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Effects of Localized Irrigation and Fertilizer on Woody Plant Establishment in Degraded Semi-Arid Environments

Holley M. Lund
Brigham Young University

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Holley M. Lund

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Bradley D. Geary, Chair
Matthew D. Madsen
Roger T. Koide

Department of Plant and Wildlife Sciences

Brigham Young University

ABSTRACT

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Holley M. Lund
Department of Plant and Wildlife Sciences, BYU
Master of Science

Semi-arid native plant communities worldwide are often disturbed either intentionally or incidentally by human activity. In order to restore ecological function after human activities cease, native plant communities need to be restored. Woody plants are important to ecological function for many reasons including reducing erosion and providing food and shelter for wildlife. Unfortunately, woody plant establishment in these areas has proven to be challenging. Direct seeding efforts can be hindered by poor germination and low seedling emergence. To overcome this, seedling transplants are often used in harsh sites. However, transplanted woody seedlings often experience high mortality during the first year, predominantly as a result of stress during the summer. The Waterboxx® device is a tool that collects precipitation and condensates into a polypropylene reservoir, slowly releasing the water into the soil next to the seedling. Low soil fertility can also limit seedling establishment. In two studies, we evaluated the use of Waterboxx® devices with one wick or two wicks, and/or fertilizer as tools for establishing seedlings on a reclaimed waste rock pile. We also looked at the effects of either placing the Waterboxx® on the soil surface or burying the Waterboxx® partway into the ground. The first study focused on different species in the Waterboxx®. Species planted in the first study were *Atriplex canescens*, *Cercocarpus ledifolius*, *Pinus edulis*, *Purshia tridentata* and *Rhus glabra*. The second study focused on number of wicks, addition of fertilizer, and method of Waterboxx® installation. This study was conducted with only one species: C. *ledifolius*. In both studies, the Waterboxx® device improved survival and vigor. In the second study, fertilizer was detrimental to seedling survival, and Waterboxx® devices installed on top of the soil had no difference in survival or vigor compared to the control, but partially buried devices were better than the control and Waterboxx® devices with two wicks had the best *C. ledifolius* seedling survival. Based on the results obtained, Waterboxx® devices were a viable method for most of these species in improving their establishment on mine land overburden sites in the semi-arid mountain west and additional research is merited for other areas of the world.

Keywords: restoration, Waterboxx®, transplant, woody plant establishment, water management

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CHAPTER 1

Waterboxx® Water Collection for the Improvement of Woody Plant Species Establishment on Mine Overburden

Holley M. Lund, Bradley D. Geary, Kate Ruebelmann, Roger T. Koide, Dennis L. Eggett, Matthew D. Madsen
Department of Plant and Wildlife Sciences, Brigham Young University, Provo, UT
Master of Science

ABSTRACT

Reclamation of mine and associated waste rock dumps can improve site aesthetics and ecosystem function. In the mountain west region of the United States, mining activities commonly occur in zones dominated by native woody plant cover. Woody plants are important to ecological function for many reasons, including reducing erosion and providing food and shelter for wildlife. Unfortunately, restoration of woody plants to these areas has proven to be challenging. Direct seeding efforts can be hindered by poor germination and low seedling emergence. To overcome this, seedling transplants are often used in harsh sites. However, transplanted woody plant seedlings frequently experience high mortality during the first year, particularly as plants are stressed during the summer drought period. This study evaluated the use of Waterboxx® devices as a tool for establishing seedlings on a waste rock pile. The Waterboxx® device collects precipitation and condensates into a polypropylene reservoir and then slowly releases the water into the soil next to the seedling. We planted 400 seedlings composed of five native woody plants, with and without a Waterboxx®, between the fall of 2020 and spring of 2021. Species planted included *Atriplex canescens*, *Cercocarpus ledifolius*, *Pinus edulis*, *Purshia tridentata* and *Rhus glabra*. The Waterboxx® device improved soil water availability and subsequently survival for four of the five species. The Waterboxx® device also improved vigor for three of the five species depending on the planting season. Based on the results obtained, Waterboxx® devices appear to be a viable method for most of these species in improving their establishment on mine land overburden sites in the semi-arid mountain west. The effectiveness of the Waterboxx® device in the semi-arid west of Utah suggests this technology could be used globally where water is a limiting factor for seedling establishment of some species; however, additional research is merited for other areas of the world.

INTRODUCTION

Land is often impacted by both natural and human-made events, which can lead to degradation. Depending on location and environmental factors, degradation can look like increased flooding, reduced streamflow, redeposition of soil, impacts on wildlife and a loss of biodiversity (Milton et al. 1994; James et al. 2013). The excavation of minerals from soil and rock can result in ecosystem disturbance which requires mitigation and remediation (Lovich & Bainbridge 1999). However, mineral products from mining are important for modern society and essential for the continued development of modern technology.

Globally, as of 2020, approximately 57,277km^2 of land is actively being mined (Maus et al. 2020). These operations move and reshape natural landscapes with large-scale excavation of ore and overburden rock, removal of vegetation, and deposition of overburden and tailings; material that may have geochemical conditions that are challenging to revegetate such as high acidity or low organic content (Mendez and Maier 2008). Reclamation of these sites is essential for improving site aesthetics and ecosystem functions (Sodhi & Ehrlich 2010).

Late-successional woody plants are often one of the most challenging groups of species to reestablish in woody plant land ecosystems impacted by mining or other natural or artificial disturbances (Paschke et al. 2002; McAdoo et al. 2013; Shriver et al. 2019; Pyke et al. 2020). Direct seeding efforts can be hindered due to poor germination and low seedling emergence and establishment (Ungar 1978; Ungar & Khan 2001). To overcome this bottleneck, nursery-grown seedlings are commonly transplanted in harsh sites (Pilliod et al. 2017; Pyke et al. 2020).

Transplanting container seedlings can result in greater establishment success than direct seeding but can still experience failure, which is often due to inadequate root systems to survive low precipitation during the summer months. However, after the first year growing season, many semi-arid woody plant species can tolerate severe drought because root systems are sufficiently established to support the plant (Bainbridge 2007). Consequently, reclamation technologies and techniques that can improve water availability directly after planting have the potential to increase transplanting success (Lovich and Bainbridge 1999).

There are several different technologies for increasing the quantity of available water to a transplanted seedling. Selecting a technology that will be most efficient for a site depends on many factors. These include plant species and size, soil type, climate, microclimate, local water availability, weed competition, project budget, site access, and available labor and tools (Kulkarni et al. 2011; Tapia et al. 2019).

Water collection systems are among the most effective water management tools for mitigating drought conditions (Bainbridge 2007; Tapia et al. 2019). These systems consist of a catchment device with a storage tank that collects precipitation, and with some designs, they also collect condensation. The captured water can then be stored and locally distributed to seedlings planted nearby even when precipitation is low (Kulkarni et al. 2011; Serra-Wittling et al. 2019; Tapia et al. 2019; Gil-Docampo et al. 2020).

The Waterboxx® device (Groasis Water Saving Technologies, Steenbergen, North Brabant, Netherlands) is a localized water catchment system that is installed over transplanted seedlings to provide supplemental water. This technology has been utilized in semi-arid environments from Alicante, Spain to the Galapagos Islands, Ecuador (Tapia et al. 2019; Gil-Docampo et al. 2020). It consists of a 50 cm diameter cylindrical container that serves as a reservoir with a central opening where two seedlings are planted. Water is fed into the soil through capillary action via a rope wick connected to the base of the reservoir. Soil water lost to evaporation is minimized by the presence of a cover on the soil surface surrounding the seedlings. The plastic that forms the device has a high specific heat capacity and a low thermal conductivity which allows the material to absorb a lot of heat but also prevent that heat from moving too much (Groasis Ecological Water Saving Technology 2021). Due to this, more energy is needed to warm the device and the device stays cool longer. When the device is cooler than the surrounding night air, the dew point is more quickly reached, and condensation may occur (Groasis Ecological Water Saving Technology 2021). This condensation, and any precipitation, is collected by a concave, grooved cover, and stored in the reservoir thereby resupplying the water released to the soil.

The Waterboxx® has the potential to improve transplant survival and expand the window seedlings can be planted. For example, in regions of the western United States where most precipitation is received during the winter period, seedlings are commonly planted in the fall. Seedlings planted in the fall have more time to develop adequate root systems before drought stress, in contrast to planting in spring, which provides minimal time before the onset of summer drought (Davidson et al. 2019; Clements & Harmon 2019). However, fall plantings can also experience mortality as the need to tolerate freezing temperatures and frost heaving of the soil (Davidson et al. 2019). The Waterboxx® has the potential to expand the window in which seedlings are sown by buffering against inhospitable growing conditions at multiple times of the year.

Here, we present a study to assess the Waterboxx® in its ability to 1) improve soil water status, 2) increase the survival and vigor of native tree and woody plant transplants; and also 3) evaluate if there are differences in planting success between fall and late spring planting seasons.

The research was conducted at the Bingham Canyon Mine near Salt Lake City, Utah U.S.A. This mine is ideal for evaluating the performance of the Waterboxx® due to the extensive reclamation efforts being conducted on site, which includes a focus on the reintroduction of various native woody plants. This mine began operations in 1903 on the porphyry copper deposit (Tooker 1990) and has produced more than three billion metric tons of waste rock, referred to as overburden, deposited in valleys and inclines in the nearby Oquirrh Mountain Range (Borden & Black 2005). Our research was focused on evaluating the Waterboxx® for improving plant establishment on a reclaimed overburden hillside at the Bingham Canyon Mine.

MATERIALS AND METHODS

Study Site

Waterboxx® devices were installed at the Bingham Canyon Copper Mine located in the Oquirrh mountain range, on the Yosemite waste rock dump (40.51263889, -112.1182611). The location of the site is associated with the Mountain Loan (Oak) (R047XA432UT) ecological site (Soil Survey Staff 2022). This area is located at an elevation of 1873 m within the mountain brush zone, which forms a transition between coniferous forest above and pinyon-juniper woodlands at lower elevations (Banner 1992). Prior to being covered by mine overburden, the site was most likely dominated by small trees and woody plants.

Overburden materials deposited on the hillslope consist of varying ratios of monzonite, quartzite, and limestone (Borden 2001; Borden 2003). In 2015, the site was reclaimed by decreasing the slope of the hill to approximately 12% and covering the area with a 1-m thick layer of crushed rock and topsoil. This growth media was then ripped perpendicular to the slope using dozers to create small terraces ~ 0.5 m wide and spaced ~ 1 m apart. The site was then hydroseeded with a seed mix of comprised of native and introduced species, set forth by the

Division of Oil and Gas Mining. Introduced perennial grasses were the most successful at establishing with *Thinopyrum intermedium* L. (intermediate wheat grass), being the dominant species. There were also smaller amounts of other native and introduced grasses and forbs, and only a trace number of woody plants, except for *Ericameria nauseosa* ex Pursh G.L. Nesom & Baird (rubber rabbitbrush). Ten soil samples were collected in a random pattern across the Yosemite waste rock dump at a depth of 30cm. All samples were combined and then submitted to the BYU Environmental Analytical Laboratory for analysis. The combined soil had a pH of 7.5, with a gravelly clay loam soil texture and Mean yearly precipitation at the site is ~613 mm (Figure 1) (Prism Climate Group 2021).

Evaluation of Difference Species in Waterboxx® Field Trial

The Waterboxx® field experiment was installed as a randomized split-split-plot design with ten replicates installed in two different planting seasons. The ten main plots were split by planting season with one season randomly assigned the north or south side of each plot. These sub plots were further split by the five native woody species, planted with and without a Waterboxx®. Planting occurred in the fall (November 2020) and in late spring (May 2021). *Cercocarpus ledifolius* Nutt. (curl leaf mountain mahogany), *Rhus glabra* L. (smooth sumac), *Pinus edulis* Englem. (pinyon pine), *Atriplex canescens* [Pursh] Nutt. (fourwing saltbush), and *Purshia tridentata* [Pursh] DC. (antelope bitterbrush) were planted in both seasons. For plantings without the Waterboxx®, we planted two seedlings spread ~15 cm apart with the same cardinal orientation.

