process.

Colorado Parks and Wildlife - Denver, CO 7/2017 – 12/2017

Aquatic Biologist Intern

Assisted in environmental research used to generate reports of Colorado aquatic species in this seasonal job. Conducted fieldwork and sample preparation for laboratory analysis. As well as labor intensive electroshocking of various water bodies around Colorado to collect aquatic specimen.

- Sample preparation including labeling and logging relevant site information and sample numbers using GPS units to locate previous and ongoing study areas in order to continue data collection.
- Use of electroshocking in various streams, rivers, and lakes around the state of Colorado assessing population, annual growth, spawn rates and disease rate estimates of riparian species.
- Knowledge of aquatic species in Colorado and ability to predict dynamic hydraulic events and corresponding riparian responses.
- Administrated routine maintenance on fleet vehicles and facilities.

Colorado Mesa University- Grand Junction, CO 1/2013 – 5/2017

Student Carpentry Manager

Served in a manager position at Colorado Mesa University conducting physically demanding tasks. This includes framing, drywall, preventative maintenance, and repairs.

- Promoted to the head of the student carpentry team.
- Learned how to operate power tools, heavy equipment, build, and complete entire projects by reading blueprints.
- Demonstrated ability to complete tasks independently and adapt to unforeseen problems.

RESEARCH PROJECTS

- Conducted disease and genetic testing of endangered Greenback Cutthroat Trout (*Oncorhynchus clarki stomias*) in Colorado tributary waters in addition to aquatic population surveys.
- Participated in a reclamation project involving application of Rotenone and water diversion within Rock Creek near Fairplay, Colorado; to remove Greenback Cutthroat Trout infected with whirling disease.
- Conducted Phase I, II, and III environmental assessments through Alpine Remediation detecting and remediating chlorinated solvents and hydrocarbons present in commercial properties.
- Extensive work in environmental monitoring projects that involved water table, surface water,

and soil sampling to ensure adherence to NPDES, SPCC, county, and local permitting requirements.

- Created, wrote, and presented an Environmental Assessment (EA) for Croke Reservoir remediation to the city of Northglenn, Colorado, and state environmental officials within CPW, EPA, and CDPHE; which was accepted and implemented following the NEPA process.
- Created, wrote, and presented management solutions for Denver Mountain Parks that host two populations of *B. bison*. This comprised of two separate documents, one assessing and scoring herd viability, and one assessing current and future management considerations.
- Installed pitfall traps for dung beetles (*Scarabaeine spp.*), which were collected, identified, and statistically analyzed to quantify contributions to nutrient cycling within Denver Mountain Parks.

SKILLS

- Extensive experience using heavy equipment such as band saw, planer, jointer, chop saw, table saw, belt sander, drill press, and tile cutting equipment.
- Ability to use the statistical software R for data analysis.
- Conducted field studies that utilize ArcGIS, Pathfinder Office, and Terrasync that were combined to display data and results.
- Knowledge of remote sensing and ENVI software including analyzing and interpreting LIDAR, elevation, and spatial data.
- Conducted environmental range management practices involving line point transects, meter plots, soil analyte sampling, endangered species stocking into environment, and environmental analysis of native flora; all involving heavy use of statistical methods.

CHAPTER 3: JOURNAL MANUSCRIPT

Assessing Effectiveness of Tamarisk Removal Treatments Through a Meta Regression Analysis

Abstract

Tamarix spp. has invaded many river systems within the southwestern United States and is a major consideration when managing riparian environments. *Tamarix spp*. is a leading cause of degradation to biodiversity and native habitat within systems it infests. Four methods of remediation are commonly used to remove *Tamarix spp.*: biocontrol, chemical, burn, and mechanical treatment. To determine which of these four treatments is most effective, I compared their effectiveness at *Tamarix spp.* removal through a meta-analysis of the available literature. Through the culmination of available data from nearly a thousand journal articles, before and after treatment percent of *Tamarix spp*. cover was used to calculate Hedges' d and its variance for each study. I then fit a series of meta regressions to analyze the effectiveness of these four tamarisk removal treatment strategies. All treatments successfully reduced the percent cover of *Tamarix spp*., but biocontrol had a significantly greater effect size indicating a greater reduction of percent cover. Specifically, biocontrol and mechanical treatments had similar effect sizes, while chemical and burn had the lowest effect sizes and were significantly lower than biocontrol. This result coincides with management recommendations advocating the integration of biocontrol treatment with less effective treatments such as chemical or burn treatments to achieve greater stand mortality.

Introduction

Tamarix spp. (hereafter, tamarisk) is an invasive plant species found in riparian environments of the southwestern United States. First introduced in 1823, tamarisk was identified as a solution to bank destabilization that was pervasive in riparian corridors of the southwestern United States (Brock, 1994; Murray et al., 2019). Tamarisk was intentionally planted across the United States without considering innate characteristics would degrade the riparian corridors (Larson et al., 2019; Nagler et al., 2021). Tamarisk was eventually identified as a noxious weed that rapidly spread through efficient dispersion of propagules (Bay & Sher, 2008), and rapid germination which degraded riparian biodiversity and habitat (Brooks et al., 2008). The invasive has an ability to establish quickly after a disturbance and is estimated to occupy 500,000 to 650,000 ha within the western United States (Paxton & Sogge, 2011). Additionally, tamarisk has been documented to spread up to 20km each year (Brock, 1994). This spread has degraded riparian areas that are being replaced with tamarisk monocultures.

Riparian management is predicated on the retention of native species biodiversity and is typically modeled on historic or reference conditions. However, the proliferation of tamarisk displaces native riparian vegetation with monocultures of dense vegetation (McLeod, 2018), which decreases biodiversity of the surrounding flora and fauna (Kennard et al., 2016; Setshedi & Newete, 2020). Nutrient cycling, ecosystem function, soil biota, and riparian resilience decrease in response to tamarisk invasion (Murray et al., 2019; Setshedi & Newete, 2020). These invasive monocultures also impact river morphology by decreasing water availability, altering flow regimes, and sediment loadings (Harms & Hiebert, 2006; Kennard et al., 2016; York et al., 2011). The culmination of impacts has increased the response of managers to curtail tamarisk spread which is evidenced by the abundance of remediation studies.

Remediation of tamarisk is vital to retain ecosystem services, endemic flora, and native species habitat (Dudley & Deloach, 2004; Finch et al., 2006). Managers typically use one of four different remediation techniques to achieve tamarisk removal goals. The most common remediation strategy is mechanical removal using heavy machinery and is typically very costly. Chemical treatment involves stem cutting or mowing of tamarisk with application of a chemical agent (e.g., Triclopyr and Imazapyr) brushed on the remaining stems (Harms & Hiebert, 2006). A chemical agent is applied to hinder the innate ability of tamarisk to regenerate from fragments of its root system, stem, and crown area (Brock, 1994; Deloach et al., 2000). Another strategy is the application of controlled burns to an area impacted by tamarisk which may also receive a chemical application resembling the chemical treatment method (Harms & Hiebert, 2006). The final method involves the release of northern tamarisk beetle (Chrysomelidae: *Diorhabda carinulata*) as a biocontrol agent. Biocontrol defoliation occurs over several consecutive seasons before stand mortality is achieved through carbon starvation that reduces production and growth of tamarisk (Kennard et al., 2016). These four different treatments are employed in tandem with reseeding of native vegetation to facilitate the return of native flora to invaded streams.

