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Restoration Strategies for Wetlands in the Arid West: Seeding and Planting Approaches for Lakeshore Ecosystems

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RESTORATION STRATEGIES FOR WETLANDS IN THE ARID WEST: SEEDING AND PLANTING APPROACHES FOR LAKESHORE ECOSYSTEMS

by

Jes Braun

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Ecology

Approved:

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UTAH STATE UNIVERSITY
Logan, Utah

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ABSTRACT

Restoration Strategies for Wetlands in the Arid West: Seeding and Planting Approaches for Lakeshore Ecosystems

by

Jes Braun, Master of Science

Utah State University, 2023

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Department: Watershed Sciences

Wetlands are crucial ecosystems that provide essential benefits such as water purification, habitat for biodiversity, carbon storage, and flood control. Human activities such as the introduction of invasive species, nutrient loading, draining, and filling have heavily impacted wetlands, making restoration critical. This is especially important in the arid West, where drought and upstream water diversions result in water scarcity and dramatically changing water levels. One invasive species that has particularly impacted wetlands is *Phragmites australis*, which creates dense stands, reduces habitat quality and quantity, and colonizes open water habitats. While management efforts have greatly reduced *Phragmites* cover in Utah Lake, the desired plant communities are not returning at the desired rate, cover, or diversity.

Here, I investigated the best practices for revegetating wetlands in the arid West, particularly in lakeshore wetlands. My research focused on the best ways to seed and plant along different elevations of a lakeshore, including the addition of seeds, the density of seeding, the elevation of seeding, as well as the addition of plugs, the arrangement of plugs, and the elevation of plug planting. I found that seeding had a positive effect on the cover of native species regardless of seeding density and seeding at lower elevations increased establishment success. The addition of plugs greatly increased the cover of both planted species (*Distichlis spicata* (salt grass) and *Schoenoplectus acutus* (hardstem bulrush)), with higher success in the lower elevations closest to the water line. The arrangement of plugs mattered with a dispersed planting arrangement leading to the highest percent cover.

Additionally, I conducted a literature review of best practices for lakeshore restoration and integrated my research findings into a guidebook on how to approach the restoration and management of lakeshores in the eastern Great Basin. Nine best practices are suggested, including strategies to improve outcomes for restoration and facilitate informed research and decision-making. This research offers practical applications and background information to improve wetland restoration outcomes, particularly in the arid West, and prevent the re-invasion of *Phragmites* and other undesirable species.

(154 pages)

PUBLIC ABSTRACT

Restoration Strategies for Wetlands in the Arid West: Seeding and Planting Approaches for Lakeshore Ecosystems

Jes Braun

Wetlands are widely recognized for their valuable benefits such as providing habitat, improving water quality, and reducing the impacts of flooding. However, wetlands face threats from development, drought, and invasive species. This is particularly apparent in the arid west, where upstream water use and drought make water scarcer and contribute to dramatically changing water levels. Here, I investigated revegetation techniques for lakeshore wetlands, using Utah Lake as a case study. Although recent management efforts have minimized invasive *Phragmites* cover, the desired plant communities are not returning as quickly as needed, highlighting the need to research restoration techniques. Through my research, I discuss the optimal seeding density and elevation, as well as the ideal arrangement of plugs to promote establishment success without excessive competition. The findings suggest that seeding at lower elevations and planting plugs at a less dense arrangement can lead to better outcomes. Additionally, I provide a guidebook for restoration and management of lakeshores in the eastern Great Basin, offering practical applications and background information for nine recommended best practices. Overall, I emphasize the importance of effective revegetation techniques for wetland restoration and the need for further research and decision-making to facilitate successful outcomes for wetlands in the eastern Great Basin.

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I would like to thank my advisor, Dr. Karin Kettenring, for the dedication, mentorship, and now championship of my work. I’d like to thank my committee members, Drs. Erin Rivers and Frank Howe, for their guidance over the last few years. I would also like to acknowledge the hardworking group of wetland managers that I am grateful to have worked with. Thank you to the whole WERL lab for their help and support. Thank you to Susan Durham for her statistical expertise. A big shout out to all my friends, family, and mentors who supported me locally and from afar. I wouldn’t have succeeded in grad school during a global pandemic without them.

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Chapter I

Introduction

Wetlands are some of the most valuable ecosystems on Earth. They filter pollutants, support biodiversity, recharge groundwater, store carbon, and reduce flood damage (Zedler & Kercher, 2005; Endter-Wada et al., 2020). However, wetlands have been heavily impacted by humans due to the introduction of invasive species, nutrient loading from agricultural and urban runoff, and draining and filling (Niemuth et al., 2004; Mitsch & Gosselink, 2015). Restoration of wetlands is even more critical in the arid West of the United States, where wetlands are also negatively affected by drought and upstream water diversions that result in water scarcity and dramatically changing water levels. Additionally, many lakes in the arid West are engineered to serve as reservoirs (Wantzen et al., 2008). These water storage systems assist the needs of growing human populations but also exacerbate the stress on adjacent and downstream wetlands and the surrounding plant communities due to the resulting extreme water-level fluctuations. On top of this, wetlands have been invaded by the non-native species *Phragmites australis*. This plant creates dense, monotypic stands with high seed rain and rapid rhizomatic spread (Long et al., 2017). The spread of *Phragmites* results in the replacement of native vegetation and colonization of open water habitats, severely reducing the quality and quantity of habitat (Dibble et al., 2013; Rohal et al., 2019). *Phragmites* management has focused primarily on control, but more work needs to be done to ensure successful revegetation of native species after *Phragmites* removal (Hazelton et al., 2014).

In Utah Lake, the focal research area for this thesis, intensive recent management efforts have greatly reduced *Phragmites* down to minimal cover (Madison & Madison,

2019) however, the desired plant communities are not returning at the cover, diversity, or speed desired (Keith Hambrecht, personal communication, August 5, 2020). Identifying ways to restore these communities to prevent the re-invasion of *Phragmites* and other undesirable species is imperative. Seeding is an effective and budget friendly method for reintroducing native species (Kettenring & Tarsa, 2020). However, determining at what rate to seed is important. Seeding at too low of a density can result in incomplete resource use and provide opportunities for undesirable species to establish (Byun et al., 2013) but seeding at excessive rates can lead to unwanted competition between the native species, resulting in mortality and wasted resources (Burton et al., 2006; Pearson et al., 2016). Planting plugs can be an effective way to overcome the seed germination bottleneck experienced by seeds—90 to 95% of seeds are lost globally at the germination and emergence stage (Kildsheva et al., 2016). Similar to the seed density questions, identifying the best arrangement of plug plantings for the environment is critical. Denser arrangements can alleviate stress and foster positive plant feedback (Fajardo & McIntire, 2011; Silliman et al., 2015). However, too dense of an arrangement can increase competition between the plugs. Current research on plug planting arrangement has been done in salt marshes (Balke et al., 2012; Fajardo & McIntire, 2011; Renzi et al., 2019; Silliman et al., 2015; Temmink et al., 2020) and its potential benefits in lakeshore wetlands is currently theoretical and explored in my research here. On top of the need to develop revegetation techniques for these types of systems, the water levels along the lakeshores are highly dynamic due to extreme water level fluctuations. Identifying suitable areas for seeding along these shorelines is a challenge (Allen & Klimas, 1986). The long-term benefits of manipulating elevation of planting in lakeshore restoration has not been thoroughly evaluated, although research by Wang et al., (2022) on floodplain lakes provides some insights.

In this thesis, I investigated the best practices for revegetating lakeshore wetlands in the arid West. In Chapter 2, I explored the best ways to seed and arrange plugs along Western wetland lakeshores. In Chapter 3, I pulled back the lens from Utah Lake and looked broadly at lake and reservoir systems throughout the eastern Great Basin. I offered a guidebook on how to approach the restoration and management of these lakeshores in the eastern Great Basin. I suggested practical applications and provided background information for nine best practices. In both chapters, I discussed strategies to improve outcomes for restoration, facilitating informed research and decision making for wetlands in the Intermountain West.

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Chapter II

The Effect of Seeding, Plug Planting, and Elevation on Plant Community Assembly in Utah Lake Wetlands

Abstract

Lakeshore wetlands play a critical role in provisioning of ecosystem services such as biodiversity conservation, water filtration, flood control, carbon storage, and recreation. Lakeshore wetlands have been heavily impacted by humans by draining and filling, the introduction of invasive species, and nutrient loading from agricultural and urban runoff. In arid lands, lakeshore wetlands are also negatively affected by drought and upstream water diversions that result in water scarcity and dramatically changing water levels. Restoration of vegetation in lakeshore wetlands is important to recover lost functions and services. However, best practices for revegetation are unknown including how to reintroduce species by seeds (including at what density) and plants (including in what configuration) as well as at what elevation given the sometimes dramatically changing water levels. This study aims to investigate the best strategies for lakeshore wetland restoration. In paired restoration experiments I examined the effects of (1) seeding, density of seeding, and elevation of seeding along with (2) arrangement of plugs, and elevation of planting on native and invasive plant cover following *Phragmites* control on the Utah Lake shoreline. In the seeding experiment, seeding target restoration species increased native plant community cover and species richness but seeding density did not have a strong influence on recovering native plant communities. Elevation of seeding was important in restoration outcomes with higher cover of seeded species associated with

lower elevations. The plug experiment showed that plant cover was affected by the interaction of elevation and planting arrangement, with *D. spicata* and *S. acutus* performing better in dispersed planting arrangements in the lower elevations. Together these results suggest that seeding or planting native species along lower elevations of lakeshores can significantly increase native plant cover but there are nuances in approach: higher seeding densities may not matter but the arrangement of plugs does matter.

Introduction

Wetlands are important to society for habitat provisioning, water filtration, flood control, and recreation, but have been greatly impacted by humans through drainage, filling, native vegetation removal, invasive species, and hydrologic alterations (Endter-Wada et al., 2020; Zedler & Kercher, 2005). Lakeshore wetlands are similarly threatened and provide unique features along lakes, especially their vegetation. In arid regions, lakeshores are also vulnerable to impacts related to water diversions, drought, and eutrophication (Mitsch & Gosselink, 2015; Niemuth et al., 2004). The consequences of these changes can be severe, leading to an increase in undesirable plant species that thrive in high-nutrient environments and are better adapted to colonize after disturbances (Mack et al., 2000). Additionally, many lakes in the arid West are engineered to serve as reservoirs. These water storage systems assist the needs of growing human populations but also exacerbate the stress on adjacent and downstream wetlands and the surrounding plant communities due to the resulting extreme water-level fluctuations (Wantzen et al., 2008). Therefore, it is imperative that we protect and restore these lakeshore habitats.

The restoration of lakeshore wetlands is crucial given the valuable ecosystem services they provide to society and the critical role they play in supporting the health of the entire lake ecosystem. However, best practices for lakeshore revegetation are underdeveloped, especially successful strategies for lakes that experience dramatically changing water levels such as those in arid regions (but see Chapman et al., 2013; Vanderbosch & Galatowitsch, 2010). For instance, previous research into lakeshore revegetation best practices found that the highest failure occurred along the shoreline compared to more upland plantings (Vanderbosch & Galatowitsch, 2010). Conversely, planting along shorelines can be beneficial and cause a breakwater effect as sediment settles between the restored area and the shoreline and dissipates wave energy (Jellinek, 2016), which can help recruit seeds to settle and germinate in these areas. There are still significant uncertainties surrounding the most effective methods for reintroducing plant species—including appropriate seed density, plant configuration, and elevation—particularly in the context of the dynamic and rapidly-changing water levels of lakeshore wetlands.

Seeding is an effective method to reintroduce native species, particularly in areas where there has been soil disturbance, existing vegetation has been removed, or declining water levels result in newly exposed soil at the edge of lakeshores (Godefroid et al., 2011; Kettenring & Tarsa, 2020). Global estimates of plant recruitment from seed are low (90–95% average seed loss globally), with seed germination and seedling emergence comprising the most limiting stages in plant establishment (Kildisheva et al., 2016). Plant access to, or location near, water can be a major factor in establishment success (Wang et al., 2022). This sensitivity during the early stages of plant development highlights that if hydrology is not ideal—which for many wetland species is moist/saturated to very shallowly flooded conditions (Webb et al., 2012)—there is likely to be high seed and seedling mortality (Kettenring & Tarsa 2020; Ma et al., 2010). Suboptimal environmental conditions can be overcome by increasing seeding rates to counteract high mortality (van Katwijk et al., 2016) and seeding at a range of elevations to increase the likelihood that some seeds land in appropriate moisture microsites. However, excessive seeding rates may result in unwanted competition between native species, leading to mortality and ultimately wasting restoration resources (Burton et al., 2006; Pearson et al., 2016). Choosing a lower seeding rate may be more cost-effective and prevent competition among seeded and naturally recolonizing native species, but it can, unfortunately, result in incomplete resource utilization and provide opportunities for undesirable species to establish and grow (Byun et al., 2013). Therefore, it is crucial to empirically determine these optimal seeding rates.

Planting plugs (small pots with a few seedlings) is a common method used for reintroducing native species which bypasses the germination and emergence bottlenecks and in so doing can be particularly effective in areas where seeding alone may not be sufficient (i.e., where soil erosion, high water levels, or other environmental factors make it difficult for seeds to germinate and establish). Plug planting allows for greater control over the number of individuals and placement of individual plants which can be important for achieving specific restoration goals. In highly dynamic environments, strategic planting approaches can alleviate plant stress and foster positive plant feedback through conspecific facilitation (Fajardo & McIntire, 2011; Silliman et al., 2015,). A clumped planting arrangement can increase facilitation because roots of close neighbors leaking oxygen can counter rhizosphere anoxia and the associated buildup of toxic compounds thereby mitigating flooding stress (Bertness & Hacker, 1994; Silliman et al., 2015; Stagg & Mendelssohn, 2011). Furthermore, by increasing vegetation density, a clumped planting arrangement can facilitate greater water infiltration into the soil via root penetration and decrease soil evaporation through shading (Rietkerk et al., 2004) thereby alleviating drought stress. However, much of the research on the benefits of clumped plantings and associated facilitation has been done in coastal salt marshes (Balke et al., 2012; Fajardo & McIntire, 2011; Renzi et al., 2019; Silliman et al., 2015; Temmink et al., 2020) and its potential benefits in lakeshore wetlands is theoretical.

Water levels along lakeshores are highly dynamic and likely to increase in magnitude within global climate change scenarios, especially in arid lands where drought and upstream water diversions are frequent (Abrahams, 2008; Leira & Cantonati, 2008; Wantzen et al., 2008; Zohary & Ostrovsky 2011). The elevation of seeding and planting exerts a strong influence on plant establishment and survival because of seed and plant requirements (Vanderbosch & Galatowitsch, 2010) but identifying where to seed and plant along rising and falling water levels is difficult because defining the shoreline can be challenging (Allen & Klimas, 1986). One approach to mitigating this stress is to plant at multiple elevations, or shorelines, to increase the likelihood that the plants are introduced into environments where the water levels are suitable for survival. But the multi-year benefits of this approach have not been evaluated thoroughly in the lakeshore restoration literature (but see Wang et al's (2022) research on floodplain lakes).

In a two-year field experiment, I addressed these uncertainties related to seeding, plug planting, and elevation in lakeshore restoration. First, I examined the effects of seeding, density of seeding, and elevation of seeding on native and invasive plant success. I predicted that an addition of native seeds would improve native plant community recovery (higher native cover, lower invasive cover, higher native species richness), particularly at higher densities. I expected that the higher seeding density treatment would not be too high to cause density-dependent mortality due to the likely high mortality rate that seeds/seedlings would experience under field conditions. I predicted that the highest level of native plant community recovery would occur in the middle elevations of the lakeshore restoration while seeds in the lowest and highest elevations would experience extremes in inundation and drought which would negatively impact their survival. Second, I asked, does the addition of plugs, plug planting arrangement, and the elevation of planting impact native plant community recovery? I predicted that adding plugs would increase native plant cover, decrease invasive plant cover, and increase native species richness. I expected to see the greatest benefit with the clustered planting arrangement as opposed to evenly dispersed because of potential conspecific facilitation. As with the seeding treatments, I expected that elevation of planting would be important with the highest native recovery occurring in the middle elevations.

Methods

Site description and history

We conducted a restoration experiment on the north shore of Utah Lake, Utah (Figure 2.1). Utah Lake's shoreline changes dramatically year to year and within years due to its shallow bathymetry and due to substantial upstream diversions of its natural inflows (Merritt 2017). Utah Lake's shorelines have lost a substantial amount of native, historic vegetation due to hydrologic alterations, urban expansion, and the introduction of invasive species (Richards et al., 2019). Although Utah Lake's shoreline was dominated with invasive *Phragmites* for decades (Rohal et al., 2018), more recent intensive management efforts have reduced *Phragmites* down to minimal cover (Madison & Madison 2019; Figures A2.1 & A2.2). Revegetation of these areas following herbicide management is rarely attempted by land managers and desired plant communities are not necessarily returning at the cover, diversity, or speed desired (Keith Hambrecht, personal communication, August 5, 2020).

Experiment overview and plot layout

In this experiment (2021–2022), I evaluated the effects of seeding (± a native seed mix), seeding density (low (1x) or high (5x), and elevation of seeding (4 levels (in a perpendicular transect to the lake waterline, moving upland)) on plant community recovery. I also determined the effects of plug planting (± the addition of plugs), plug planting arrangement (clumped together or evenly dispersed), and elevation of planting (4 levels) on plant community recovery. The seeding and plug planting treatments were arranged along transects (n=5) arranged perpendicular to the water line, starting at the current water line on planting day. Along each transect, at four elevations (= blocks in the statistical design), plots of plug plantings (1.5 m × 1.5 m) and seedings (1 m × 1 m) were arranged (randomized with each experiment type—seeding or planting) (Figure 2.2). The transects were characterized at the lakeshore end by wave-washed and sparsely vegetated beaches with a high amount of plant litter. The upland end of the transects were more moderately vegetated with monotypic stands of plants, largely made up of cattail (*Typha spp.*), situated at the edge of the transitional plant zone between emergent and upland plants. The middle two blocks were placed at distinct transitions of plant and litter communities. The four blocks occupied distinct plant community zones.

Seed sourcing, viability testing, dormancy breaking, and seed sowing in the field

The seeding treatments consisted of 19 native species, which were chosen based on an extensive literature review of historic and current vegetation (Brotherson, 1981; Chadde, 1998; Coombs, 1970; Coottam, 1926; USDA NRCS, 2020), surveying native species already found on site, and input from Utah Lake land managers. I focused on creating a high diversity seed mix as an increase in canopy complexity and increase in functionally different species would be more likely to compete with *Phragmites australis* for resources (Byun et al., 2013). Seeds of all species were collected in late summer and early fall of 2020 following protocols (Basey et al., 2015) to maximize genetic diversity of the seed lot—I collected from at least 100 individuals from at least 5 sites that are hydrologically similar and spatially close to Utah Lake.

The seeds were sown at two different rates, 1x and 5x density. The 1x seeding rate was the current recommended seeding rate by local land managers and calculated based on their PLS (Pure Live Seed) rate. The PLS rates were calculated as PLS (seed number or mass) = purity (proportion) × viability (proportion) × bulk seed (seed number or mass) (Rieger et al., 2014). This seeding rate was 180 PLS times the area of the plot (10.8 ft^2 or 1 m^2) divided by the number of species used in the seed mix (Tarsa et al., 2022). This calculation was then divided by the viability of the seeds, which is determined through tetrazolium (TZ) testing. The result of this calculation is the number of seeds that should be seeded per species per plot. The 5x seeding rate follows the same calculations as above and then multiples the number of seeds needed by 5. Seeds of all species were stored dry at room temperature, in paper bags prior to viability testing with tetrazolium (3 × 100 seeds per species × seed source were tested following the methods of Miller et al., 2010). Prior to sowing the seeds in the field, dormancy was broken following species-specific protocols (Table 2.1). Seeds were sown on May 27th, 2021, into 1 m^2 plots surrounded by a 0.76 m high organza mesh fence barrier (Figure A2.3). Seeds were sown into the plots in a slurry with Turbo Tackifier brand tackifier to further help keep the seeds in place at a rate of 0.31 g of tackifier m^{-2} (Figure A2.4). Control plots also received the tackifier addition (minus the seeds) and were used to document the effects of the tackifier alone interacting with the background community emerging from the seed bank.

Plug propagation and planting

Plugs of *Schoenoplectus acutus* and *Distichlis spicata* were grown in the greenhouse prior to installation. Approximately 20 seeds of each species (grown separately) were sown onto All-Purpose Lambert soil that was moistened and inserted into cone-tainers. (Ray Leach SC10R; 21 cm deep and 4 cm in diameter; Figure A2.5). Plugs were grown under 16-hour photoperiod at 2100 µmol m-2 s-1 (Gavita Pro 1000e) with daytime temperatures of 85°F (29.4°C) and nighttime temperatures of 65°F (18.3°C). The plugs were watered via aerial sprinklers to maintain a consistently moist growing condition. The seedling plugs were grown out for 6 weeks and thinned at 4 weeks to reduce competition. During the last week of growth, the plugs were hardened to field conditions by gradually placing them in the sunlight and ceasing watering for increasingly longer periods of time each day.

In the field, the plugs in the dispersed plots were planted in a 3 × 3 grid pattern 0.5 m from each other. In the clumped plots, the plants were planted in the center of the plot so that all plugs were touching (Figure 2.3).