Prior to planting, seedlings were caged with Vexar®, (Forestry Suppliers, Jackson, Mississippi), a flexible UV inhibited polyethylene and polypropylene material (Figure 2). Each seedling was wrapped in its entirety to deter herbivory of roots and shoots from rodents and ungulates (Figure 2). Holes for planting were dug with a 30.5 cm diameter motorized auger (Kohler Co., Kohler, Wisconsin) and debris was cleaned out by hand with a shovel. Seedlings were planted deep enough that the soil level met the root flare.

Waterboxx® devices were installed according to manufacturer recommendations (Groasis Ecological Water Saving Technology 2021). Prior to planting, evaporation covers (i.e., rectangular corrugated plastic designed to discourage soil water evaporation) were trimmed to fit around the seedling pairs on top of the soil. Waterboxx® devices were placed over the seedlings with the wicks pointing inward toward the seedlings and lightly covered in soil. The water filling caps in the cover were positioned to face north (Figure 2). These boxes were backfilled around the outside with soil and rock ~10 cm high to hold them in place. We applied 3 L of water to both seedling pairs planted with and without a Waterboxx®. Waterboxx® devices were then filled with 15 L of water.

Soil water potential was measured on the *C. ledifolius* plantings with and without a Waterboxx®, in three blocks per planting season. Soil water potential was measured at 10, 20, and 40 cm depths below the soil surface with Teros 21 water potential sensors (METER Group, Inc. Pullman, WA, USA). These are dielectric matric potential sensors that measure the charge-storing capacity of a ceramic disc to determine its water content and then use the moisture characteristic of the disc to convert water content to water potential. Water potential measurements were taken every two hours with values stored with EM50/ZL6 data loggers (METER Group, Inc. Pullman, WA, USA).

Seedling survival was evaluated on 15 June 2020, 14 October 2020, and 5 May 2022 and was determined by a scratch test, which was done by using a fingernail to gently scratch 0.5 cm of bark approximately halfway up the stem to reveal the cambium layer. Seedlings with stems that revealed wet, green cambium tissue were rated living. Those with dry, brittle, and brown cambium were rated dead.

Vigor was evaluated on 5 May 2022 and was determined by rating on a scale from 1 to 5. Rating categories were designated in this manner: 1- seedling was dead; 2- seedling had 0-25% leaf cover on existing branches; 3- seedling had 26-50% leaf cover on existing branches; 4- seedling had 51-75% leaf cover on existing branches; 5- seedling had 76-100% leaf cover on existing branches.

Data Analysis

All analyses were conducted with JMP® version 16 (SAS Institute Inc., Cary, NC). Repeated measures mixed model analysis was used to analyze percent survival. Blocks were considered random effects while season, species, and treatment were considered fixed effects and sampling date was the repeated measure. Three- and four-way interactions between species, treatment, planting season, and sample date were included in initial models, but in order to form simpler models, model terms were dropped when not found to be significant. Student t-tests were used to compare the difference with and without a Waterboxx® among the same species and sampling period.

Mixed model analysis was used to analyze percent average vigor rating. Plots and side of plot were considered random effects while season, species, and treatment were considered fixed effects. Three- and four-way interactions between species, treatment, planting season, side of plot, and plots were included in initial models, but in order to form simpler models, model terms were dropped when not found to be significant. For these metrics Student t-tests were used to compare the difference with and without a Waterboxx® among the same species.

Sensors measuring soil water potential were averaged by soil depth and treatment and 95% confidence intervals were determined. Treatment effects were considered significant if the confidence intervals did not overlap each other.

RESULTS

Precipitation and Air Temperature

The research site had just been through a severe drought when the study was installed in November 2020 (Figure 1). This trend continued with precipitation in the first 3 months of the study ranging between 37- 46% of normal. Except for February, the site remained dry through the winter. During the spring planting in May 2021 conditions were also dry with precipitation 14% of normal. From June 2021-December 2021 precipitation varied highly from month to month ranging between 12 - 290% of normal. Air temperatures were also above average for most of the study, with some periods being well above average, particularly during the summer months of July 2020 and June 2021 (Figure 1).

Soil Water Potential

For the fall planting, the water potential sensors reported extremely negative values during the winter month 2020-2021, which may be due to inadequate contact with the soil in combination with freezing conditions (Figure 3). Sensors began to be operational by late winter.

Soil water potential associated with the fall and spring plantings was generally wetter under Waterboxx® devices than sites without a Waterboxx®, for most of the study (Figure 3). In May, the beginning of spring, soil water potential began to drop from full saturation (Figure 3). The decrease was slower with Waterboxx® devices at all depths with water potential at 40 cm dropping below -1 MPa at the end of June compared to the control that dropped below that point at 40 cm by the end of May (Figure 3). Mid-August was also another example where the

Waterboxx® devices decreased the rate and severity of drying during a drought period (Figure 3).

Survival Percentage

Overall seedling survival was not different between fall and spring plantings, (*P*= 0.863), but there was an interaction between season and treatment (*P*<0.001). This interaction was primarily due to *C. ledifolius*, *P. edulis,* and *P. tridentata. Cercocarpus ledifolius* had relatively high survival in the fall for both treatments but with the spring planting, survival at the end of the sampling period was increased by the Waterboxx® from 30% to 65% (Figure 4). *Pinus edulis* had relatively high survival in the spring for both treatments but with the fall planting survival at the end of the sampling period was increased by the Waterboxx® from 35% to 75% (Figure 4). By May 2022, *Purshia tridentata* had no difference in fall planting among treatments, but in the spring planting the Waterboxx® treatment increased survival at the end of the sampling period from 15% to 55% (Figure 4).

Treatment and species were significant (*P*<0.001) and there was an interaction between these effects (*P*<0.001), which indicates that species responded differently to treatments (Table 1). Seedlings transplanted in the fall of 2020 had significant increases in seedling survival for *P. edulis, P. tridentata,* and *R. glabra* with increases in survival of 40%, 25% and 45%, respectively by May 2022. There were no differences in transplant survival with and without a Waterboxx® for *C. ledifolius* and *A. canescens*, as most of the transplants for these species had high survival rates (77.5% and 92.5% respectively) (Figure 4). Seedling survival for all species tended to decrease over time with *C. ledifolius, P. edulis,* and *P. tridentata* decreasing more in the summer months from May to October, but the Waterboxx® devices clearly increased survival during this low water period for *P. edulis*, *P. tridentata*, and *R. glabra* (Figure 4).

Purshia tridentata and *R. glabra* seedlings transplanted in the spring of 2021 had significant increases in survival through the summer months of 2021 when transplanted with Waterboxx® devices (Figure 4). However, after winter 2021-2022, *P. edulis* no longer had significant increases in survival with Waterboxx® devices, and *C. ledifolius* for the first time had significant increases in survival with Waterboxx® devices (Figure 4). *Atriplex canescens* seedlings with no Waterboxx® (control) were not significantly different from seedlings with Waterboxx® devices (Figure 3). Survival of seedlings over the summer (June – Oct) tended to decrease but *P. tridentata* and *R. glabra* remained constant when transplanted with Waterboxx® devices (Figure 4).

Vigor

Treatment and species vigor were significantly different ($P<0.001$) and there was an interaction between the species and season ($P=0.003$; Table 2). For the fall planting, *P. edulis* and *Rhus glabra* seedlings had higher average vigor ratings when planted with a Waterboxx® device (Figure 5). For the spring planting, *C. ledifolius*, *P.* edulis, and *P. tridentata* seedlings had higher vigor ratings on average when planted with a Waterboxx® device (Figure 5). *Atriplex canescens* was the only species not significantly affected by treatment in either planting season (Figure 5).

DISCUSSION

Mining in the United States Mountain west often occurs in semi-arid regions dominated by native trees and woody plants. Restoration efforts using native tree and woody plant seedlings in these areas has proven to be challenging as transplanted seedlings experience high mortality during the first year, likely due to limited water resources. Water management tools like the Waterboxx® can help native tree and woody plant establishment and survival in semi-arid environments by providing water during hot, dry periods (Tapia et al. 2019; Gil-Docampo et al. 2020). As hypothesized, the results of our study provide evidence that Waterboxx® devices are a viable method for improving the establishment of native trees and woody plants on mine land overburden sites for most species. Survival and vigor rating were greater with Waterboxx® devices for four of the five species depending on the planting season.

Improved seedling survival and vigor with the Waterboxx® may a result of mitigating drought stress on the seedlings during dry summer months. The results of our study indicate that the Waterboxx® devices may lower drought stress by providing higher and more constant soil moisture with the initial 15 L of water and/or condensates collected by the device.

During the summer months, high temperatures increase the risk of heat damage which can be minimized by leaf cooling through transpiration (Hetherington & Woodward 2003). However, increased transpiration requires increased water use that may not be available during the summer drought period. Since drought drastically reduces transpiration, it can be very difficult to separate the direct effects of high temperature from those of drought (Gates 1968). Our results suggest the Waterboxx® device addresses both effects of high temperature and drought. Combined with the water supplied to the soil from the devices, this potentially reduces heat stress and drought stress through increased soil water available for transpiration.

Soil water potential is a measure of the energy necessary for removing water from soil. Drought reduces the soil water potential and thereby the ability of plants to remove water from the soil (Munns 2011). Soil moisture data from installed sensors suggest the water supplied to the soil from Waterboxx® devices helped maintain higher and more constant soil water potentials. In our study, the soil water potential beneath seedlings with Waterboxx® devices was generally higher and decreased more slowly, while soil water potential beneath seedlings without a Waterboxx® device decreased rapidly and reached much lower water potentials.

According to the manufacturer's installation instructions, when a Waterboxx® device is installed, seedlings planted inside should be watered directly with 3 L of water and an additional 15 L should be used to fill the Waterboxx® reservoir. This additional 15 L can be seen as part of the Waterboxx® device system. Because there was not a separate treatment consisting of a Waterboxx® device without the initial 15 L, it is not known if the 15 L of water, the Waterboxx® devices, or the combination of the initial 15L and the Waterboxx® device are responsible for the improved seedling survival. However, the Waterboxx® device system as a whole did improve seedling survival and increase vigor in our study.

Three seedling species had higher survival rates when planted with Waterboxx® devices than without for only one of the planting seasons. These were: *C. ledifolius* planted in spring, *P. edulis* planted spring, and *P. tridentata* planting in fall. Vigor ratings were higher in the fall planting *for P. edulis* and *R. glabra* and higher in the spring for *C. ledifolius, P. edulis*, and *P. tridentata*. Survival and vigor of *A. canescens* was not affected in either season.

Overall, *A. canescens* seedlings had high survival rates and vigor ratings regardless of treatment and may establish well without the aid of water management tools due to the species. This species is widely distributed in semi-arid regions and has been used extensively in reclamation projects for erosion control due to its resistance to soil salinity, drought, and its overall strong environmental adaptability (Benzarti et al. 2013; Al-Masri et al. 2014; Dengke et al. 2022). This adaptability is shown in this species' ability to grow in areas where the mean annual precipitation is less than 100-400mm, the elevation is anywhere from sea level to 2800m, the soil is sandy to heavy in clay content, and the temperature drops below -20℃ (LeHouerou

1992; Fitzsimmons et al. 1998; Alfonso et al. 2011; Chahouki & Zarei 2011; Al-Masri et al. 2014). Our results suggest *A. canescens* is a good species for mine land restoration in semi-arid environments that may not need the aid of water management tools, and survival of the seedlings may be due to something other than the additional water the Waterboxx® devices provide.

For the fall planting, *C. ledifolius* seedlings showed no difference in survival between treatments but there was a difference for the spring planting. Seedlings used for spring planting were smaller in size than those used for fall planting and may have affected survival for this planting. However, overall seedling survival and average vigor ratings for both treatments were high, which may be due to the species ability to grow in dry conditions and poor soils, similar to *A. canescens* where the additional water may not be the limiting factor in seedlings survival. *Cercocarpus ledifolius* is a broadleaf evergreen native to western North America that grows at high elevations on warm, dry, rocky ridges and slopes (Davis and Brotherson 1991). It can grow on a variety of soil types, even rocky, gravelly, and shallow soil (Wasser 1982). Like other species of this genus, it has been documented to form nodules with nitrogen fixing bacteria that may help with nutrient deficiencies in low fertility soils by converting free nitrogen to ammonia, which the host plant can use (Youngberg and Hu 1972). Our results suggest *C. ledifolius* is a good species for mine overburden restoration in semi-arid environments, with or without the aid of water management tools.