Reseeding after remediation is a measure employed to increase competition to regenerating tamarisk fragments and replaces riparian habitat for obligate species (Harms & Hiebert, 2006). The success of remediation is predicated on how much tamarisk cover was reduced through treatment and native competition. Assessing reduction of tamarisk cover before remediation and after remediation allows the opportunity to aggregate success across all study areas and remediation techniques. Through the application of a synthetic empirical approach, trends of removal effectiveness and native community reestablishment can be gleaned using data accrued from studies that report a decrease in percent cover of tamarisk.

A meta-analysis is a powerful research synthesis method and can provide an objective summarization of tamarisk remediation effectiveness by correcting for unequal precision and bias in studies through the accumulation of results across environmental gradients (Koricheva & Gurevitch, 2013). Remediation sites are separated spatially and temporally which makes detecting generalizable trends of success difficult. The application of a meta-analysis identifies a definitive level of tamarisk removal that varies throughout spatially vast riparian areas. If tamarisk remediation is successful, tamarisk cover will be significantly lower than measurements reported before remediation. It is expected that overall tamarisk cover is significantly reduced after remediation through disturbance of plant functionality (Murray et al., 2019). I hypothesized that (1) all treatments would reduce tamarisk cover because removal of tamarisk by any method reduces percent cover, and (2) that biocontrol would be the most effective due to the historical success of releases (Bean & Dudley, 2018; Kennard et al., 2016). Through the application of a meta-regression analysis, comparative trends in tamarisk removal will be revealed to determine a hierarchy of treatment effectiveness.

Methods

Literature Search and Selection

I searched for relevant literature and compiled articles into a spreadsheet with the program Publish or Perish (v. 8.0, 2021). This program exclusively used Google Scholar to search for journal articles. I tested numerous search terms and the combination of keywords that returned the most results was retained for the meta-analysis. Using the keywords "Tamarisk", "Tamarix", "Salt Cedar", "Biodiversity", and "Impacts" returned 980 journal articles, which exceeded all other search combinations and was selected for the meta-analysis.

After articles were aggregated into a spreadsheet, I systematical reviewed each entry for treatment data. Each entry was sorted into five different categories (i.e., data, relevant, non-relevant, copy, and no access) based on relevance to tamarisk remediation or removal. I assessed the relevance of each article by reviewing the abstract followed by the results section if the abstract was relevant to tamarisk remediation. If the journal article had in-text or graphical results it was categorized as "data". If results were related to tamarisk remediation but did not identify a measure of error, or provide data the article was categorized as "relevant". If articles were not relevant, a copy, or not accessible the entry was discarded from the meta-analysis.

Data Aggregation

Data collected on tamarisk remediation reported many metrics, including percent cover, richness, evapotranspiration, defoliation, soil chemistry, and tamarisk mortality. For data to be considered for analysis, both before and after treatment metrics had to be present to allow for comparisons of effectiveness. Additionally, reported data had to be spatially independent to avoid pseudo-replication. If a journal reported metrics over many years, I only used the data before treatment and the last reported year of treatment. This method of data sifting substantially reduced the volume of studies that could be fit into the meta regression.

After selecting for studies that contained before and after treatment data and were independent, percent cover was represented in the greatest number of studies (n>30 observations). Usable percent cover data was found in 16 journal articles for a total sample size of 34 observations. I manually transcribed percent cover data or used Web Plot Digitizer (Version 4.5, 2021) to capture data within figures. The data I extracted were precent cover means, sample sizes, standard deviations, and standard errors. I back-transformed standard error to standard deviation which was required for further analysis. I formatted data with the treatment type, percent cover, and standard deviation into a comma separated value (.csv) file.

Statistical Analysis

The statistical software R was used to analyze the remediation data (R Core Team, 2022). From the complied data, I calculated Hedges' d and its variance for each study, and, in doing so, generated an equally-scaled and unitless effect size among studies. I fit fixed or random-effect only models with and without weighting using the R package "metafor" (Viechtbauer, 2010). I also fit a mixed-effect meta-regression with treatment type as the moderating variable.

Models were compared using model.sel from the "MuMIn" package (Burnham & Anderson, 2002). The model with the lowest corrected Akaike information criterion (AICc) value was selected as the model of best fit. A funnel plot in the "metafor" package visualized outliers that lacked precision and had excessive weight in the model of best fit (Viechtbauer, 2010). Identified outliers were removed and the models were calculated again with improved accuracy, but the previously selected model of best fit remained the top preforming model.

Results

The search results generated 980 papers of which 15.6% were relevant and 1.6% had usable percent cover data (Figure 1). Using the available data, I calculated Hedges' d and its variance. Two outliers in the burn treatment data were identified from a funnel plot and were removed from subsequent analyses. A weighted mixed-effect model with a modifier of treatment type performed better than all other models and was similar to the unweighted mixed-effect model (min.deltaAICc=0.14). The weighted mixed-effect model was selected as the best fit because it drastically outperformed both fixed effect models (min.deltaAICc=305.4).