Soils at Study Area

To determine the general characteristics of the soils at the restoration site, I collected soil samples in April along three gradients of the North Shore area of Utah Lake. One elevation was nearest the water-land interface (low), one was at the top of the exposed beach (high) and one was along the middle transect (middle). Multiple collections were taken at each elevation level: low, middle, and high. These single collections were mixed according to elevation levels and homogenized to create one sample per elevation. Soil testing was conducted in May of 2021 by Utah State University's Analytical Laboratories. Conductivity (in dS/m), pH, total phosphorus (using the Olsen NaHCO3 Method and testing for available P) and nitrogen (using combustion and testing for N2, NOx,) were tested for. The pH across all three gradients was 7.4. The conductivity was 2.9 dS/m closest to the shoreline, 1.78 dS/m in the middle elevation and 3.14 dS/m in the highest elevation. Total phosphorus was consistent across all three elevations at 0.07%. Total nitrogen was 0.23% (low elevation), 0.09% (middle elevation), and 0.22% (high elevation). These soil tests illustrated that no clear soil nutrient patterns were associated along the shoreline elevations in this system.

Assumptions can be made that current plant establishment is not likely linked to soil nutrient availability.

Data collection

Data collection took place June 4, 2021–September 16, 2021; and June 8, 2022–September 18, 2022. For both the seeded plots and the plug plots, plant performance was assessed using total percent cover and individual species cover (seeded native species, hereafter 'seeded'; invasive species (Downard et al., 2017), hereafter 'invasive'; and native species that were not seeded, hereafter 'unseeded native'). The following cover classes were used: ≤1%, 1–10%, 11–20%, 21-30%, 31–40%, 41–50%, 51–60%, 61–70%, 71–80%, 81–90%, 91–98%, >98-100%. Cover data were collected by one person throughout the season to maintain consistency with data collector calibration using a percent cover data template. Cover was collected visually by standing over the plot and identifying all species present in the plot and what percent of the plot that species covered. Although cover was collected by the same person throughout the experiment, a second researcher was also in attendance for second opinions and cover calibrations.

Water level data were collected to monitor elevation-level water fluctuations. These data were collected from 20—1.6 m tall wells installed in the middle of every block and buried 1 m below the soil surface. The wells were constructed of 5 cm wide and 0.5 cm thick PVC that were slotted at the bottom to allow for air flow and reduce pressure inside the well. Water levels in the well were measured with a 1.83 m long stick painted with black chalkboard paint and coated in the field with carpenter's chalk

(IRWIN Strait-Line Marking Chalk in Permanency 1 (Standard)) prior to insertion in the well.

Analysis

For the analysis of seeding and plug planting experiments, I created generalized linear mixed effects models using the “glmmTMB” package (version 1.1.4) in R (Brooks et al., 2017). The fixed effects were either seeding density (3 levels: unseeded control, 1× density or 5× density) or plug arrangement (3 levels: unplanted, dispersed or clumped) as well as elevation for both experiments (four levels: 1 to 4 with elevation 1 being closest to the shoreline). Random effects were transect (n=5) and plots (n=8) and the repeated measure of the sampling time. Model fit was assessed using both the residual plots produced with the “DHARMa” package (version 0.4.6) in R (Hartig, 2022) and the comparisons of raw data with the model estimates. Interactions that were supported by the data were investigated using pertinent contrasts. I tested variable effects as appropriate with the Analysis of Deviance (“Anova” function from the “car” package (version 3.1-1) in R (Fox & Weisberg, 2019)) for our beta distribution models. Because beta distribution does not accommodate values of zero, zeros were converted to a small non-zero value (0.005) prior to analysis. Post hoc pairwise comparison tests that were Tukey-adjusted for family-wise Type II errors (using the “emmeans” package version 1.8.2 in R (Lenth 2022)) were used to further evaluate seeding and planting treatment differences. Percent cover estimates (mid-points of cover classes) were converted from percentages to proportions for the native and invasive cover analysis. For analysis of the species richness data, I calculated the Hill Diversity as the response metric using the

“MeanRarity” package (version 0.0.1.0004) in (where ℓ equals 1) (Roswell & Dushoff, 2022) which estimates and visualizes Hill diversity in terms of the average species rarity.

I used nonmetric multidimensional scaling (NMDS) to visually assess the association of seeding treatment and elevation on community composition in plots at the end of the growing season. I used the “metaMDS” function (with k = 2) in the “vegan” package (version 2.6-4) in R (Simpson et al., 2022). To prepare for the ordinations, I excluded species that occurred in fewer than 5% of quadrats to reduce the disproportionate influence of rare species (McCune et al., 2002).

I collected water level data for both the 2021 and 2022 growing seasons. However, due to the extreme drought conditions, our ability to formally investigate how water levels affected plant community assemblage was limited. Although this environmental condition was not included in statistical models, our monitoring results are included for qualitative assessments to provide context (Fig A2.6).

Results

Seeding experiment

Cover. The positive effect of seeding was evident in the first year, with seeded species (regardless of density) having the highest cover relative to the unseeded control (Figure 2.4a) including when averaged across elevations (Figures 2.5a, 2.5b; Tables 2.2a & 2.3a). However, there were no differences between the two seed density treatments within elevations in the first growing season (Figure 2.4a). Both invasive and unseeded native plant communities had minimal cover in 2021 (Figure 2.4a). The following monitoring year, the seeded plant community continued to have the higher cover in the two seed density treatments relative to the unseeded control (Figure 2.4b, Tables 2.2b & 2.3b). While the invasive and unseeded native communities generally increased in cover in 2022, overall cover of the seeded communities decreased (Figure 2.4b). The 5x density treatment had significantly lower invasive cover than the unseeded control in 2021, however that effect did not persist into the second growing season (Figures 2.5c & 2.5d, Tables 2.4 & 2.5).

Plant community assemblage changed over the course of the experiment, particularly for the unseeded native community (Figures 2.6a & 2.6b). In 2021, the dominant species were all seeded species: the fast-growing forbs *Bidens* spp. and *Rumex maritimus*, along with the sedge *Cyperus erythrorhizos* (Figure 2.6a). The following year, the plant communities shifted from being driven by fast-growing seeded species to being dominated by a mix of life strategies characterized by native unseeded species and seeded in both perennial and annual life forms. The *Helianthu*s species (*Helianthus nuttalli* and *Helianthus annuus*) were only present in the seeded mixture and became a dominant species in many plots (Figure 2.6b) Additionally, *Populus* spp. and *Symphyotrichum ciliatum* were highly present in the background community. Seeded species had higher establishment in the seeded plots than the controls, but there was no difference in end of season cover between the 1x and 5x seeding treatments. (Table 2.3)

Elevation significantly affected seeded species cover at the end of the season, with the largest differences between elevations 1 & 4 and 2 & 4, across both growing seasons (Tables 2.2 & 2.6). Overall, I found higher seeded species cover and lower invasive cover in the lower elevations (Figures 2.4 & 2.7, Tables 2.6 & 2.7). Lower elevations had higher cumulative mean cover of seeded and unseeded native plant communities (Figure 2.5). An interaction effect between elevation of seeding and seeding treatment was not detected (Table 2.2).

Species richness. Species richness was also affected by the seeding treatments (Table 2.8). Higher species richness was associated with the lower density seeding across both years (Table 2.9; Figures 2.6e & 2.6f). Seeding density had a marginally significant effect on species richness the first year as indicated by Tukey pairwise comparison tests (Table 2.9). Notably in the second year, the differences between the two seeding densities was reduced. The 1x seeding treatment resulted in significantly more species establishing than the control in both years. Differences between the lower seeding density and control were significant (Table 2.9). I found no evidence that elevation of planting was significantly linked to species richness (Table 2.8).

Plug planting experiment

Plant cover in the plug experiment was affected by the interaction of elevation and planting arrangement across both species and both years (Tables 2.10 & 2.11). *Distichlis spicata* consistently performed better in the dispersed planting arrangement in the lower elevations, with higher native cover found in elevations 1, 2, and 3 across both years and invasive cover was low regardless of treatment and elevation (Figures 2.8 & 2.9). There was significantly higher *D. spicata* cover in the clumped and dispersed treatments than the control plots (Table 2.12). The second year, only the lower elevations had significant differences in *D. spicata* cover between planting arrangements. Similarly, cover of *S. acutus* was highest in the dispersed planting arrangement in the lowest elevation across both years (Figures 2.10 & 2.11). *Schoenoplectus acutus* established better in the clumped and dispersed plots at elevation 1 and 2 both years (Table 2.13). The dispersed plantings had significantly higher cover of *S. acutus* than the clumped plantings at elevation 2 in 2021, there were no other significant differences between the two planting arrangements.

Discussion

Restoring native plant communities along lakeshores is essential for reestablishing lost habitat and other aspects of ecosystem functioning, yet the uncertainties of *how* to seed and plant and *where* along dynamic shorelines to reintroduce species limit restoration practice. In paired restoration experiments, I assessed the effects of (1) seeding, density of seeding, and elevation of seeding along with (2) plug planting, the arrangement of plugs, and elevation of planting on native and invasive plant cover on the Utah Lake shoreline. In the seeding experiment, I found that seeding had a positive effect on the cover of the seeded native species regardless of seeding density but there was no benefit of a higher seeding density (5× vs. 1×). The highest native cover (both in seeded and unseeded species) and lowest invasive cover occurred consistently in lower elevations. In the plug experiment, I found that in many cases the addition of plugs greatly increased the cover of both planted species (*D. spicata* and *S. acutus*), especially when compared to their establishment in the seeding density plots. Dispersed plug plantings generally performed better (i.e., higher cover) than clumped plantings, especially for *D. spicata* and to some extent for *S. acutus*. The elevation of plug planting had a significant effect on the cover of both species planted as plugs with higher success in the lower elevations closest to the water line. Together these results suggest that seeding or planting native species along lakeshores can substantially increase native plant cover and more specifically that higher seeding densities may not matter but the arrangement of plugs does matter (dispersed not clumped). Restoration practitioners should expect wide variation in outcomes based on seeding or planting elevation—planting on the lower and middle elevations can help achieve native plant restoration goals and set up restored communities for longer term invasion resilience.

Seeding target restoration species increased native plant community cover and species richness

There has been a longstanding assumption in wetland restoration that native plant communities will recover naturally with minimal intervention (Mitsch & Gosselink, 2015). However, restoration research has challenged this notion, highlighting the need for active revegetation strategies in a wide range of wetland types (Farrell et al., 2021; Galatowitsch & van der Valk, 1996; Tarsa et al., 2022). Yet, the benefits of revegetation along lakeshores are less well known (but see Haskell et al., 2017 and Vanderbosch & Galatowitsch, 2010). In light of this, I conducted a study to investigate the impact of a functionally diverse 19-species seed mix on native cover in wetland communities. I predicted that the higher native seeding density would lead to increased species richness compared to the lower density as the increased seed amounts would increase the probability that all species would overcome the limiting seed-to-seedling threshold where most mortality occurs. Additionally, with increased native cover and species richness, I predicted a decrease in invasive plant cover likely due to more complete canopy shading from native plants. I found a significant increase in total cover and species richness with seeding, despite a pretty extensive native seed bank.

Over the course of two years, the plant communities shifted from being driven by fast-growing seeded species to being dominated by a mix of life strategies characterized by native unseeded species and seeded in both perennial and annual life forms. These first season results were consistent with similar studies in dryland restoration, which revealed that ruderal annual species play a dominant role in driving plant community composition in unseeded plots (Farrell et al., 2021), suggesting that harnessing the fast-growing adaptations of certain species can help increase establishment success. Species selection was found to be the dominant driver in emergence bottlenecks in wetlands, in a 2023 study by Zhao et al., who found a few species emerge under a wide range of environmental conditions, implying that species selection during the early planning stages of restoration can drive species establishment. Balancing fast growing, highly adaptive, annual natives with desirable perennial native grasses and forbs can be an important component of seeding success. To better understand the nuances of seed-based wetland restoration, careful species selection through mining historic literature, noting existing community structures, and incorporating input from land managers, coupled with carefully researched dormancy and germination requirements are key.

Seeding density did not have a strong influence on the recovering plant community

Increasing seeding density, whether in natural ecosystems or restoration settings, is likely to increase the number of colonizing individuals at least until a density dependence threshold is reached (Burton et al., 2006; Kettenring & Tarsa, 2020). I predicted that the higher native seeding density would lead to greater cover and increased species richness compared to the lower density as the increased seed amounts would increase the probability that all species would be more likely to overcome the limiting seed-to-seedling threshold where most mortality is likely to occur. I also predicted that the high-density seeding treatment in this experiment was still low enough that a density dependence mortality threshold would not be reached (Burton et al., 2006; van der Walk 2018). A higher density seeding can drive establishment, as an increase in the number of seeds will increase the likelihood that species will be able to germinate, establish, and persist (van Katwijk et al., 2016). Conversely, a low-density seeding could leave empty niches and unused resources (particularly light) that might leave native communities susceptible to further invasion (Byun et al., 2013; Tarsa et al., 2022). Contrary to my prediction, I found no significant difference in seeded cover between the density treatments. Interestingly, in Burton et al., (2006) study, they found that the most efficient seeding density was between 750 and 1,500 PLS m^{-2}, although my high density seeding of 900 PLS/m2 falls in this threshold and was not more efficient. Additionally, I found with an increased seeding density, there was a slight reduction in species richness, perhaps driven by intra-specific competition for resources, as predicted by Burton et al., (2006) study. Surprisingly, invasive cover was very low regardless of density treatment. Site preparation conducted ahead of time effectively reduced the immediate threat of reinvasion as well as a robust native seed bank (see Figure A 2.1 for a history of invasive species management on site).

There was some overlap between the species composition of the unseeded and seeded native species, especially in the first year of monitoring. Specifically, we found that seeded species *Bidens* spp, *C. erythrorhizos*, and *R. maritimus* were also prevalent in our unseeded control plots, indicating their presence in the seed bank. These fast-growing annual species were successful in my seed mix and in the background community, suggesting seeding species with similar traits could increase establishment success in similar environments. The use of tackifiers in this experiment was done to replicate the current method for applying seeds to a site. During the span of this research, management practices shifted to discing as the preferred site prep method, as managers found discing holds the seeds in place, is easier to implement on a larger scale, and seems to promote germination and establishment better than tackifiers (Keith Hambrecht, personal communication, August 5, 2020). Tackifiers might still be used for smaller, more specific applications along dikes - similar to traditional applications of hydroseeding.

Elevation shaped community assembly

Wetland plant seeds and seedlings are highly sensitive to water level extremes (Chapman et al., 2013; Wei et al., 2019). Climate change is intensifying the already severe water level fluctuations in lakeshores, leading to a new normal characterized by alternating periods of intense flooding and prolonged droughts (Rodell & Li 2023). To develop effective strategies for the management of lakeshore wetlands in the face of current and predicted extreme water level fluctuations, it is fundamental to understand how the elevation of planting affects community establishment. With this in mind, I was curious to understand how the highly dynamic Utah Lake shoreline might impact revegetation outcomes. I predicted that intermediate elevations, likely to experience moderate annual and interannual water level variations, would have the highest levels of plant success (cover). Conversely, I anticipated that the highest and lowest elevation blocks would experience decreased plant performance due to more frequent and extreme flooding or drought. My findings revealed that the elevation of planting significantly impacted native plant cover, though not entirely as I predicted. In the first and second year, the highest cover of seeded species was in the first and second elevations (closest to the water line), as partially predicted. This finding was similar to research by Casanova and Brock in 1999 who found a link between increased flooding stress and a reduction in wetland plant performance (here measured as biomass). In the present experiment, invasive cover was highest in elevations 3 and 4 vs. 1 and 2 across all three seed density treatments in the second year of monitoring. Propagule pressure from nearby stands of invasives was likely driving this increase in cover in 2022. In lake systems, Perales et al., (2020) noted that the broader ecological implications of water level fluctuations are poorly understood. Based on the study findings, the recommendation is to seed in lower elevations to achieve the highest establishment success.

Interaction between plug planting and planting elevation mattered

Increasing facilitation through clumped plant arrangements has been shown to increase plant performance in high-stress restoration settings in coastal wetlands (Silliman et al., 2015). Here I was interested to see if manipulating the arrangement of plant plugs in lakeshore wetlands would have a similar beneficial effect on planted communities. I predicted that the clumped planting arrangement would lead to higher establishment success with flooding due to facilitation between the plugs (i.e., oxygenating an otherwise anoxic root zone). The results indicate significant interaction between elevation and planting treatment for both species of plugs over two years. While differences in planting arrangements were not always clear, there were significant differences in clumped and dispersed *D. spicata* arrangements in the first year. Overall, the data suggest that *D. spicat*a plugs, particularly in dispersed planting treatments, are highly effective at establishing and persisting in this system. There was less wave and water fluctuation stress than anticipated due to extreme drought conditions affecting the region. These results are consistent with previous studies, which found that under low stress conditions, where competitive interactions dominated, dispersed designs maximized growth (Hammann et al., 2021; Woods et al., 2023). My research suggests that in these systems, particularly considering the predicted extreme weather events resulting from climate change, lower elevations coupled with dispersed plug planting may be the most effective strategy for promoting establishment success. Additionally, a bet-hedging strategy of planting over multiple elevations (starting at the lowest possible elevation) can be useful for unpredictable futere snowpack and weather conditions that could increase the lake level.

Conclusions

In conclusion, the findings of this study suggest that seeding is an effective strategy to increase native plant community cover and species richness in lakeshore wetlands. While there was no difference between the two seeding densities on native plant recovery, the act of seeding itself did increase native plant cover. Additionally, elevation of seeding played a crucial role in restoration outcomes, with lower elevations showing higher cover of seeded species. The results of the plug planting experiment demonstrated that the interaction between planting arrangement and elevation was significant, with the dispersed planting arrangement leading to the highest native cover in both *D. spicata* and *S. acutus* in the lower elevations. These findings highlight the importance of considering seeding and planting strategies, as well as elevation, when restoring degraded lakeshore wetlands to promote the recovery of native plant communities.

A limitation of this study is Utah Lake had a robust native seed bank, and passive restoration was occurring. This made teasing out the drivers of seeding more nuanced. Additionally, the site experienced prolonged drought during the sampling period. Prolonged flooding was not documented during this study, although the following year record breaking snowpack occurred in the surrounding watershed. An additional year of studying this system in the face of intense flooding could elucidate the effects of these extreme water level fluctuations on both the plug planting arrangement and seeding density, further strengthening this study.

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Figures

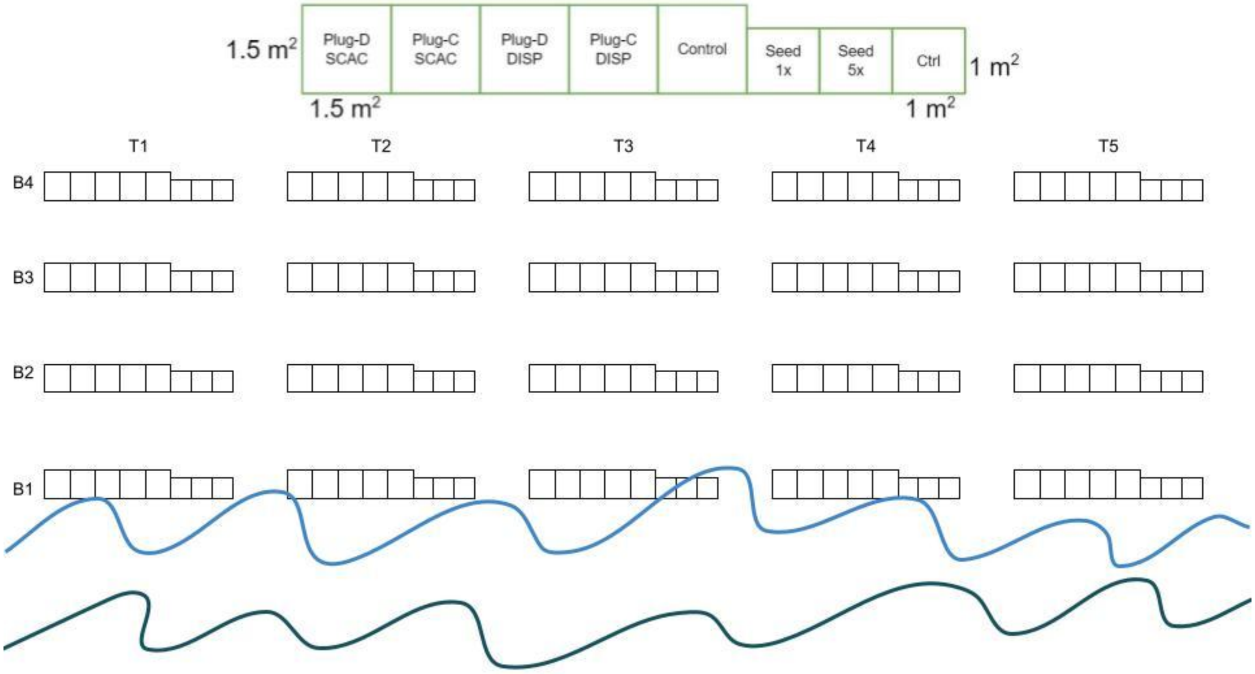
Figure 2.1

Utah Lake Field Site Location

Note. Field site location (green pin) on Utah's sovereign lands on the north shore of Utah Lake, UT, USA.