Pinus edulis seedlings planted in the fall had a significant difference in survival between treatments, but for the spring planting, there was no difference. There was, however, a difference between treatments for vigor rating for both planting seasons. *Pinus edulis* is a beneficial species because it has been used previously to restore degraded sites and aid with erosion control (Wood et al. 1995). This species also forms relationships with ectomycorrhiza that enhance nutrient and water uptake (Gehring & Whitham 1994). Communities of *P. edulis* also provide food and shelter for large game, small mammals, and a variety of bird species (Rasmussen 1941; Meeuwig & Bassett 1983).

Purshia tridentata is a favorable shrub for restoration because it is a key forage for large mammals (Guenther et al. 1993), a source of seed for granivores (Vander Wall 1994), and an early season source of pollen and nectar for a variety of insects (Furniss 1983). Similarly, *R. glabra* also provides food for native animal species. Though the forage is considered poor, this species is grazed by large game and its fruits are consumed by a variety of birds (Strauss 1991; Johnson 1995). This species is also considered valuable because it can grow on disturbed sites for erosion control and reclaim land disturbed by mining due to its strong stress tolerance (Adams et al. 1986; Temple 1989).

Most restoration planting is done in fall or spring for various reasons. According to the Utah State University Forestry Extension (2022), the optimal time for planting seedlings is in the spring as moderate temperatures and adequate soil moisture are favorable for establishment. Though fall planting is possible, conditions may be drier and weather less favorable. A benefit of fall planting is it may allow people and equipment to get on site to plant the seedlings. Our results indicate that both planting seasons are favorable for woody plant restoration on mine overburden when using Waterboxx® devices, and that other factors (site accessibility, etc.) may influence planting time more than seedling survival.

The constant supply of water from the Waterboxx® device helps transplanted woody plants tolerate environmental stresses and increases successful establishment. Most native woody plant species do significantly better with the aid of the Waterboxx® device, but some native woody plant species are able to cope with the limited water and still establish depending on when they are planted. These woody plants may be considered better options in areas that are difficult to access with equipment other than hand tools. Woody plant seedling health has an influence on survival and needs to be studied for optimal results regardless of whether or not a Waterboxx® device is used.

Additional considerations for future restoration work with Waterboxx® devices should include prevention of debris and unwanted weeds on and inside the devices. During the study, many Waterboxx® devices were clogged with wind-blown soil and plants, mostly grasses, growing on the cover and inside the reservoir hydroponically. Debris and plants were removed by hand during data collections. Though the water use by these hydroponic plants was likely small, the blockage of collection tubes may significantly impact the ability of Waterboxx® devices to collect precipitation and condensates and, therefore, affect seedling survival.

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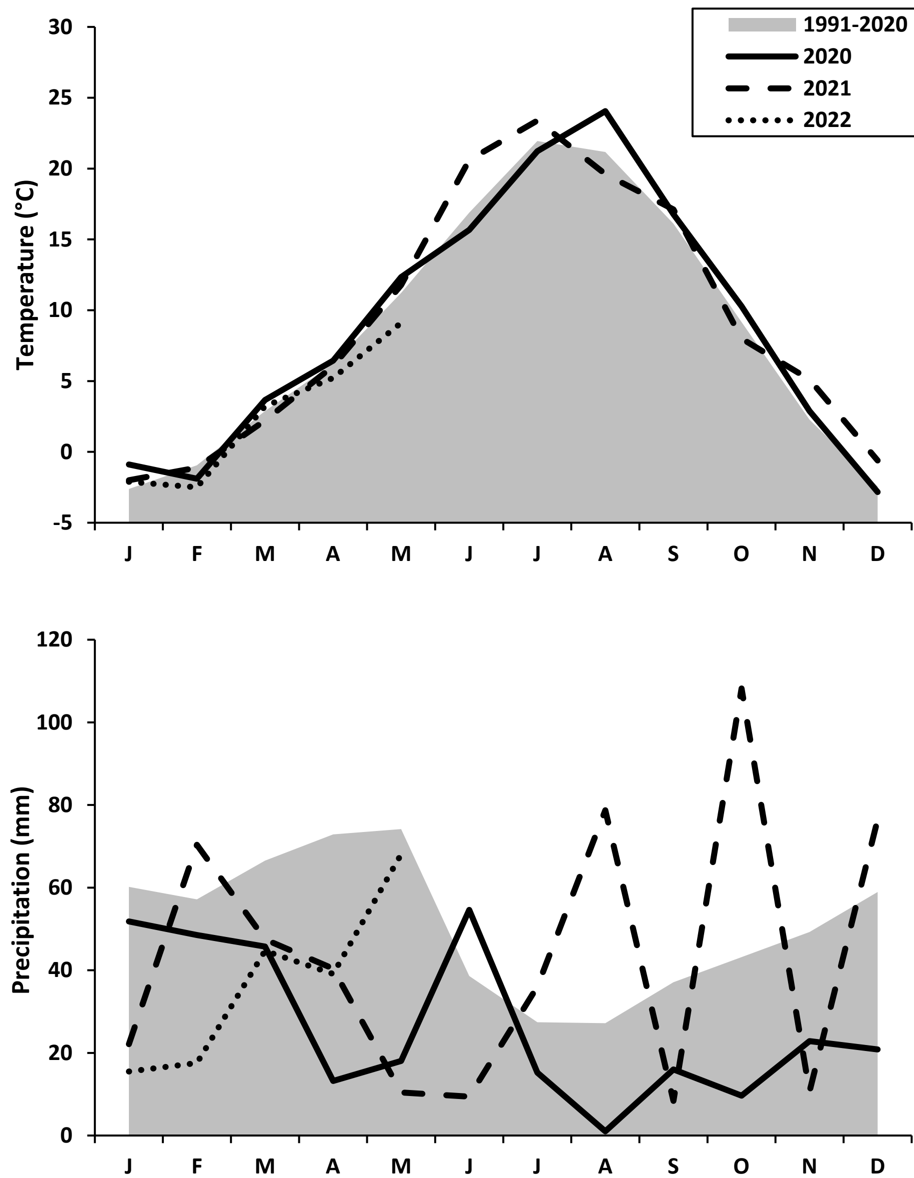

Figure 1 A comparison of precipitation and ambient temperatures experienced during the study (2020-2022) compared to long-term averages (1991-2021) at the study site.

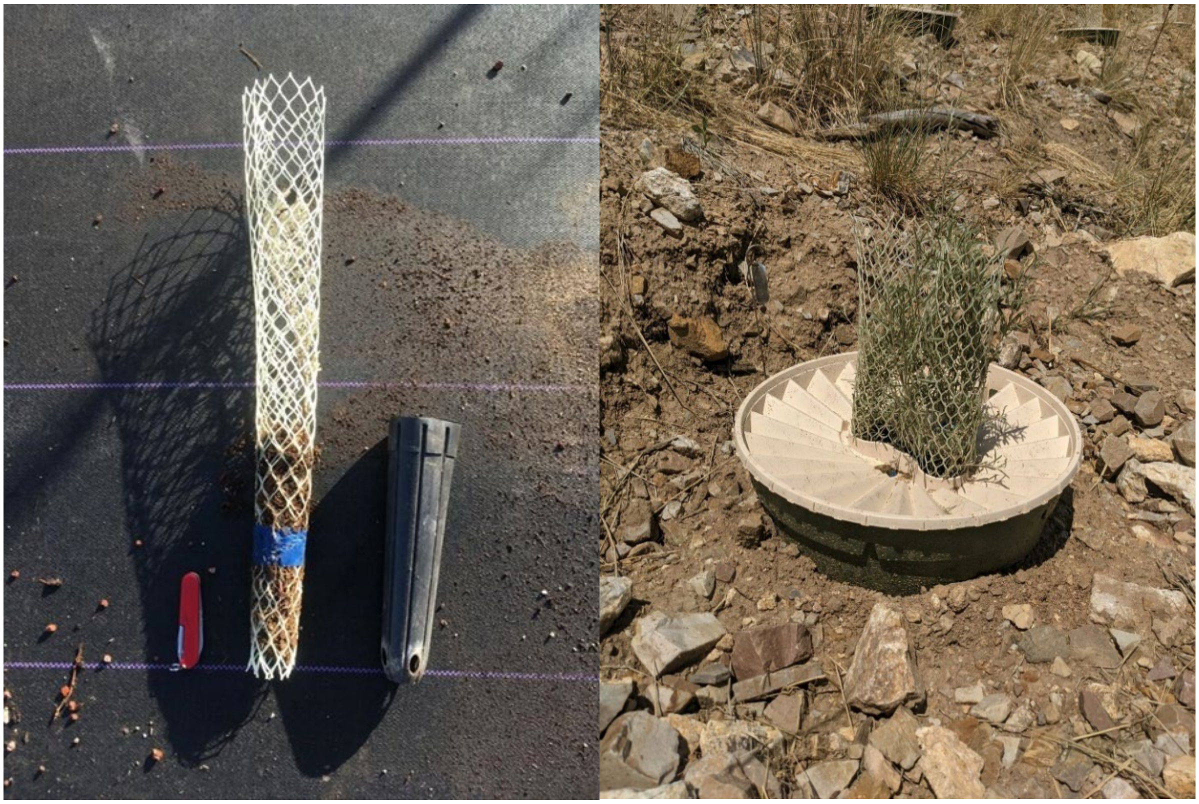

Figure 2 Atriplex canescens seedling grown in a ~655 cm3 tree pot, wrapped with Vexar® caging before plantings (left) and (right) A. canescens seedling grown after planting and installation of Waterboxx® device

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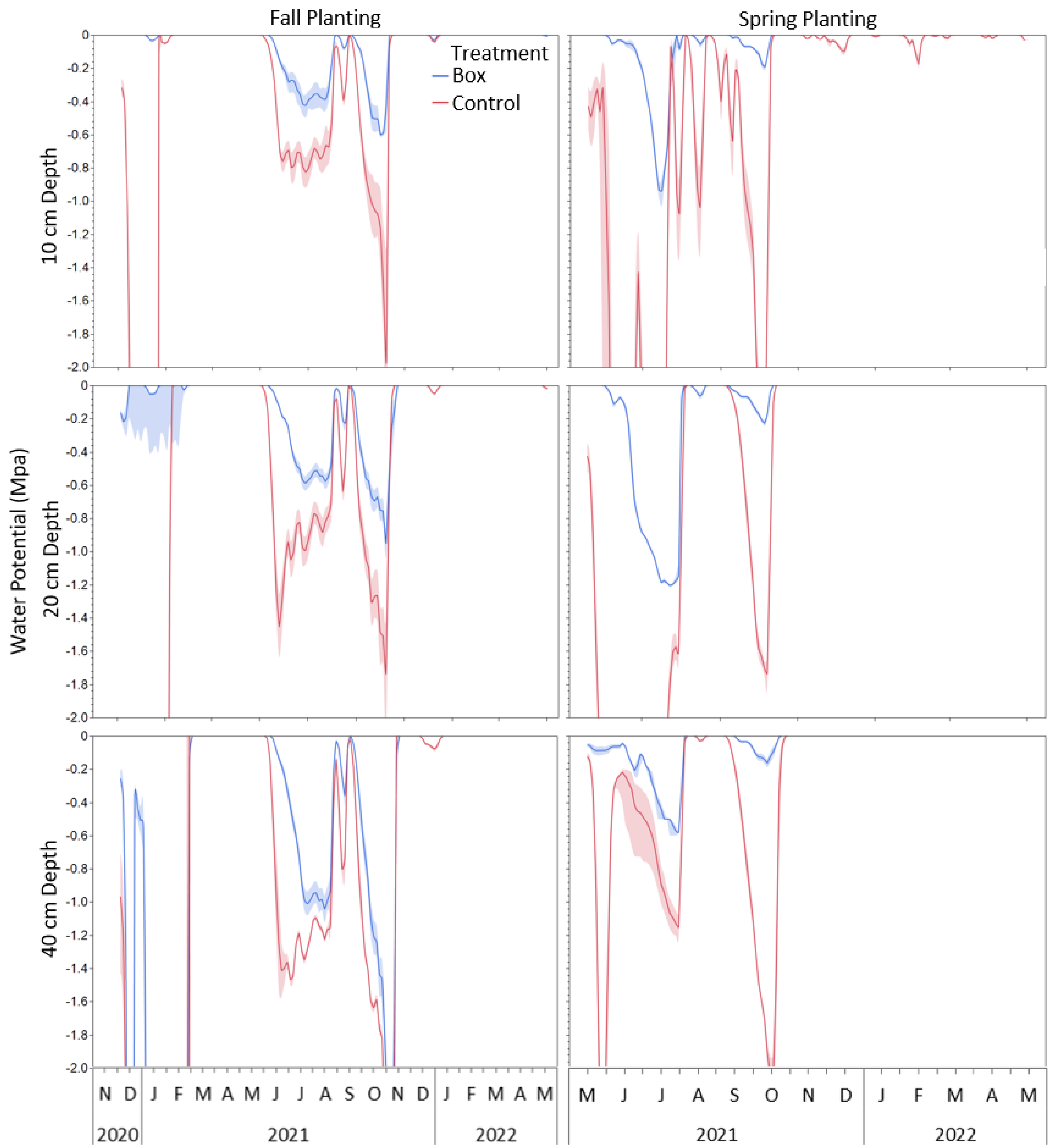