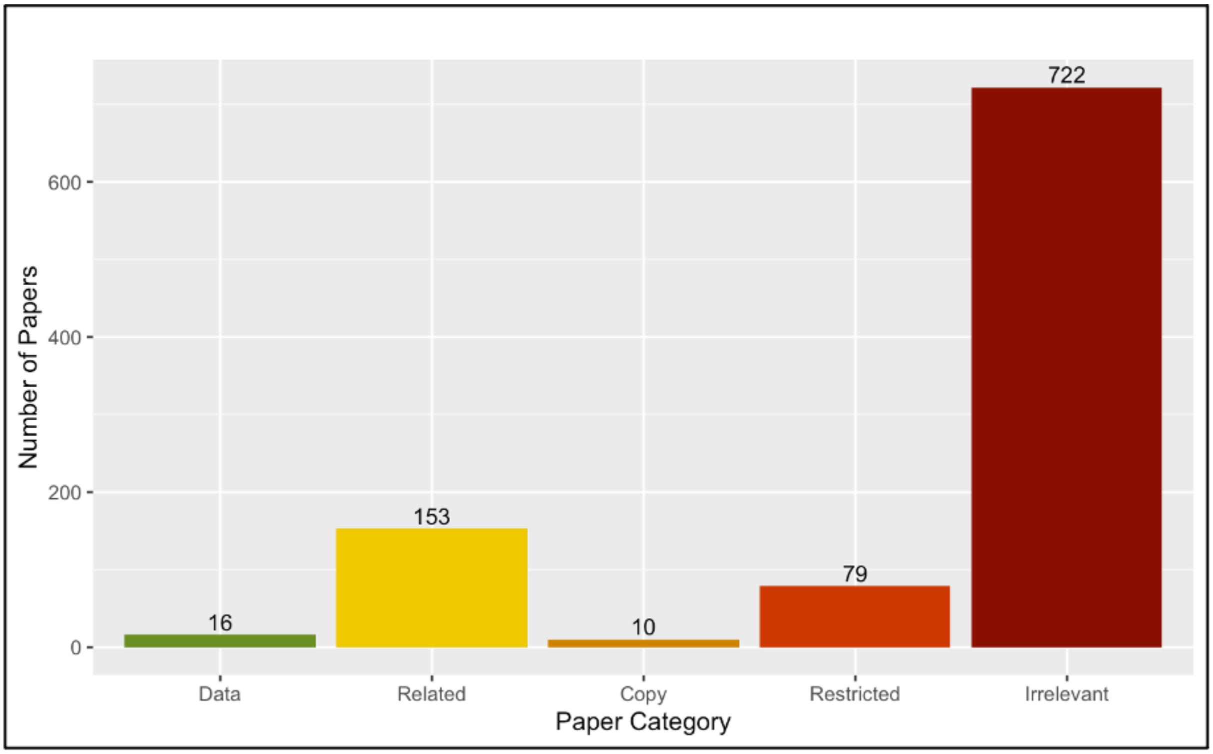

Figure 1: Number of studies assessed for the tamarisk removal meta-analysis.

The adjusted mixed-effect model returned estimates that were greater than 0 for all treatments of tamarisk, indicating that each treatment reduced tamarisk cover (Figure 2). The biocontrol treatment had the largest effect size (est.=1.76 ± 0.36; $p < 0.0001$). Mechanical removal of tamarisk had the second largest effect size (est.=1.14 ± 0.42; $p= 0.142$). Treatment of tamarisk with a controlled burn had the third largest effect size (est.= 0.85 ±0.44; $p = 0.042$). Chemical treatment returned the lowest effect size (est.=0.7691 ± 0.44; $p = 0.024$). Mean effect size of biocontrol treatments was significantly greater than the chemical and burn treatments, but was not significantly greater than the effect size of mechanical treatment (Figure 3).

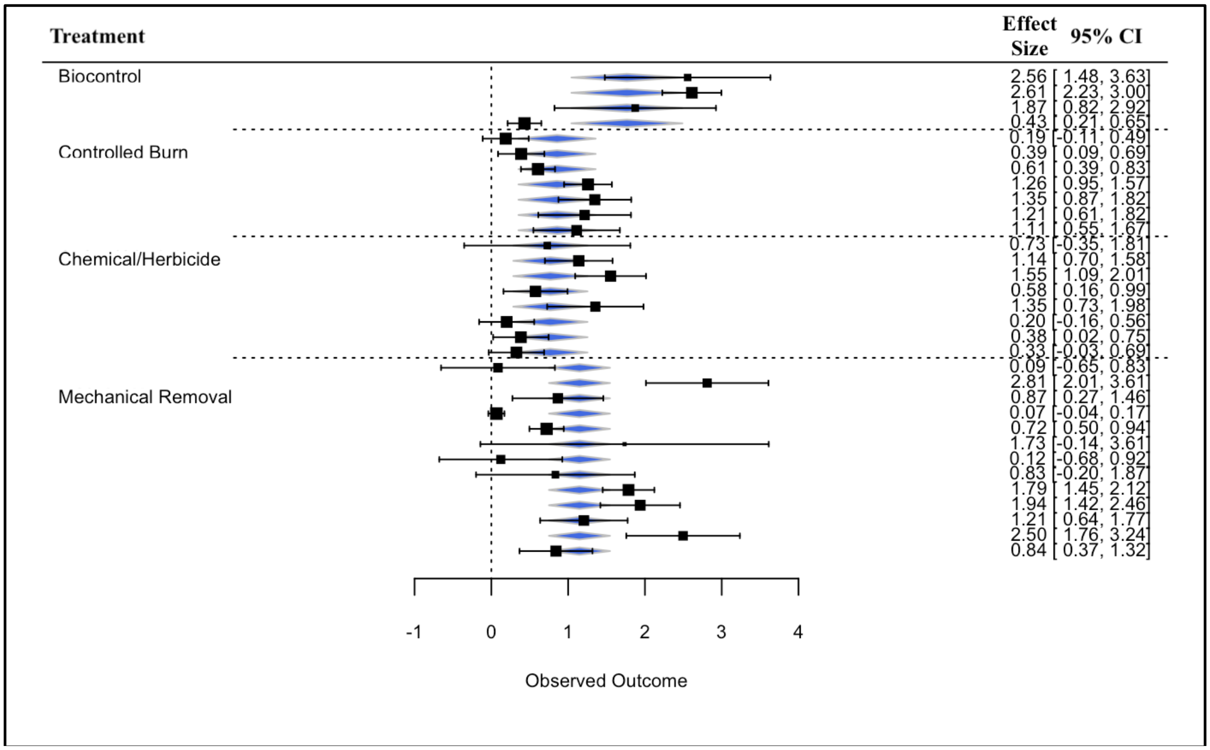

Figure 2: Forest plot of the differing treatments applied to stands of tamarisk. The larger the square symbol indicates a larger weight associated to the study data. The square represents the mean while the lines indicate the 95% confidence interval around the mean. This data is also in the columns on the right side of the forest plot.