Figure 2.2

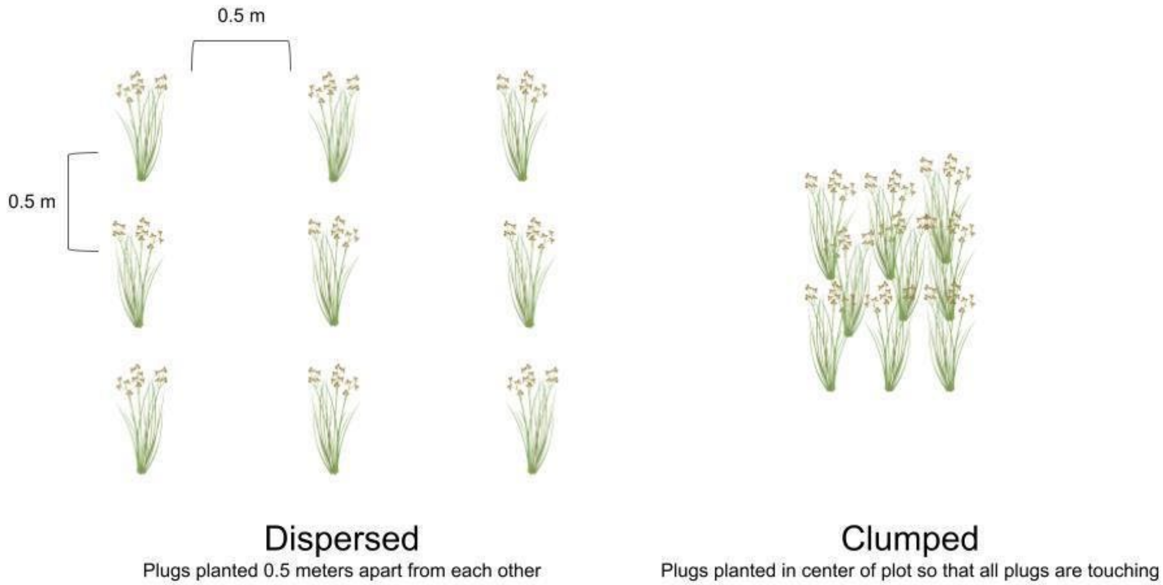
Transect (T1–T5) and Plot Layout for the Restoration Experiments



Note. Transect (T1–T5) and plot layout for the restoration experiments. The seeding (Seed 1×, Seed 5×, and control) and planting (Plug-D for dispersed or Plug-C for clumped, SCAC for *S. acutus* and DISP for *D. spicata*) plots were arranged together in a row (= blocks in the statistical design shown here as B1–B4) although randomization only occurred within the experiment type (seeding or planting) since the datasets were to be analyzed separately. The blue and green wavy lines at the bottom simulate the changing water levels present at the restoration site.

Figure 2.3

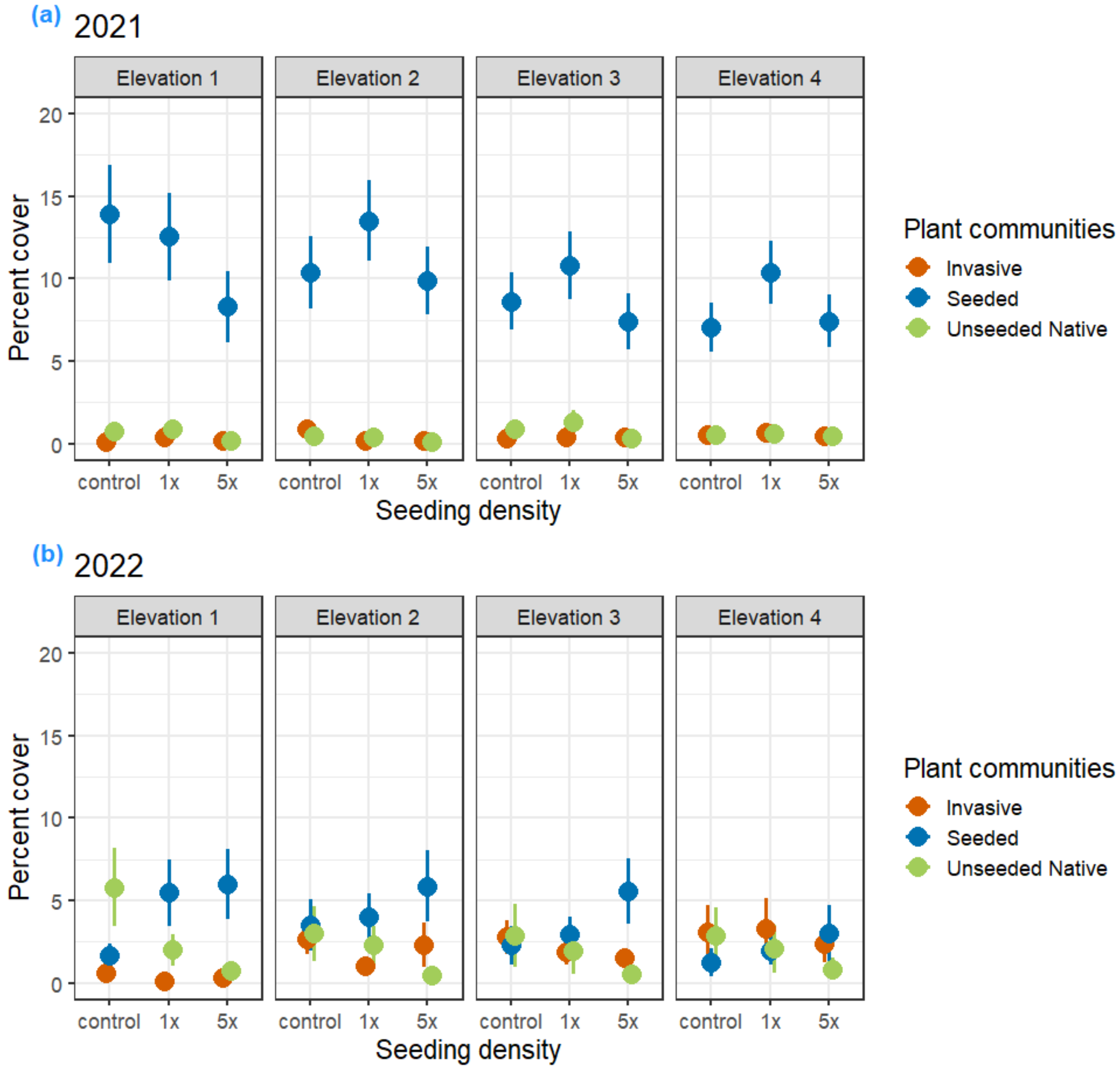
Dispersed versus Clumped Planting Arrangement



Note. Dispersed versus clumped planting arrangement.

Figure 2.4

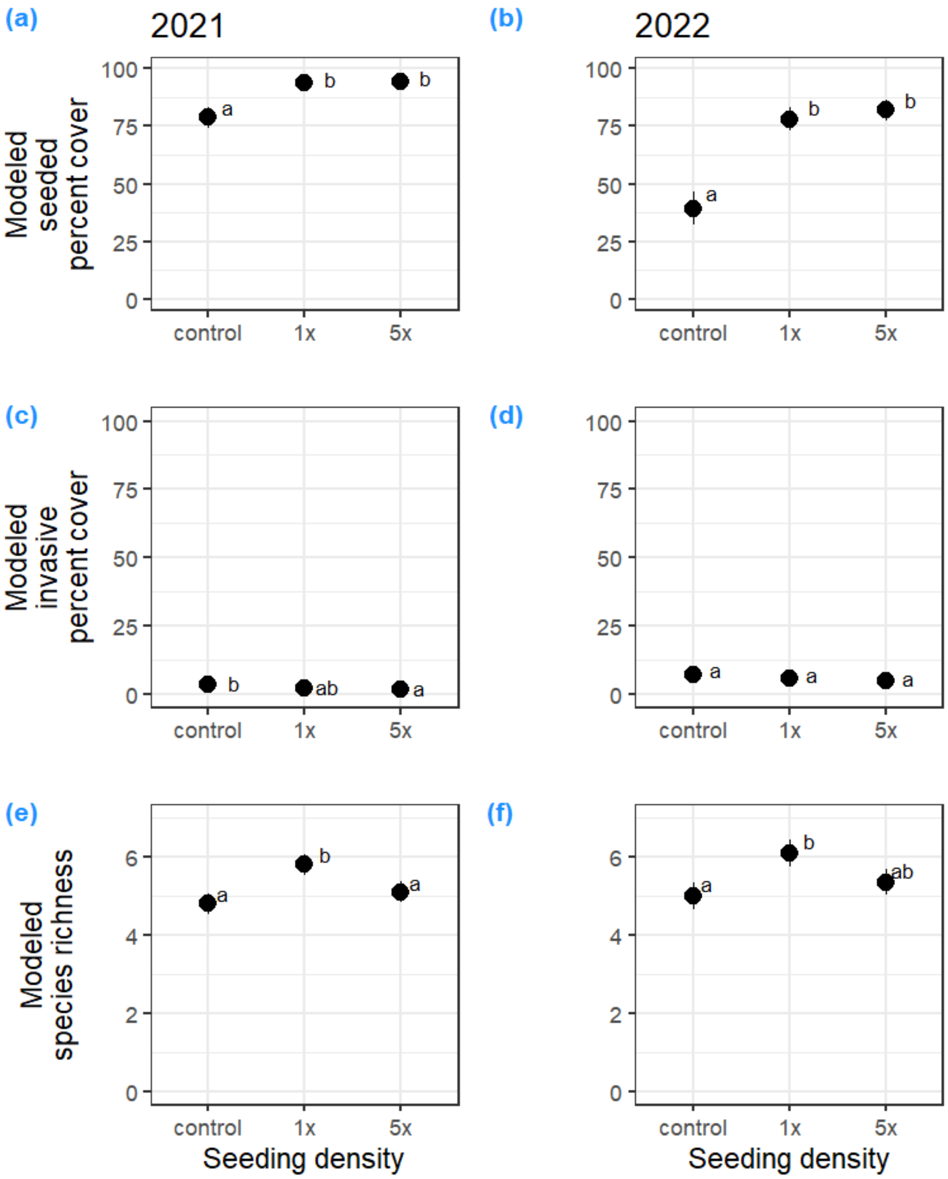
The Effect of Seeding Density and Elevation on End of Season Performance



Note. The effect of seeding density and elevation on end of season performance (cover) of three plant communities in (a) 2021 and (b) 2022. Raw data are shown (n=5). Plant communities (Invasive, Seeded, and Unseeded Native) are jittered on plot for readability. Elevation is displayed on a gradient that runs from the planting shoreline (Elevation 1) to upland (Elevation 4), on a transect that is perpendicular to the lake.

Figure 2.5

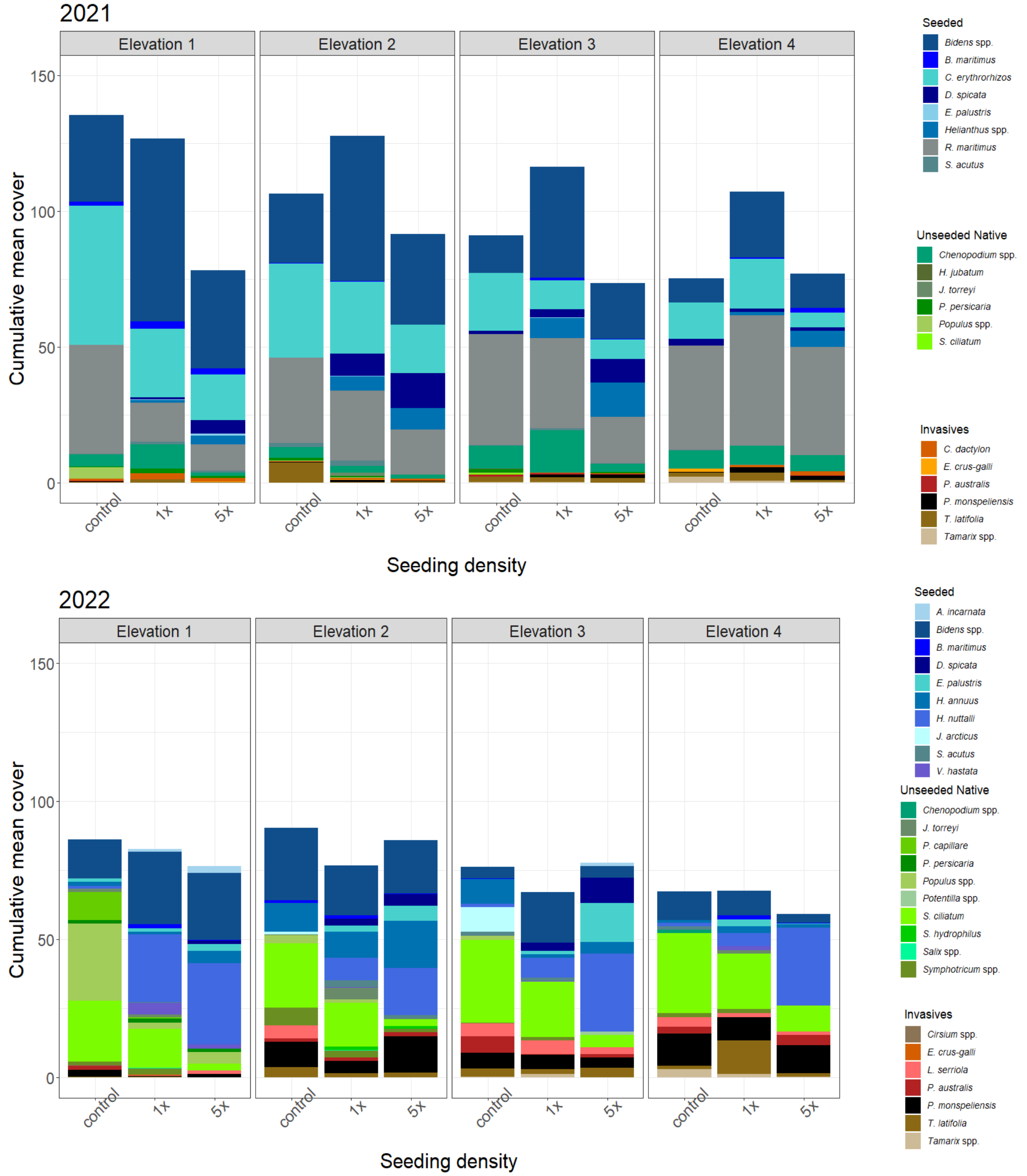
Modeled Proportion of Cover across Seeding Density Treatments



Note. Modeled proportion of native seeded cover (a & b), invasive cover (c & d), and species richness (e & f) across the seeding density treatments in 2021 (left column: a, c, & e) and 2022 (right column: b, d, & f). Modeled data are shown (n=20). The lower-case letters (a, b, ab) denote statistical differences between groups with an alpha of 0.05.

Figure 2.6

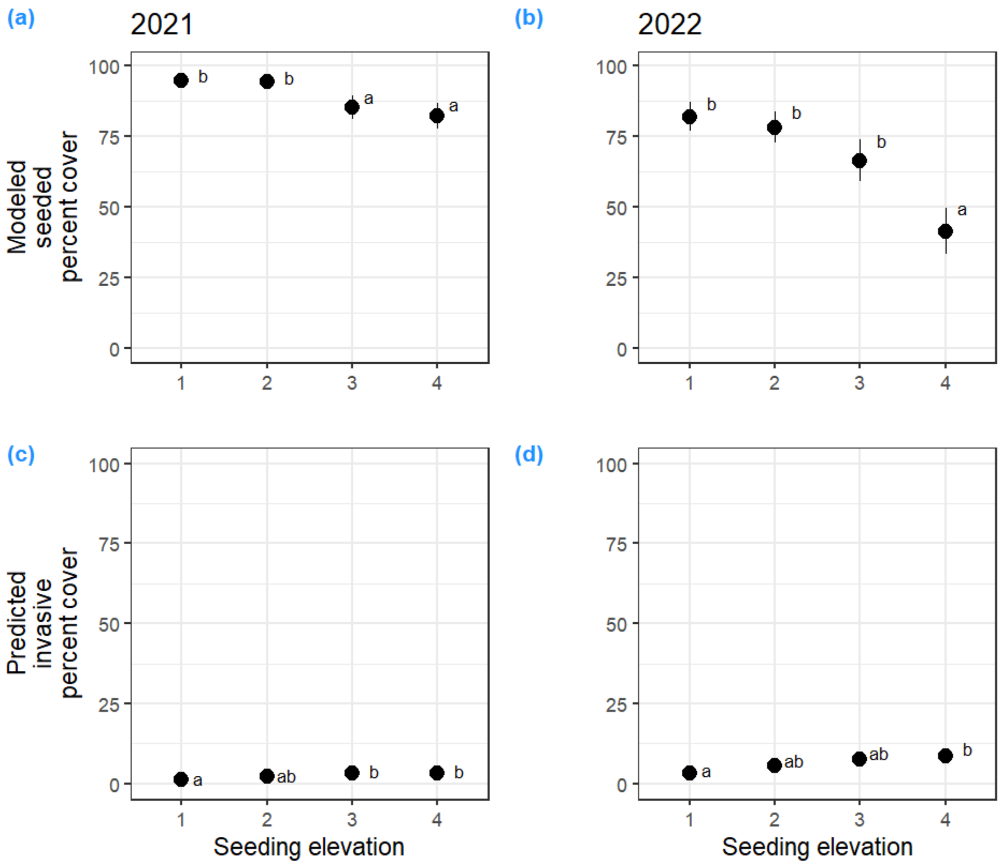
The Effect of Seeding Density and Elevation of Seeding on End of Season Species Assemblage



Note. Raw data are shown (n=5). Years are (a) 2021 (top) and (b) 2022 (bottom). Species are stacked according to plant communities (Seeded, Unseeded Native, and Invasives) and in alphabetical order within the stacks. 'Cumulative mean cover' on the y-axis represents the additive covers of the plant groups.

Figure 2.7

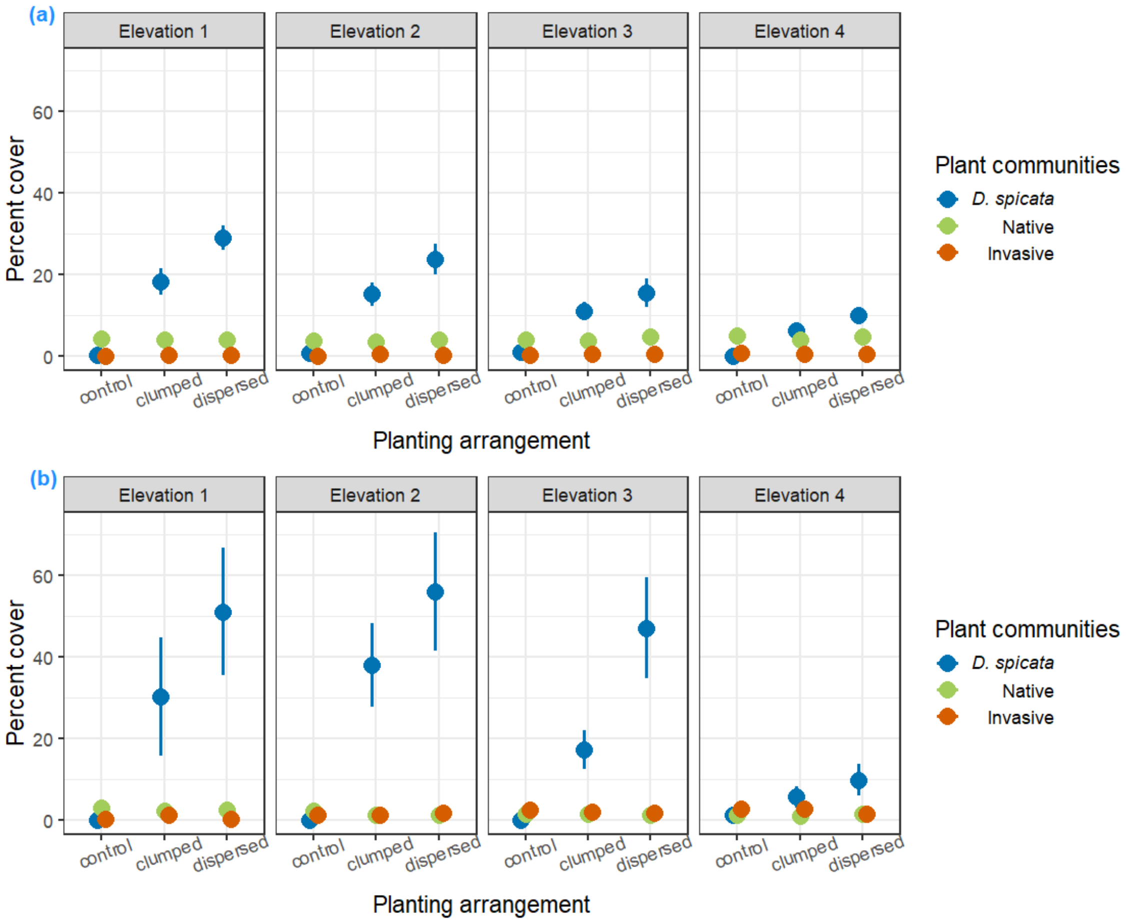
Modeled Proportion of Cover Across Four Elevations



Note. Modeled proportion of native seeded cover (a & b), invasive cover (c & d) across the four elevations in 2021 (left column: a & c) and 2022 (right column: b & d). Modeled data are shown (n=20). The lower-case letters (a, b, ab) denote statistical differences between groups with an alpha of 0.05.