Figure 3 Fall and spring planting soil water potential at 10, 20, and 40cm below seedlings with Waterboxx® devices (Box) and without (Control). Error bars show a 95% confidence of fit.

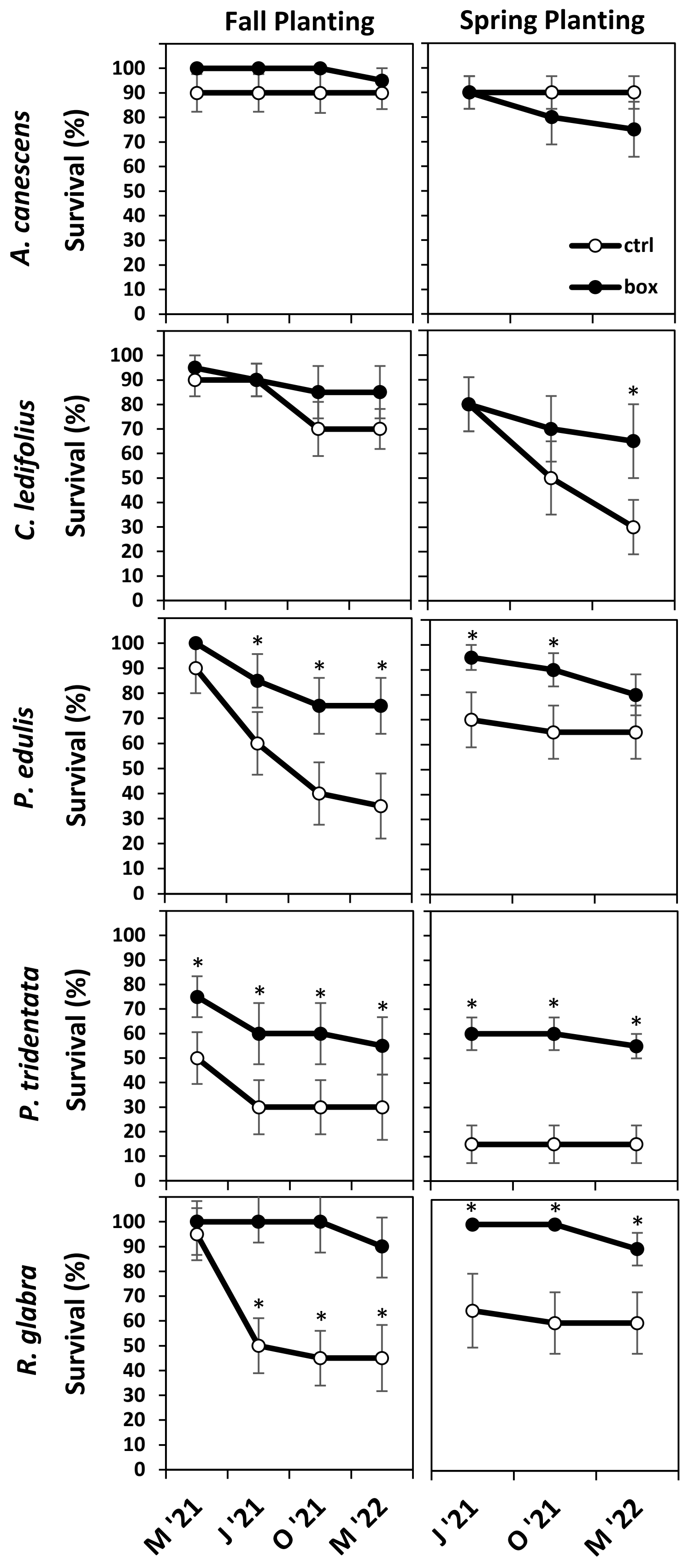
Fall Planting
Spring Planting
A. canescens
C. ledifolius
P. edulis
P. tridentata
R. glabra
Survival (%)
ctrl
box
*
M '21
J '21
O '21
M '22
J '21
O '21
M '22

Figure 4 Percent seedling survival when planted in fall of 2020 and spring of 2021 with Waterboxx® devices and without (control). Student t-tests were used to compare the difference in percent survival between treatments among the same species at each sample date. *Significant differences (P<0.05)

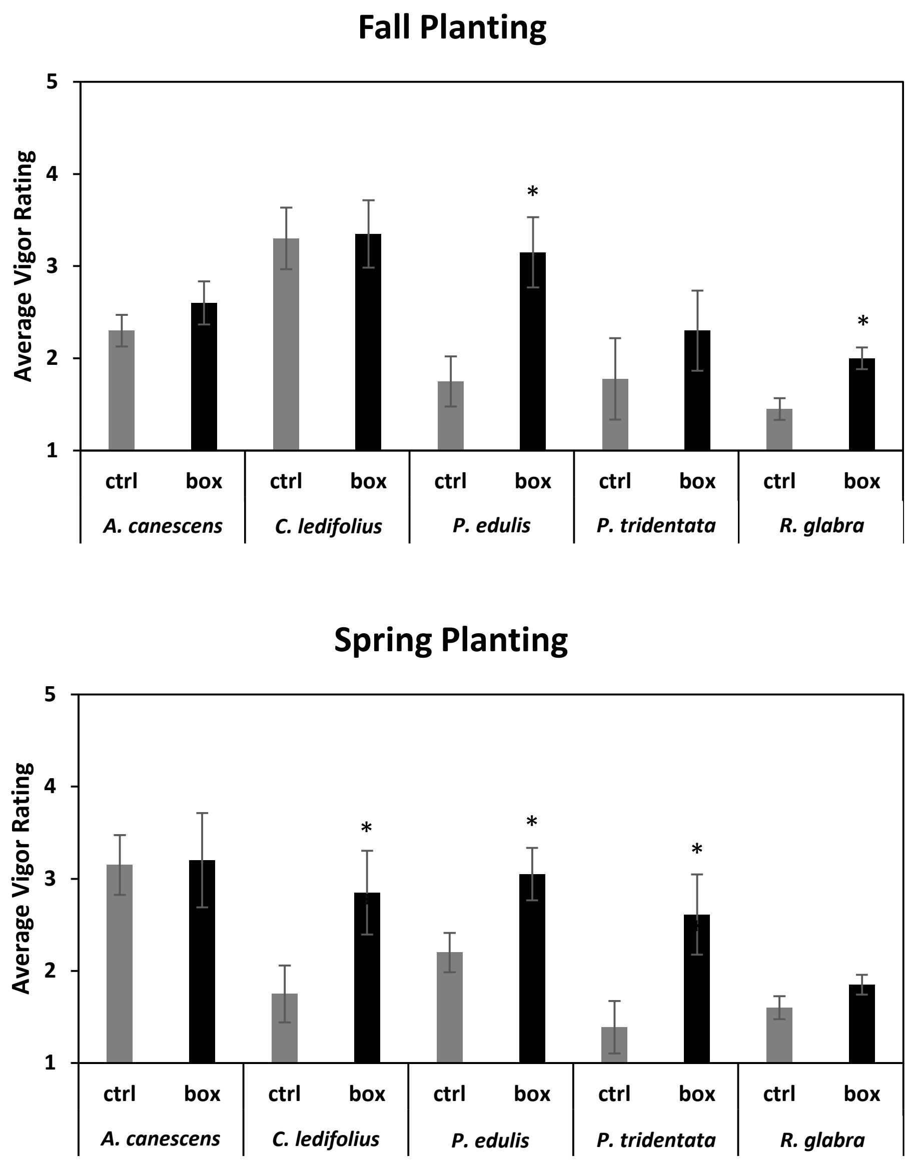

Figure 5 Average vigor ratings for each species by treatment. Student t-tests were used to compare the difference in average vigor rating between treatments among the same species. *Significant differences (P<0.05)

TABLES

Table 1 Mixed ANOVA results for the effects of species, treatment, and season on percent survival after insignificant three- and four-way interactions were removed from the model.

Source	DF (Num, Den)	F Ratio	Prob > F
Species	4, 4	42.84	**<0.001***
Treatment	1, 1	90.43	**<0.001***
Species*Treatment	4, 4	10.13	**<0.001***
Season	1, 1	0.30	0.863
Species*Season	4, 4	8.75	**<0.001***
Treatment*Season	1, 1	0.37	0.5441

*Significant differences (P<0.05) are highlighted in bold.

Table 2 Mixed ANOVA results for the effects of species, treatment, and season on vigor rating after insignificant three- and four-way interactions were removed from the model.

Source	DF (Num, Den)	F Ratio	Prob > F
Species	4, 4	9.38	**<0.001***
Treatment	1, 1	20.28	**<0.001***
Species*Treatment	4, 4	1.46	0.216
Season	1, 1	0.01	0.918
Species*Season	4, 4	4.21	**0.003***
Treatment*Season	1, 1	0.28	0.596
Species*Treatment*Season	4, 4	1.39	0.264

*Significant differences (P<0.05) are highlighted in bold.

CHAPTER 2

Evaluation of Techniques for Transplanting Curl Leaf Mountain Mahogany Seedlings on Mine Overburden using the Groasis Waterboxx®

Holley M. Lund, Bradley D. Geary, Kate Ruebelmann, Roger T. Koide, Matthew D. Madsen
Department of Plant and Wildlife Sciences, Brigham Young University, Provo, UT
Master of Science

ABSTRACT

Semi-arid native plant communities worldwide are often disrupted through human activity. When the activity stops the areas need to be restored back to native plant communities for ecological function. *Cercocarpus ledifolius* is a valuable woody browse species native to western North America and is important for soil renewal and wildlife habitat. It is capable of growing in rocky soil and steep slopes, which makes it a good candidate for restoration of disturbed sites in the semi-arid mountain west. Woody plant establishment in this region is often difficult due to summer drought conditions and low soil fertility. Direct seeding efforts can be hindered by poor germination and low seedling emergence. To overcome this, seedling transplants are often used in harsh sites. Irrigation and fertilizer may also be necessary for restoration efforts. This study evaluated the use of Waterboxx® devices and fertilizer as tools to aid in the establishment of *C. ledifolius* seedlings on a mine land overburden site. This study also evaluated effects of burying Waterboxx® devices according to manufacturer recommendations or installing them on the soil surface. The Waterboxx® works by collecting precipitation and condensation into a reservoir and then slowly releasing the stored water to the soil via a rope wick. We planted 96 *C. ledifolius* seedlings with no Waterboxx®, a one wick Waterboxx® device, a two wick Waterboxx® device, fertilizer, or a combination thereof in the spring of 2021. An additional 32 seedlings were planted with either a one wick Waterboxx® device or a two wick Waterboxx® device that were installed on the soil surface. When evaluated in summer of 2022, survival was substantially improved with buried Waterboxx® treatments relative to control. Vigor was improved with buried Waterboxx® devices containing one or two wicks; howver, they were not significantly different from each other. Regardless of whether Waterboxx® devices were placed on the soil surface or partially buried, survival was statistically better over time. Based on the results obtained, *C. ledifolius* seedlings appear to be a viable species for mine land overburden restoration in the semi-arid west of Utah and Waterboxx® devices significantly improve survival over time.

