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RESEARCH ARTICLE

The use of Groasis Waterboxx devices to improve mineland reclamation efforts by increasing transplant survival and growth of five native woody species

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The reclamation of disturbed lands worldwide is a difficult and increasing problem. In the Mountain West region of the United States, mining activities commonly occur in zones dominated by native woody plants. The restoration of woody plants in these areas is challenging, and direct seeding efforts result in poor seedling emergence and establishment. Therefore, seedling transplants are often used, but they frequently experience high mortality during the first year, particularly due to summer stresses. We evaluated if the Groasis Waterboxx device could be used to mitigate drought stress on seedling transplants and improve their establishment on a reclaimed waste rock dump. The Waterboxx device collects precipitation into a polypropylene reservoir and slowly dispenses water onto the soil next to the seedling. To test such a hypothesis, 400 seedlings from five native woody plants (*Atriplex canescens*, *Cercocarpus ledifolius*, *Pinus edulis*, *Purshia tridentata*, and *Rhus glabra*) were planted with and without a Waterboxx. The Waterboxx device improved soil water potential, at 40 cm, it took 1 month longer to go below −1 MPa under a Waterboxx. Survival increased 30–65% in four of the five species, and seedling vigor increased for three of the five species. Vigor was higher with all plant species at both planting times and was significantly better in 50% of comparisons. Results support the use of the Waterboxx for improving seedling establishment on mineland overburden sites in the semiarid mountain west. The effectiveness of the Waterboxx device provides merit for future testing where drought challenges seedling establishment.

Key words: *Atriplex canescens*, *Cercocarpus ledifolius*, mineland restoration, *Pinus edulis*, *Purshia tridentata*, revegetation, *Rhus glabra*

Implications for Practice

- Woody plant seedlings can be transplanted into disturbed semiarid regions and increase survivability and vigor when supplemental water is applied through a Waterboxx device.
- The visual appeal and ecological vitality of disturbed semiarid locations can be enhanced by promoting the growth of mid- to late-seral plants, thereby enriching wildlife habitats and minimizing erosion concerns.
- The Groasis Waterboxx device gives land managers the flexibility to plant seedlings in multiple seasons of the year with increased plant establishment, making restoration efforts more accommodating.

Introduction

Mineral products from mining are vital for society and the continued use of modern technology (U.S. Geological Survey 2016). Global estimates from 2020 approximate that 57,277 km^2 of land is actively being mined each year (Maus et al. 2020). Mining operations reposition and reshape natural landscapes with vegetation removal, large-scale excavation of ore and overburden rock, and deposition of overburden and tailings, exposing natural materials that have biological and geochemical conditions (e.g. high acidity, low organic content, low fertility, and minimal microbial counts) that inhibit the natural recovery of the site (Kesler 2007; Mendez & Maier 2008; Di Carlo et al. 2019). For mining to occur sustainably, successful postmining reclamation efforts need to be implemented to

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restore the esthetics of the site and ecosystem functions (Waitkus 2022). Revegetation is one of the most critical reclamation activities needed to reverse the degradation from mining activities (Navarro-Ramos et al. 2022).

Late-successional woody plants are often some of the most challenging species to reestablish in ecosystems impacted by mining (Paschke et al. 2003; McAdoo et al. 2013; Shriver et al. 2019). In general, direct seeding efforts in arid and semiarid landscapes are hindered by poor germination, low seedling emergence, and high seedling mortality due to erratic precipitation, temperature extremes, and soils unconducive to growth (Ungar & Ajmal Khan 2001; Sodhi & Ehrlich 2010; Bateman et al. 2021).

To overcome this bottleneck, nursery-grown seedlings are commonly transplanted to circumvent the high mortality that occurs during the early stages of plant development (Ohsowski et al. 2017; Pilliod et al. 2017; Pyke et al. 2020). Utilizing seedlings in restoration efforts may improve establishment and help reach desired visual outcomes sooner, but transplants may still experience survival failure. Transplant mortality is usually due to inadequate root systems failing to access water resources during low precipitation and high temperature conditions. If transplants can survive the first year, they can better tolerate severe drought due to established root systems that are able to access water resources deeper in the soil and support the plant (Bainbridge 2007). Consequently, reclamation tools and techniques that can improve water availability immediately after planting and extending through the first year of transplanting have the potential to increase transplant survival and improve revegetation (Lovich & Bainbridge 1999).