Figure 2.8

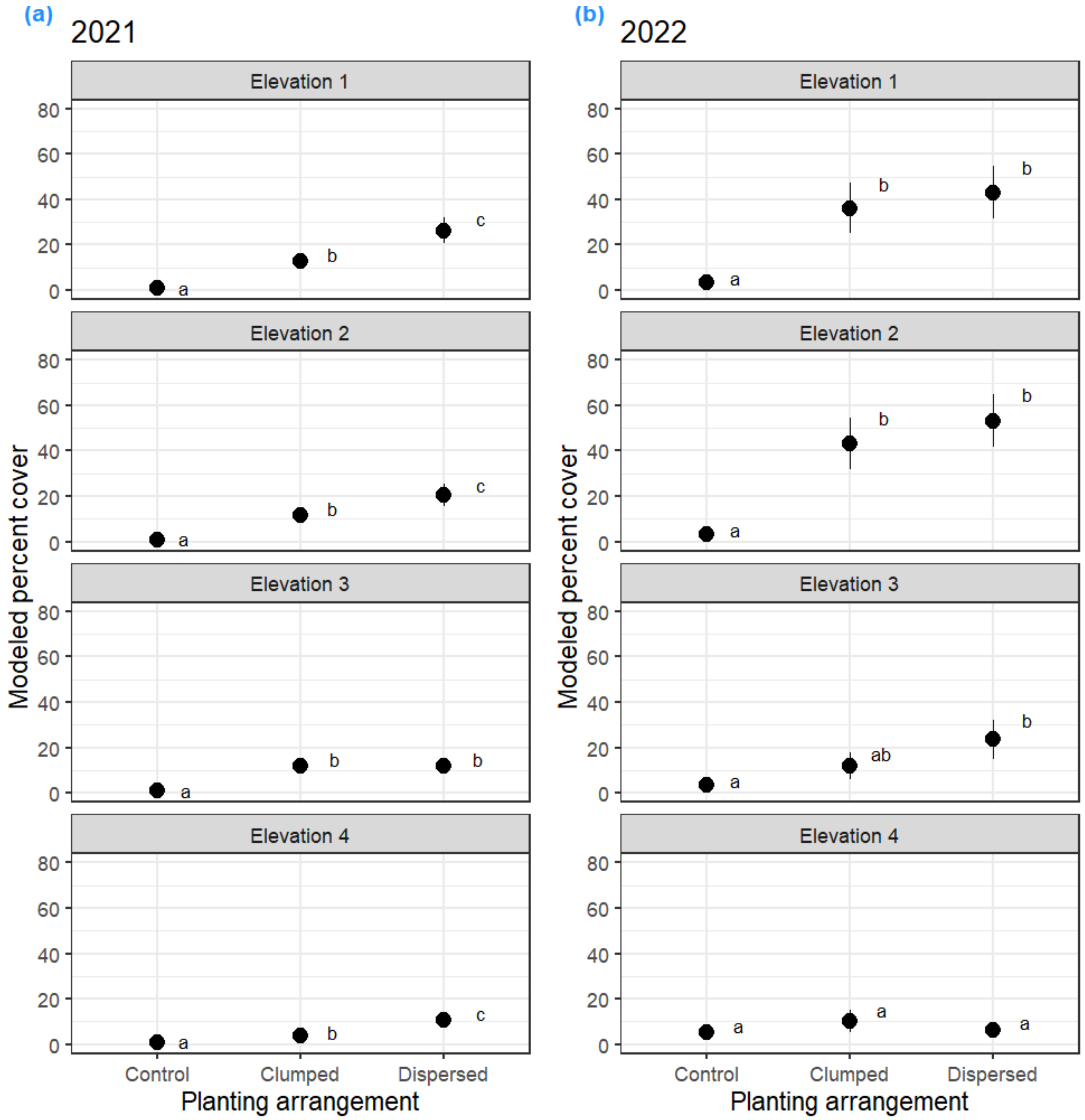
The Effects of Planting Arrangement and Elevation on End of Season Cover



Note. This cover is across the three communities in (a) 2021 and (b) 2022. Raw data are shown (n=5). The plant communities are *D. spicata* (blue), Native (unplanted, in green), and Invasive (red) and are jittered on plot for readability. Elevation is displayed on a gradient that runs from the planting shoreline (Elevation 1) to upland (Elevation 4), on a transect that is perpendicular to the lake.

Figure 2.9

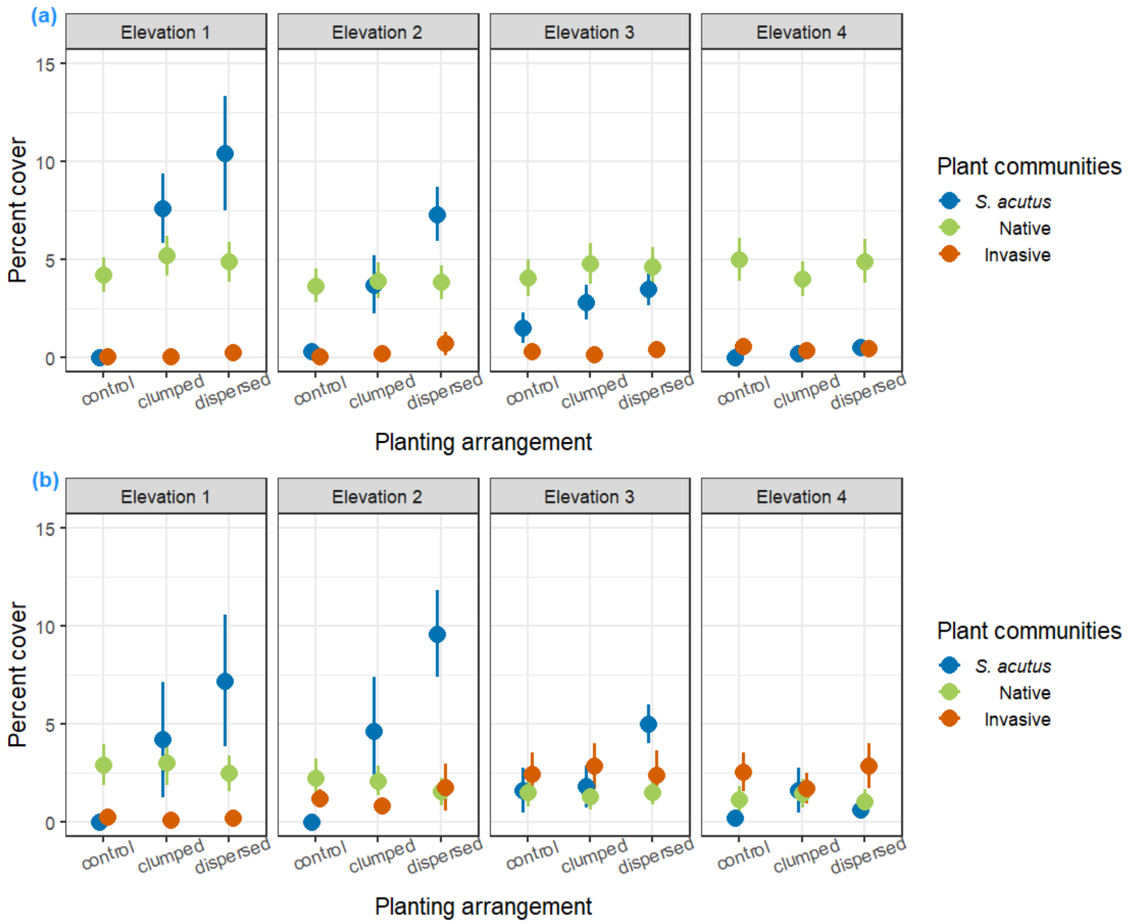
Model Predicted Responses for Percent Cover of Distichlis spicata *Across all Elevations*



Note. For years (a) 2021 and (b) 2022. Modeled data are shown (n=5). The lower-case letters (a, b, c, ab) denote statistical differences between groups with an alpha of 0.05.

Figure 2.10

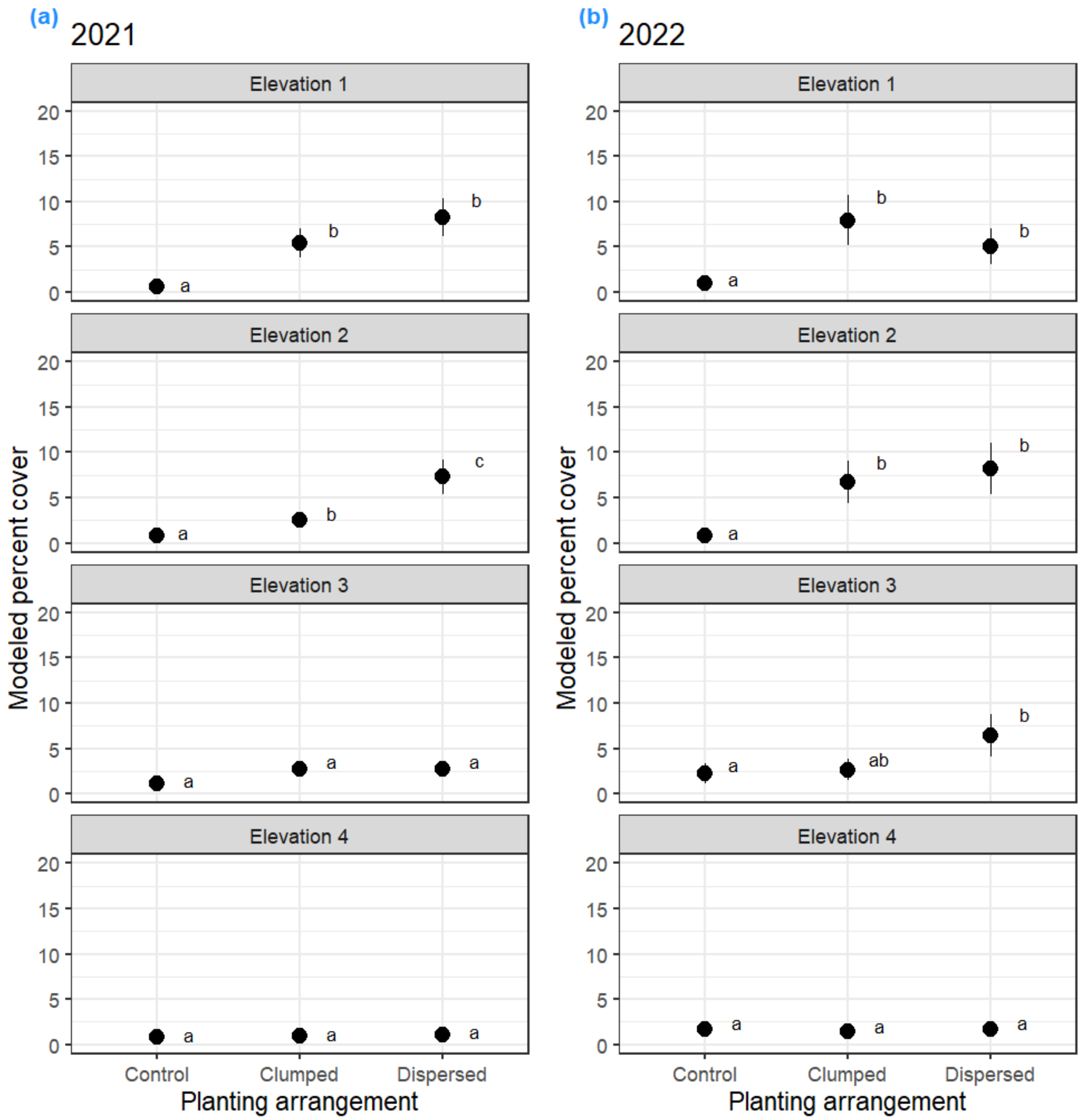
The Effects of Planting Arrangement and Elevation on End of Season Cover



Note. Shown across the three communities in (a) 2021 and (b) 2022. Raw data are shown (n=5). The plant communities are *S. acutus* (blue), Native (unplanted, in green), and Invasive (red) and are jittered on plot for readability. Elevation is displayed on a gradient that runs from the planting shoreline (Elevation 1) to upland (Elevation 4), on a transect that is perpendicular to the lake.

Figure 2.11

Model Predicted Responses for Percent Cover of Schoenoplectus acutus



Note. Across all elevations in (a) 2021 and (b) 2022. Modeled data are shown (n=5). The lower-case letters (a, b, c, ab) denote statistical differences between groups with an alpha of 0.05.

Tables

Table 2.1

Native Species Seeded at Utah Lake, Utah and Their Dormancy Breaking Requirements

Latin Name	Common Name	Dormancy Breaking Requirements
Asclepias incarnata	swamp milkweed	Stratification for 4 to 12 weeks at 35 to 38 °F[1] Scarification worked (95% germination) in preliminary lab test and more research is needed here[2]
Asclepias speciosa	showy milkweed	Stratification for 4 to 12 weeks at 35 to 38 degrees °F[1] Scarification worked (95% germination) in preliminary lab test and more research is needed here[2]
Bidens cernua	nodding beggartick	Stratification for 10 weeks[2]
Bolboschoenus maritimus	alkali bulrush	Scarify with a 1:1 bleach: water solution for 48 hours[3]
Carex nebrascensis	nebraska sedge	Stratification for 32 days[4]
Carex praegracilis	clustered field sedge	No stratification requirements but stratification recommended[1,2]
Cyperus erythrorhizos	redroot flatsedge	Moist stratification at 50 °F (10 C) for 3-9 months[5]
Distichlis spicata	saltgrass	Stratification for 6 weeks minimum[2]
Eleocharis palustris	common spikerush	Scarify with 3% bleach solution for 24 hours, then rinse before sowing[2]
Epilobium ciliatum	fringed willowherb	Readily emerged in a preliminary greenhouse test. Stratification recommended[2]
Eutrochium maculatum	joe pye weed	Cold, moist stratification (30 days)[6]
Helenium autumnale	common sneezeweed	Needs light to germinate. Kept at 70°F, seed germinates in 10-21 days[7]
Helianthus nuttallii	nuttall's sunflower	No requirements[1]
Juncus arcticus	Arctic or baltic rush	No requirements[2]

Rumex maritimus	golden dock	Readily emerged in a preliminary greenhouse test. Stratification recommended[2]
Schoenoplectus acutus	hardstem bulrush	Stratification required[3]
Schoenoplectus americanus	threesquare bulrush	Stratification required[3]
Senecio hydrophilus	water ragwort	No information could be found, and further research is needed to understand dormancy breaking requirements. Stratification was recommended[2]
Verbena hastata	swamp verbena	It self-seeds readily and is very easy to germinate[8]

[1]USDA Plants Database; [2]USU WERL Lab; [3]Marty & Kettenring, 2017; [4]Baskin & Baskin, 2014; [5]*Plants of Lousiana* (n.d.); [6]*Eutrochium maculatum - Joe Pye Weed.* (n.d.); [7]*Helenium Seeds - Sneezeweed*. (n.d.); [8]*Verbena hastata - Blue Vervain*. (n.d.).

Table 2.2

Type II ANOVA Table for End of Season Cover of Seeded Species

a. Model for 2021	X^2	*Df*	$Pr(>X^2)$
Elevation	20.796	3	**<0.001**
Treatment	24.694	2	**<0.001**
Elevation × Treatment	2.109	6	0.909
b. Model for 2022	X^2	*Df*	$Pr(>X^2)$
Elevation	17.883	3	**<0.001**
Treatment	26.553	2	**<0.001**
Elevation × Treatment	6.508	6	0.368

Note. Across the four elevations in (a) 2021 and (b) 2022. Treatments significant at α=0.05 are in bold.

Table 2.3

Tukey Pairwise Comparison

a. Contrast for 2021	**Estimate**	**SE**	***df***	**t.ratio**	**p.value**
1× - 5×	-0.087	0.334	45	-0.260	0.964
1× - Control	-1.375	0.325	45	-4.238	**<0.001**
5× - Control	-1.462	0.340	45	-4.296	**<0.001**
b. Contrast for 2022	**Estimate**	**SE**	***df***	**t.ratio**	**p.value**
1× - 5×	-0.239	0.359	45	-0.667	0.784
1× - Control	1.706	0.390	45	4.374	**<0.001**
5× - Control	1.946	0.394	45	4.943	**<0.001**

Note. Between the seeding treatments at end of season in (a) 2021 and (b) 2022. Treatments significant at α=0.05 are in bold.

Table 2.4

Type II ANOVA Table for Seeding Treatments on End of Season Invasive Cover

a. Model for 2021	***X^2***	***Df***	***Pr(>X^2)***
Elevation	7.433	3	*0.060*
Treatment	6.143	2	**0.046**
Elevation × Treatment	10.465	6	0.106
b. Model for 2022	***X^2***	***Df***	***Pr(>X^2)***
Elevation	6.411	3	*0.093*
Treatment	2.693	2	0.260
Elevation × Treatment	2.464	6	0.872

Note. Across the four elevations in (a) 2021 and (b) 2022. Treatments significant at α=0.05 are in bold. Marginally significant treatments at α=0.10 are italicized.

Table 2.5

Tukey Pairwise Comparison

Contrast for 2021	**Estimate**	**SE**	***df***	**t.ratio**	**p.value**
1× - 5×	0.206	0.239	45	0.860	0.668
1× - Control	0.426	0.234	45	1.822	0.174
5× - Control	0.632	0.244	45	2.592	**0.033**

Note. Between seeding treatments and invasive cover at end of season in 2021, 2022 treatment had no significant comparisons. Treatments significant at α=0.05 are in bold.

Table 2.6

Tukey Pairwise Comparison Between Elevations of Seeding Treatments

a. Contrast for 2021	**Estimate**	**SE**	***df***	**t.ratio**	**p.value**
Elev 1 - Elev 2	0.115	0.380	45	0.302	0.990
Elev 1 - Elev 3	1.173	0.382	45	3.067	**0.019**
Elev 1 - Elev 4	1.402	0.395	45	3.551	**0.005**
Elev 2 - Elev 3	1.057	0.371	45	2.852	**0.032**
Elev 2 - Elev 4	1.287	0.373	45	3.454	**0.006**
Elev 3 - Elev 4	0.230	0.363	45	0.632	0.921
b. Contrast for 2022	**Estimate**	**SE**	***df***	**t.ratio**	**p.value**
Elev 1 - Elev 2	0.229	0.406	45	0.564	0.942
Elev 1 - Elev 3	0.828	0.426	45	1.942	0.225
Elev 1 - Elev 4	1.850	0.453	45	4.082	**0.001**
Elev 2 - Elev 3	0.599	0.416	45	1.440	0.482
Elev 2 - Elev 4	1.621	0.439	45	3.694	**0.003**
Elev 3 - Elev 4	1.022	0.432	45	2.369	*0.098*

Note. At end of season in (a) 2021 and (b) 2022. Treatments significant at α=0.05 are in bold. Marginally significant treatments at α=0.10 are italicized.

Table 2.7

Tukey Pairwise Comparison Between Elevations of Seeding Treatments and Invasive Cover

a. Contrast for 2021	**Estimate**	**SE**	***df***	**t.ratio**	**p.value**
Elev 1 - Elev 2	-0.513	0.370	45	-1.387	0.514
Elev 1 - Elev 3	-0.936	0.360	45	-2.600	*0.059*
Elev 1 - Elev 4	-0.898	0.359	45	-2.504	*0.072*
Elev 2 - Elev 3	-0.423	0.347	45	-1.220	0.617
Elev 2 - Elev 4	-0.385	0.342	45	-1.126	0.676
Elev 3 - Elev 4	0.0375	0.323	45	0.116	1.000
b. Contrast for 2022	**Estimate**	**SE**	***df***	**t.ratio**	**p.value**
Elev 1 - Elev 2	-0.578	0.424	45	-1.365	0.527
Elev 1 - Elev 3	-0.918	0.429	45	-2.141	0.156
Elev 1 - Elev 4	-1.036	0.423	45	-2.447	*0.083*
Elev 2 - Elev 3	-0.339	0.401	45	-0.846	0.832
Elev 2 - Elev 4	-0.458	0.398	45	-1.150	0.661
Elev 3 - Elev 4	-0.118	0.386	45	-0.306	0.990

Note. At end of season in (a) 2021 and (b) 2022. Treatments significant at α=0.05 are in bold. Marginally significant treatments at α=0.10 are italicized.

Table 2.8

Type *II ANOVA Table for Species Richness Model Output*

a. Model for 2021	X^2	***Df***	$Pr(>X^2)$
Elevation	6.002	3	0.112
Treatment	33.417	2	**<0.001**
Elevation × Treatment	8.097	6	0.231
b. Model for 2022	X^2	***Df***	$Pr(>X^2)$
Elevation	2.423	3	0.488
Treatment	8.54	2	**0.014**
Elevation × Treatment	1.464	6	0.962

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Note. Across the four elevations in (a) 2021 and (b) 2022. Treatments significant at $\alpha=0.05$ are in bold.

Table 2.9

Tukey Pairwise Comparison for Species Richness Models

a. Contrast for 2021	**Estimate**	**SE**	***df***	**t.ratio**	**p.value**
1× - 5×	0.282	0.137	45	2.133	*0.095*
1× - Control	1.0	0.328	45	3.048	**0.011**
5× - Control	0.3	0.328	45	0.914	0.634
b. Contrast for 2022	**Estimate**	**SE**	***df***	**t.ratio**	**p.value**
1× - 5×	0.75	0.385	45	1.950	0.137
1× - Control	1.10	0.385	45	2.859	**0.017**
5× - Control	0.35	0.385	45	0.910	0.637

Note. For years (a) 2021 and (b) 2022. Treatments significant at α=0.05 are in bold. Marginally significant treatments at α=0.10 are italicized.

Table 2.10

Type II ANOVA Table for Distichlis spicata *Treatments*

a. Model for 2021	X^2	*Df*	$Pr(>X^2)$
Elevation	12.420	3	**0.006**
Treatment	201.373	2	**<0.001**
Elevation × Treatment	18.457	6	**0.005**
b. Model for 2022	X^2	*Df*	$Pr(>X^2)$
Elevation	16.114	3	**0.001**
Treatment	19.465	2	**<0.001**
Elevation × Treatment	15.940	6	**0.014**

Note. On end of season cover across the four elevations in (a) 2021 and (b) 2022. Treatments significant at α=0.05 are in bold.

Table 2.11

Type II ANOVA Table for Total End of Year Cover of Schoenoplectus acutus *Treatments*

a. Model for 2021	***X^2***	***Df***	***$Pr(>X^2)$***
Elevation	22.804	3	**<0.001**
Treatment	49.047	2	**<0.001**
Elevation × Treatment	23.652	6	**<0.001**
b. Model for 2022	***X^2***	***Df***	***$Pr(>X^2)$***
Elevation	4.743	3	0.192
Treatment	19.534	2	**<0.001**
Elevation × Treatment	18.901	6	**0.004**

Note. Across the four elevations in (a) 2021 and (b) 2022. Treatments significant at α=0.05 are in bold.