INTRODUCTION

Woody plant and tree establishment in disturbed semi-arid plant communities can be difficult due to poor soil conditions and low precipitation during summer months. Ecosystems in western North America that have been disturbed, either through mining or other anthropogenic influences, experience impacts to ecosystem functions such as biomass production and nutrient cycling (Sodhi & Ehrlich 2010). In such areas, native plant communities need to be restored to improve both the previously mentioned functions as well as the overall aesthetic component of the area. *Cercocarpus ledifolius* Nutt. (curl leaf mountain mahogany) is a broadly distributed tree native to western North America and is an important species in restoration. In younger stages, communities of *C. ledifolius* are valuable winter browse for large game such as deer, elk, and bighorn sheep (Smith et al. 1950; Hoskins & Dalke 1955). Not only is this species highly palatable but it's also one of few woody plant species that surpasses the protein requirements of wintering deer (Welch & McArthur 1979). Older communities additionally provide winter shelter for large as well as small animals like rodents and birds.

Cercocarpus ledifolius communities are capable of growing in habitats few other woody species can manage, such as rocky outcrops or steep slopes, and can therefore be used to physically stabilize soil in disturbed systems (Davis & Brotherson 1991). In the northern parts of its range, this species is distributed from 610-1372 m in elevation and down to 300 m or more in southern parts of its range (Martin 1950). Since *C. ledifolius* can grow and establish well while stabilizing terrestrial environments, it is valued by land managers as a plant to revegetate disturbed hillsides in semi-arid regions like those in the western U.S.

In semi-arid lands, drought is often a major limiting factor for seedling establishment and, therefore, irrigation may be beneficial for restoration efforts in these areas and can dramatically improve survival and growth of native species of interest (Bainbridge, 2007). After the first critical year or two when *C. ledifolius* and other native woody plants are trying to establish a root system that can access water and nutrients, many of these semi-arid species can tolerate severe drought (Bainbridge, 2007).

The Waterboxx® (Groasis Water Saving Technologies, Steenbergen, North Brabant, Netherlands) device is a tool that collects condensation and precipitation, stores it in a reservoir, and applies it into the soil through capillary action via a rope wick on the bottom of the reservoir. It has been used to aid establishment of transplants in many semi-arid environments (Tapia et al., 2019; Gil-Docampo et al., 2020). These devices are typically installed by placing the device over seedlings and backfilling with soil approximately half the height of the Waterboxx® to keep the device in place (Groasis Ecological Water Saving Technology 2021).

A second rope wick can be added to the base of the Waterboxx® prior to planting to allow water to be released more rapidly to the soil. The wicks are oriented near the transplanted seedlings to provide moisture to the soil and roots, helping the seedlings to grow and establish with the purpose of being self-sufficient within one or two years. The increase in water released to the soil with a second wick may potentially increase survival and vigor of seedlings planted in the Waterboxx® device.

After drought, low soil fertility can be a limiting factor for seedling establishment. Fertilizer is often used in restoration projects to relieve poor soil fertility caused by disturbance (Rodgers

& Anderson 1995; Eastham et al. 2006). Fertilization of these sites has met with some success in certain situations such as revegetation of waste rock piles in northern Idaho (McGheehan 2009).

Here we present a study to assess the ability of fertilizer, the Waterboxx® device with one or two wicks, and installation of Waterboxx® device relative to soil level to 1- improve the survival of *C. ledifolius* and 2- improve the vigor of *C. ledifolius*.

The research was conducted near Salt Lake City, Utah U.S.A at the Bingham Canyon Mine. This site is ideal for evaluating the performance of fertilizer and the Waterboxx® due to the extensive reclamation efforts being conducted, which include an emphasis on the reintroduction of *C. ledifolius*. This mine began operations on the porphyry copper deposit in 1903 (Tooker 1990) and has since produced more than three billion metric tons of waste rock, referred to as overburden, subsequently deposited in valleys and inclines nearby in the Oquirrh Mountain Range (Borden & Black 2005). Our research was focused on evaluating the use of fertilizer and the Waterboxx® for improving plant establishment on a reclaimed overburden hillside at the Bingham Canyon Mine.

Cercocarpus ledifolius occurs naturally in the neighboring hillsides in the Oquirrh Mountain Range in dominant communities alongside *Quercus gambelii* Nutt. (gambel's oak) and has been found on some overburden sites as natural volunteer vegetation between an elevation of 2000 and 2400 m (Borden and Black, 2005). Due to this, and its ability to grow in rocky outcrops and steep slopes, this species is a prime candidate for restoration efforts at the Bingham Canyon overburden sites.

MATERIALS AND METHODS

Study Site

Waterboxx® devices were installed at the Bingham Canyon Copper Mine located in the Oquirrh mountain range, on the Yosemite waste rock dump (40.51263889, -112.1182611). The location of the site is associated with the Mountain Loan (Oak) (R047XA432UT) ecological site (Soil Survey Staff 2022). This area is located at an elevation of 1873 m within the mountain brush zone, which forms a transition between coniferous forest above and pinyon-juniper woodlands at lower elevations (Banner 1992). Prior to being covered by mining overburden the site was most likely dominated by small trees and woody plants.

Overburden materials deposited on the hillslope consist of varying ratios of monzonite, quartzite, and limestone (Borden 2001; Borden 2003). In 2015, the site was reclaimed by decreasing the slope of the hill to approximately 12% and covering the area with a 1-m thick layer of crushed rock and stockpiled topsoil. This growth media was then ripped perpendicular to the slope using dozers to create small terraces ~ 0.5 m wide and spaced ~ 1 m apart. The site was then hydroseeded with a seed mix comprised of native and introduced species, which is reviewed and approved by the Division of Oil Gas and Mining. Introduced perennial grasses were the most successful at establishing with *Thinopyrum intermedium* L. (intermediate wheat grass), being the dominant species. There were also smaller amounts of other native and introduced grasses and forbs, and only a trace number of woody plants, except for *Ericameria nauseosa* ex Pursh G.L. Nesom & Baird (rubber rabbitbrush). Ten soil samples were collected in a random pattern across the Yosemite overburden site at a depth of 30cm. All samples were combined into one and then submitted to the BYU Environmental Analytical Laboratory for analysis. The combined soil had a pH of 7.5, with a gravelly clay loam soil texture. Mean yearly precipitation at the site is ~613 mm (Figure 7) (Prism Climate Group 2021).

Modification to Waterboxx® Devices with Fertilizer Field Trial

Cercocarpus ledifolius Nutt. (curl leaf mountain mahogany) seedlings were planted in late spring (May 2021) in a randomized factorial design with eight blocks. Seedling pairs were planted ~15 cm apart on an east-west arrangement, with each pair given one of eight treatments: 1- planted with no Waterboxx® (control), 2- planted with a one wick Waterboxx® or 3- a two wick Waterboxx®, 4- planted with fertilizer (The Scotts Company, LLC, Marysville, Ohio) and no Waterboxx®, 5- fertilizer and a one wick Waterboxx®, 6- fertilizer and a two wick Waterboxx®, 7- planted with a one wick Waterboxx® placed on the soil surface, or 8- planted with a two wick Waterboxx® placed on the soil surface.

Twenty-one-gram long-lasting fertilizer tablets with a rating of 20-10-5 NPK and minor amounts of Ca, Mg, Su, B, Cu, Fe, Mn, and Zn were used. The fertilizer treatment was applied by placing one tablet in each hole, covered lightly with soil with the seedlings planted directly above either with or without a Waterboxx®.

Prior to planting, seedlings were caged with Vexar®, (Forestry Suppliers, Jackson, Mississippi), a flexible UV inhibited polyethylene and polypropylene material. Each seedling was wrapped in its entirety to deter herbivory to roots and shoots from rodents and ungulates (Figure 8). Holes for planting were dug with a 30.5 cm diameter motorized auger (Kohler Co., Kohler, Wisconsin) debris was cleaned out by hand with shovels. Seedlings were planted deep enough that the soil level met the root flare.

Waterboxx® devices were installed according to manufacturer recommendations unless receiving the surface Waterboxx® treatment (Groasis Ecological Water Saving Technology 2021). Prior to planting, evaporation covers, rectangular corrugated plastic designed to discourage soil water evaporation, were trimmed to fit around caging and placed around the seedling pairs on top of the soil. Waterboxx® devices were placed over seedlings positioned inside the central openings, wicks pointing inward toward the seedlings and lightly covered in soil. Insulation plates were placed inside, covers placed on top and drainage tubes pressed into holes in the covers. Water filling caps in the cover were positioned to face north (Figure 7). These boxes were either placed on the surface or backfilled around the outside with soil and rock ~10 cm high to hold them in place depending on the treatment. Both seedling pairs planted with and without a Waterboxx® were watered directly with 3 L. Waterboxx® devices were then filled with 15 L of water.

Seedling survival was evaluated on 15 June 2020, 14 October 2020, 5 May 2022 and 7 July 2022 and was determined by a scratch test, which was done by using a fingernail to gently scratch 0.5 cm of bark approximately halfway up the stem to reveal the cambium layer, or evaluating leaf production. Seedlings with stems that revealed wet, green cambium tissue were rated living. Those with dry, brittle, and brown cambium were rated dead.

Vigor was evaluated on 5 May 2022 and again 7 July 2022 and was determined by rating on a scale from 1 to 5. Rating categories were designated in this manner: 1- seedling was dead; 2- seedling had 0-25% leaf cover on existing branches; 3- seedling had 26-50% leaf cover on existing branches; 4- seedling had 51-75% leaf cover on existing branches; 5- seedling had 76-100% leaf cover on existing branches.

Data Analysis

All analyses were conducted with JMP® version 16 (SAS Institute Inc., Cary, NC). One way ANOVA and mixed model analysis was used to analyze both percent survival and vigor rating. Differences were considered significant when $P < 0.05$.

RESULTS

Precipitation and Air Temperature

The long-term averages (1991-2020) for precipitation show most precipitation occurs in winter and spring with maximum monthly precipitation (~74 mm) being reached in May. Over the following summer months, precipitation steadily decreases by month with a minimum (~27 mm) reached in July and August. Beginning at the end of August, precipitation steadily increases into winter. Precipitation during the years of the study (2021-2022) do not follow the pattern of the long-term averages and vary greatly between years.

Our study was installed May 2021. That first year (2021) had ~94 mm less yearly precipitation with steep increases in precipitation in February, June, August, October, and December immediately followed by steep decreases. The highs and lows of the peaks were more extreme than the long-term averages by month (Figure 6). The sum of monthly precipitation for January to May 2022 was ~146 mm less than the long-term average for those months.

The long-term averages (1991-2020) for ambient air temperature for the study site show similar patterns for each year of the study (2021-2022) (Figure 6). Temperatures were lowest during the winter, often reaching a yearly minimum between December and February. Then temperatures slowly increased at the beginning of March, reaching a yearly maximum of 18-21°C by July or August, before slowly decreasing into winter. June and July of 2021 had slightly higher average monthly temperatures than the long-term averages for those months.

Survival Percentage

Fetilizer, Waterboxx® treatment, and sample date were significant (P=0.001; <0.001; 0.010) and there were no interactions (Table 3). Fertilizer decreased *C. ledifolius* seedling survival and was significantly lower than seedling survival in Waterboxx® devices with no fertilizer (Figure 8). Fertilizer in Waterboxx® treatments were not significantly different from Waterboxx® devices without fertilizer but there was a clear trend of lower seedling survival. Seedlings grown in a Waterboxx® with either one or two wicks had 100% and 175% increase in the number of plants that survived to the end of the study, respectively (Figure 8). Waterboxx® devices installed on the surface had sirgnificantly better survival in May 2022 than the control but were not significantly different in July because of a slight decrease in survival with Waterboxx® devices on the surface. Howerver, buried Waterboxx® devices were significantly different than the control at any evaluation period in 2022 (Table 4; Figure 10).