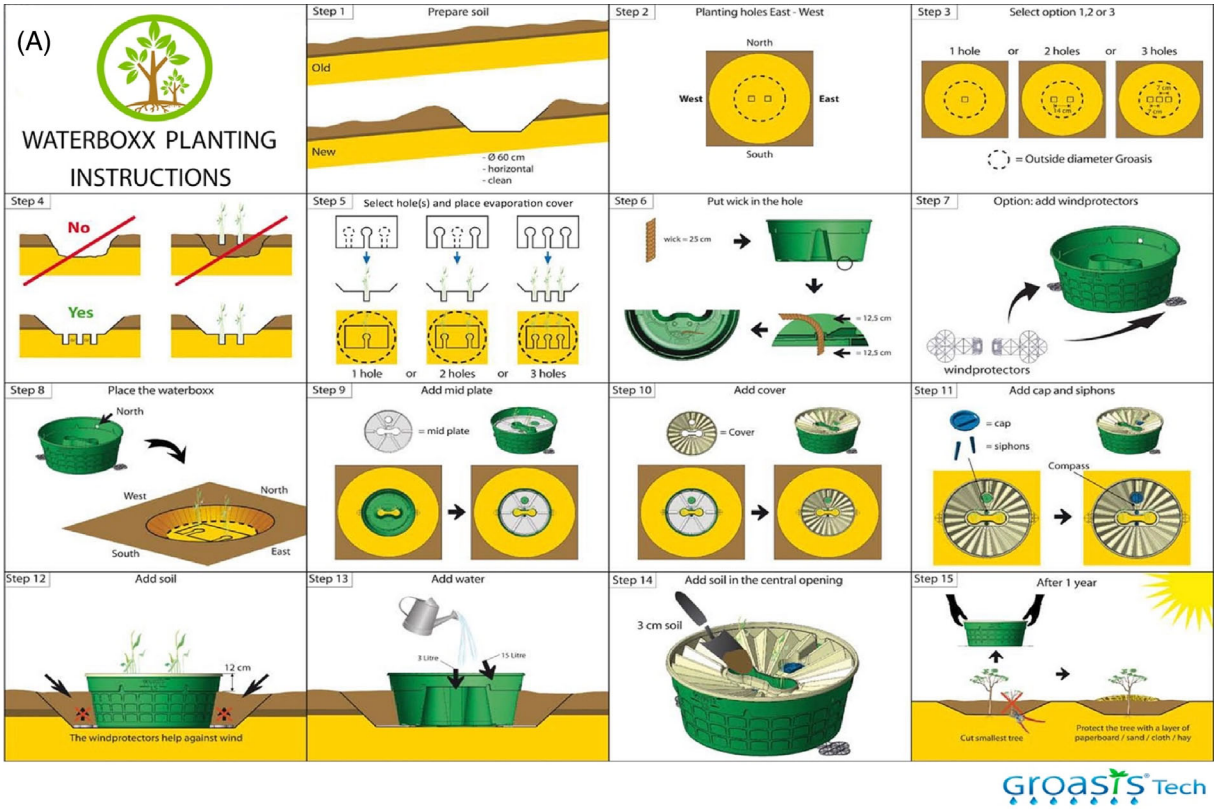
There are several different water management tools for increasing the quantity of available water to a transplanted seedling. Selecting the most efficient one for a particular site depends on several considerations. These include plant species and size, soil type (influences hydraulic conductivity), climate, microclimate, local water availability, weed competition, project budget, site access, and available labor and tools (Kulkarni 2011; Tapia et al. 2019). Water collection systems are among the most effective water management tools for mitigating drought conditions and satisfying application considerations (Bainbridge 2007; Tapia et al. 2019). Collection systems have a catchment device with a storage tank that accumulates and stores precipitation, with some designs collecting condensation as well. Captured water is stored and distributed via capillary action through a cotton wick within the vicinity of seedlings even when there is little to no precipitation (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 water catchment system designed to be installed around transplanted seedlings to provide supplemental water. The device has been utilized in semiarid environments, including Alicante, Spain (Gil-Docampo et al. 2020), the Galapagos Islands, Ecuador (Tapia et al. 2019; Díaz et al. 2022), and parts of Asia (Liu et al. 2014). It consists of a 50 cm diameter cylindrical container that serves as a reservoir with a central opening where two seedlings are planted (Fig. 1). The container has a wick at the bottom connected to the base of the reservoir, which extends from inside the reservoir onto the soil. As the reservoir fills and the concentration of water increases, water will diffuse out through the wick into the dry soil allowing access to the plants' roots. Soil water lost to evaporation is minimized by a cover on the soil surface surrounding the seedlings. The plastic used to make the Waterboxx has a high specific heat capacity and a low thermal conductivity; these features, paired with the water it contains, improve its' ability to absorb and retain heat (Groasis 2003). Therefore, more energy is needed to warm the device and it stays cool longer, which can ease some of the temperature stress on the seedlings during the summer heat. When the device is cooler than the surrounding night air, the dew point is more quickly reached, and condensation may occur, helping to replenish the reservoir (Groasis 2003). Condensation and precipitation are 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 during a year when 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 transplanted in the fall. Seedlings planted in the fall have more time to develop adequate root systems before drought stress, in contrast to planting in the spring, which provides minimal time before the onset of summer drought (Clements & Harmon 2019; Davidson et al. 2019). However, fall plantings can also experience mortality due to 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 multiple times a year. Therefore, we present this study to assess the ability of the Waterboxx to: (1) improve soil water status around transplanted woody seedlings; (2) increase the survival and vigor of five native woody plant transplants; and (3) evaluate if there are differences in planting success between November and May planting times.

Methods

This research was conducted in a semiarid environment at the Bingham Canyon Mine near Salt Lake City, Utah, United States. This mine began operations in 1903 on the porphyry copper deposit (Tooker 1990) and has produced more than 3 billion metric tons of waste rock, referred to as overburden, which has been deposited in valleys and inclines of the Oquirrh Mountain Range where the mine is located (Borden & Black 2005). Native plant species used in this study have important ecosystem functions, the plants were Curl-leaf mountain mahogany (*Cercocarpus ledifolius* Nutt.), Smooth sumac (*Rhus glabra* L.), Piñon pine (*Pinus edulis* Englem.), Fourwing saltbush (*Atriplex canescens* [Pursh] Nutt.), and Antelope bitterbrush (*Purshia tridentata* [Pursh] DC.). This mine is ideal for evaluating the performance of the Waterboxx device with the five late-successional woody plants due to the extensive reclamation efforts being conducted on-site, which include a focus on the reintroduction of various native woody plants.