Table 2.12

Tukey Pairwise Comparison of Treatment and Elevation Interactions on Distichlis spicata

a. Contrast for 2021	**Estimate**	**SE**	***df***	**t.ratio**	**p.value**
Elevation 1:					
Control - Clumped	-2.683	0.399	45	-6.731	**<0.001**
Control - Dispersed	-3.577	0.390	45	-9.171	**<0.001**
Clumped - Dispersed	-0.894	0.179	45	-4989	**<0.001**
Elevation 2:					
Control - Clumped	-2.612	0.389	45	-6.720	**<0.001**
Control - Dispersed	-3.267	0.386	45	-8.472	**<0.001**
Clumped - Dispersed	-0.655	0.181	45	-3.627	**0.002**
Elevation 3:					
Control - Clumped	-2.817	0.417	45	-6.754	**<0.001**
Control - Dispersed	-2.812	0.420	45	-6.692	**<0.001**
Clumped - Dispersed	0.005	0.202	45	0.022	1.000
Elevation 4:					
Control - Clumped	-1.496	0.453	45	-3.301	**0.005**
Control - Dispersed	-2.592	0.413	45	-6.276	**<0.001**
Clumped - Dispersed	-1.096	0.294	45	-3.726	**0.002**
b. Contrast for 2022	**Estimate**	**SE**	***df***	**t.ratio**	**p.value**
Elevation 1:					
Control - Clumped	-2.752	0.642	45	-4.284	**<0.001**

Control - Dispersed	-3.047	0.678	45	-4.493	**<0.001**
Clumped - Dispersed	-0.295	0.466	45	-0.632	0.803
Elevation 2:					
Control - Clumped	-3.071	0.687	45	-4.467	**<0.001**
Control - Dispersed	-3.471	0.696	45	-4.985	**<0.001**
Clumped - Dispersed	-0.401	0.448	45	-0.894	0.647
Elevation 3:					
Control - Clumped	-1.341	0.673	45	-1.993	0.126
Control - Dispersed	-2.177	0.756	45	-2.878	**0.017**
Clumped - Dispersed	-0.835	0.568	45	-1.470	0.315
Elevation 4:					
Control - Clumped	-0.728	0.624	45	-1.166	0.479
Control - Dispersed	-0.195	0.619	45	-0.315	0.947
Clumped - Dispersed	0.533	0.610	45	0.874	0.660

Note. End of season cover (a) 2021 and (b) 2022. Treatments significant at α=0.05 are in bold.

Table 2.13

Tukey Pairwise Comparison of Treatment and Elevation Interactions on Schoenoplectus acutus

a. Contrast for 2021	**Estimate**	**SE**	***df***	**t.ratio**	**p.value**
Elevation 1:					
Control - Clumped	<0.001	0.416	45	-5.150	**<0.001**
Control - Dispersed	<0.001	0.417	45	-6.208	**<0.001**
Clumped - Dispersed	<0.001	0.232	45	-1.933	0.141
Elevation 2:					
Control - Clumped	<0.001	0.439	45	-2.516	**0.040**
Control - Dispersed	<0.001	0.399	45	-5.581	**<0.001**
Clumped - Dispersed	<0.001	0.297	45	-3.780	**0.001**
Elevation 3:					
Control - Clumped	<0.001	0.445	45	-2.103	0.101
Control - Dispersed	<0.001	0.445	45	-2.103	0.101
Clumped - Dispersed	<0.001	0.331	45	0.000	1.000
Elevation 4:					
Control - Clumped	<0.001	0.498	45	-0.236	0.970
Control - Dispersed	<0.001	0.488	45	-0.559	0.842
Clumped - Dispersed	<0.001	0.480	45	-0.324	0.944
a. Contrast for 2022	**Estimate**	**SE**	***df***	**t.ratio**	**p.value**
Elevation 1:					
Control - Clumped	-2.171	0.515	45	-4.212	**<0.001**

Control - Dispersed	-1.692	0.523	45	-3.235	**0.006**
Clumped - Dispersed	0.479	0.371	45	1.293	0.407
Elevation 2:					
Control - Clumped	-2.181	0.537	45	-4.065	**<0.001**
Control - Dispersed	-2.400	0.520	45	-4.611	**<0.001**
Clumped - Dispersed	-0.218	0.318	45	-0.686	0.773
Elevation 3:					
Control - Clumped	-0.172	0.537	45	-0.320	0.945
Control - Dispersed	-1.096	0.458	45	-2.391	*0.054*
Clumped - Dispersed	-0.924	0.442	45	-2.093	0.103
Elevation 4:					
Control - Clumped	0.139	0.556	45	0.250	0.966
Control - Dispersed	-0.028	0.562	45	-0.049	0.999
Clumped - Dispersed	-0.167	0.548	45	-0.304	0.950

Note. On end of season cover (a) 2021 and (b) 2022. Treatments significant at α=0.05 are in bold. Marginally significant treatments at α=0.10 are italicized.

Chapter III

Restore the shore—a guide to lakeshore revegetation in the Great Basin

Introduction

In the semi-arid West of the U.S., lakes are vital resources for humans and wildlife (Endter-Wada et al., 2020; Zedler & Kercher, 2005). The vegetation of lakeshores supports many valuable aspects of lake ecosystems: foraging areas for birds, rearing grounds for fish, and aesthetic, cultural, and spiritual values (Strayer & Findlay, 2010). Yet, the vegetation of many lakeshores has been lost or heavily impacted by humans. What can be done to restore lakeshore vegetation to ensure that lakes remain healthy for future generations?

We summarize best practices for lakeshore revegetation (i.e., the process of actively reintroducing vegetation, usually native species, to a restoration site through seeding and planting) in the Great Basin. Although we focus on the Great Basin region (**Figure 3.1**), many of the issues and strategies described below are relevant to other regions of the semi-arid West of the U.S. or even other parts of North America. Some elements may also be relevant to reservoirs (human-made lakes) where some of the same plants can be supported even if the site was not historically a lake. This guide is for public land managers, restoration practitioners, private landowners, or anyone who is looking to restore and revegetate a lakeshore.

For each topic, we offer background information and practical applications for carrying out restoration and management activities, which translates into nine best practices for reestablishing lakeshore vegetation, each with a summary of background information and how to apply the practice. Here we define restoration as the process of assisting the recovery of an ecosystem that is degraded, damaged, or destroyed (Restoration Resource Center (n.d)). This guide emphasizes the importance of prioritizing and balancing different factors such as workload, budget, time, and environmental conditions when making decisions and implementing strategies.

What exactly is a lakeshore wetland?

We define lakeshore wetlands (hereafter lakeshores) as the vegetated edges of lakes where flooding or saturated soils support wetlands, hydric soils (i.e., wetland soils that form due to low oxygen conditions from flooding or saturation; Hydric Soils, n.d.; Rohal et al. 2017), and hydrophytes (i.e., vegetation that survives and often thrives under flooded, low oxygen soil conditions in wetlands). These lakeshores may include some of the following types of wetlands (**Figure 3.2**; adapted from Downard et al., 2017):

- **Playa wetlands** (playa for short; also called salt flats) have shallow, temporary flooding or no flooding but saturated soil for at least part of the year (usually just spring). These wetlands form when soils are salty (due to salts wicking to the surface after moisture from spring flooding/soil saturation evaporates) and thus have a distinct plant community of short-statured, salt-tolerant species like pickleweed (*Salicornia rubra*) interspersed with bare ground.
- **Mudflats** occur when emergent and submergent wetlands are drawn down (which can happen roughly every few years) and the largely unvegetated “mud” layer is exposed. These areas are often dominated by short-lived annual species (i.e.,

plants that complete their whole life cycle in one growing season) that thrive under these temporary, high light, moist environments (**Figure 3.3**)

- **Meadow wetlands** are shallow and seasonally flooded. They are dominated by medium-sized plants like sedges, rushes, and grasses.
- **Shallow to mid-depth emergent wetlands** have semipermanent to intermittent flooding and are dominated by taller, emergent plants (i.e., plants that are rooted in the soil but whose leaves and stems extend out of the water) like cattails (*Typha* spp.) and bulrushes (*Schoenoplectus* spp.).
- **Shrub and forested wetlands** have temporary or seasonal flooding or a high-water table that forms hydric soils. Vegetation is largely shrubs and trees that can handle flooding and soil saturation.
- **Deep emergent and submergent wetlands** have deeper, permanent flooding and are dominated by aquatic vegetation (rooted, submerged plants, which have most of their structures below the water surface; rooted, floating-leaved plants; and unrooted, floating plants).

Beyond these lake depths (~2 m), vegetation is sparse due to light limitation in the deeper water. Just as lakes in this region can range from fresh to saline so can lakeshores.

Why should we care about lakeshore vegetation?

Lakeshore vegetation occurs in the transitional area where uplands meet lakes. It is an area that provides food and habitat for animals, cleans and cycles nutrients, and stores carbon. Additionally, lakeshores offer great areas for fishing and hunting and reflect cultural heritage and spiritual values.

How have humans impacted lakeshore vegetation?

We focus on human impacted lakes in the Great Basin region of the U.S. where lakeshores have experienced varying degrees of plant and animal invasions (like the highly invasive grass *Phragmites australis* (hereafter phragmites) and carp (*Cyprinus carpio*)), dramatically changing water levels (such as from water withdrawals and reservoir storage), inappropriate cattle grazing, excess nutrients, declining water quality, and degraded wildlife habitat (Allen & Klimas, 1986; Chambers et al., 1999; Chapman et al., 2013; Duncan et al., 2019; Yuckin & Rooney, 2019; Zohary & Ostrovsky, 2011).

Lakeshore revegetation in relatively unimpacted sites is already challenging due to the continuously changing nature of this transitional environment (sandwiched between terrestrial environments and the deepwater lake) where plants must withstand wetting and drying; potentially anoxic (lacking oxygen) soil conditions; herbivory from birds, muskrats, and beavers; and waves and ice shearing (Gasith & Gafny, 1990; Rietkerk et al., 2004; Wantzen et al., 2008). These environmental stressors (i.e., naturally occurring environmental conditions that can make life difficult for plants, animals, and microbes such as flooding and high salinity) and disturbances combined with human impacts mean that efforts to revegetate lakeshores must be carefully planned, expertly carried out, and extensively monitored to ensure long-term ecosystem recovery. Here we provide concrete suggestions for how to do just that.

1. Evaluate the site as thoroughly as possible

Background

Before revegetation starts, it is important to take the time to gain information about the potential site and reflect on its future restoration possibilities. A more complete understanding of the site (historical *and* present conditions) and its future possibilities will inform appropriate revegetation interventions. Here we focus on five main areas for consideration (1) watershed location, topography, and soils, (2) hydrology, (3) climate, (4) plants and animals, and (5) human impacts. Together these factors influence the environmental conditions of the site including environmental stressors as well as disturbances, which determine what plants can survive and thrive at the site. Thus, gathering, synthesizing, and sometimes mapping information about all aspects of the site will guide the choice of ecologically appropriate interventions. Although the revegetation planning timeline may not always align with funding cycles and staff capacity, time invested before "breaking ground" at the site will pay off in the long term. Here we provide a framework for how to proceed (**Table 3.1**).

Application

1. Assess **watershed location, site topography, and soils** to determine how they may impact proposed restoration goals and activities.
2. Characterize site **hydrology**, especially changes in inundation across and within years as well as the movement of water through the site.
3. Recognize the general **climate** of the site (temperature, precipitation) and how it may influence what plants and animals can thrive there.

4. Determine the common **plants** (including target species for revegetation and invasive species for removal) and identify native plants that desired **animals** would benefit from.
5. Assess past and on-going **human impacts** to the site.
6. Use **site visits**, conversations with **landowners**, existing published or online **restoration resources**, **mapping tools**, and plant **databases** to inform revegetation planning.

2. Build the foundation for a solid revegetation plan

Background

Project planning for revegetation is a multi-stage process addressing ecological and social factors. As discussed above, the ecological conditions of the site and the watershed in which it is located are critical aspects of restoration context driving outcomes. The social context is equally important to assess. Some key considerations to address are described below.

Identify, organize, and engage stakeholders

Stakeholders are the people actively involved in the project ('project stakeholders') and those impacted by or simply interested in the project ('community stakeholders') (Howell et al., 2012; Shackleton et al., 2019). The project stakeholders are usually self-evident, i.e., those with training and expertise in implementing revegetation like plant ecologists, botanists, and native plant growers. The community stakeholders may require more effort to identify and engage but they should not be ignored. If there is a misalignment between the stakeholder groups—like the project stakeholders want to prioritize plant diversity in the restoration while the community stakeholders want to prioritize recreational use of the site—the project may be slow to progress and ultimately unsuccessful. Enlisting a professional trained in engaging public stakeholders may be essential depending on the size and complexity of the project (Adams et al., 2021).

Articulate the broad goals

A key question to ask here is, *what are the broad goals of the project that align with the ecological context and the needs and desires of stakeholders?* For lakeshore revegetation it is important to recognize the often-divergent goals of stakeholders that may differ from what is possible given the watershed context. For instance, community stakeholders might prioritize high quality bird habitat at a site but extensive degradation in the watershed might limit the bird species that might inhabit the site. More nuanced revegetation goals will be required then to assure that goals can be met given the watershed context including the extent of human impacts.

Design SMART objectives

Project objectives should be **SMART**: **S**pecific, **M**easurable, **A**chievable, **R**ealistic, and **T**ime-bound (Doran, 1981). SMART objectives ensure that project stakeholders know exactly what they are trying to achieve so that by the end of the project funding period, it is possible to assess if the project was successful. Outlining SMART objectives is surprisingly difficult especially in areas where lakeshore revegetation is a relatively new endeavor, where project stakeholders might have limited experience working, or where watershed or site degradation is high.

Identify the ecological references

Ecological references are the desired ecological state of the revegetation site (Clewell & Aronson, 2013). References are closely aligned with the project objectives and are important to identify. This task can be done by finding nearby healthy lakeshore sites that the restoration project site can (ideally) recover to resemble. Or, if such healthy sites do not exist, the project team may turn to historical accounts of the project site and what vegetation existed there prior to human disturbance and how different species occurred naturally across the site. In some sites, returning to historic or reference conditions may not be possible (e.g., due to climate change or drastic alterations to the site). Here, managers should instead establish a desired future condition (balancing project goals with the site's limitations) to use as a guide. Either way, the project team needs a visual and written guide to know what the revegetation site should ultimately look like once the project is completed and to determine if success has been achieved (Clewell & Aronson, 2013).

Assess organizational capacity of the project team

The budget is one consideration when assessing organizational capacity, but human capacity is also important (Bohnen & Galatowitsch, 2020). Specifically, does the restoration team include members who have experience in lakeshore revegetation and in managing the logistics of large, potentially complicated projects? A small budget with a less experienced team can still achieve restoration goals but acknowledging limitations up front is key to mapping out a successful project within the capacity of the team.

Develop a realistic project timeline

Project timelines should consider what is required for the ecological development of the site (e.g., how long might the plant community take to reestablish?). Timelines should also recognize that projects with highly degraded sites or watersheds as well as inexperienced revegetation teams may take substantially longer to complete than initially expected. A ‘one and done’ approach to restoration does not work in most situations and may require multiple years of invasive species management and planting given the extent of site degradation, weather that limits plant establishment, and other factors.

Application

1. Organize project stakeholders and engage community stakeholders.
2. Articulate the broad goals of the project.
3. Design SMART objectives that are specific, measurable, achievable, realistic, and time bound.
4. Identify ecological references, whether they be nearby reference sites or written descriptions of the ultimate desired state of the revegetation project site.
5. Assess organizational capacity of the revegetation team, both the budget available and the experience of team members with lakeshore revegetation.
6. Develop a realistic project timeline for restoration activities and post-project monitoring.

3. Tackle nutrient pollution and sedimentation

Background

Nutrient and sediment accumulation in lakes and reservoirs is affected by upstream land-use (e.g., agricultural practices, urban development, etc.), frequency of lake drawdown (Carmignani & Roy, 2017), and the geology of the watershed (Soranno et al., 2015). Although the transport of nutrients and sediment from the upper to the lower watershed is a natural process, in excess, sediments can lead to the filling of lakes over time (Paul et al., 2008) and excess nutrients can favor the establishment of invasive or other undesirable species over native species (Zedler & Kercher, 2004). Practitioners should consider, to the extent possible, the implementation of strategies that can minimize unnatural nutrient and sediment transport *throughout the lake's watershed* while also mitigating nutrient and sedimentation issues *at the restoration site* itself.

Practitioners can support watershed-wide strategies to lessen nutrient and sediment issues (e.g., activities to improve soil health, enhance wetland and riparian habitats throughout the watershed, minimize point-source pollution, address inappropriate grazing practices, etc.). Such efforts are often led by watershed coordinators, watershed councils, conservation districts, and county Extension agents. At the restoration site, reducing excess nutrient pollution in wetland soil prior to revegetation could favor the establishment of native plants over invaders (Iannone & Galatowitsch, 2008; Zedler & Kercher, 2004). A history of Inappropriate livestock grazing on the site may have resulted in elevated soil and water nutrients as well as compacted soil that may need to be mitigated before revegetation efforts ("Rangeland Health and BLM Grazing Programs", 2022; Western Watersheds Project, 2022). However, the extensive addition of soil amendments is likely impractical for most projects (Iannone et al., 2009; Kettenring & Adams, 2011). As such, the prioritization of long-term invasive species monitoring and removal (see 4. Lessen the impacts of invasive plants) in areas experiencing a high influx of nutrients (e.g., a culvert, canal, etc.) is a more practical strategy (Blossey, 1999; Lombard et al., 2012). In some restoration contexts, it may be possible to select species to revegetate that will support bioremediation processes (see 5. Choose appropriate plant species).

Sediment accumulation can both positively and negatively affect lake hydrology and consequently, lakeshore wetland vegetation zones. Accumulation of sediment may cause breakwater effects in shallower zones. These higher ridges of sediment can encourage the establishment of submerged aquatic or emergent vegetation (Jellinek et al., 2016). Alternatively, increased sediment may limit the storage capacity of the lake, leaving lakeshores drier for longer periods of time, making it more difficult to support wetland plants (Espa et al., 2019; Gonzalez et al., 2023; also see **Table 3.2** for more information about the selection of species that can tolerate drier conditions). Increased sediments in lakes has been linked to a litany of direct and indirect negative effects on fish population, like increased mortality and decreased egg and larvae survival (Donohue & Molinos, 2009) A large part of these effects can be attributed to an exposed and vegetation-free lakeshore which perpetuates turbidity issues in the lake itself, limiting light and making it challenging to establish native submergent and emergent species (Austin et al., 2017; “Turbidity and Water”, 2019). Simultaneously, above the water line, this newly exposed area would be susceptible to invasion by unwanted species (Kercher & Zedler, 2004; see 4. Lessen the impacts of invasive plants).

In some cases, practitioners may need to pursue sediment removal techniques (e.g., flushing, dredging, etc.) at the site to restore desired basin morphology (Peterson

1981). If earth-moving activities are pursued, invasive plant monitoring and on-going weed management will be vital, as many invasive plants thrive in highly disturbed environments (Kercher & Zedler, 2004; Zedler & Kercher, 2004).

Application

1. Support watershed-wide best management practices to minimize the transport of excess nutrients and sediments.
2. Prioritize areas with high influx of nutrients and sediments for invasive species monitoring and removal.
3. Revegetate with species that can increase nutrient uptake and bioremediation.
4. Determine the extent to which sediment removal techniques should be applied while minimizing plant invasions in the disturbances.

4. Mitigate the impacts of invasive plants

Background

For many land managers, invasive species management is a large drain on resources and time. Invasive plants reduce biodiversity, degrade habitat, disrupt food webs, modify nutrient cycling, and alter salinity (Zedler & Kercher, 2004). There are many common lakeshore plant invaders in the Great Basin spanning grasses, forbs, shrubs, and trees (**Figure 3.4**; Chambers, 2008). For any revegetation project to be successful, invasive species must be effectively identified and managed before proceeding to reintroduce native plants. The approaches taken will vary depending on the species present and each species’ ecology (Weidlich et al., 2020) as well as the extent of their invasion but there are general principles to guide management regardless, as discussed below.

Manage invasive plants broadly and continuously

Invasive species are successful (and problematic) because of their aggressive growth and reproduction (Zedler & Kercher, 2004). As a result, any native revegetation is unlikely to be successful if the invader(s) is not thoroughly managed (Kettenring & Tarsa, 2020). Complete removal of an invader is rarely possible, nonetheless existing invader patches must be greatly reduced and their seed banks (i.e., the natural storage of seeds in leaf litter, on the soil surface, or in the soil which serves as a repository to produce subsequent generations of plants) must be depleted. Seed bank depletion involves triggering invader seedlings to grow from the soil and killing them before they reach reproductive maturity. The area surrounding the restoration site will need to be managed as well, as invader seeds can "rain" onto the site (e.g., Kettenring & Galatowitsch, 2011). Furthermore, any invasive species legacies (i.e., negative effects of invasive species that can persist after the species' removal, which can inhibit native plant reestablishment and reinforce invasion (Corbin & D'Antonio, 2012) must be addressed. As one example, many invasive species are so prolific that when they are killed with herbicide, they still leave behind lots of dead plant material that can blanket the ground (**Figure 3.5;** e.g., Holdredge & Bertness, 2011). This litter (the plant matter left behind, such as leaves and woody debris, after a plant has died outright or died back for the season) can shade out seeds of native species and prevent them from growing so managers will need to mow, burn, or graze this litter to break it down more quickly to prepare the site for revegetation.

Prioritize certain invasive species and areas when faced with limited funds, personnel, and time

In almost all instances, the number and extent of invasive species present will far exceed a manager's operations budget as well as the personnel needed to sufficiently manage all problematic species (Larson et al., 2011). When faced with this scenario, a prioritization scheme can guide decision-making and management actions. The best way to proceed, when faced with limited management budgets, is to first limit new infestations because often once species become well-established, they are challenging to manage (Moody & Mack, 1988; Rieger et al., 2014; Taylor & Hastings, 2004). Furthermore, these small infestations contribute more year-to-year to the overall area a species covers across the landscape than does expansion of existing, larger patches (Moody & Mack, 1988). From there move onto medium-sized infestations and visit the area repeatedly over a few years to ensure that follow-up treatments address any returning invader. It is not until small and medium-sized infestations are under control that it is best to move onto large, more challenging infestations. These areas will require many years of aggressive management and highly effective revegetation to keep the invader at bay.