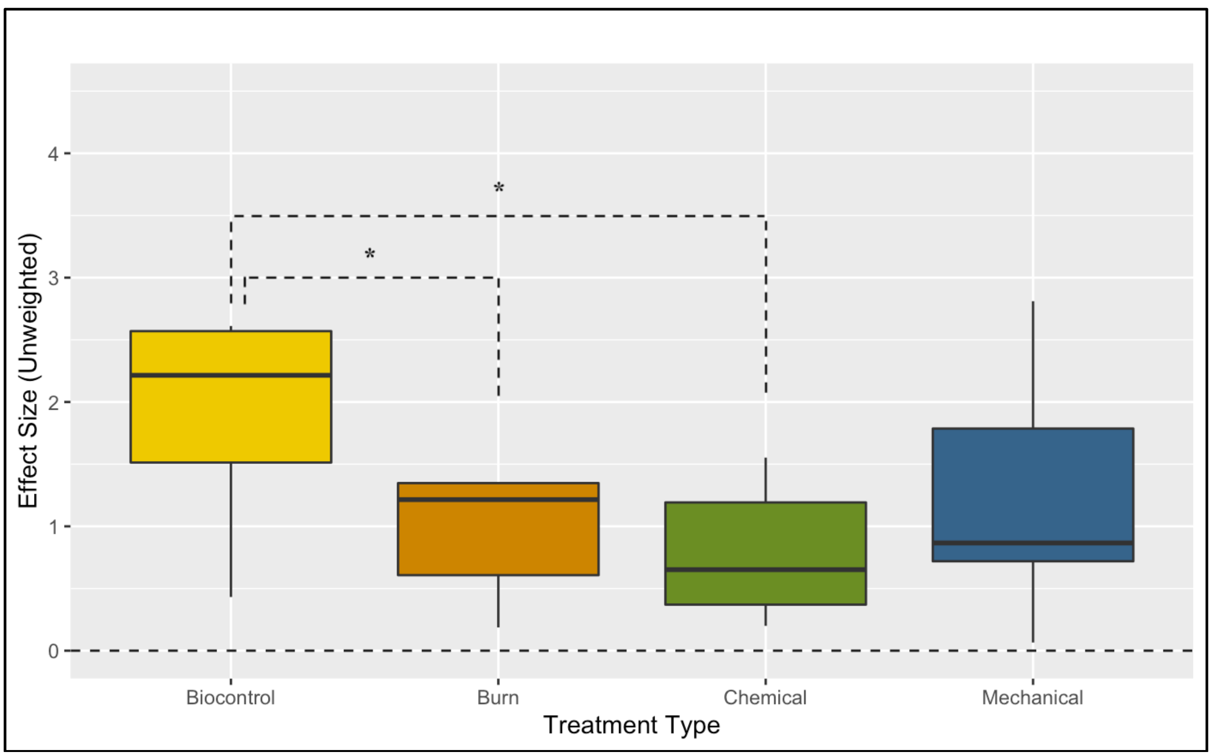

Figure 3: Unweighted mixed-effect meta regression effect sizes between differing treatments. Treatment types included a defoliating biocontrol, controlled burn, chemical application, and mechanical removal. An asterisk indicates treatments that had significantly different effect sizes from the biocontrol treatment.

Discussion

This meta-analysis of tamarisk remediation quantitatively compared the effectiveness of biocontrol, burning, chemical, and mechanical treatment methods. Nearly a thousand papers were aggregated to attain percent cover changes after implementation of the four remediation strategies. My first hypothesis was supported because all four treatments had a positive effect demonstrating tamarisk cover reductions. My second hypothesis was mostly supported because biocontrol had the largest effect size that was significantly larger than chemical and burn treatments; however, biocontrol and mechanical effect sizes were not significantly different.

My first hypothesis, that all four treatments will be effective at reducing tamarisk cover, was supported according to the meta-analysis which returned effect sizes larger than when treatment began. Analogously, Sher et al. (2018) found overall reductions in tamarisk cover after comparing mechanical, chemical, and biocontrol treatments. Mechanical treatment was not significantly different from biocontrol indicating that both treatment methods have comparable rates of cover reduction. Chemical and burn treatment had significantly lower mean effect sizes than biocontrol, indicating that these treatment methods were not as effective as biocontrol and mechanical treatment methods in reducing tamarisk cover. These results indicate that the hypothesis two, that biocontrol would outperform all other treatments, is partly supported.

Although mechanical and biocontrol treatments had similar effect sizes, biological control has the potential to be more beneficial for a number of reasons. Biocontrol causes substantial plant mortality (Bean & Dudley, 2018) and can be implemented in more remote areas (Dudley & Deloach, 2004). Additionally, biocontrol treatments have historically been more cost effective than chemical, burn, and mechanical treatments (Dudley & Deloach, 2004). While mechanical treatment has been successful at decreasing canopy cover, it often fails to result in tamarisk mortality (Murrey et al., 2019). Mechanical treatments can be prohibitively expensive as well. For example, mechanical treatments that include removal of dead tamarisk have been found to be 300% more expensive than chemical application (Barz et al., 2009). There is also evidence that tamarisk increases the number of stems produced by resprouts and has increased vigor after mechanical treatments (Douglass et al., 2015). This illustrates that mechanical removal is not a viable treatment for large-scale remediation, and other options should be considered regardless of the effectiveness of this method identified in this meta-analysis.

An alternative remediation strategy that has been successful involves integrating two different treatments simultaneously to decrease cover and achieve stand mortality (Douglass et al., 2015; Harms & Hiebert, 2006). Implementing biocontrol with burn or chemical treatments decreased tamarisk cover and increased native cover more effectively than individual treatments alone (Murray et al., 2019). A combination of an aerial chemical application and a biocontrol release shortly thereafter would be a cost effective and potent treatment for tamarisk (Barz et al., 2009). The scale of tamarisk remediation can be large and force managers to reduce the cost that is allocated to each acre (Douglass et al., 2015).

Cost is typically the most significant determinate for implementing tamarisk removal strategies (Douglass et al., 2015). Although my analysis found similar biocontrol and mechanical treatment cover reductions, cost and labor are likely a better indicator of which treatment is most prudent to apply. Overall cost of treatment should be seriously considered for tamarisk management due to the large response that is needed for effective riparian remediation. Future management of tamarisk should consider implementing a dual treatment strategy of chemical and biocontrol treatment which is efficient and cost-effective (Brooks et al., 2008).

Although a biocontrol in conjunction with chemical or burn treatments is beneficial for tamarisk removal, there may be unintended consequences to non-target species. Each treatment has drawbacks and implementation should be considered on a case-by-case basis. For example, the use of a biocontrol has been recently discontinued to preserve critical habitat for the southwestern willow flycatcher (*Empidonax traillii extimus*), which relies on tamarisk for breeding habitat (Bean & Dudley, 2018). Chemical treatments when applied can persist in soils for up to a year stymie native establishment with toxic soils (Douglass et al., 2015). Similarly, burn treatments can cause stand clearing fires that are fueled by tamarisk and decrease habitat for riparian obligate species (Brooks et al., 2008).

Despite the negative impacts remediation may cause, integrating biocontrol with chemical or burn treatments is a better alternative than further establishment of tamarisk monocultures (Dudley & Deloach, 2004). However, implementation of tamarisk treatments involves management of an entire ecosystem, and treatments should be selected with specific ecosystem constraints and risks in mind. Additionally, to facilitate a large response to spatially diverse tamarisk populations will require interagency communication and cooperation to facilitate a unified response. A coordinated integration of biocontrol and chemical or burn treatments can produce long term benefits for riparian ecosystems impacted by tamarisk (Bean & Dudley, 2018). A subsequent meta-analysis to quantify native cover after treatments would expand on the meta-analysis presented here. It is also recommended that direct and indirect effects of tamarisk treatment should be expanded as argued by Bean & Dudley (2018), which would provide more data for a subsequent meta-analysis.

Acknowledgements

I would like to thank Tyler S. Imfeld Ph.D. for contributing r-script for Hedges' d calculation, diligent revisions, and incisive interpretation and syntax for this entire chapter.