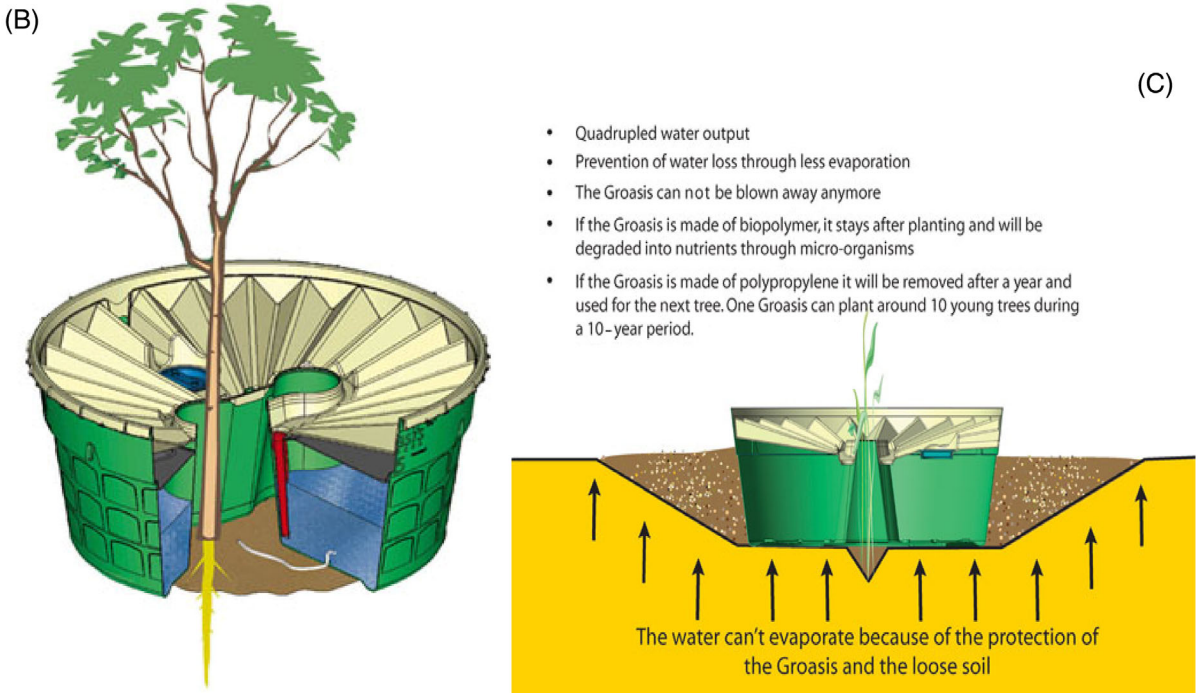


Figure 1. Pictorial representations of (A) the implementation of the Waterboxx device; (B) the Waterboxx device and plant as a partial cross-section demonstrating Waterboxx features when installed and planted with a woody plant; and (C) illustration of the Waterboxx device on soil below the device. *Source*: The picture was taken from Groasis Ecological Water Saving Technology Planting Manual (2003).

Plant Species

We evaluated the Waterboxx device on five different species native to the research study area: *C. ledifolius*, *R. glabra*, *P. edulis*, *A. canescens*, and *P. tridentata*. Seedlings were purchased from a commercial nursery (High Mountain Nursery, Heber City, Utah) and were approximately 1 year old and grown in D40 pots with a cell diameter of 5.1 cm and a depth of 25.4 cm. *Cercocarpus ledifolius* is a broad-leaf evergreen that grows at high elevations on warm, dry, rocky ridges, and slopes (Davis & Brotherson 1991). As with other *Cercocarpus* species, *C. ledifolius* forms nodules with nitrogen-fixing bacteria that may help low-fertility soils (Youngberg & Hu 1972). Although its fruits are consumed by various birds, *R. glabra* is considered a poor forage species (Strauss 1991; Johnson 1995). However, it is a valuable restoration species because it can grow on disturbed sites to reduce erosion (Adams et al. 1986; Temple 1989). *Pinus edulis* is of value for restoring degraded sites (Wood et al. 1995), as it provides food and shelter for large game, small mammals, and various bird species (Rasmussen 1941; Meeuwig & Bassett 1983). *Atriplex canescens* is widely distributed in semiarid regions and has been extensively used in reclamation projects for erosion control due to its resistance to soil salinity, drought, and wide environmental adaptability (Benzarti et al. 2013; Al-Masri et al. 2014; Ma et al. 2022). *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 (Vanderwall 1994), an early season source of pollen and nectar for a variety of insects (Furniss 1997), and is capable of establishing on harsh rocky sites (Zlatnik 1999).

Study Site

Our research was conducted at the Bingham Canyon Copper Mine in the Oquirrh Mountain Range on the Yosemite waste rock dump (40.51263889, −112.1182611). The site is a Mountain Loam (Oak) (R047XA432UT) ecological site (Web Soil Staff 2022). At approximately 1873 m elevation, the research site occurs within the mountain brush zone, which is a transition between the coniferous forest above and the piñon-juniper woodland below (Banner 1992). Prior to being covered by mine overburden, the site was most likely dominated by woody plants that were used in this study.

Overburden materials deposited on the hillslope were of varying ratios of monzonite, quartzite, and limestone (Borden 2001, 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 layer of crushed monzonite, quartzite, limestone, and topsoil. The site was then terraced perpendicular to the slope using dozers, terraces were approximately 0.5 m wide and spaced approximately 1 m apart. In the fall of 2019, the site was hydroseeded with a mixture of seeds comprising grasses and woody species. None of the five transplanted species used in this study were included in the hydroseeded mixture. Perennial grasses were the most successful at establishing themselves, with *Thinopyrum intermedium* L. being the dominant species. *Ericameria nauseosa* ex Pursh G.L. Nesom & Baird was the dominant woody species to establish from the hydroseeding.

Ten soil samples were collected randomly across the Yosemite waste rock dump to a depth of 30 cm. All samples were combined and submitted to the BYU Environmental Analytical Laboratory for analysis (https://pws.byu.edu/eal). The soil had a pH of 7.5, organic matter was 1.1%, and cation exchange capacity (CEC) was 17.5 meq/100 g, with a gravelly clay loam soil texture containing 44.2, 26.0, and 29.8% sand, silt, and clay, respectively, gravel greater than 0.635 cm was 11.8%, and gravel greater than 2 mm less than 0.635 cm was 17.6%. Soil elemental analysis is given in Table 1. Mean yearly precipitation for the previous 30 years at the research site and maximum and minimum temperatures were obtained using PRISM (2022).

The mean annual precipitation in 2020 and 2021 was 53% (317.1 mm) and 87% (518.8 mm) of the 30 year mean (597.5 mm), respectively (Fig. 2). During the first 3 months of the study (November and December 2020, January 2021), precipitation ranged between 37 and 46% of normal. February precipitation was slightly above normal, but the site remained dryer than normal the rest of the winter months (Fig. 2). During May 2021 when the second half of the seedlings were planted, conditions were also dry, with precipitation 14% of normal. From June 2021 to December 2021 precipitation varied highly from month to month ranging between 12 and 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 (Fig. 2).

Evaluation of Different Woody Species in the Waterboxx Field Trial

The Waterboxx experiment was installed as a split-block design with 10 blocks. Each block was 18 m long (across the hill along the terraces) and 8 m wide (eight terraces). The block was split by planting date and randomly assigned to be planted in November 2020 or May 2021 (Fig. S1). Treatments within each block were *C. ledifolius*, *R. glabra*, *P. edulis*, *A. canescens*, and

Table 1. Soil chemical properties at the rock dump research site, any element below minimal detectable level is identified by <MDL.