However, the size of the infestation is not the only consideration. When faced with deciding which of many species to manage, it is best to first target the most aggressive invaders (especially before they become well established) and species with the greatest negative impact on the ecosystem (Rieger et al., 2014). If multiple species fit these criteria, prioritizing them based on the size of the infestation would be best.

Know the invaders and apply the appropriate management techniques

Techniques to manage invasive species include herbicide, mowing, burning, trampling, hand removal, and grazing (Weidlich et al., 2020). The choice of which combination of techniques to apply will depend on the invader. A quick internet search will often reveal best practices for managing the most common invaders; look for resources by the USDA and university Extension programs as they are often based on empirical research (see Rohal et al., 2017 for an example of a recommended resource). When faced with numerous management options, an important principle to guide decision-making is to match the management technique to the biology of the species (i.e., how the plant spreads, establishes, and grows) (Weidlich et al., 2020). For example, for a species that is known to spread both by seeds and clonally, management must address both forms of reproduction by preventing seed production (treating the plant before it sets seed, by mowing, for instance) *and* managing the patch of adult plants to prevent patch expansion (e.g., through the use of herbicides) (e.g., Rohal et al., 2019a, b). Also, note that many plants, including invaders, are most vulnerable as seeds and seedlings (Zedler & Kercher, 2004), thus any management targeted at this plant life stage is expected to have an outsize negative effect on the invader. See **Figure 3.6** below for an example of a lake that had significant invasive species established and has since recovered 75% of the shoreline back.

Utilize aggressive native plant revegetation to keep invaders at bay

Because invasive species management often disturbs natural areas, leaving the wetland more vulnerable to new and on-going invasions, it is important to quickly reestablish native vegetation to hold the ground (Kettenring & Adams, 2011; Kettenring & Tarsa, 2020). There are many considerations to how to do this revegetation effectively. Ideally, some of the native plants that are reintroduced are those that compete well against the invader (see 5. Choose appropriate plant species). In addition, the density at which the native species are seeded or planted (see 6. Restore functionality with plant material types, timing, and arrangements) should be sufficiently high to occupy the open space that remains after invader management and to quickly capture available resources: light, nutrients, water, and space to the detriment of the invader (Tarsa et al., 2022).

Prioritize follow up treatments and monitoring

Because invasive species are unlikely to ever be completely removed from a site or watershed, it is imperative to prioritize follow-up management of previously treated areas and continual monitoring to identify new infestations. Spot spraying returning invaders is the most common follow-up management approach. The monitoring can be paired with revegetation monitoring as described in 9. Monitor projects for continuous learning.

Application

1. Complete any necessary multi-year invasive species management efforts prior to revegetation.
2. Management should address both invaders on-site as well as nearby patches (to the extent possible) to prevent future invasions.

3. Prioritize small infestations and the most aggressive invaders first before tackling more extensive patches and less aggressive species.
4. Match management approaches the biology of the invader to maximize effectiveness.
5. Aggressively revegetate with native plants following management especially to mitigate any disturbances that result from invasive species management.
6. Prioritize follow-up invader management treatments and monitoring.

5. Choose appropriate plant species

Background

The choice of which species to seed or plant should be based on restoration goals and objectives. Furthermore, the chosen species will need to be adapted to site conditions, particularly natural stressors like inundation regimes and salinity, as well as to future site conditions likely to occur with climate change.

Consider restoration goals and objectives

Practitioners should consider restoration goals and objectives (see 2. Build the foundation for a solid revegetation plan) when selecting species for revegetation. Specific plant species or communities can facilitate goals such as bioremediation, erosion control, invasive species resistance (i.e., functionally different species for more complete resource use), and the provisioning of habitat for people and wildlife. For example, if one of the restoration goals is to improve waterfowl habitat, the selection of plant species should take into account relevant characteristics such as growth form, reproductive mode, size, and seasonal timing. that are most relevant to habitat (see **Table 3.2** for potential species with different desired characteristics). The selection of plant species for revegetation should be based on their functional roles within the ecosystem. Consideration should be given to various traits such as flower color, size, structure, and timing of flowering, especially when improving habitat for pollinators. Additionally, the quality and quantity of seed production by plant species may be relevant for food production for waterfowl. In cases where bioremediation is a restoration goal, certain plant species that accumulate nutrients and heavy metals more effectively than others can be introduced to enhance the process (Yan et al., 2020).

Consider site specific stressors

Shoreline environments can be hydrologically stressful for plants (Vanderbosch & Galatowitsch, 2010). Plants experience drought and flooding at relatively unpredictable times, exceeding physiological tolerances (Allen & Klimas, 1986). These water level changes, and other factors such as geomorphology, climate, and land use history, can also influence salinity at the site. Also, shallow waters are more prone to changes in water chemistry due to reduced volume, which can result in concentrated salts with upstream diversions and summer evaporation. With complete dewatering, soil surfaces can form salt crusts as water wicked up from deeper depths with evaporation bringing salt to the soil surface. Choosing the right species, sources, and planting methods (see 6. Restore functionality with plant material types, timing, and arrangement) that align with site conditions is a tool to ensure plant community establishment and persistence. Some plant species have evolved to be more adaptable to water level stressors and salt stress (see Table 6), whether that is through a more generalist approach (species with broad physiological tolerances) or through local adaptation (e.g., seed sources that are adapted to site conditions).

Plan that site environmental conditions will change (potentially a lot) with climate change

Watersheds of lake and reservoir systems foster a diverse set of ecosystems; however, climate change is heavily impacting these lands (Abrahams, 2008; Leira & Cantonati, 2008; Wantzen et al., 2008; Zohary & Ostrovsky, 2011). An already highly dynamic shoreline environment can experience further fluctuations that exceed historical levels and happen at unpredictable times. Whether by prolonged periods of drought, heavy downpours with sharp influxes in water levels, or increased sedimentation due to upland fires, restoration practitioners should expect and plan for these weather extremes as the “new norm”. One approach is to choose suitable species for a site that can establish and persist not only now but into the future. Most areas in the Great Basin are trending towards hotter and drier growing seasons with unpredictable swings in snowpack and rainfall. Choosing plants that can handle longer periods of drought, heavy flooding, higher salinity, and heat waves will be key to maintaining native plant communities in the future.

Application

1. Choose functionally diverse species that will support restoration goals and objectives.
2. Design the seed mix to include species with a range of tolerances to current and future flooding, drought, and salinity scenarios.

6. Determine the optimal plant material type, planting timing, density, and arrangement

Background

Choosing the right plant species for a restoration is a crucial step in revegetation decision-making. From there, it is important to decide which plant material type(s) are suitable for the restoration as species can be introduced as seeds, seedling plugs, poles and cuttings, rhizomes, and mats. The timing of when to introduce seeds and plants will depend on the species' requirements and site environmental conditions (see 5. Choose appropriate plant species). Finally, seeds and plants can be introduced across a range of densities and arranged in a clumped or dispersed fashion, which represent restoration choices that we outline below.

Choose suitable plant material types

There are numerous types of plant material—such as seeds, plugs, poles and cuttings, rhizomes, and mats—that can be introduced into a restoration site (**Table 3.3**).

Decide on the optimal timing of seeding and planting

Timing when to introduce seeds or plants to the restoration site must align with the basic environmental needs of the chosen species including seed and plant temperature requirements and tolerances to inundation or drought. Dormant seeds and plants can be introduced to the site outside the growing season, but more commonly they are introduced towards the start or end of the growing season (potentially avoiding temperature extremes that can be lethal to seeds and immature plants). There is some promising data that suggests that native seeds planted a few weeks prior to the germination and emergence of invasive plants can have a vastly higher chance of competing, and winning, over invasive recruits (Tarsa et al., 2022).

Working with the changing shoreline water levels can also be challenging. The first few weeks of a transplant or seeds' time in the field is when the highest mortality occurs. Timing planting for when the water level is moderately high and gradually receding is likely to enhance establishment. Rising water levels may wash away seeds or drown vulnerable seedlings while rapidly falling water levels may cause drought conditions that kill seeds and seedlings. If the target lake level recedes substantially over the year (e.g., from upstream diversions during the agricultural irrigation season), opt for multiple plantings throughout the growing season following the falling shoreline, either at multiple planting times or multiple planting elevations. See **Figure 3.7** for an example site that varied planting elevations. If the site is likely facing a drought, consider short-term, supplemental irrigation to protect the revegetation investment if nearby water sources (groundwater, canals, etc.) can be tapped with irrigation lines, or manually watering the transplants and seeds during their first few weeks of growth. If the site is likely facing extreme flooding due to a higher-than-average snowpack, delay the restoration until water levels have fallen back to normal levels.

Choose ideal seeding and planting densities

The density of planting and seeding in restoration is often based on adult plant distributions and budgets (Houck, 2009; Kettenring & Tarsa, 2020; Rieger et al., 2014). As a result, many revegetation projects fail to introduce plants and seeds at sufficient densities to overcome the high mortality that occurs for seeds and seedlings. Seeding and planting at higher rates can lead to increased establishment and cover due to a higher likelihood that the seeds and seedlings overcome mortality (Burton et al., 2006) and harness facilitation (i.e., when when closely growing neighboring plants have a positive effect on each other's survival, growth, and fitness; Silliman et al., 2015). However, densities that are too high can lead to competition within the seed mix or planted species (Burton et al., 2006). Thus, it is important to strike the balance between failing to overcome high seedling mortality rates from using too low of a density versus using such a high density that seed mixes or planted communities compete with each other and waste restoration resources (Tarsa et al., 2022). Seeding rates are typically based on the viability—or percent of live seed—which can either be found on the bags of commercially purchased seeds or calculated by a lab. This seeding rate is referred to as PLS (Pure Live Seed) which is equal to the % of pure seed times the viability of the seed all divided by 100 (Rieger et al., 2014). In grassland ecosystems, it is suggested that a 2x increase in current restoration seeding rates (currently 400-600 PLS m^{-2}) and a 4x increase in seed mix diversity (currently 3-10 species) may result in better restoration outcomes (Barr et al., 2017); however, the ideal sowing density is likely highly dependent on restoration objectives, such as establishing a desired percent cover of species or a specific density of individuals (Rieger et al., 2014, Burton et al., 2006, Sullivan 2001). Higher sowing densities (1,500–6,000 PLS m^{-2}) increased native plant density in upland systems the first year, but plant density fell the following year as a result of mortality that was density dependent (Burton et al., 2006). In a recent study on Utah Lake, Braun and Kettenring (2023), found that seeding had a positive effect on the establishment of desired native species, but the density of seeding (when comparing a 1x and 5x (960 PLS

m^{-2}) density) had no effect. The required seeding and planting densities are highly restoration specific based on the site context (e.g., extent of high mortality flood or drought events) and will require fine tuning to ensure high plant community recovery at a particular site.

Determine appropriate planting arrangements

Another approach to mitigating high stress for plants along lakeshores is to use clumped (as opposed to dispersed) planting arrangements that harness positive plant feedback called facilitation. Facilitation occurs when closely growing neighboring plants have a positive effect on each other's survival, growth, and fitness (Silliman et al., 2015). This facilitation promotes establishment under otherwise harsh environmental conditions such as the stress from the lack of oxygen in the root zone of flooded plants, but when planted closer together plants can benefit from neighboring plants that are also releasing oxygen from their roots, which cumulatively change the root zone environment for all plants (Bertness and Hacker 1994; Silliman et al., 2015). In another example, grasses and sedges planted closely together can mitigate erosion stress generated by waves or high currents (Silliman et al., 2015). The belowground root and rhizome systems of plants absorb most of the wave and current stress which reduces erosion around more interior plants. Clustered planting along shorelines can cause a breakwater effect because sediment settles between the restored area and the shoreline. This planting arrangement further facilitates the recolonization of wetland plants along the water's edge (Jellinek et al., 2016). However, facilitation is not always at play especially when plant stress from flooding, salinity, and waves is minimal thus, the need for clustered planting is context dependent. Placing plants too close together in low stress situations can inhibit future growth by causing them to compete with each other for resources. Careful consideration of site-specific stressors can help guide these arrangement decisions.

Application

1. Work with the changing shorelines. If the general annual ebbs and flows of the system are known, plant at a time that will provide the most moisture during the first month of growth of the transplants or seeds. Pay attention to and work around extreme weather years.
2. Select the plant material type(s) that works best with the budget and site.
3. Find a seeding balance: Higher seeding densities = higher establishment but too high of a density can increase costs and competition among seeded species and individuals.
4. In high wave and flooding stress situations, placing plants close together can increase establishment and stress resistance through facilitation.

7. Use tactics to secure and protect seeds and plants along lakeshores

Background

Many lakeshores are high energy, highly dynamic environments where fetch and waves can disrupt revegetation activities by dislodging new plantings, flushing seeds away, and depositing plant litter and sediments that can bury seedlings and small plants (Doyle, 2001). In one study of lakeshore restoration in Minnesota, the greatest revegetation failure occurred along the shoreline, at the land to water transitional zone versus the more upland and aquatic zones (Vanderbosch & Galatowitsch, 2010).

However, there are potential solutions. Choosing structures to disperse wave energy or secure newly installed plants and seeds can improve plant establishment. Sites with protected shorelines are more likely to support native vegetation. Additionally, using wave break tools can lead to higher establishment success. Choosing one, or a combination, of these options can help new plants establish on site.

Employ wave breaks

Implementing structures to dissipate wave energy can reduce plant mortality and dislodgement. These structures should be used until plants are well-established, sometimes up to 3 or 4 years. In coastal areas, concrete wave barriers are widely used (Cuong et al., 2015). Wave break structures made of PVC and placed in a 'double-nested V' shaped formation are also effective (Clark et al., 1999). While these wave breaks are beneficial, many biodegradable options exist that better align with stakeholder values for restoring more natural lakeshores. Wooden wave breaks, called fascines, can be created using bundles of sticks bound together (with biodegradable materials) and rooted to the soil (see **Figure 3.8**). If live sticks are harvested from species that reproduce clonally and are properly cared for, these wave breaks can take root, and create a small band of trees that can double as a windbreak once fully established (Irvine & Ohio Department of Natural Resources, n.d.; USDA NRCS, 1996). Coconut coir rolls can be implented as wave breaks and double as a method to introduce plantings (Massachusetts Office of Coastal Zone Management, 2013).

Anchor plants in place

A different approach to protecting new plantings is anchoring plants to the soil. This anchoring can be done with burlap, staples, or lattice. Seedlings can be planted within *burlap bags* filled with sand to provide a stable sediment environment for establishment. Small pieces of rhizomes that have stems can also be woven into a coarse weave mat of *burlap* to anchor them to the ground and help stabilize sediments. This transplanting should be done in a narrow time frame from harvesting to planting (roughly 24–36 hours) to keep the rhizomes healthy. Both of these burlap uses have also been shown to help with seed recruitment, an added bonus. In fact, restoration practitioners have successfully used bare strips of burlap, attached to the shoreline, to facilitate seed entrapment and subsequent seedling establishment (Irving et al., 2013). *Staples* can be used to stabilize rhizomes or plugs and to prevent them from being uprooted by wave inundation or herbivory). With *lattice planting*, plugs are planted into the lattices and pinned to the ground. Lattices are usually constructed of plastic, but some recent forms are made of biodegradable starches, allowing the whole structure to be left on site (Temmink et al., 2020). The pinned lattices can keep the plants protected from uprooting until they reach maturity. Lattice plantings require less maintenance than burlap and staples, and some of these lattices are large enough to double as wave breaks.

Secure seeds in place

Tackifiers can be used to help secure the seeds to soils. Tackifier is essentially a binding or glue-like material that can be made up of plant material, adhesive, or even mulch. These are best used in areas with little wave action as the tackifiers do break down under extended inundation. Most tackifiers are applied using heavy machinery as part of a hydroseeding process, so consider accessibility to the site(s). It can make seeding a larger area proceed more quickly, as well as help reduce erosion and dislodgement. Alternatively, mesh fencing can be placed around seeds in smaller areas to prevent them from washing away. This fencing should be slightly embedded in the soil and can be made from any thin, water permeable cloth to allow water and sunlight in but keep the seeds contained (e.g., bridal veil material). If not biodegradable, the material will need to be removed at some point.

Consider creative seeding approaches

Additional restoration technologies such as utilizing cover crops and seed coatings can help overcome potential issues with erosion, drought, and flooding. If there is a large area of land that is susceptible to erosion, consider using a cover crop. These crops can be planted right away, are typically fast-growing annuals, and do not compete with most perennial (i.e., a species that has its whole life cycle over two or more growing seasons) seeded species (Espeland & Perkins, 2013). These cover crops should be sterile and non-persistent and can help stabilize the land with their roots while a concurrent or second succession of plants can be planted in the area and given more time to establish. Furthermore, in a light limited restoration area, cover crops can help prevent some invasive species from establishing (Perry & Galatowitsch 2006).

If the site has troubles with herbivory (see next section for a more in-depth look at managing unwanted animal impacts) or consistently lightly flooded water, seed coating technologies could be a solution. Seed coats ‘wrap’ seeds in a binding, dissolvable layer. This layer can provide oxygen to a drowning seed at an integral moment of its germination, increasing the seedling's chance of survival. It can also decrease the loss of seeds due to animal herbivory, as the seeds will not be easily recognizable to predators (Taylor et al., 2020). Seed coats can also help weigh a seed down and keep it in place if there are waves or other water dislodgement obstacles (Madsen et al., 2016, Pedrini 2016).

Application

1. Protect new plantings from wave energy by creating wave breaks (i.e., live or wooden fascines or coconut coir rolls,).
2. Anchor plugs, seeds, and rhizomes to the soil with burlap, staples, or lattices.
3. Secure seeds to the soil by using a mesh fencing or tackifier.
4. Emerging restoration tools, like sterile cover crops and seed coatings, can be a great choice for ameliorating unfavorable restoration conditions.

8. Manage unwanted animal and human impacts

Background

Newly revegetated areas are particularly vulnerable to damage by fish, mammals, and birds particularly for species that may be attracted to fresh plant material and abundant, fresh seeds. Nearby sites may also harbor species like deer and beaver that can easily access the restoration site and may cause damage. Curious humans may inadvertently cause damage by trampling the restoration area. What can be done? We discuss some options below.

Remove nuisance fish

Restoration of submergent and emergent wetland communities may require mitigation of the negative impacts of invasive or nuisance fish. Submerged Aquatic Vegetation (SAV,) in particular, are threatened by fish like carp that bottom-feed—uprooting plants and increasing turbidity (Lathrop et al., 2013). Nuisance fish can be managed with various methods (i.e, intentional harvesting, piscicides like Rotenone, etc.). In some situations, underwater exclosures can be built to mitigate direct impacts of these fish on freshly planted SAV, at least when working at smaller scales.

Manage livestock

Grazing pressure of intense duration or frequency, especially in the first year, may limit plant establishment, growth, and reproduction. Temporary fencing can be installed to keep animals out of particular areas or to contain them in others. Solar powered electric fences are an option, however regular inspection and maintenance is recommended (Wenzel & Shaw 2008). Two-strand barbed wire electric fencing is used commonly in the region for cattle grazing in and around wetlands but 5-strand, non-electric barbed wire fencing is also an option, although it is more expensive than the two-strand (Duncan et al., 2019). The timing of when to introduce grazing to the site is a point to consider. Regenerative grazing or grazing that closely manages where and for how long animals forage, may be beneficial (Fountain 2021). Carefully monitoring for declining native species and increasing invasive species can help guide livestock management decisions (Phillips-Mao 2017).

Mitigate nuisance small mammals

Nuisance muskrats, beaver, and other small mammals can be controlled with a variety of methods. Some states have options for the public to hunt, trap, or translocate nuisance animals. Some state agencies, like the Utah Division of Wildlife Resources, have programs to translocate nuisance beavers to areas where their dam-building efforts are critical to restoring watershed hydrology (Davis, 2018). In some instances, exclosures around newly installed plants will be necessary (RiversEdge West, 2014). For restoration plantings threatened by beaver, exclosures around trees, between the trees and the river, or painting around the base of the tree with sand, red maple extract, or predator feces may be relatively low-cost strategies (Pollock et al., 2015; Vanderhoof 2017).

Prevent bird damage

Early in the restoration, when ground cover is short and minimal, geese or other birds may be tempted to land in open restoration areas and disturb the newly established vegetation. During this stage of the restoration, strategies to protect the vegetation, such as fencing around or bird netting above newly planted areas, may be necessary (Seattle Audubon Society, 2022). Alternatively, flagging tape strung across stakes in the ground above open water or emergent wetland areas may prevent geese from landing in planted areas (Wenzel & Shaw, 2008). If geese and humans are likely to inhabit the area soon after restoration, be sure to post signs to inform the public to avoid feeding geese, as that would further attract them to the vulnerable restoration area (Seattle Audubon Society, 2022).

Minimize human impacts

Signs may be necessary in highly trafficked areas to notify the public of the restoration while exclosures can keep people off of sensitive areas. Intentional walking paths with wood chips can be used to strategically guide public access, or sometimes thorny native plants can be introduced into areas to prevent public access in a more natural way. Additionally, public outreach regarding the restoration site may help reduce negative impact on the site. Consider reaching out to local radio and news sources as well as doing field tours to share your project and increase public awareness around restoration.

Application

1. Eliminate herbivore pressure via management strategies within or outside the restoration area.
2. Monitor and maintain exclosures during the first year and possibly longer-term as needed.
3. Minimize human impact via signs, exclosures, public outreach, or guided access.