References

Barz, D., Watson, R. P., Kanney, J. F., Roberts, J. D., & Groeneveld, D. P. (2009). Cost/benefit considerations for recent saltcedar control, middle pecos river, New Mexico. *Environmental Management*, *43*(2), 282–298. https://doi.org/10.1007/s00267-008-9156-9

Bay, R. F., & Sher, A. A. (2008). Success of active revegetation after Tamarix removal in riparian ecosystems of the Southwestern United States: A quantitative assessment of past restoration projects. *Restoration Ecology*, *16*(1), 113–128. https://doi.org/10.1111/j.1526-100X.2007.00359.x

Bean, D., & Dudley, T. (2018). A synoptic review of Tamarix biocontrol in North America: tracking success in the midst of controversy. *BioControl*, *63*(3), 361–376. https://doi.org/10.1007/s10526-018-9880-x

Brock, J. H. (1994). Tamarix spp. (Salt Cedar), an invasive exotic woody plant in arid and semi-arid riparian habitats of western USA. *Ecology and Management of Invasive Riverside Plants*, *1982*, 27–44. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.208.6941&rep=rep1&type=pdf

Brooks, M., Dudley, T., Drus, G., and Matchett, J., 2008, Reducing wildlfire risk by integration of prescribed burning and biocontrol of Invasive Tamarisk (Tamarix spp.). Final Report for Joint Fire Science Project 05-2-1-18. El Portal, California, 40 p.

Burnham, K. P. and Anderson, D. R (2002) *Model selection and multimodel inference: a practical information-theoretic approach*. 2nd ed. New York, Springer-Verlag.

Darrah, A. J., & van Riper, C. (2018). Riparian bird density decline in response to biocontrol of *Tamarix* from riparian ecosystems along the Dolores River in SW Colorado, USA. *Biological Invasions*, *20*(3), 709–720. https://doi.org/10.1007/s10530-017-1569-z

Deloach, C. J., Carruthers, R. I., Lovich, J. E., Dudley, T. L., & Smith, S. D. (2000). Ecological interactions in the biological control of saltcedar (*Tamarix spp* .) in the United States : Toward a New Understanding. *Proceedings of the X International Symposium on Biological Control of Weeds.*, 69.

Douglass, C. H., Nissen, S. J., & Hart, C. R. (2015). Tamarisk Management. *Tamarix*, *Robinson 1965*, 333–353. https://doi.org/10.1093/acprof:osobl/9780199898206.003.0020

Dudley, T. L., & Deloach, C. J. (2004). Saltcedar (*Tamarix spp.*), Endangered species, and biological weed control—can they mix? 1 . *Weed Technology*, *18*(sp1), 1542–1551. https://doi.org/10.1614/0890-037x(2004)018[1542:stsesa]2.0.co;2

Finch, D., Galloway, J., & Hawksworth, D. (2006). Monitoring Bird Populations in Relation to Fuel Loads and Fuel treatments in Riparian Woodlands with Tamarisk and Russian-olive Understories. *USDA Forest Service Proceedings*, 113–120.

Harms, R. S., & Hiebert, R. D. (2006). Vegetation response following invasive tamarisk (Tamarix spp.) removal and implications for riparian restoration. *Restoration Ecology*, *14*(3), 461–472. https://doi.org/10.1111/j.1526-100X.2006.00154.x

Hultine KR, Dudley TL, Koepke DF, Bean DW, Glenn EP, Lambert AM (2014) Patterns of herbivory-induced mortality of a dominant non-native tree/ shrub (Tamarix spp.) in a southwestern US watershed. Biol Invasions 17:1729–1742

Kennard, D., Louden, N., Gemoets, D., Ortega, S., González, E., Bean, D., Cunningham, P., Johnson, T., Rosen, K., & Stahlke, A. (2016). Tamarix dieback and vegetation patterns following release of the northern tamarisk beetle (Diorhabda carinulata) in western Colorado. *Biological Control*, *101*, 114–122. https://doi.org/10.1016/j.biocontrol.2016.07.004

Koricheva, J., & Gurevitch, J. (2013). Place of meta-analysis among other methods of research synthesis. *Handbook of Meta-Analysis in Ecology and Evolution*, *2013*, 3–13. https://doi.org/10.23943/princeton/9780691137285.003.0001

Larson, D. M., Dodds, W. K., & Veach, A. M. (2019). Removal of Woody Riparian Vegetation Substantially Altered a Stream Ecosystem in an Otherwise Undisturbed Grassland Watershed. *Ecosystems*, *22*(1), 64–76. https://doi.org/10.1007/s10021-018-0252-2

McLeod, M. A. (2018). Unintended consequences: Tamarisk control and increasing threats to Southwestern Willow Flycatcher. *Riparian Research and Management: Past, Present, Future. Volume 1*, 62–84.

Microsoft Corporation. (2018). *Microsoft Excel*. Retrieved from https://office.microsoft.com/excel

Murray, L., Schutte, B. J., Sutherland, C., Beck, L., Ganguli, A., & Lehnhoff, E. (2019). Integrating conventional management methods with biological control for enhanced Tamarix management. *Invasive Plant Science and Management*, *12*(3), 176–185. https://doi.org/10.1017/inp.2019.20

Nagler, P. L., Barreto-Muñoz, A., Borujeni, S. C., Nouri, H., Jarchow, C. J., & Didan, K. (2021). Riparian area changes in greenness and water use on the lower Colorado river in the USA from 2000 to 2020. *Remote Sensing*, *13*(7), 1–49. https://doi.org/10.3390/rs13071332

Paxton, E. H., Theimer, T. C., & Sogge, M. K. (2011). Tamarisk biocontrol using tamarisk beetles: Potential consequences for riparian birds in the southwestern United States. *Condor*, *113*(2), 255–265. https://doi.org/10.1525/cond.2011.090226

R Core Team (2022). *R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.*

Setshedi, K. T. A., & Newete, S. W. (2020). The impact of exotic tamarix species on riparian plant biodiversity. *Agriculture (Switzerland)*, *10*(9), 1–16. https://doi.org/10.3390/agriculture10090395

Sher, A. A., El Waer, H., González, E., Anderson, R., Henry, A. L., Biedron, R., & Yue, P. P. (2018). Native species recovery after reduction of an invasive tree by biological control with and without active removal. *Ecological Engineering*, *111*(December 2017), 167–175. https://doi.org/10.1016/j.ecoleng.2017.11.018

Venables WN, Ripley BD (2002). *Modern Applied Statistics with S*, Fourth edition. Springer, New York. ISBN 0-387-95457-0, https://www.stats.ox.ac.uk/pub/MASS4/.

Viechtbauer W (2010). "Conducting meta-analyses in R with the metafor package." *Journal of Statistical Software*, **36**(3), 1-48. https://doi.org/10.18637/jss.v036.i03.