Vigor

Waterboxx® treatments significantly (P=0.0015) improved seedling vigor, but fertilizer did not (Table 3). There was no statistical improvement in vigor with a one wick Waterboxx® but seedlings growing from a two wick Waterboxx® had 154% higher ratings than the control (Figure 9). Vigor of seedlings in Waterboxx® devices buried or installed on the surface did not significantly differ from each other but buried Waterboxx® seedlings had significantly better vigor than control seedlings (Figure 10). Waterboxx® devices installed on the surface were not significantly different than the control (Table 4; Figure 11).

DISCUSSION

Restoration work in semi-arid regions of the Western United States, as well as other parts of the world, struggle for perennial plant establishment primarily due to limited water resources and low soil fertility. Use of irrigation devices may help improve revegetation success. *Cercocarpus ledifolius* is a valuable woody species native to the mountain west and adapted to a semi-arid environment. It is a good candidate for restoration of disturbed sites due to its ability to grow in rocky soil and steep slopes (Davis & Brotherson 1991). Our results provide evidence that *C.*

ledifolius is a viable species for mine overburden restoration with Waterboxx® devices but without the addition of fertilizer.

Higher temperatures during summer months increase the risk of heat damage to seedlings but this damage can be lessened by leaf cooling through transpiration (Hetherington & Woodward 2003). However, increased transpiration necessitates increased water use during the summer drought period when additional water may not be available. The Waterboxx® device may provide additional water to mitigate this drought stress on seedlings and our results recognize *C. ledifolius* seedling survival and vigor is significantly improved with a Waterboxx® device.

Results of our study demonstrated the Waterboxx® substantially improved seedling survival relative to the control, with seedlings grown from a Waterboxx® with either one or two wicks had 100% and 175% increase in the number of plants that survived to the end of the study, respectively (Figure 8). As for vigor, there was no statistical improvement with a one wick Waterboxx® but seedlings growing from a two wick Waterboxx® had 154% higher ratings than the control (Figure 11). Results also showed that combining the Waterboxx® with fertilizer provided no additional improvement in plant survival or vigor, regardless of the number of wicks in the Waterboxx®.

In the next analysis, we looked at the effect of either placing the Waterboxx® on the soil surface or burying the Waterboxx® partway into the ground. At first, an analysis was performed with the model, including both one and two-wick Waterboxx® devices, but no significant effect was detected. The one-wick Waterboxx® treatment was then dropped and ran the study with the two-wick Waterboxx®, as this was the top-performing treatment in the previous analysis. Results indicated that the improvement in seedling survival and plant vigor was not statistically greater than the control when the Waterboxx® was placed on the soil surface. Clearly, the buried Waterboxx® with two wicks improved both seedling survival and vigor.

Fertilizer is often used in restoration projects to combat low soil fertility with some success in promoting growth of desired plants (McGeehan 2009); however, addition of fertilizer has often promoted growth of invasive species over native plants due to the latter's tendency to be adapted to low soil fertility (Gendron & Wilson 2007). Similarly to our study, other in field fertilization studies, decreased plant growth rates in plants adapted to low fertility soils compared to plants adapted to higher fertility soils during drought (Chapin 1980). Fehmi and Kong (2012) observed fertilizer resulted in a decline of semi-arid plant establishment on three soil types by more than 50%. Fertilizer treated seedlings in our study and other studies may have had lower vigor because of combined effects with drought creating a phytotoxic effect.

Overall, these results indicate that when *Cercocarpus ledifolius* is transplanted on reclaimed overburden dump sites, a Waterboxx® device can substantially improve success. A Waterboxx® device containing two-wicks, and buried in the soil as suggested by the manufacturer, with no fertilizer, was the best treatment to improve *C. ledifolius* seedling survival and vigor. *Cercocarpus ledifolius* will benefit mine overburden areas by physically stabilizing soils in these areas and creating an environment that will foster additional plants naturally migrating into the area thus improving the soil and wildlife habitat.

Additional considerations for future restoration work with Waterboxx® devices should include prevention of debris and unwanted weeds on and inside the devices. During this study, many Waterboxx® devices were clogged with wind-blown soil and plants, mostly grasses, growing on the cover and inside the reservoir hydroponically. Debris and plants were removed by hand during data collections. Though the water use by these hydroponic plants was likely small, the blockage of collection tubes may significantly impact the ability of Waterboxx® devices to collect precipitation and condensates and, therefore, affect seedling survival.

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FIGURES

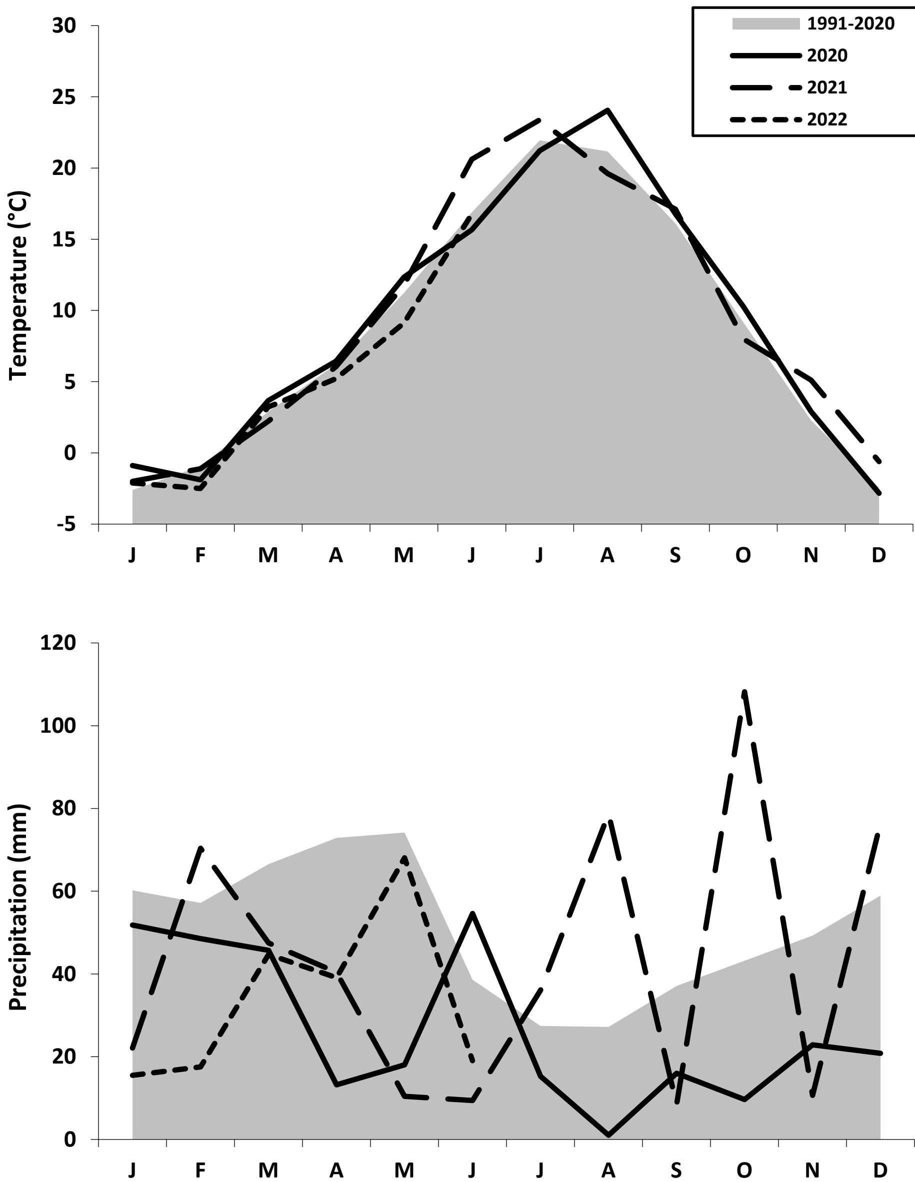


Figure 6 A comparison of precipitation and ambient temperatures experienced during the study (2021-2022) compared to long-term averages (1991-2021) at the study site.

Figure 7 Seedling grown in a ~655 cm3 tree pot, wrapped with Vexar® caging before plantings (left) and (right) *Cercocarpus ledifolius* seedlings growing in a Waterboxx® device.

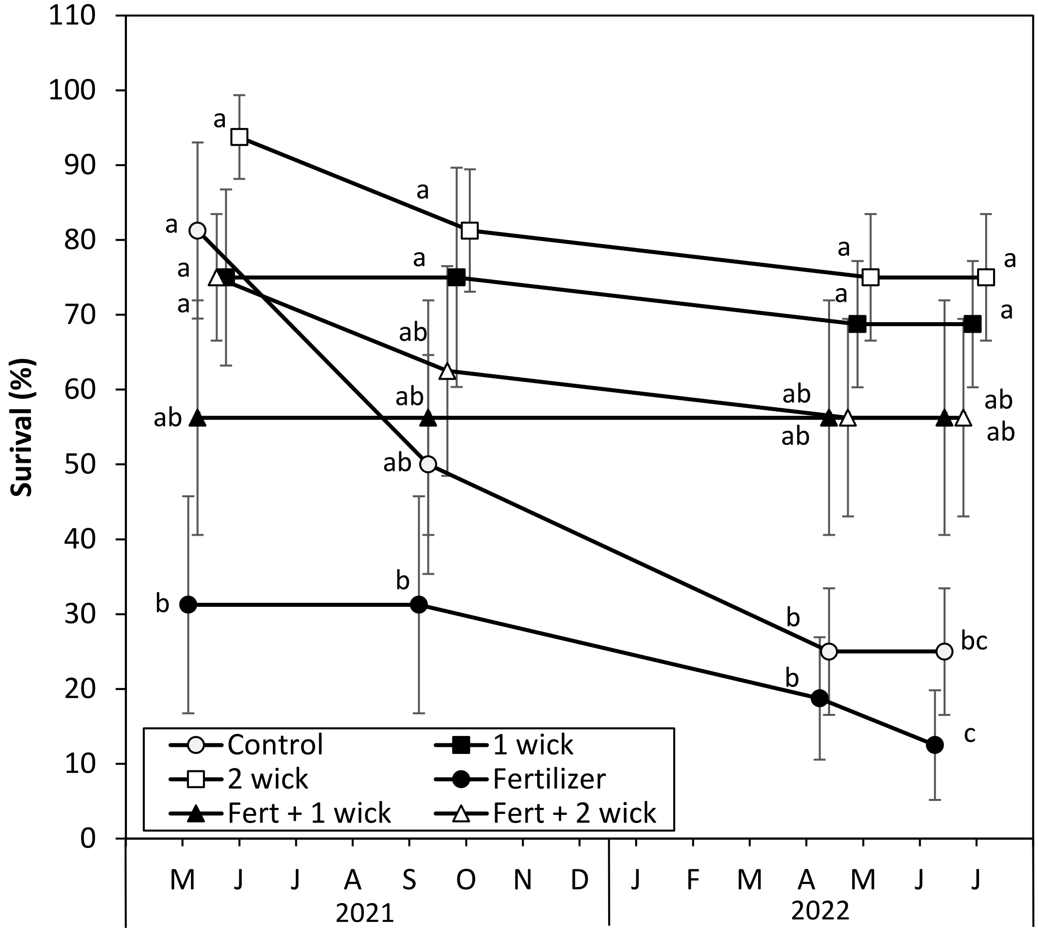


Figure 8 Percent seedling survival over the course of the study for *Cercocarpus ledifolius* seedlings planted with no treatment (Control), in a Waterboxx® with one wick (1 wick), Waterboxx® with two wicks (2 wick), and these three different treatments planted with fertilizer. The graph shows mean values and its associated standard error. Values for given sample date that are superseded by the same letter are not significantly different as determined with the Tukey pairwise comparisons (*P<0.05*).