NO_3-N mg/kg	*P mg/kg*	*K mg/kg*	*Salinity dS/m*	*Zn mg/kg*	*Fe mg/kg*	*Mn mg/kg*	*Cu mg/kg*	*Na absor. ratio*	*Ca mg/kg*
3	26	255	0.5	3.6	11.4	5.7	26.0	0.01	30
Mg mg/kg	*Na mg/kg*	*Cd mg/kg*	*Co mg/kg*	*Cr mg/kg*	*Mo mg/kg*	*Ni mg/kg*	*Pb mg/kg*	*Se mg/kg*	
3.0	0.3	0.12	0.07	0.01	0.11	0.21	14.2	<MDL	

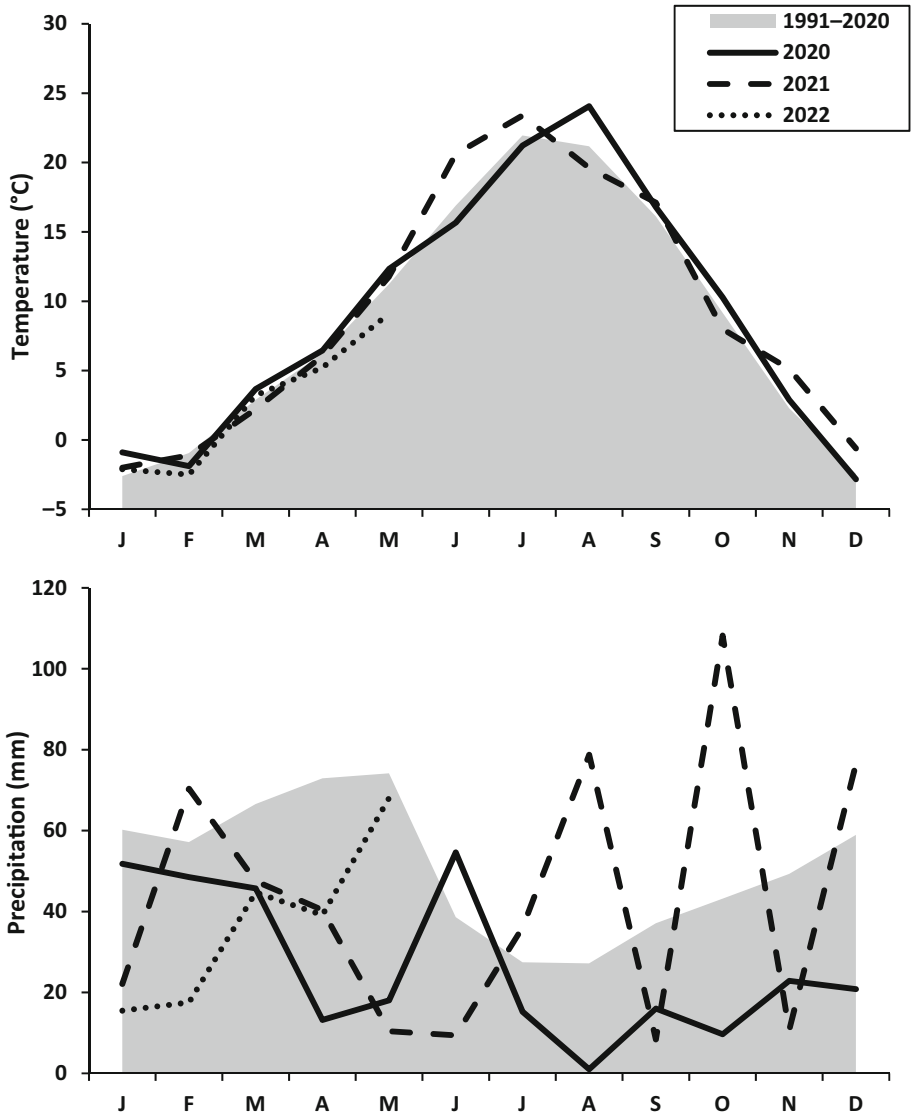


Figure 2. Monthly precipitation and ambient temperatures during the study (2020, 2021, and 2022) were charted along with the 30-year average precipitation and temperature (1991–2021) near the study site.

P. tridentata seedlings planted with and without (control) a Waterboxx device. Treatments within a block were 3 m apart within the terrace row and 2 m apart between planted terrace rows. Seedlings of the same species were transplanted in pairs 15 cm apart to fit the Waterboxx device spacing for two plants (Fig. 1A–C). For control treatments without the Waterboxx, two transplanted seedlings, again of the same species, were also spaced 15 cm apart with the same north–south orientation as the seedlings planted in a Waterboxx device. Four-hundred transplanted seedlings (2 planting times × 5 woody species × 10 blocks × 2 seedlings/planting location × 2 treatments—Waterboxx device or no device = 400) were planted for this study.

Prior to planting, all seedlings were individually wrapped with Vexar fencing (Forestry Suppliers, Jackson, Mississippi), a flexible UV-resistant polyethylene and polypropylene material used to deter herbivory of roots and shoots from rodents and ungulates (Fig. 3). Holes to transplant the seedlings were approximately 46 cm deep and 30.5 cm wide; a motorized auger was used to dig each hole (Kohler Co., Kohler, Wisconsin). Two seedlings of the same species were planted in the same hole and deep enough that the soil level met the root flare.

Following seedling plantings, Waterboxx devices were installed according to manufacturer recommendations found in the Waterboxx manual for planting trees in desert areas (Groasis 2003). In short, the Waterboxx devices were assembled prior to planting—by inserting the mid-plate into the box, then placing the water collection lid on top, making sure to align holes in the lid with holes in the mid-plate, and finally placing siphons next to the eight-shaped opening in the lid (Fig. 1A). Evaporation covers (i.e. rectangular corrugated plastic designed to minimize soil water evaporation that come with the Waterboxx device)



Figure 3. *Atriplex canescens* seedling grown in a approximately 655 cm^3 tree pot, wrapped with Vexar caging before plantings (left— *Source*: photo credit Tom Glass) and (right) *A. canescens* seedling grown after planting and installation of Waterboxx device.

were trimmed to fit around the two seedlings, then laid on top of the soil around the seedlings and lightly covered with soil. Preassembled Waterboxx devices were then placed over planted seedlings, with the wick pointing inward toward the seedlings, making sure the wick had good soil contact (Fig. 1B). The water-filling caps in the Waterboxx cover were positioned to face north. Waterboxx devices were backfilled around the outside with soil and rock. The soil and rock surrounded the Waterboxx device up to approximately 18 cm from the top and held it in place so the devices were not moved by wind, snow, or animals (Fig. 3). Three liters of water were applied to the soil surrounding all seedlings, whether planted with or without a Waterboxx device. Each Waterboxx device was then filled with 15 L of water.