York, P., Evangelista, P., Kumar, S., Graham, J., Flather, C., & Stohlgren, T. (2011). A habitat overlap analysis derived from maxent for tamarisk and the south-western willow flycatcher. *Frontiers of Earth Science*, *5*(2), 1. https://doi.org/10.1007/s11707-011-0154-5

CHAPTER 4: STAKEHOLDER ANALYSIS

Legal Challenges of Tamarisk Removal in the Southwestern United States

Introduction

The Southwestern Willow Flycatcher (*Empidonax traillii extimus*) is an endangered species listed under the Endangered Species Act (ESA) that resides in habitat along riparian corridors of the southwestern United States. The species have been observed building nests in invasive tamarisk (*Tamarix spp.*) stands that have replaced native willow species (Finch et al., 2002). These stands decrease Southwestern Willow Flycatcher (hereafter, flycatcher) populations because water and soil quality are reduced (Sherry et al., 2016), and tamarisk provides diminishing ecosystem services to riparian ecosystems (Paxton et al., 2011). However, removal of tamarisk will negatively impact flycatcher abundance through loss of habitat and foliar cover from predators (Dickie et al., 2014).

Federal intervention from the United States Fish and Wildlife Service (USFWS) and the Animal Plant and Health Inspection Service (APHIS) has halted tamarisk removal. This decision was predicated on preservation of "critical habitat" (i.e., tamarisk) that flycatchers unwisely use for nesting. Flycatcher use of tamarisk has the unintended consequence of further reducing populations through decreased reproductive success (Deloach et al., 2000). Proponents of designating tamarisk critical habitat argue it is the right decision because adverse impacts to the flycatcher will be minimized (Harms and Hiebert; 2006). In contrast, opponents to preserving tamarisk for habitat contend that the overall harm of tamarisk to co-occurring taxa outweighs the possible extinction of the flycatcher (Dudley & Deloach, 2004).

Southwestern Willow Flycatcher

The Southwestern Willow Flycatcher is a subpopulation of a larger taxon that includes four different flycatcher subspecies that are migratory riparian obligates (Paxton et al., 2007). Southwestern Willow Flycatchers are a sensitive niche species that nests within native willows found in southwest riparian regions (Mathewson et al., 2013). Human expansion as pressured riparian habitat throughout the flycatchers' range, facilitating the fragmentation of already dwindling populations (Graf et al., 2002). As a result of human disturbance and the continued spread of tamarisk, flycatcher critical habitat now coincides with tamarisk invasion areas. It has been reported that flycatcher reproduction is decreased in tamarisk stands due to poor habitat quality (Sogge et al., 2008); however, tamarisk removal without native replacement also decreased flycatcher reproduction (Harms & Hiebert, 2006). Alternatively, lack of sufficient vegetative cover has been reported to decrease flycatcher populations from increased predation (Dickie et al., 2014).

Tamarix Spp.

Tamarisk is an invasive woody shrub that has deleterious impacts to river corridors in the southwestern United States (Kerns et al. 2009). Tamarisk invasion is a catalyst for profound riparian alterations that alter flow regimes and soil chemistry, and ultimately decreases native biodiversity (Bean & Dudley, 2018; Deloach et al., 2000). Specifically, native cottonwood (*Populus spp.)* and willow (*Salix spp.*) populations in the American southwest are largely being outcompeted by phenotypic advantages of tamarisk (Hatten et al., 2010; York et al., 2011). The competitive advantages innate to tamarisk allow for rapid germination, water exploitation, and resistance to hydrological disturbances (Friggens & Finch; 2015; Kennard et al., 2016).

Tamarisk is a facultative phreatophyte, meaning it can uptake water from surface soils or groundwater through the morphological adaptation of a taproot (Hultine et al., 2020; Kerns et al., 2009). Monopolization of water by tamarisk decreases available surface water and contributes to water table drawdown (Brock, 1994). Additionally, as a xerophytic species, tamarisk tolerates drought conditions extremely well (Diehl et al., 2020). Tamarisk survival is bolstered through physiological adaptations that increase water retention in periods of water stress (Kerns et al., 2009).

Halophilic characteristics of tamarisk from physiological adaptations allow for survival in high saline concentrations. Salt concentrations are excreted from tamarisk leaves and deposited onto the surrounding topsoil annually (Brock, 1994). Excreted salt concentrations hinder native seed germination, and concentrations are compounded from the addition of saline-rich leaf litter (Sherry et al., 2016). Tamarisk establishment is not affected from increased drought frequency or saline concentrations, which promotes monotypic tamarisk stands within riparian ecosystems (Bean & Dudley, 2018; Brock, 1994).

Climate Impact on Tamarisk and Flycatchers

Climate change is intensifying the replacement of native riparian fauna because of tamarisk adaptations to drought conditions (Diehl et al., 2020; Hinojosa-Huerta et al., 2013). Impacts of climate change within the southwestern United States will give a competitive advantage to tamarisk populations (Friggens & Finch, 2015). Rising temperatures increase water stress and the frequency of fire disturbances (Diehl et al., 2020; Stella & Bendix, 2019). Fluctuating water levels restructure vegetation increasing dry fuel provided by tamarisk (Bean & Dudley, 2012) that directly influences fire frequency (McLeod, 2018), fire severity, and decreases available riparian habitat (Deloach et al., 2000).

Flycatcher populations are also sensitive to climate variability that alters temperature, water regimes, and the composition of riparian vegetation (Hatten et al., 2010). Scarcity of water analogues to predicted climate change conditions would decrease flycatcher habitat fostering increased levels of intraspecific competition (Friggens & Finch; 2015). Additionally, drought conditions were attributed to declines in the reproductive success of flycatchers (Paxton et al., 2007). Drought conditions that triggered flow reductions in riparian ecosystems were correlated with a decline in flycatcher abundance and habitat (Hinojosa-Huerta et al., 2013).

Tamarisk Remediation

Historically, tamarisk remediation relied on mechanical removal that uses heavy machinery and equipment to fell tamarisk. Heavy machinery is used for mulching, spinning blades or chains, and are then burned which effectively decreases tamarisk cover (Brock, 1994). However, mechanical removal is costly, unable to be implemented in remote areas (González et al., 2017), and typically does not result in mortality (Brock, 1994). Additionally, the wide spectrum removal has non-target impacts, thus decreasing native vegetation (Darrah & van Riper, 2018).

Remediation using a chemical treatment has been a successful and cost-effective alternative to mechanical removal (Barz et al., 2009). Chemical tamarisk treatment uses aerial applications or a cut-stump method of cutting and brushing herbicide on tamarisk to induce mortality (Barz et al, 2009; Brock, 1994). However, this method has similar pitfalls to mechanical removal by having non-target impacts to native species (Darrah & van Riper, 2018). Similarly, burning treatment is effective, however tamarisk fires generally burn too intensive and decreases avifauna reproduction success (Deloach et al., 2000).