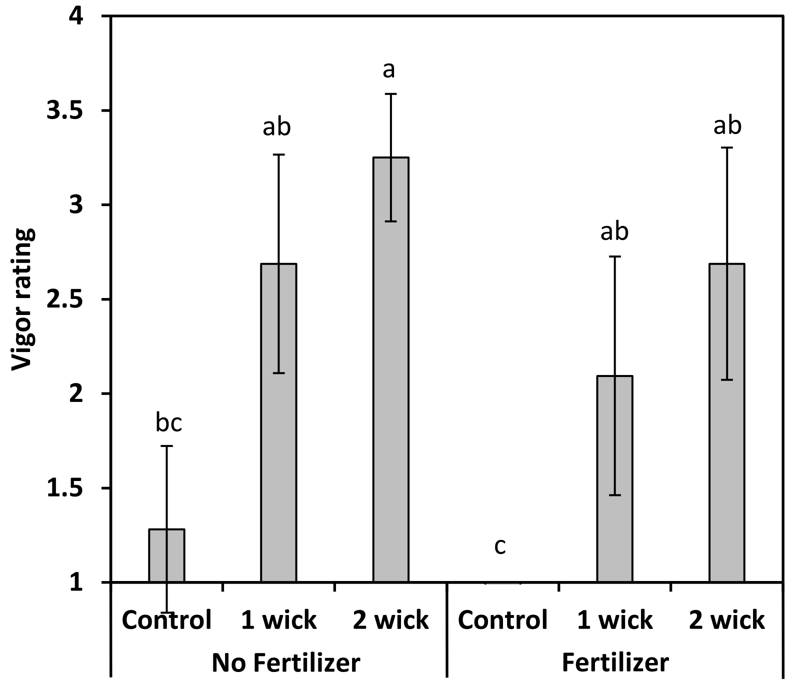


Figure 9 Mean (±SE) vigor estimates of *Cercocarpus ledifolius* seedlings planted with and without fertilizer and either left with no further treatment or planted with a Waterboxx® that has one wick (1 wick), or two wicks (2 wick). Values with different lower-case letters are significantly different as determined with the Tukey pairwise comparison test ($P<0.05$).

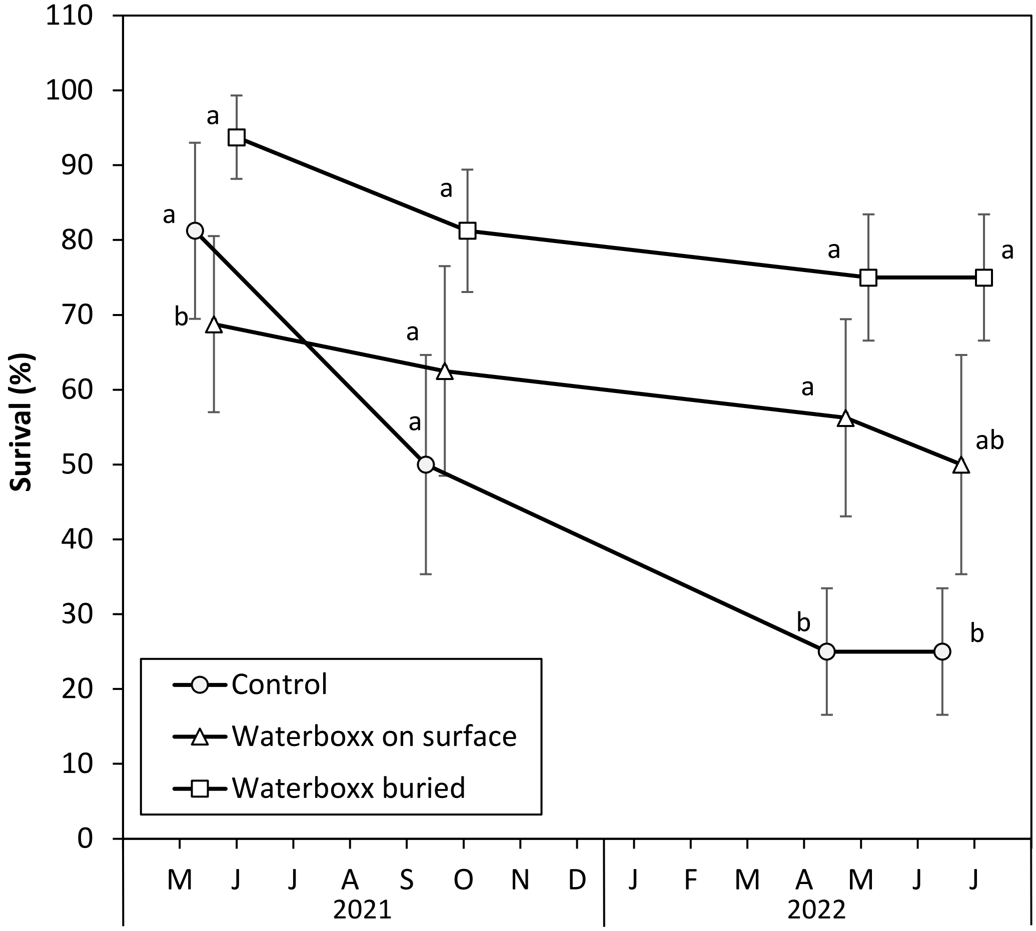


Figure 10 Percent seedling survival over the course of the study for *Cercocarpus ledifolius* seedlings planted with no treatment (Control), in a two wick Waterboxx® that was either place on the soil surface or buried 20 cm into the soil. The graph shows mean values and associated standard error. Values for given sample date that are superseded by the same letter are not significantly different as determined with the Tukey pairwise comparisons ($P<0.1$).

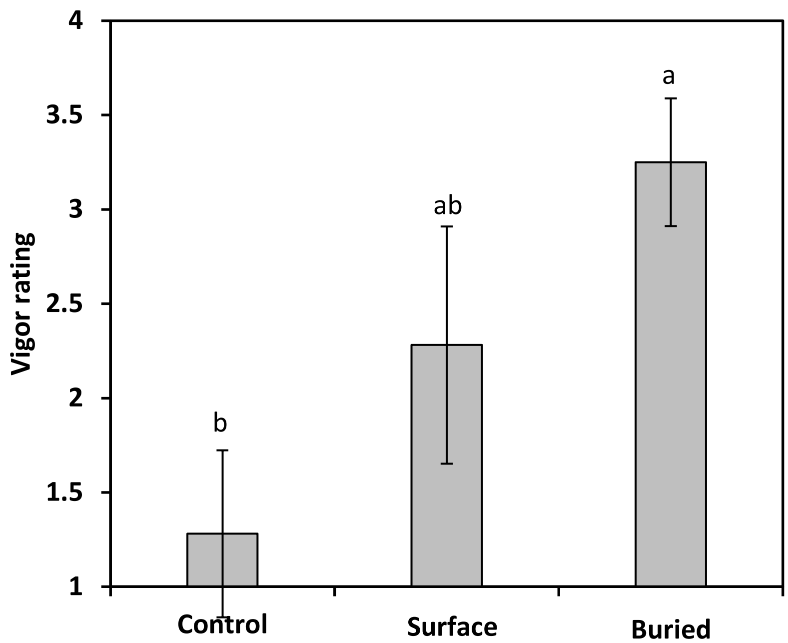


Figure 11 Mean (±SE) vigor estimates of Cercocarpus ledifolius seedlings planted with and without fertilizer and either left with no further treatment or planted with a Waterboxx® that has one wick (1 wick), or two wicks (2 wick). Values with different lower-case letters are significantly different as determined with the Tukey pairwise comparison test (*P<0.1*).

TABLES

Table 3 Degrees of freedom (df), *F*, and *P* (*Pr>F*) values for an analysis of variance for the effect of fertilizer, Waterboxx® (W.Box), sample date (S. date) and their interactions on seedling survival. Table also shows the same statistical measures from a Mixed Model Analysis on the effect of plant vigor from the effect of fertilizer, Waterboxx® and these two interactions. *P* values in bold are statistically significant (*P*<0.05).

	Survival			Vigor		
	df	*F Ratio*	*Prob > F*	*df*	*F Ratio*	*Prob > F*
Fertilizer	1,180	11.8	**0.001**	1,42	2.15	0.1503
W. Box	2,180	17.5	**<0.001**	2,42	7.7	**0.0015**
S. Date	1,180	6.8	**0.010**			
Fertilizer+W.Box	2,180	0.1	0.896	2,42	0.1	0.9625
Fertilizer+Date	1,180	0.8	0.379			
W. Box+S. Date	2,180	1.7	0.178			
Fertilizer+W.Box+S.Date	2,180	0.4	0.676			

Table 4 Degrees of freedom (df), *F*, and *P* (*Pr>F*) values from a Repeated Measures Mixed Model analysis for the effect of treatments, sample date (S. date) and their interactions on seedling survival. Treatments included planting seedlings with and without a Waterboxx®, with the Waterboxx® either burred in the ground or placed on the soil surface. Table also shows the same statistical measures from a Mixed Model Analysis on the effect of plant vigor from the effect of the treatments. *P* values in bold are statistically significant (*P*<0.1).

	Survival			Vigor		
	df	*F Ratio*	*Prob > F*	*df*	*F Ratio*	*Prob > F*
Treatment	2,90	9.03	**0.001**	2,21	3.3	**0.057**
S. Date	1,90	11.7	**0.001**			
Treatment X S.Date	2,90	2.0	0.145			

APPENDIX

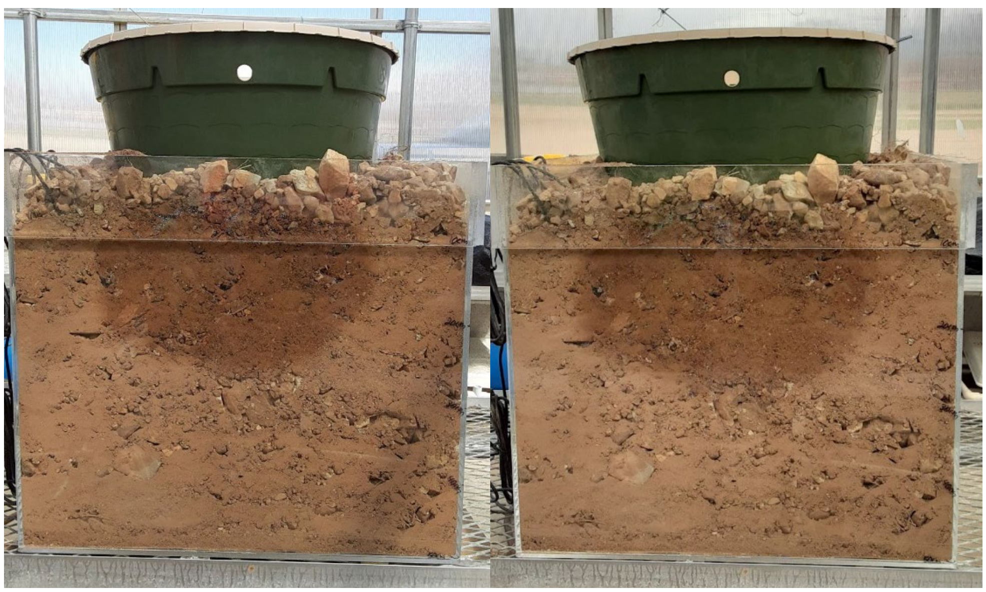
SUPPLEMENTAL STUDIES

Soil Water Movement Greenhouse Trial

This study was conducted to observe water movement patterns of one and two wick Waterboxx® devices in soil. Soils were collected from two locations in Utah: the Yosemite waste rock dump where field trials were conducted and Elberta, UT from undisturbed public lands. The study was designed as a paired comparison design with three replicates. Their respective soil textures were gravelly clay loam and sandy loam, which were placed into Plexiglas® boxes to observe soil moisture movement.