Soil water potential was measured under *C. ledifolius* transplanted seedlings in 3 of the 10 blocks. Teros 21 water potential sensors (METER Group, Inc., Pullman, WA, U.S.A.) were placed at 10, 20, and 40 cm depths below the soil surface of *C. ledifolius* seedlings with and without a Waterboxx at each planting time (November 2020 or May 2021). A total of 36 sensors were used in the study (3 sensors at differing depths × 2 Waterboxx treatments × 2 planting seasons × 3 blocks = 36). Teros 21 sensors 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 2 hours during the duration of the study. Values were stored on EM50/ZL6 data loggers (METER Group, Inc., Pullman, WA, U.S.A.).

Seedling survival was evaluated on 3 May 2021, 15 June 2021, 14 October 2021, and 5 June 2022. Vigor was also evaluated on a scale from 1 to 5 at the final sampling. Rating categories were: 1—dead; 2—0 to 25% leaf cover on existing branches; 3—26 to 50% leaf cover on existing branches; 4—51 to 75% leaf cover on existing branches; 5—76 to 100% leaf cover on existing branches.

Data Analysis

All statistical analyses were conducted in JMP version 16 (SAS Institute Inc., Cary, NC). The mean (± 95% confidence interval) water potential of the soil was calculated for plots with or without a Waterboxx device at each of the three measured soil depths. Treatment effects were considered significant if the confidence intervals did not overlap.

Repeated measures mixed-model analysis was used to analyze percent survival. Blocks were considered random effects, while season, species, and Waterboxx treatment were considered fixed effects, and the sampling date was the repeated measure. Three- and four-way interactions between species, with or without a Waterboxx, planting season, and sample date were included in initial models, but model terms were dropped when found insignificant in order to form simpler models. Mixed-model analysis was used to analyze the average vigor rating. Plots and north–south orientation of the transplanted seedlings were considered random effects, while month planted, species, and treatment were considered fixed effects. Again, model terms were dropped when found insignificant. Student *t*-tests were used to compare differences between a Waterboxx device and no Waterboxx device among the same species.

Results

Soil Water Potential

Water potential sensors recorded the most negative soil moisture values (down to a −14 MPa) during the winter months of 2020–2021, immediately after the November seedlings were

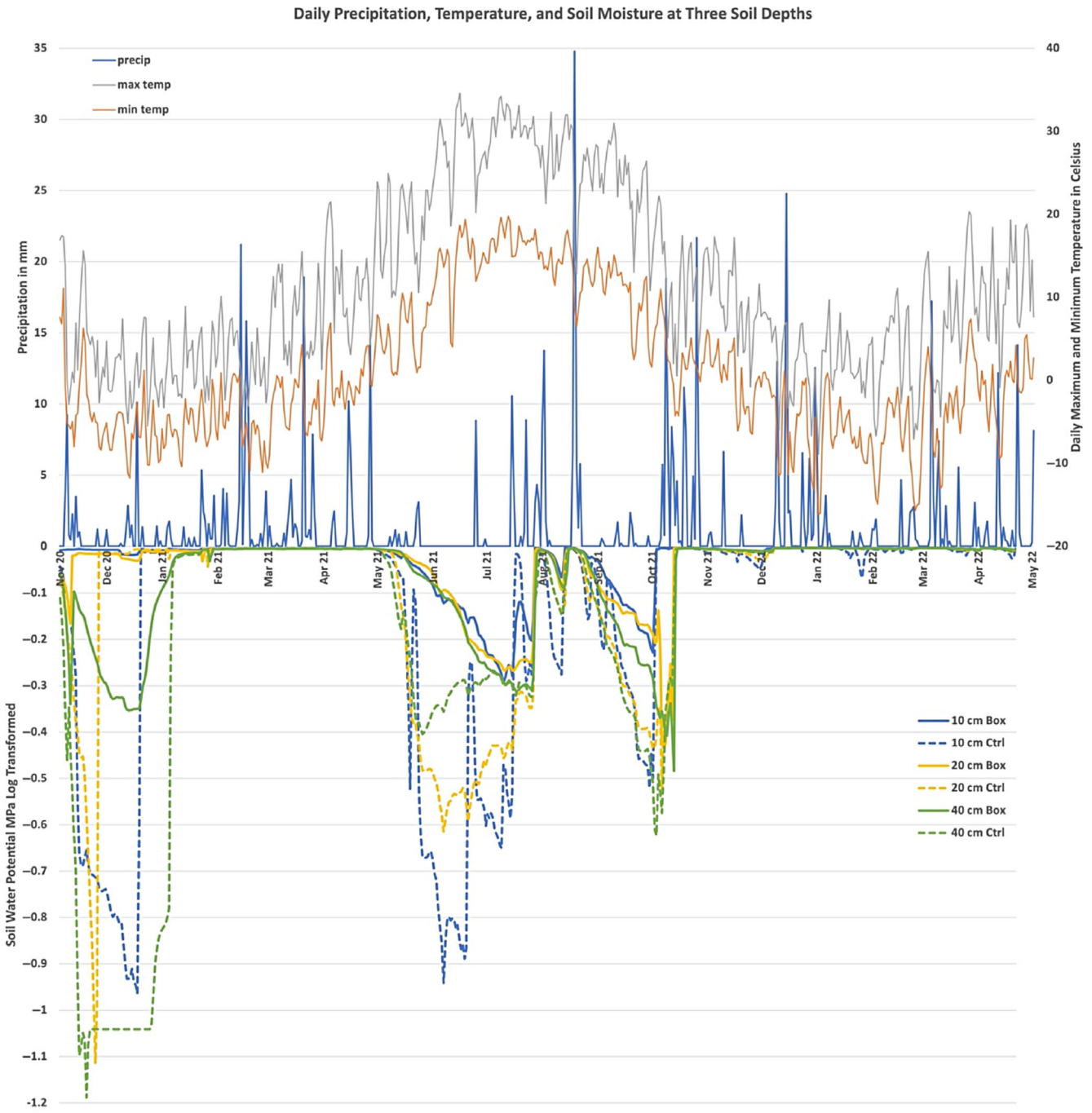


Figure 4. Daily precipitation, and maximum and minimum temperatures for the duration of the study collected from PRISM Climate Group. Average daily soil water potential with a log transformation at 10, 20, and 40 cm below seedlings with Waterboxx devices (Box) and without (Ctrl).

transplanted and sensors were installed (Fig. 4). Sensors under seedlings with no Waterboxx device had the lowest water potentials, as evidenced by the dotted lines (water potential data in Fig. 4 was Log transformed for visual clarity). Daily minimum temperatures during the winter months of 2020–2021 were below 0°C, as were many of the daily maximum temperatures. The most negative soil water potential reading was −14 MPa at the 40 cm sensors with no Waterboxx (Fig. 4). Inadequate soil sensor contact in combination with freezing conditions may have influenced readings during the first 2–3 months following installation, but sensor results were greater than a −0.1 by late winter.