Notably, the introduction of a biocontrol that has been very successful at removing tamarisk stands (Dudley & Deloach, 2004). The tamarisk leaf-beetle (*Diorhabda carinulata*) defoliates tamarisk stands which incrementally causes the plants to die from carbon starvation (Bean & Dudley, 2012; Kennard et al., 2016). After introduction of the biocontrol into riparian ecosystems, tamarisk mortality can be up to 80% after 5 years (Kennard et al., 2016). This method of tamarisk removal is also less costly than other methods of removal that are labor intensive, require heavy machinery, or broad-spectrum herbicides (Dudley & Deloach, 2004).

Southwestern Willow Flycatcher and Biocontrol

In 1995 the US Fish and Wildlife Service (USFWS) listed the riparian obligate species, the southwestern willow flycatcher, as an endangered species (McLeod, 2018). In riparian areas that are dominated by tamarisk (>90%) there have been recorded southwestern willow flycatcher nests that comprise 9% of the total species breeding habitat (Finch et al., 2002). Upon realizing flycatcher nesting habitat overlapped with tamarisk dominated reaches, tamarisk stands were designated as “critical habitat” by the USFWS and ostensibly protected tamarisk (Dudley & Deloach, 2004).

Biocontrol releases were stopped by Animal and Plant Health Inspection Service (APHIS) who previously endorsed the release. This was partly due to a lawsuit filed by the Maricopa Audubon Society that sought to protect the endangered species after beetle distributions exceeded their expected range (McLeod, 2018). Proponents of the discontinued release argue that tamarisk defoliates too quickly to have native reestablishment, which will dramatically reduce flycatcher populations (Harms & Hiebert, 2006). Opponents of the discontinued release argue that reestablishment has been achieved simultaneously with biocontrol defoliation (Dudley & Deloach, 2004), and furthermore defoliation is a slow process (Kennard et al., 2016).

Stakeholders Conflicts

The USFWS has listed the flycatcher as endangered due to decreased populations of the southwestern willow flycatcher. They are bound to this decision as is stipulated by the ESA. Additionally, APHIS is bound to this decision and previously had authorized releases of the biocontrol with the condition that the biocontrol would not coincide with critical habitat of the flycatcher (McLeod, 2018). If beetles invaded flycatcher habitat, it was thought that the rate of tamarisk removal would jeopardize flycatcher reestablishment (Harms and Hiebert, 2006).

When there were observed beetle populations within the critical habitat, the Maricopa Audubon Society filed suit to protect the remaining endangered population. Beetle impacts to the flycatcher were evidenced by reports of increased predation and habitat loss that is indicative to the species decline (Dudley & Deloach, 2004). Additionally, the Maricopa Audubon Society argued that specific plant species are not as important to breeding, but more the physical structure tamarisk or willows provide (Sogge et al., 2008). The structure of tamarisk or native willows was being protected since both provide cover from predators when flycatchers are nesting (Dickie et al., 2014).

A local environmental group, the Tamarisk Coalition, has argued for continuing the release of the biocontrol. The Tamarisk Coalition contends that allowing tamarisk to remain unopposed will decrease flycatcher populations and other riparian obligate species. This assertion was evidenced by an increase in nest abandonment within tamarisk-dominated landscapes (McLeod, 2018). This lends to the argument that preserving tamarisk habitat is an ecological trap or has diminishing returns to species and will lead to subspecies collapse (Sogge et al., 2008). The longer tamarisk remains in flycatcher habitat, the more degraded the habitat becomes.

Recommendations for Management

Although the Maricopa Audubon Society sued for the preservation of tamarisk as a protection measure for the endangered flycatcher, this argument has little justification within the literature (Bean & Dudley, 2012; Dudley & Deloach, 2004; McLeod, 2018). Sogge et al. (2008) affirms the Tamarisk Coalition's stance that tamarisk preservation will provide poor habitat to flycatchers, further decreasing populations. Additionally, tamarisk has been recorded to take years to achieve stand mortality (Kennard et al., 2016), providing ample time for native revegetation after removal as suggested by Harms and Hiebert (2006). Considering the detrimental effects of tamarisk to the overall ecosystem, biocontrol measures should be reimplemented to protect all riparian species.

Typically, it takes many seasons of defoliation to decrease tamarisk populations, which can give native vegetation a chance to establish and replace tamarisk (Dudley & Deloach, 2004). While there is contention on how fast the biocontrol can induce tamarisk mortality, it seems like managers have little choice but to continue to remove tamarisk. The increasing salt concentrations found in tamarisk-dominated topsoil has compounded this problem. The longer managers allow tamarisk to proliferate, the less likely natural revegetation will succeed. Small scale remediation efforts using the biocontrol will likely have a small impact on riparian habitat needed for the endangered species.

To protect the southwestern willow flycatcher and other riparian obligates, a middle ground between the stakeholders must be reached. Stopping the release of the biocontrol will not stop the spread of current distributions of the beetle. Alternatively, continuing release without replacement of critical habitat will severely decrease flycatcher populations. The protection of critical habitat can be supplemented with the reintroduction of native biota. Harms and Hiebert (2006) argue that replanting natives in tandem with small scale biocontrol implementation can serve both parties' interests.

Conclusion

To implement this plan, stakeholders will need to find common ground and make concessions. The Maricopa Audubon Society will have to accept that the flycatcher populations will be impacted by tamarisk populations that will overtake future riparian vegetation. Even if tamarisk populations did not exist, the outlook of the flycatcher is grim due to sensitivity to water levels and vegetation restructuring. Additionally, adopting single species management that allows tamarisk to spread will have far reaching and devastating effects on riparian biodiversity.

Alternatively, the Tamarisk Coalition will have to accept that tamarisk stands will continue to spread and widescale biocontrol implementation may no longer be feasible. Tamarisk removal, even with biocontrol, is a problem that is exceedingly large in scale and costly. When considering that native vegetation is likely to be outcompeted during increasingly common droughts, this invasive becomes more unmanageable. While large-scale removal using a biocontrol is not impossible, it is daunting and is rife with challenges.

Assuming that all parties are satisfied with a combined revegetation and biocontrol remediation effort, APHIS may grant a provisional release to continued tamarisk remediation. Through adoption of this recommendation, riparian habitats can undergo rehabilitation that can bolster the southwestern willow flycatcher populations. In its current state, retaining tamarisk populations in riverine ecosystems can only further decrease the endangered species' populations, and failing to reach a consensual course of action will only continue this, hopefully, preventable decline.