9. Monitor projects for continuous learning

Background

The initial restoration project has been completed, so now what? Monitoring the vegetation project is an essential step in the restoration process because it can identify revegetation techniques that worked well, mistakes that can be avoided in the future, and issues that need to be addressed promptly like a failed planting method. Monitoring also helps identify any new or existing invaders that need to be managed.

First and foremost, monitor the recovery of native vegetation. Take good notes on how plants respond at the site. Did one of the planting techniques work well? Can potential problems or obstacles be identified and avoided in the future? All of this information helps not only the current project but builds on knowledge that other restoration practitioners and scientists can learn from.

As discussed in step 4. Lessen the impacts of invasive plants, it is crucial after a restoration to treat any returning invasive species because the act of restoration often results in disturbances that favor the return of old invaders or the arrival of new invaders (D'Antonio & Meyerson, 2002; Kettenring & Adams, 2011). Invasive species will always be a problem, but monitoring and responding to them early prevents them from becoming long-term and highly costly problems. Once the native vegetation establishes in the site, invasion opportunities will decline. Until then, most of the restoration budget will likely go toward invasive plant control (Bohnen & Galatowitsch, 2005; Kettenring & Adams, 2011)

Each year, take stock of seedings and plantings. If they failed to establish or had subpar establishment, you will want to replant and reseed. Building these restoration activities (reseeding, replanting) into the project budget will be essential. Monitoring, invasive treatment, and ideally reseeding/replanting should be kept up for a minimum of 5 years. Although costly in terms of money, personnel, and logistics, such intensive initial steps will have long-term payoffs.

Application

1. Monitor for invasive species as well as native plant recovery.

2. Spot treat any returning or new invasive species.
3. Reseed and replant each year if native species do not establish in sufficient quantity (cover, density, etc.) and quality (e.g., diversity of species) to meet restoration goals.
4. Take good notes of what revegetation activities worked or failed.
5. Share what was learned with other managers, practitioners, and researchers.
6. Repeat the above steps for at least 5 consecutive years.

Conclusion

The introduction of invasive species, loss of native vegetation, dramatically changing water levels, and declining water quality have had a significant impact on lakeshores in the Great Basin, threatening both wildlife habitat and human recreation. Here we outline a comprehensive approach to restoring lakeshores in the region through nine best practices for reestablishing lakeshore vegetation. We emphasize the importance of prioritizing and balancing different factors—such as ecological, logistical, and cost considerations—when making decisions and implementing strategies. Our aim is to empower others to restore the vegetation of lakeshores in the Great Basin and ensure that these vital resources remain healthy for future generations. With the implementation of the strategies and practices outlined in this guide, lakeshores in the Great Basin can continue to support the valuable aspects of lake ecosystems and ensure their continued existence for years to come.

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Figures

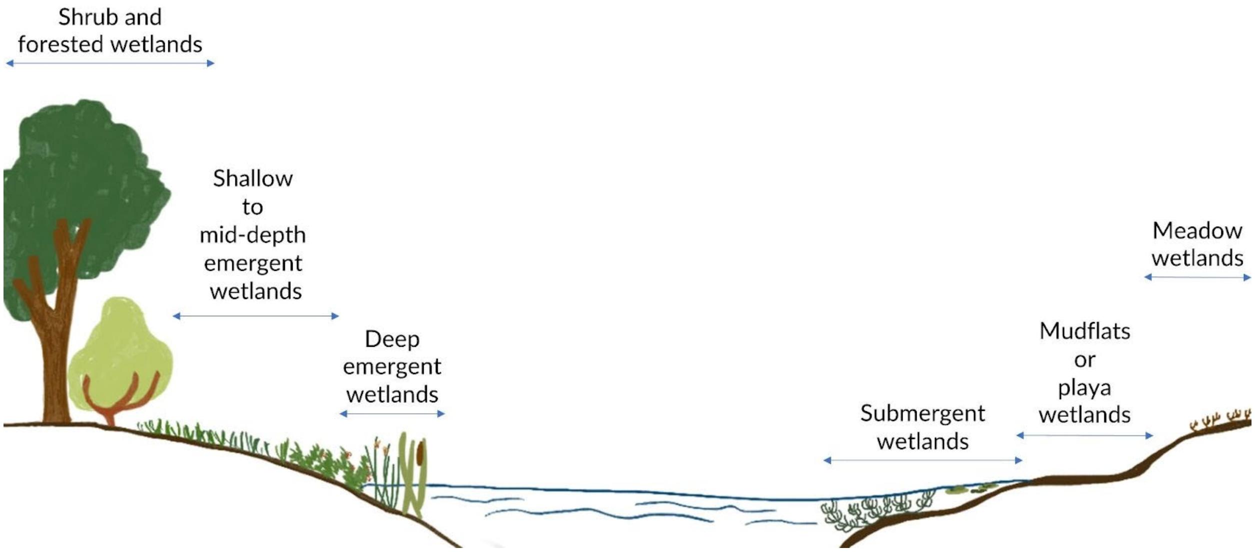
Figure 3.1

A Map of the Great Basin Region

Note. The Great Basin covers much of the western portion of the United States. It is an area of land with little rainfall and drains internally with no outlet to the ocean. Map by Jes Braun.

Figure 3.2

Wetland Diagram



Note. Some of the types of wetlands that occur on the vegetated periphery of lakes, i.e., lakeshores. Differences in the plant communities is largely driven by water depth and frequency of flooding. Diagram by Jes Braun, adapted from Wilcox et al., (2012) and Cowardin et al., (1979).

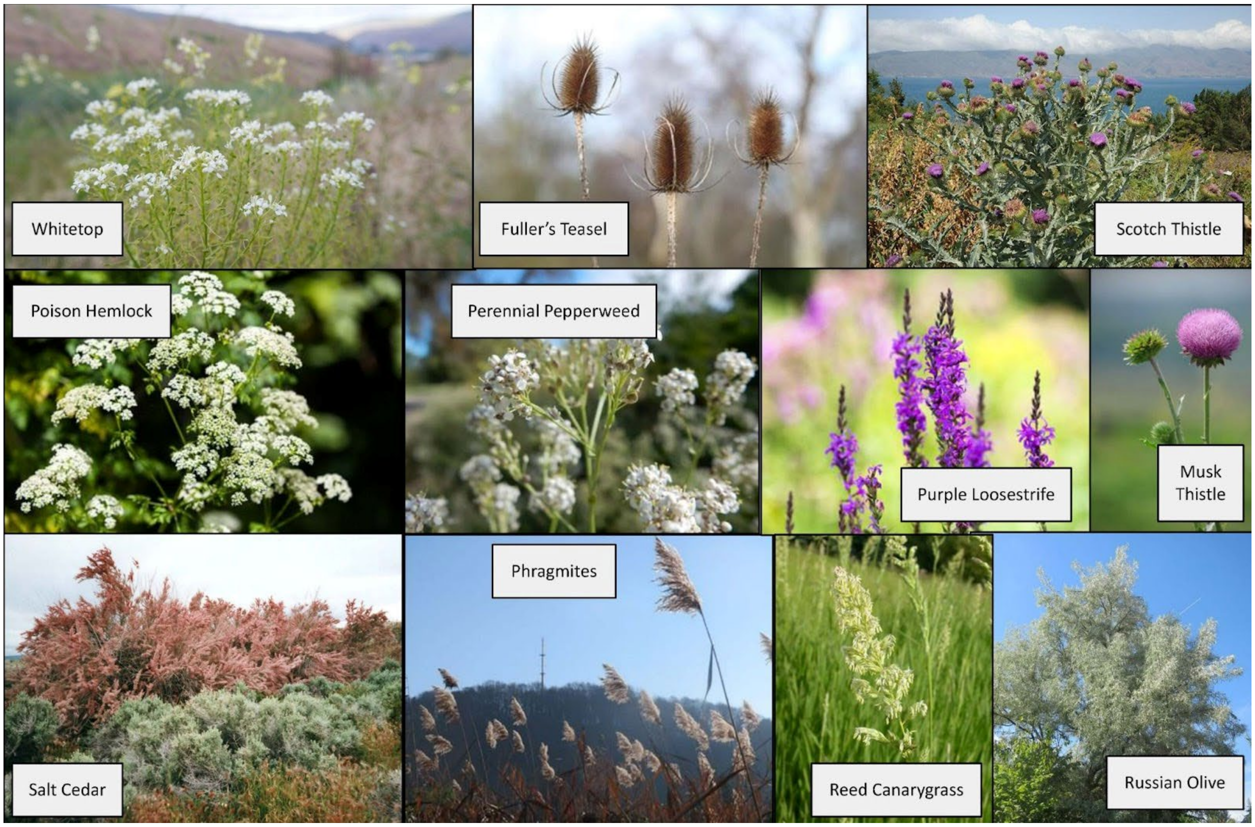
Figure 3.3

Photo of a Mudflat

Note. A mudflat is exposed as the shoreline from Utah Lake, Utah, is drawn down due to drought and upstream water diversions. Photo by Jes Braun.

Figure 3.4

Common Invasive Plants in the Great Basin



Note. Plants are in order from top left to bottom right; Whitetop (*Lepidium draba*), Fuller's teasel (*Dipsacus fullonum*), Scotch thistle (*Onopordum acanthium*), poison hemlock (*Conium maculatum*), perennial pepperweed (*Lepidium latifolium*), purple loosestrife (*Lythrum salicaria*), musk thistle (*Carduus nutans*), salt cedar (*Tamarix* spp.), phragmites (*Phragmites australis*), reed canarygrass (*Phalaris arundinacea*), and Russian olive (*Elaeagnus angustifolia*). Photo credits: Joost J. Bakker IJmuiden, David Reber, Matt Lavin, Andreas Rockstein, Melissa McMasters, Liz West, Walter Baxter, Andreas Rockstein, Royal Botanic Gardens Kew, Anita Gould, Kerry Wixted, and Thayne Tuason. Compiled by Jes Braun.

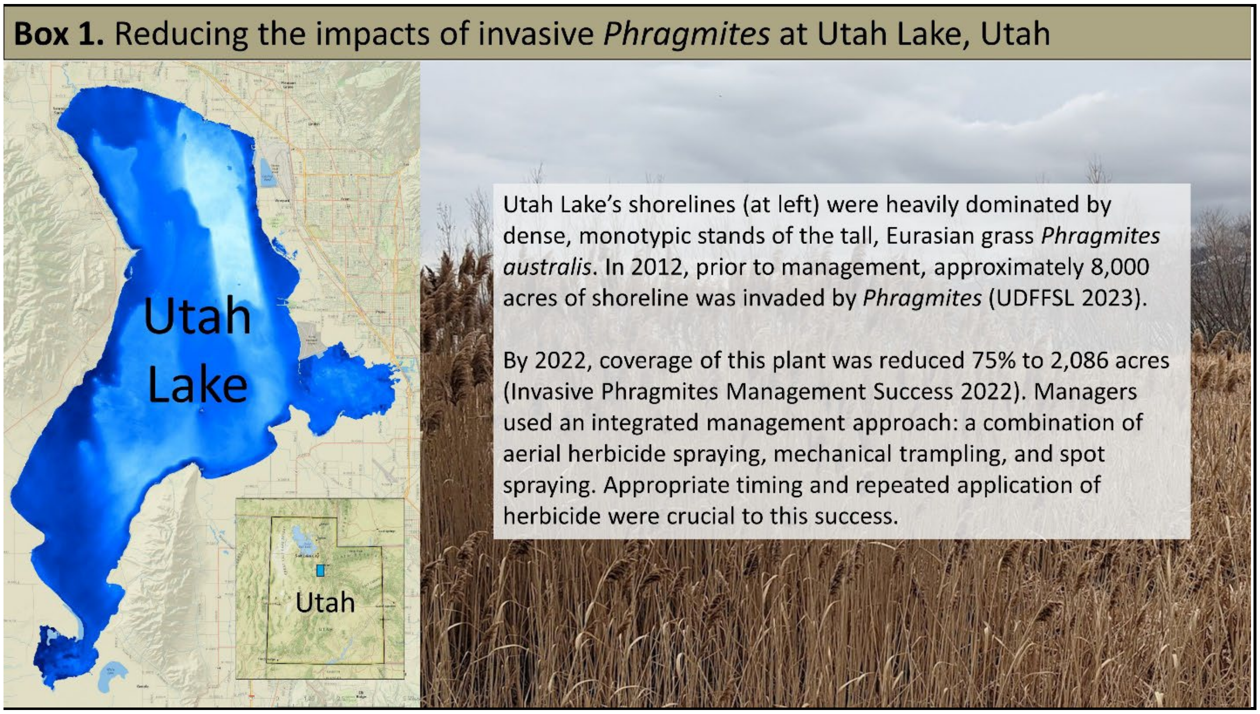
Figure 3.5

A Photo of Dead Plant Material

Note. A field of dead plant material, also called litter, left behind after herbicide treatment of phragmites. Photo by Karin Kettenring.

Figure 3.7

Breakout Box 1



Box 1. Reducing the impacts of invasive *Phragmites* at Utah Lake, Utah

Utah Lake's shorelines (at left) were heavily dominated by dense, monotypic stands of the tall, Eurasian grass *Phragmites australis*. In 2012, prior to management, approximately 8,000 acres of shoreline was invaded by *Phragmites* (UDFFSL 2023).

By 2022, coverage of this plant was reduced 75% to 2,086 acres (Invasive Phragmites Management Success 2022). Managers used an integrated management approach: a combination of aerial herbicide spraying, mechanical trampling, and spot spraying. Appropriate timing and repeated application of herbicide were crucial to this success.

Figure 3.8

Breakout Box 2

Box 2. Varying elevation in a restoration seeding at Utah Lake, Utah

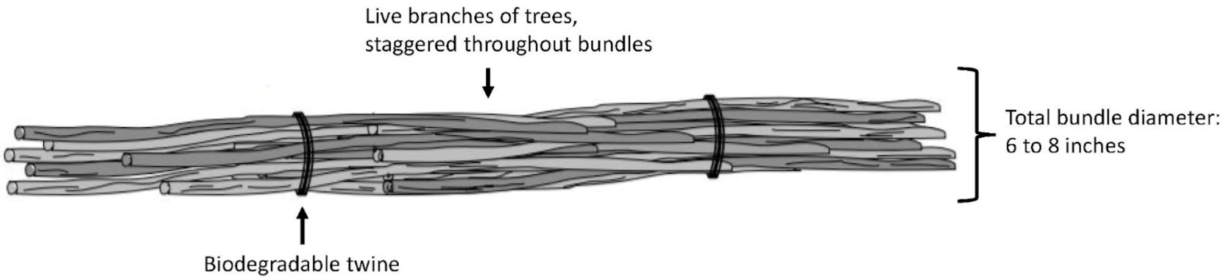
To potentially mitigate the negative effects of declining lakeshore water levels on restored plant communities, Braun (2023) evaluated the effects of the elevation of seeding (perpendicular to the water line; at left) on the plant community.

They found that the elevation of seeding significantly affected plant cover. The highest seeded species cover, and the lowest invasive cover were in the lowest elevation plots closest to the water line.

Although restoring broad bands of wetlands along shorelines is often desirable, in reality, seedings are likely to be most successful immediately adjacent to the water line.

Figure 3.8

Fascine Diagram



Note. A bundle of sticks bound together is called a fascine. These bundles are used as wave breaks and for shoreline stabilization. They can also be used simultaneously as a way to introduce plants if live sticks are used from species like willows that reproduce clonally and will root and grow from these bundles. Image created by Jes Braun, with fascine drawing sourced from USDA NRCS (1996).

Tables

Table 3.1

Considerations, Questions for Practitioners to Answer, and Resources Suggested for Site Reconnaissance and Restoration Planning

Consideration	**Questions to answer**	**Resources and actions to help answer questions**
Watershed location, topography, and soils	How big is the lake? Is it situated in an open basin or is it surrounded by steeper foothills or canyon walls? →*This will affect site hydrology, environmental stressors (e.g., inundation, salinity), and what plant communities are suitable for site conditions.* →*If the site is located in a terminal basin, like the Great Salt Lake, species selection and plant survival may be restricted due to the high salinity conditions.* →*Some lakes with a large fetch (i.e., the distance wind can travel across open water) will experience waves that may threaten seeding and planting efforts.* What are the soil types and soil conditions at the restoration site?	• Site visits • Soil tests and maps • Geospatial tools (e.g., Google Earth) • Digital Elevation Model (DEM) data, lakebed topography maps, slope

	→Consider how the soil composition (sand, silt, or clay as well as soil organic matter) may affect species choice and plant material types. *→Soil tests may help identify any issues related to salinity, nutrient deficiencies, or contaminants (Allen & Klimas, 1986) that may restrict plant establishment and survival.* What is the area that is likely to be most successful? *→Site selection for the first restoration can be the 'low hanging fruit' of the area. Starting with a small and achievable area can help inform future decisions and instill confidence in restoration efforts*	
Hydrology	How do the timing, extent, and depth of inundation vary within and between years? How does water move through the site? *→Details and extent of surface water, groundwater, and springs as well as locations of water control structures should be noted.*	• Use of site visits and aerial imagery to better understand changing lake levels throughout the year and among years. • Publicly available hydrological data sets (e.g., usgs.gov). • Vegetation surveys/wetland delineations because

		vegetation and soils can reflect past inundation patterns. • Consultation with lakeshore landowners and other knowledgeable people about historical patterns. • Consultation with professional hydrologists who can conduct more formal assessments.
Climate	When will there be favorable temperature and moisture conditions for revegetation? *→Answers will be based on the regional climate, weather patterns in the year(s) of revegetation actions, elevation, species choice, and planting method.* What extreme weather or climate-related events could affect revegetation? *→Consider how revegetation could be implemented to better tolerate a severe weather event (e.g., flooding, extreme drought, or wildfire).*	• Publicly available temperature and precipitation data online (e.g., MesoWest). • Consultation with lakeshore landowners and other knowledgeable people about historical patterns.
Plants and animals	What native plant and animal species are commonly found here?	• Plant resources: University Extension documents, plant identification guides, plant identification apps like Seek and iNaturalist, USDA online

	→Pre-restoration vegetation monitoring is important for getting a sense of the species that are currently established at the site. *→Are there animals present near the site that can impact vegetation (e.g.,browsers or grazers like ungulates or beavers) or benefit from certain plant species.* Are there any rare or endangered plant species that demand special attention? What invasive plant and animal species are there and what is the history of invasive species management at the site and nearby areas (i.e., nearby potential sources of seeds to the site)? *→Map invasives and note relative patch sizes and relative densities (e.g., high, moderate, low).*	plant database, and the Intermountain Biota platform to search herbarium records. • Animal resources: Local land management offices can provide additional knowledge and resources, especially the U.S. Fish & Wildlife Service. • Management agencies should have records of past invasive plant and animal species treatments. • Successful passive restoration is rare but can work if a robust native seed bank is present and invasive species are not a threat. • May require multiple years of planting given lake level fluctuations.
Human impacts	How degraded is the restoration site? *→If the potential site is highly degraded, consider adjusting restoration goals*	• Site visits. • Knowledge of land-use practices in the upper watershed as well as public use of/access to the area.

	or choose a new site with better prospects. Will the restoration site be vulnerable to vandalism or trampling? *→Brainstorm ways to prevent potential damage.*	• Consultations with private landowners, local environmental stewards, and the general public.

Note. Adapted from Apfelbaum & Haney (2012) and Rieger et al. (2014).

Table 3.2

A List of Recommended Plant Species for Revegetating Lakeshores in the Great Basin Region

Latin name	**Common name**	**Family**	**Type of plant community and lifeform**	**W.I.S.**	**Sun/ shade tolerance**	**Adaptations and notable features**
Allenrolfea occidentalis	iodine bush	Chenopodiaceae	playa; shrub	FACW	☀	Thrives in saturated saline wetlands[1]. Drought tolerant and great for soil stablization (roots can spread up to 10 m)[2].
Asclepias incarnata	swamp milkweed	Asteraceae	emergent; forb	OBL	☀ ◐	Can tolerate a pH up to 8.0, deer resistant[3].
Asclepias speciosa	showy milkweed	Asteraceae	upland; forb	FAC	☀	Drought tolerant, extensive root system and minimal nutrient requirements make it good for stabilization and restoration[3].
Bidens cernua	nodding beggar-tick, bur marigold	Asteraceae	meadow; forb	OBL	◐	Tolerates seasonal flooding for short durations[3]. Can be weedy (fast growth rate)[3].

Bolboschoenus maritimus	alkali bulrush	Cyperaceae	emergent; sedge	OBL	☀	Can handle a pH up to 9.0, can survive flooding up to 1 m deep, and is resistant to fire[3].
Carex nebrascensis	Nebraska sedge	Cyperaceae	emergent; sedge	OBL	◐	Dense root mass makes species resistant to soil compaction and erosion[4]. Great for soil stabilization[4].
Carex praegracilis	clustered field or meadow sedge	Cyperaceae	meadow; sedge	FACW	☀ ◐	Tolerant of alkalinesoils[5]. Can thrive in wet to seasonally dry meadows[5].
Cleome serrulata	Rocky Mountain bee plant	Cleomaceae	upland; forb	FACU	☀ ◐	Pink flowers attract bees, and the seeds are important food for doves and other small birds[6]. Drought and salinity tolerant[6]. Annual; reseeds easily[6].
Distichlis spicata	saltgrass	Poaceae	meadow; grass	FAC	☀	Useful for revegetating unusually saline, interior areas[5]. Its extensive, creeping rhizomes enable it to colonize an

						area quickly[5]. The grass adapts to drier soils including silts, clays, and even sands[5].
Eleocharis palustris	common spikerush	Cyperaceae	meadow; sedge	OBL	◐	Can grow in water up to 1 m deep[7]. Rhizomatous plant that will eventually fill in large areas[5].
Epilobium ciliatum	fringed willow-herb	Onagraceae	emergent; forb	FACW	☀ ◐	Rapid grower and can complete its life cycle from seed to seed in as little as nine to ten weeks[8].
Euthamia occidentalis	western goldentop	Asteraceae	emergent; forb	FACW	☀	Stout and branching perennial species ideal for stream side plantings and bank stabilization[9].
Eutrochium maculatum	Joe Pye weed	Asteraceae	meadow; forb	OBL	☀ ◐	Resistant to damage by deer[10]. Root system is fibrous and rhizomatous[10]. Forms small clonal colonies[10].
Grindelia squarrosa	curly cup gumweed	Asteraceae	upland; forb	FACU	☀	High ability to survive and grow under adverse

						conditions[11]. Seedlings were transplanted easily to the field and grew rapidly[11]. Drought resistant due to deep roots and resinous secretions[10]. Facultative selenium absorber[11].
Helenium autumnale	common sneeze-weed	Asteraceae	meadow; forb	FACW	☀ ◐	Easy to grow in most sunny sites[12]. Thrive in wet or evenly moist soil but will tolerate a bit of drought after establishment[12]. Pest resistant and unpalatable to deer and other herbivores[12].
Helianthus annuus	common sunflower	Asteraceae	upland; forb	FACU	☀	Spreads rapidly by seed, especially in disturbed sites[5]. Shown to have an allelopathic effect on other plants[5].
Helianthus nuttallii	Nuttall's sunflower	Asteraceae	meadow; forb	FACW	☀	Can grow up to 4 m tall[13]. Great host for up to 27 different butterflies and moths[13].