Soil water potential associated with November plantings was in 0–0.1 MPa from February 2021 until mid-May 2021, when soil moisture levels dropped. Most soil water potentials stayed in the −0.1 to −1.0 MPa range during the summer months of

2021, when daily maximum and minimum temperatures were their highest (Fig. 4). Soil water potentials fluctuated with summer precipitation events. Soil water potentials under Waterboxx devices did not fluctuate as much as those with no device, and there was more soil moisture under the Waterboxx devices (Fig. 4). In May, soil water potential began to drop from 0.0 MPa. 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. Mid-August was another example where the Waterboxx devices decreased the rate and severity of drying during periods with little precipitation (Fig. 4).

Survival Percentage

Seedling survival was not different between November and May plantings ($p = 0.863$), but there was an interaction between month planted and Waterboxx or no Waterboxx device ($p < 0.001$). This interaction was primarily due to *Cercocarpus ledifolius*, *Pinus edulis*, and *Purshia tridentata*. *Cercocarpus ledifolius* had relatively high survival when transplanted in November with and without a Waterboxx, but with the spring planting, survival at the end of the sampling period was increased by the Waterboxx devices from 30 to 65% (Fig. 5). There were significant differences ($p < 0.001$) in plant species survival when they were planted in November or May (Table S1). *Pinus edulis* had relatively high survival in May regardless of a Waterboxx, but with the November planting, survival at the end of the sampling period was increased by the Waterboxx devices from 35 to 75%. When sampling in June 2022, *P. tridentata* had no difference in November planting among Waterboxx or no Waterboxx, but with the May planting, the Waterboxx device increased survival at the end of the sampling period from 15 to 55% (Fig. 5).

Waterboxx versus no Waterboxx and plant species were both significantly different ($p < 0.001$), and there was an interaction between these effects ($p < 0.001$), indicating that species responded differently to having a Waterboxx device (Table S1). Seedlings transplanted in November 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 June 2022. There were no differences in transplant survival with and without a Waterboxx for *Atriplex canescens*, as most of the transplants for these species had high (approximately 92.5%) survival rates (Fig. 5). 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* (Fig. 5).

Purshia tridentata and *R. glabra* seedlings transplanted in May of 2021 had significant increases in survival through the summer months of 2021 when transplanted with Waterboxx devices (Fig. 5). 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

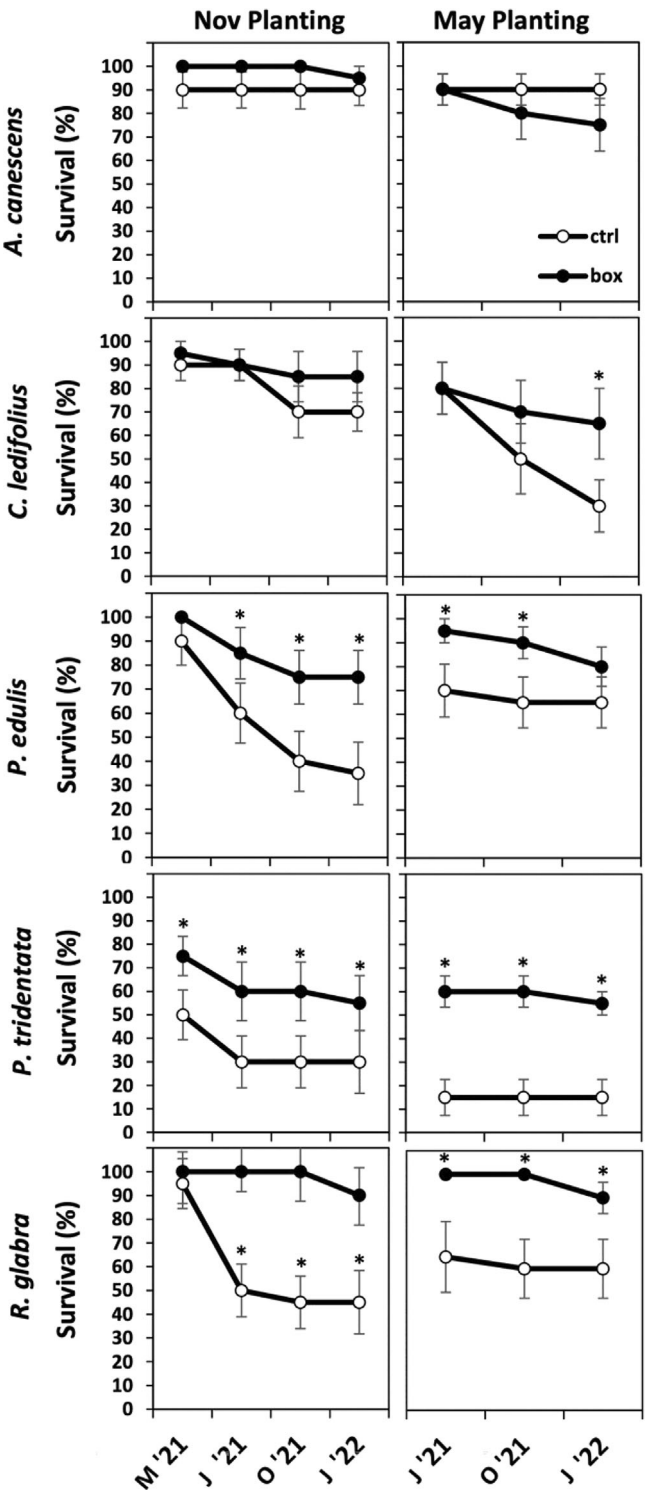


Figure 5. Percent seedling survival of five native woody species when planted in November of 2020 and May of 2021 with (box) or without (ctrl) Waterboxx devices. Seedling survival was evaluated in May (M) 2021, June (J) 2021, October (O) 2021, and June (J) 2022. Data represent the average response (±2 SD) from species seedling survival. An asterisk above the bar indicates significant differences ($p < 0.05$) between a Waterboxx and no Waterboxx at sampling time for that plant species.