References

Bean, D., & Dudley, T. (2018). A synoptic review of Tamarix biocontrol in North America: tracking success in the midst of controversy. *BioControl*, *63*(3), 361–376. https://doi.org/10.1007/s10526-018-9880-x

Brock, J. H. (1994). Tamarix spp. (Salt Cedar), an invasive exotic woody plant in arid and semi-arid riparian habitats of western USA. *Ecology and Management of Invasive Riverside Plants*, *1982*, 27–44. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.208.6941&rep=rep1&type=pdf

Barz, D., Watson, R. P., Kanney, J. F., Roberts, J. D., & Groeneveld, D. P. (2009). Cost/benefit considerations for recent saltcedar control, Middle Pecos River, New Mexico. *Environmental Management*, *43*(2), 282–298. https://doi.org/10.1007/s00267-008-9156-9

Darrah, A. J., & van Riper, C. (2018). Riparian bird density decline in response to biocontrol of Tamarix from riparian ecosystems along the Dolores River in SW Colorado, USA. *Biological Invasions*, *20*(3), 709–720. https://doi.org/10.1007/s10530-017-1569-z

Deloach, C. J., Carruthers, R. I., Lovich, J. E., Dudley, T. L., & Smith, S. D. (2000). Ecological Interactions in the Biological Control of Saltcedar (Tamarix spp .) in the United States : Toward a New Understanding. *Proceedings of the X International Symposium on Biological Control of Weeds.*, 69.

Dickie, I. A., Bennett, B. M., Burrows, L. E., Nuñez, M. A., Peltzer, D. A., Porté, A., Richardson, D. M., Rejmánek, M., Rundel, P. W., & van Wilgen, B. W. (2014). Conflicting values: Ecosystem services and invasive tree management. *Biological Invasions*, *16*(3), 705–719. https://doi.org/10.1007/s10530-013-0609-6

Diehl, R. M., Wilcox, A. C., & Stella, J. C. (2020). Evaluation of the integrated riparian ecosystem response to future flow regimes on semiarid rivers in Colorado, USA. *Journal of Environmental Management*, *271*(June), 111037. https://doi.org/10.1016/j.jenvman.2020.111037

Dudley, T. L., & Deloach, C. J. (2004). Saltcedar (Tamarix spp.), Endangered Species, and Biological Weed Control—Can They Mix? 1 . *Weed Technology*, *18*(sp1), 1542–1551. https://doi.org/10.1614/0890-037x(2004)018[1542:stsesa]2.0.co;2

Finch, D. M., S. I. Rothstein, J. C. Boren, et al. 2002. Final Recovery Plan: Southwestern Willow Flycatcher (Empidonax traillii extimus). Albuquer- que, NM: Region 2, U.S. Fish and Wildlife Service. 10 p.

González, E., Sher, A. A., Anderson, R. M., Bay, R. F., Bean, D. W., Bissonnete, G. J., Bourgeois, B., Cooper, D. J., Dohrenwend, K., Eichhorst, K. D., El Waer, H., Kennard, D. K., Harms-Weissinger, R., Henry, A. L., Makarick, L. J., Ostoja, S. M., Reynolds, L. V., Robinson, W. W., & Shafroth, P. B. (2017). Vegetation response to invasive Tamarix control in southwestern U.S. rivers: A collaborative study including 416 sites. *Ecological Applications*, *27*(6), 1789–1804. https://doi.org/10.1002/eap.1566

Graf, W. L., Stromberg, J., & Valentine, B. (2002). Rivers, dams, and willow flycatchers: A summary of their science and policy connections. *Geomorphology*, *47*(2–4), 169–188. https://doi.org/10.1016/S0169-555X(02)00087-9

Harms, R. S., & Hiebert, R. D. (2006). Vegetation response following invasive tamarisk (Tamarix spp.) removal and implications for riparian restoration. *Restoration Ecology*, *14*(3), 461–472. https://doi.org/10.1111/j.1526-100X.2006.00154.x

Hatten, J. R., Paxton, E. H., & Sogge, M. K. (2010). Modeling the dynamic habitat and breeding population of Southwestern Willow Flycatcher. *Ecological Modelling*, *221*(13–14), 1674–1686. https://doi.org/10.1016/j.ecolmodel.2010.03.026

Hinojosa-Huerta, O., Nagler, P. L., Carrillo-Guererro, Y. K., & Glenn, E. P. (2013). Effects of drought on birds and riparian vegetation in the Colorado River Delta, Mexico. *Ecological Engineering*, *51*, 275–281. https://doi.org/10.1016/j.ecoleng.2012.12.082

Hultine, K. R., Froend, R., Blasini, D., Bush, S. E., Karlinski, M., & Koepke, D. F. (2020). Hydraulic traits that buffer deep-rooted plants from changes in hydrology and climate. *Hydrological Processes*, *34*(2), 209–222. https://doi.org/10.1002/hyp.13587

Kennard, D., Louden, N., Gemoets, D., Ortega, S., González, E., Bean, D., Cunningham, P., Johnson, T., Rosen, K., & Stahlke, A. (2016). Tamarix dieback and vegetation patterns following release of the northern tamarisk beetle (Diorhabda carinulata) in western Colorado. *Biological Control*, *101*, 114–122. https://doi.org/10.1016/j.biocontrol.2016.07.004

Kerns, B. K., Naylor, B. J., Buonopane, M., Parks, C. G., & Rogers, B. (2009). Modeling Tamarisk (Tamarix spp.) Habitat and Climate Change Effects in the Northwestern United States . *Invasive Plant Science and Management*, *2*(3), 200–215. https://doi.org/10.1614/ipsm-08-120.1

Mathewson, H. A., Morrison, M. L., Loffland, H. L., & Brussard, P. F. (2013). Ecology of Willow Flycatchers (Empidonax traillii) in the Sierra Nevada, California: Effects of Meadow Characteristics and Weather on Demographics . In *Ornithological Monographs* (Vol. 75, Issue 1). https://doi.org/10.1525/om.2013.75.1.1

McLeod, M. A. (2018). Unintended consequences: Tamarisk control and increasing threats to Southwestern Willow Flycatcher. *Riparian Research and Management: Past, Present, Future. Volume 1*, 62–84.

Paxton, E. H., Sogge, M. K., Durst, S. L., Theimer, T. C., & Hatten, J. R. (2007). The Ecology of the Southwestern Willow Flycatcher in Central Arizona — a 10-year Synthesis Report. *U.S. Geological Survey Open File Report 2007-1381*, 143.

Paxton, E. H., Theimer, T. C., & Sogge, M. K. (2011). Tamarisk biocontrol using tamarisk beetles: Potential consequences for riparian birds in the southwestern United States. *Condor*, *113*(2), 255–265. https://doi.org/10.1525/cond.2011.090226

Setshedi, K. T. A., & Newete, S. W. (2020). The impact of exotic tamarix species on riparian plant biodiversity. *Agriculture (Switzerland)*, *10*(9), 1–16. https://doi.org/10.3390/agriculture10090395

Sherry, R. A., Shafroth, P. B., Belnap, J., Ostoja, S., & Reed, S. C. (2016). Germination and Growth of Native and Invasive Plants on Soil Associated with Biological Control of Tamarisk (Tamarix spp.). *Invasive Plant Science and Management*, *9*(4), 290–307. https://doi.org/10.1614/IPSM-D-16-00034.1

Sogge, M. K., Sferra, S. J., & Paxton, E. H. (2008). Tamarix as Habitat for Birds. *Restoration Ecology*, *16*(1), 146–154.