Two Plexiglas® boxes (BYU Science Support Shop), measuring 0.5 meters in depth, width, and height, were filled with one of the two collected soils. Each box received one of two treatments: a one wick or two wick Waterboxx®. Waterboxx® devices were placed on top of the soil with the accompanying evaporation cover between it and the soil (Figure 11). The 1cm diameter rope wicks were lightly buried in the soil at a depth of 1 cm and the end of the rope wick was 1 cm from the wall of the Plexiglas® box. Waterboxx® devices were then filled with 15 L of water and the expansion of water through the soil was measured every 24 hours for three weeks. Water levels within each Waterboxx® were also recorded daily. Pictures were taken each day to visually record the shape and distribution of water movement through the soil over time.

a. b.



c. d.

Figure 12 Progression of water movement through the soil from Waterboxx® devices installed within a Plexiglas® box.

Water seeping into the soil is darker in color. a- 24 March 2021 (14 days after installation); b- 31 March 2021, c- 6 April 2021; d- 13 April 2021.

Greenhouse Sorghum bicolor Trial

Soil was collected from Elberta, Utah from the top four inches of soil under living *Artemisia tridentata* Nutt. (sagebrush). Forty 6-inch pots were filled with field soil to one inch from the top of the pot. Pots were then seeded with 15 *Sorghum bicolor* L. var. *Drummondii* (sudangrass) seeds, covered with 0.5 inches of moist vermiculite and placed on greenhouse benches with drainage. Pots were watered 2-3 times a week to saturation and allowed to drain. A calcium nitrate solution (50ppm) equivalent to one-fourth the ppm found in Hoagland's solution (Hoagland & Arnon 1950), was added once a week, 500 mL of solution was applied to each pot.

At six and twelve weeks, soil samples (~50 grams), which included fine roots, were taken down to ~3 inches below the soil surface and sieved with 500, 250, and 45 µm sieves and observed under a microscope. Numbers of mycorrhizal spores were observed and recorded. One inch root samples were also collected from the same pots and dyed with Trypan blue and examined for hyphal colonization.

Two spores total were observed from all pots (40 pots total) in sieved greenhouse *Sorghum bicolor* samples after six weeks of growth (Figure 12). No spores were observed at the twelve-week sampling when ten of 40 pots were sampled. Root colonization was observed through Trypan blue staining, at the six-week sampling period. At least two different fungi were differentiated by the presence of vesicles, terminal swellings of hyphae, observed in the roots. One fungal hyphae appeared to be an arbuscular mycorrhiza because it had vesicles. No root staining with Trypan blue was performed on roots sampled at the twelve-week interval because no spores were observed.

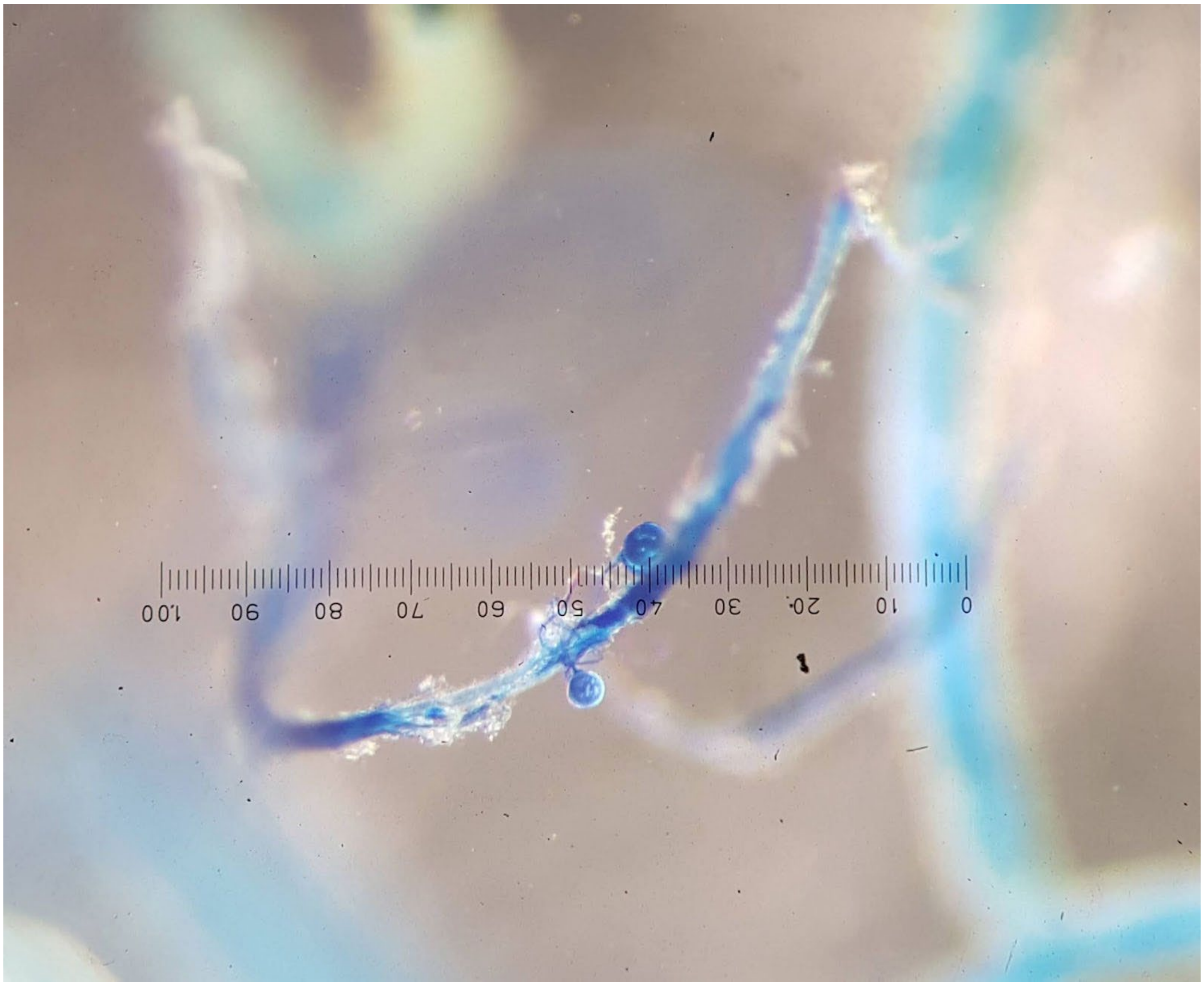


Figure 13 Sorghum bicolor roots stained with Trypan blue viewed at 40x.
Dark blue regions are mycorrhizal mycelium and vesicles.

Growth Chamber Host Plant and Soil Depth Trial

Soils collected from Elberta, Utah and native undisturbed hillsides adjacent to the Bingham Canyon Mine overburden site in August 2020 constituted the two main plots, and at each location soil was collected from the roots of living *Artemisia tridentata* Nutt. (sagebrush). Sub-plots consisted of three different soil sampling depths: 4-6 inches, 6-10 inches, and 10-14 inches below the soil surface. The sub-sub-plots included four plant host species: *Sorghum bicolor* L. var. *Drummondii* (sundangrass)*,* *Pennisetum glaucum* L. (pearl millet), *Bouteloua curtipendula*

(Michx.) Torr. (sideoats grama), and *Trifolium pratense* L. (red clover). Each combination of soil, depth, and host plant was replicated three times.

Main and sub-plot soils (all three depths) were separately mixed with sterile sand in a 1:1 mixture. The soil and sand mixtures were used to fill 6-inch pots, seeded with host species 80-100 seeds per pot, and placed in a growth chamber. Temperatures were maintained at ~32 ° C, the light-dark cycle was 12 hours of light and 12 hours of darkness. Pots were watered 1-2 times a week as needed, and pots were allowed to fully drain.

After four, eight, and twelve months, above ground vegetation was removed and soil samples (~50 grams) with fine roots were taken down to ~3 inches below the soil surface from each combination of soil, depth, and host plant. Samples were sieved with 500, 250, and 45 µm sieves and observed under a microscope. Numbers of mycorrhizal spores were observed and recorded. No spores were observed

Greenhouse Perlite Trial

Soil was collected 6 December 2022 from naturally vegetated hillsides adjacent to the Yosemite overburden site near the Bingham Canyon Copper Mine. The top four inches of soil were collected from beneath living *Artemisia tridentata* Nutt. (sagebrush). Soil was combined with perlite for two treatments: 50% perlite volume-to-volume and 60% perlite to 40% volume-to-volume mixtures. Each mixture was used to fill five 6-inch pots. All pots were seeded with 50 sudangrass seeds and placed on greenhouse benches. Pots were watered 2-3 times a week to saturation and allowed to drain. Plant fertility requirements were provided by a Hoagland's solution that was modified by removing all phosphorus and diluting it to one-quarter strength; it was applied once a week at 500 mL per pot.

After 12 weeks, soil samples (~50 grams) with fine roots were collected down to~3 inches below the soil surface from both treatments and sieved with 500, 250, and 45 µm sieves and observed under a microscope. Numbers of mycorrhizal spores were observed and recorded. No spores were observed

Commercial Mycorrhizae Trial

Soil previously collected from Elberta, Utah was air dried and sterilized in an autoclave at 121°C for 20 minutes in 1-gallon batches. Soil was used to fill nine 6-inch pots and ~10 grams of Biocoat Gold® (Advancing Eco Agriculture, Middlefield, Ohio) powder in 100mL of water was mixed into the top inch of soil in each pot. Of the nine pots, three were seeded with five *Sorghum bicolor* L. var. *Drummondii (*sudangrass) seeds, three with five *Eragrostis curvula* (Schrad.) Nees (weeping Lovegrass) seeds, and three with five *Bouteloua curtipendula* (Michx.) Torr. (sideoats grama) seeds. Pots were placed on greenhouse benches and watered two times each week to saturation and allowed to drain.

Twelve 6-inch pots were filled with sterilized Elberta soil and divided into groups of four. Each group of pots had either 100 mL of liquid Endoprime®, liquid Endofuze®, or ~10 grams of Ultrafine Endo® (MycoApply, Grants Pass, Oregon) applied to the soil. Each mycorrhizal powder product was dissolved in 100mL of water and then mixed into the top inch of soil in each pot. The four pots were replicates for each commercial mycorrhizal treatment. All twelve pots were seeded with five *S. bicolor* seeds each. Pots were placed on greenhouse benches and watered two times a week to saturation and allowed to drain.

After six weeks, soil samples (~50 grams) with fine roots were taken down to ~3 inches below the soil surface from both treatments and sieved with 500, 250, and 45 µm sieves and observed under a microscope. Numbers of mycorrhizal spores were observed and recorded.

No spores were observed

Outdoor Compost Trial

Soil was collected from the roots of living *Artemisia tridentata* Nutt. (sagebrush) from native undisturbed hillsides adjacent to the Bingham Canyon Yosemite overburden site on 25 February 2022. Soil was mixed with sterile sand at a 1:3 ratio by volume. Sand was previously sterilized by autoclaving at 121°C for 20 minutes in one-gallon batches. The mixture was used to fill six-inch pots and *S. bicolor* seedlings were transplanted into these pots. *Sorghum bicolor* L. var. *Drummondii (*sudangrass) seedlings were started in flats (10.94" W x 21.44" L x 2.44" H) of vermiculite on 28 January 2022. Flats containing the seedlings and the pots they were transplanted into were overhead watered twice a week to saturation and allowed to drain.

The last week of April, after the last frost, five 7 gallon grow bags were filled three quarters full with a 1:4 by volume compost and vermiculite mixture. Compost was collected from the Payson City, Utah landfill and has a high woody composition. A half cup of Yosemite soil was added to each grow bag and mixed thoroughly. Five *S. bicolor* seedlings were transplanted into each grow bag.

Grow bags were placed outside and watered and weeded as needed during the 2022 growing season. At the end of the growing season, *S. bicolor* senesced naturally by frost and remained outside during the winter. In spring 2023, all above ground vegetation will be removed and discarded. Roots will be harvested from the soil and cut to 1-1.5 inch segments. Soil will be sieved with 500, 250, and 45 µm sieves and observed under a microscope. Observed mycorrhizal spores will be recorded. Root segments will be dyed with Trypan blue and examined for colonization.