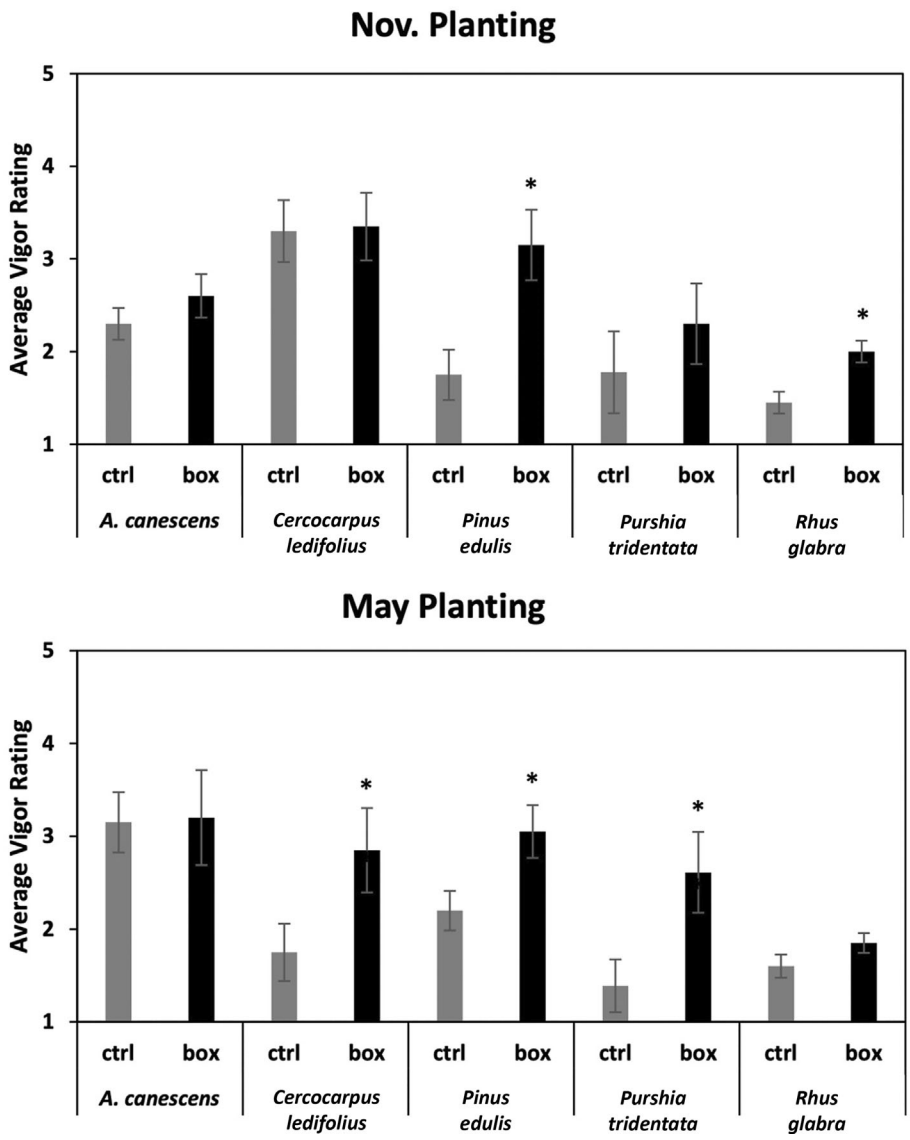


Figure 6. Average vigor ratings for each species by Waterboxx (box) or no Waterboxx (ctrl) in June 2022. Data represent the average response (±2 SD) from species seedling vigor. An asterisk above the bar indicates significant differences in vigor ($p < 0.05$) between Waterboxx and no Waterboxx at sampling time.

increases in survival with Waterboxx devices (Fig. 5). *Atriplex canescens* seedlings with no Waterboxx were not significantly different from seedlings with Waterboxx devices. Survival of seedlings over the summer (June–Oct) tended to decrease but *P. tridentata* and *R. glabra* remained constant when transplanted with Waterboxx devices (Fig. 5).

Vigor

Plant vigor with the use of a Waterboxx compared to no Waterboxx device, and species vigor were significantly different ($p < 0.001$) and there was an interaction between plant species and month planted ($p = 0.003$; Table S2). There were significant interactions for plant vigor between plant species and month planted ($p = 0.003$). For the November planting, *P. edulis* and *R. glabra* seedlings had higher average vigor ratings when planted with a Waterboxx device (Fig. 6). For the May planting, *C. ledifolius*, *P. edulis*, and *P. tridentata* seedlings had higher vigor ratings on average when planted with a Waterboxx device. *Atriplex canescens* was the only species not significantly affected by a Waterboxx device in either month planted (Fig. 6).

Discussion

Mining in the U.S. Mountain West often occurs in semiarid regions dominated by native trees and shrubs. Restoration efforts in these areas have proven to be challenging as transplanted seedlings experience high mortality during the first year, which is due in part to poor soil fertility and primarily to limited

water resources (Burdett 1990; Browne et al. 2021). Water management tools like the Waterboxx can help native trees and shrubs survive and establish in arid and semiarid 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 the Waterboxx device was a viable method for improving the establishment of woody plants on mineland overburden for four of the five native species studied. Depending on the month planted, survival and vigor was greater with Waterboxx devices. The improved seedling survival and vigor from the Waterboxx device likely resulted from the device acting as a water management tool, mitigating drought stress on the seedlings during the dry summer months.

Soil water potential is a measure of the energy necessary for removing water from soil (Or & Wraith 2002). Drought reduces the soil water potential and, thereby the ability of plants to remove water from the soil (Munns 2011). In our study, the soil water potential beneath seedlings planted inside a Waterboxx device was generally higher and decreased more slowly over time, while the soil water potential beneath seedlings without a Waterboxx device decreased more quickly and reached much lower water potentials than those with a Waterboxx device.