						Prefers loamy or clay soils[13].
Juncus arcticus	arctic, mountain, or baltic rush	Juncaceae	meadow; forb	FAC	☀	One of the most widespread plant species[14]. Thick rhizomes help bind wetland soils[14]. Tolerate saline soils[14]. Fixes nitrogen in soil[14].
Populus fremontii	Fremont's cottonwood	Salicaceae	meadow; tree	FAC	☀	Bank and sediment stabilization, water quality improvement, ground-water recharge, flood abatement, and fish and wildlife habitat[3].
Puccinellia nuttalliana	Nuttall's alkali-grass	Poaceae	emergent/ meadow; grass	FACW	☀	Tolerates saturated to shallowly flooded saline wetlands[1].
Rumex maritimus	golden dock	Polygonaceae	emergent; forb	FACW	◐	Seeds germinate easily in moist conditions[15]. Tolerate saline soils and waterlogged conditions[15,16].
Sagittaria latifolia	broadleaf arrow-head	Alismataceae	emergent; forb	OBL	☀ ◐	Underground tubers are preferred by at least 15 species

						of ducks and by snapping turtles[5].
Salicornia rubra	pickle-weed	Chenopodiaceae	playa; forb	OBL	☀	Similarly performing species: *S. europaea* and *S. utahensis*. Capable of growing in saline or highly alkaline wetlands[6].
Salix exigua	coyote willow	Salicaceae	emergent/ meadow; tree	FACW	☀ ◐	Excellent for stream stabilization as the plant suckers profusely[5].
Schoenoplectus acutus	hardstem bulrush	Cyperaceae	emergent; sedge	OBL	☀	Dense root mass; excellent choice for soil stabilization[3]. Above ground biomass provides protection from erosive wave action and stream currents[3].
Schoenoplectus americanus	Olney's three-square bulrush	Cyperaceae	emergent; sedge	OBL	☀	Can live in brackish (somewhat salty) waters[17]. Great source of food and nesting habitat for waterfowl

						and small mammals[17].
Senecio hydrophilus	water ragwort	Asteraceae	meadow; forb	OBL	◐	Can grow in standing water, including alkaline and saline water[17].
Sparganium eurycarpum	broadfruit bur reed	Sparganiaceae	emergent; forb	OBL	◐	Can form dense stands under the right conditions[18]. Buried rhizomes help plants survive periods of drought, fire, or ice scour[18]. Seeds are an important food source for waterfowl[18].
Symphyotrichum ciliatum	rayless aster	Asteraceae	meadow; forb	FACW	☀	Thrives in moist, brackish soils and areas with fluctuating water levels as well as winter-salted roadways[19].
Triglochin *maritima*	seaside arrow-grass	Juncaginaceae	meadow; forb	OBL	☀	Can thrive in saturated, saline wetlands[1]
Verbena *hastata*	swamp verbena	Verbenaceae	meadow; forb	FACW	☀ ◐ ●	Plants tolerate moderate salt levels, loamy or wet mucky soils and temporary standing

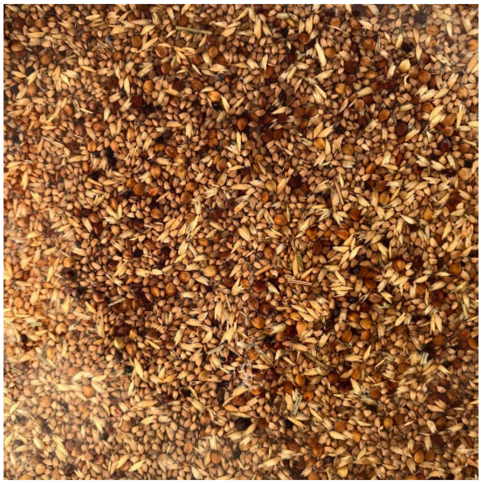
						water[20]. Bitter foliage makes plant fairly herbivore-resistant[20].

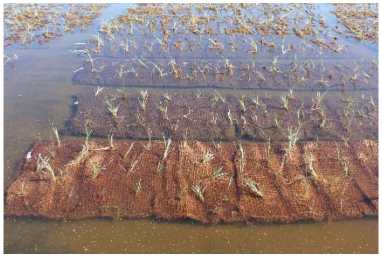
[1]Downard et al., 2018; [2] *Allenrolfea occidentalis – the Watershed Nursery*, n.d; [3]*USDA Plants Database*; [4]Tilley et al., 2012; [5]*Lady Bird Johnson Wildflower Center - the Botanic Garden of Texas*, 2023; [6]Natural Heritage Program and Montana Fish, Wildlife & Parks, 2023; *Missouri Botanical Garden*, n.d.; [8]Popay, 2022; [9]*The Watershed Nursery-Native Plants and Habitat Enhancement Service*, n.d.; [10]*Eutrochium maculatum (Joe-Pye-weed, Queen of the Meadow, Spotted Joe-pye-weed, Spotted Trumpet Weed) | North Carolina Extension Gardener Plant Toolbox*, n.d.; [11]*Grindelia squarrosa*, n.d.; [12]*Helenium autumnale Common sneezeweed from New Moon Nurseries*, n.d.; [13]*Nuttall's Sunflower, Helianthus nuttallii,* n.d.; [14]*Baltic Rush*, n.d.; [15]Dhawan, 2005; [16]Van Der Sman et al., 1988; [17]*Schoenoplectus americanus*, n.d.; [17]Water Groundsel, *Senecio hydrophilus*, n.d.; [18]Broadfruit Bur-reed, *Sparganium eurycarpum*, n.d.; [19]*Symphyotrichum ciliatum | Astereae Lab*, 2023; [20]*Verbena hastata Blue vervain from New Moon Nurseries*, n.d.

Note. "Type of plant community listed" refers to groups of plants that live together, interact with each other and the environment, and share similar ecological traits. They are classified based on factors like climate, soil type, and topography. "Lifeforms" are general categories that classify plants based on their overall structure, growth habit, and strategies for survival and reproduction. W.I.S., or Wetland Indicator Status, represents the likelihood of a species being found in wetland or upland habitats. OBL = obligate wetlands species (almost always occurs in wetlands, FACW = facultative wetland species (usually occurs in wetlands), FAC = facultative (equally likely to occur in wetlands and uplands). "Sun/shade tolerance" refers to a plant's ability to thrive and grow in different light conditions, specifically in relation to the amount of direct sunlight or shade it receives. It is an important characteristic that determines a plant's ability to adapt to specific environments. "Adaptations and notable features" are a list of important characteristics of that species of plant. These features can help guide plant selection if site specific stressors are known.

Table 3.3

Five Main Plant Material Types That Are Used in Restoration

Plant material type	**Definitions**	**Benefits**	**Drawbacks**
Seeds 	→an embryonic plant inside a seed coat; the result of pollen fertilization of the ovule	✓inexpensive compared to other plant stages ✓relatively easy to install ✓can float with changing water levels; more likely to land in the appropriate places for germination[1] ✓leads to more species and genetic diversity which benefits establishment, growth, and functioning[2]	👎high mortality; expected losses of 90-95% seeds and seedlings[3] 👎May have long lead-times for acquiring seed of desired species although that's true regardless of plant stage type[4]
Plugs	→a few seedlings growing in potting soil in a narrow (~1–1.5") but deeper (~4.5–8") "cone-tainer" with a	✓bypass the high mortality of the seed stage and generally have higher survival[5]	👎more expensive than seeds 👎requires resources and time for greenhouse growth

	well-developed root system; grown in a greenhouse setting before out-planting		👎seedlings, like seeds, can still experience high mortality due to high salinity, and hydrologic and temperature extremes
Rhizomes 	→a modified belowground stem that both stores plant food and absorbs water and nutrients, which can be harvested from existing plants (in the wild or propagation environment) and replanted to create a new clonal plant	✓high survival rates relative to seeds and plugs[6]	👎moderately expensive depending on if wild propagated or purchased from native plant vendors 👎mortality can be high if the water level conditions are suboptimal[7, 8, 9]
Sod mats (pre-vegetated coir mats or blankets) 	→mats of plants usually formed from coconut fiber lattice (coir) embedded with rhizomes or plugs that are grown for 1–2 growing	✓high establishment success[10] ✓commonly used in areas with steep elevation, waves, or currents to	👎most expensive of all plant material types 👎very time intensive to produce and

	seasons under controlled conditions to develop robust root systems prior to transplanting	prevent erosion[4,11]	requires a lot of space[4]
Poles and cuttings 	→for some woody wetland species like cottonwoods and willows, stems and branches can be harvested from dormant plants and soaked in water, or planted in moist soil to trigger rooting prior to planting during the growing season	✓can have extremely high survival rates in restorations if harvested, stored, and planted correctly[4]	👎additional logistical requirements for harvesting and storing poles and cuttings, especially if cool conditions needed[4]

[1] Bohnen & Galatowitsch, 2005; Soons et al., 2017; [2] Benayas et al., 2009; Reynolds et al., 2012; [3] Kildisheva et al., 2016; James et al., 2011; [4] Rieger et al., 2014; [5] Godefroid et al., 2011; [6] Davis & Short, 1997; [7] Yetka & Galatowitsch, 1999; [8] Qing et al., 2021; [9] Budelsky et al., 1999; [10] Hook, 2006; [11] Cubley et al., 2021

Chapter IV

Summary and Conclusions

As extreme weather events like droughts and water deluges become the new norm (Rodell & Li 2023), navigating how to effectively restore lakeshore plant communities is even more imperative (Mitsch & Gosselink 2015; Niemuth et al., 2004; Wantzen et al., 2008). The restoration of robust native plant communities through seed-based revegetation is a promising strategy, as supported by previous studies (Kettenring & Tarsa, 2020; Godefroid et al., 2011). However, where to seed and at what density to seed in these systems was unknown, especially in the face of rapidly changing shorelines. To address these gaps in both academic and management knowledge, I conducted a study addressing these uncertainties related to seeding, plug planting, and elevation in lakeshore restoration.

One of the largest drivers to plant restoration success is keying in on ideal planting locations in a highly dynamic shoreline environment. By manipulating the elevation of seeding and planting in paired research experiments, I was able to elucidate what role elevation has on plant community recovery. Elevation was a significant factor in both the increase in native seeded plant cover and the decrease in invasive plant cover. The lowest elevation plantings performed the best. For seeding, density of seeding, and elevation of seeding, I found that seeding had a positive effect on the cover of seeded native species regardless of seeding density. I suggest that seeding at lower elevations can increase establishment success. I show that the addition of plugs greatly increased the cover of both planted species (*D. spicata* and *S. acutus*). Additionally, I show that the elevation of plug planting had a significant effect on the cover of both species planted as plugs had higher establishment success and cover in the lower elevations closest to the water line. The arrangement of plugs mattered, and I suggest a less dense planting arrangement in similar systems facing drought conditions.

This study was limited to two years, both of which experienced historic drought conditions. The following year was a record-breaking snowpack year, and further insights could have been provided if the study had been extended to include the upcoming anticipated increase in lake depth. Further investigation into the effect of elevation of planting is recommended, as these types of systems are not unique. Insights gained from these investigations can help inform restoration practitioners in the face of our new norm of extreme weather events.

In conclusion, the findings of this study suggest that seeding is an effective strategy to increase native plant community cover and species richness in lakeshore wetlands. While seeding density did not have a significant effect on native plant recovery, seeding was effective at greatly increasing native cover relative to the unseeded controls. Additionally, elevation of seeding played a crucial role in restoration outcomes, with lower elevations showing higher cover of seeded species. The results of the plug planting experiment demonstrated that the interaction between planting arrangement and elevation was significant, with the dispersed planting arrangement leading to the highest native cover in both *D. spicata* and *S. acutus* in the lower elevations. These findings highlight the importance of considering seeding and planting strategies, as well as elevation, when restoring degraded lakeshore wetlands to promote the recovery of native plant communities.

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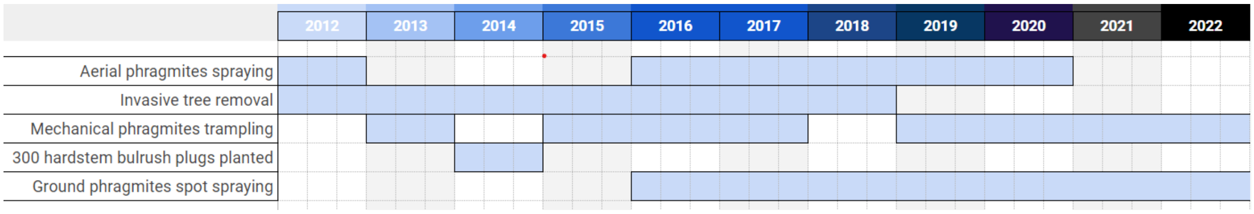
Appendices

Appendix A. Supplemental Information for Chapter II

Supplementary Figures

Figure A2.1

A Timeline of Invasive Species Management and Revegetation Projects on the North Shore Of Utah Lake, Utah.



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Aerial phragmites spraying	■				■	■	■	■	■		
Invasive tree removal	■	■	■	■	■	■	■				
Mechanical phragmites trampling		■		■	■	■		■	■	■	■
300 hardstem bulrush plugs planted			■								
Ground phragmites spot spraying					■	■	■	■	■	■	■

Note. Blue blocks indicate years of management intervention. Tree removal was focused on tamarisk (Tamarix spp.) and Russian olive (Elaeagnus angustifolia).

Figure A2.2

A Photo of Utah Lake Prior to Invasive Species Management

Note. Taken a year prior to the implementation of invasive species management. A dense, monotypic stand of *Phragmites australis* is seen in the left midline area of the photo.

Figure A2.3

A Photo of Seed Fences

Note. Organza mesh fences border seed plots on the north shore of Utah Lake, Utah. Fences were 1m^2 and 0.76 m high and ran in a transect perpendicular to the shoreline.

Figure A2.4

A Photo of the Hand Seeding with Tackifier Method

Note. A slurry of seeds, tackifier, and water being applied to a seed plot at Utah Lake. The use of tackifiers in this experiment was done to replicate the current method for applying seeds to a site. During the span of this research, management practices shifted to discing as the preferred site prep method. Tackifiers might still be used for smaller, more specific applications along dikes - similar to traditional applications of hydroseeding.

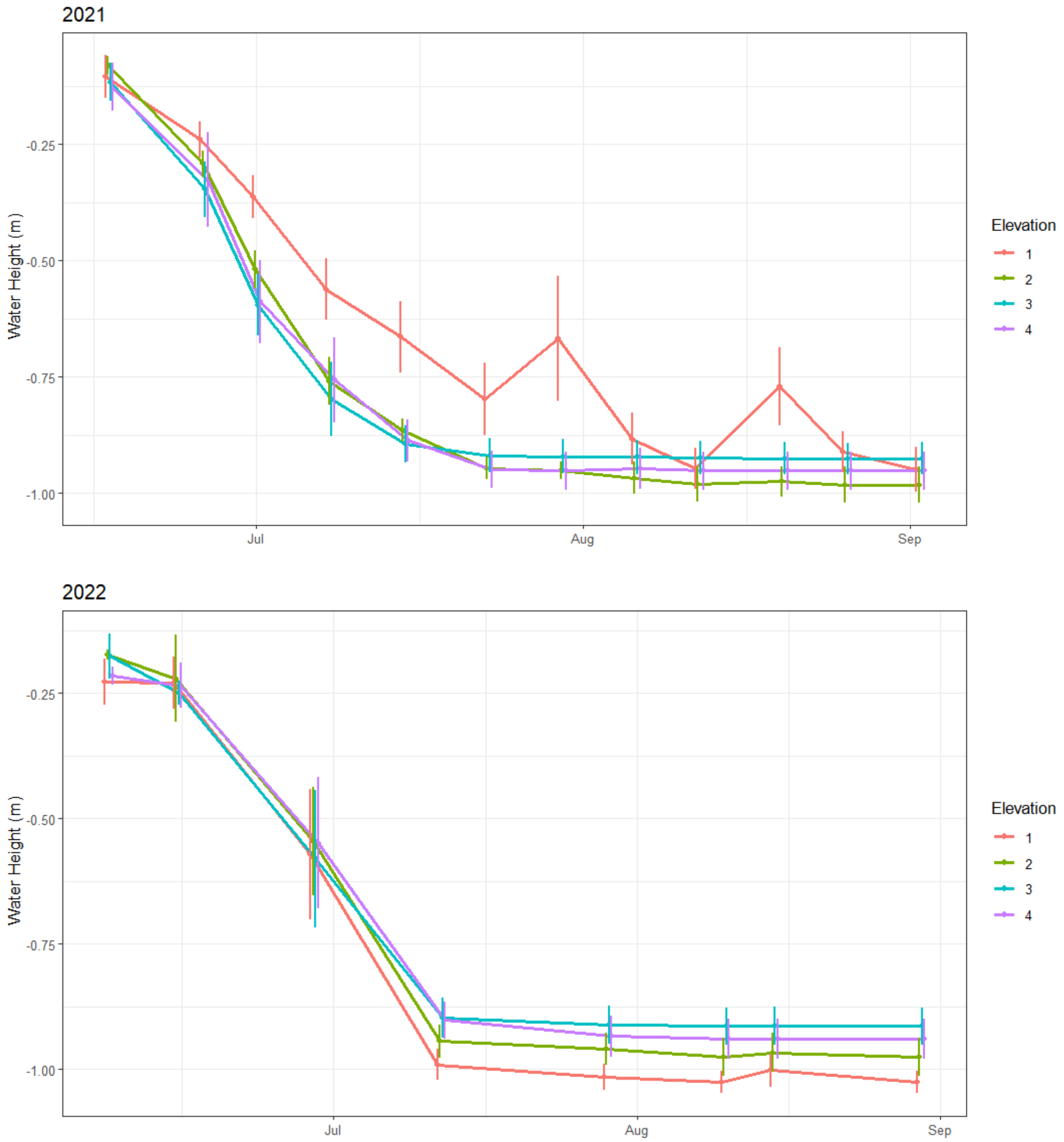
Figure A2.5

A Photo of a Cone-tainer

Note. A plug cone-tainer grown out in a greenhouse in Logan, Utah. Plugs of *Schoenoplectus acutus* and *Distichlis spicata* were seeded onto All-Purpose Lambert soil. Roughly 20 seeds were placed on top of the soil in Ray Leach SC10R cone-tainers that measured 20.955 cm deep and 3.81 cm in diameter. The greenhouse lights were Gavita Pro1000e which generated 2100 µmol m-2 s-1 of light and set on a 16-hour photoperiod. The temperature of the greenhouse was kept at daytime temperatures of 85°F (29.4℃) and nighttime temperatures of 65°F (18.3℃). The plugs were watered via aerial sprinklers to maintain a consistently moist growing condition. The seedling plugs were grown out for 6 weeks and thinned at 4 weeks to reduce competition. During the last week of growth, the plugs were hardened to field conditions by gradually placing them in the sunlight and ceasing watering for increasingly longer periods of time each day.

Figure A2.5

Water Levels Over the Growing Periods



Note. The top graph is 2021 and bottom graph is 2022 at the four block elevations (a gradient that runs from the planting shoreline (Elevation 1) to upland (Elevation 4), on a transect that is perpendicular to the lake). Water levels fell below the ability to record (below the bottom of the well) in mid-July in both years. Water level data was collected from 20—1.6 m tall PVC wells installed in the middle of every block and buried 1 m below the soil surface.

Appendix B. Restoration Planning Worksheet

Consideration	**Questions to answer**
Watershed location, topography, and soils	Is the lake situated in an open basin or is it surrounded by steeper foothills or canyon walls? What is the soil type at the restoration site? If the site is large, choose a smaller area within the site for initial restoration steps to ensure that you can meet your objectives, to test your methods, and to inform future decisions and steps.
Hydrology	How do the timing, extent, and depth of inundation vary within and between years? How does water move through the site?
Climate	When will there be favorable temperature and moisture conditions, on average, for seeding and planting at the site? What extreme weather or climate-related events could affect revegetation?
Plants and animals	What native plant and animal species are found here? Are there any rare or endangered species that demand special attention? What invasive species are there and what is the history of management at the site and nearby areas?

Human impacts	How degraded is the restoration site? What land-use practices have occurred there or in the surrounding watershed? Will the restoration site be vulnerable to vandalism or trampling?

Appendix C. Co-Author Permission to Use Form

6/9/2023

I, Rae Robinson, give Jes Braun permission to use this paper, of which I am a co-author, as a chapter in their thesis.

Signed,

Rae Robinson

Rae Robinson