According to the manufacturer's installation instructions, when a Waterboxx device is installed, seedlings planted inside the device 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 system. Because there was no separate treatment consisting of a Waterboxx device without the initial 15 L, it is not known if the 15 L of water, the Waterboxx device, or the combination of the initial 15 L and the Waterboxx device are responsible for the improved seedling survival and vigor. However, the Waterboxx device and 15 L of water as a whole system did improve seedling survival and increase vigor in our study. It should also be noted that the 3 L of water applied to transplants without a Waterboxx device may have increased survival, but it cannot be determined for sure as all transplants received 3 L of water and none went without water immediately after transplanting.

Future restoration work with Waterboxx devices might consider the prevention of debris and unwanted weeds on and inside the devices. Due to the slope and wind, dirt and rocks gathered on top of some Waterboxx devices and served as a germination point for *Thinopyrum intermedium* seeds that blew from neighboring plants. As the seeds germinated, the roots grew into the orifices and into the water of the Waterboxx device. A couple of the *T. intermedium* plants had extensive root systems, which likely reduced some water resources available to be wicked to the soil and used for our research plants, but the device was not dry at the time we discovered and removed the unintended grass. Water management, and ultimately transplant seedling survival, may be affected by these unintended plants using water from the Waterboxx devices. Plants next to the Waterboxx devices might also outcompete transplanted seedlings for the water; in this study, we removed neighboring plants that may use the water. However, during the growing season, we periodically found *T. intermedium* plants growing near our Waterboxx devices; we removed those and any other plants to minimize competition.

Atriplex canescens was the only species tested in the trial that did not show a treatment response from the Waterboxx device. The lack of treatment response is most likely because *A. canescens* seedlings did not appear to be significantly limited at the study site, as evidenced by almost all seedlings surviving in the study and the species' relatively high vigor ratings. Our finding that *A. canescens* does not need a water management device is not a complete surprise as it has been shown to have the capacity to grow in a broad range of conditions (LeHouerou 1992; Fitzsimmons et al. 1998; Saucedo-Teran et al. 2011). Our results confirm that *A. canescens* is a good species for mineland restoration in semiarid environments because it has good survivability and vigor without additional inputs (Benzarti et al. 2013; Al-Masri et al. 2014; Ma et al. 2022). We suggest that this species would be suitable to use in areas where access to the site is limited or where soils (e.g. too rocky) and topography (e.g. steep slopes) limit the practitioner's ability to install Waterboxx devices.

Our results suggest *C. ledifolius* is a suitable species for mine overburden restoration with a November planting, but would benefit from the use of a Waterboxx device when planted in May. *Cercocarpus ledifolius* seedlings transplanted in November had high survival rates regardless of whether they were transplanted into a Waterboxx device. However, planting *C. ledifolius* seedlings in May without a Waterboxx device resulted in low survival, but with the Waterboxx device, survival increased by 200%. This discrepancy in treatment response may be due to the weather conditions experienced by the seedling after planting. As is typical of the Great Basin's cold desert climate, temperatures in our study were relatively low after the fall planting and precipitation was high. Hence, seedlings planted in November have an extended establishment period that provides them with the ability to better cope with soil drying during the transition to summer and low soil moisture (Clements & Harmon 2019; Copeland et al. 2022). Seedlings planted in May have a shorter period of soil water availability and experience relatively higher temperatures in comparison to seedlings planted in November (Comstock & Ehleringer 1992). In our study, under a May planting, the reason *C. ledifolius* had relatively high seedling survival in the Waterboxx device compared to no Waterboxx is probably due to the product's ability to mitigate drought stress by providing soil moisture.

Another potential reason for the discrepancy in treatment response between *C. ledifolius* November and May plantings may be differences in the quality of the transplants used between the planting seasons. The seedlings planted in May appeared less vigorous than those used for November planting. This may be expected for seedlings like the ones we used that were grown in an outdoor nursery and are recovering from the rigors of winter. Because the seedlings seemed less vigorous at the May planting, improved growing conditions provided by the Waterboxx devices may have provided a greater benefit than if the seedlings had the same level of vigor as those planted in November.

The survival of *P. tridentata* was poor without a Waterboxx device regardless of the month it was planted. Additionally, seedling vigor was higher for seedlings planted in May. Our results indicate that a Waterboxx device should be considered when planting *P. tridentata*, but it may have the greatest utility when used in the spring time months, like May.

The Waterboxx device substantially improved *P. edulis* survival for November transplants, but for May transplants it did not provide a long-term benefit. *Pinus edulis* seedlings have been reported to have increased survival when naturally seeded under trees or shrubs (Chambers et al. 1999). It may be possible that Waterboxx devices mediated winter-time conditions, like a tree or shrub might do, and increased survival. Seedlings planted in May with and without a Waterboxx device had relatively high survival rates, and there were no significant differences. This response is interesting, as all the other species studied had higher survival from a November planting. While there was no benefit from the Waterboxx with May transplants on survival, our vigor estimates indicate that the Waterboxx still provides value to the seedling, as plants grown from a Waterboxx device were substantially more vigorous regardless of planting month. The increase in plant vigor is likely due to available water that results in more plant growth. Grossiord et al. (2017) noted increased tree growth with higher levels of precipitation; the increase in available water from the Waterboxx may have mimicked precipitation and resulted in increased plant growth.

In summary, this study provides evidence that the plant species used for restoration and the time of year when seedlings are transplanted will influence the utility of the Waterboxx device. Hence, these factors should be considered when deciding to apply this water management tool. This research provides justification for future mineland reclamation Waterboxx research and use. Waterboxx devices should be evaluated in different types of soil and climatic conditions and for different plant species to optimize restoration efforts. Our finding that the Waterboxx can improve seedling survival under drought conditions with a November and May planting suggests that it may also be possible to plant seedlings during other periods of the year, such as in the summer. In some situations, it may be more advantageous to get people and equipment on-site during the summer months when work conditions such as weather and light are more advantageous for the individuals planting the seedlings.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Mixed ANOVA results for the effects of plant species, Waterboxx and no Waterboxx treatment, and planting November or May on percent survival.
Table S2. Mixed ANOVA results for the effects of plant species, Waterboxx and no Waterboxx treatment, and planting November or May on vigor rating.
Figure S1. Research plot map of the Waterboxx study.

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