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Evaluation of dryland riparian restoration with cottonwood and willow using deep-planting and herbivore protection

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Abstract. Degradation of dryland riparian ecosystems has been linked to the lowering of alluvial groundwater tables and reduced floodplain connectivity. Establishing riparian plants in dryland ecosystems with high water-stress and herbivore pressure presents major challenges for restoration practitioners. By planting at sufficient depths to reach lowered water tables, deep-planting provides direct access to water and encourages root development within hydrated soils. While deep-planting is a promising alternative to traditional supplemental irrigation in dryland areas affected by lowered water tables, few studies have evaluated deep-planting where planting depths must exceed one-meter to reach water tables and where herbivore protection is required. To evaluate deep-planting as an irrigation alternative where lowered water tables present a challenge to riparian restoration, we conducted experimental plantings along an incised stream within a semiarid watershed using deep-planting without supplemental irrigation in combination with several tree shelter designs. Our results indicate deep-planting cottonwood (*Populus trichocarpa*) and willow (*Salix* spp.) pole cuttings in augered holes that penetrated water tables up to 1.9 m below the surface significantly increased the probability of survival, with water table penetration significantly increasing the odds of survival by a factor of 7. Deep-planting with access to lowered water tables in combination with 0.9-m vented plastic tree shelters significantly increased the probability of survival, with over 50% higher survival after three years compared to unprotected and 1.-m circular fence caged plants that were also deep-planted with access to water. However, taller fence cages significantly reduced the probability of terminal bud loss from browsers with over 25% lower browse rates after three years. Therefore, we conducted additional experimental plantings to evaluate two taller plastic tree shelter designs to maximize survival while minimizing browsing. The results of our study indicate that deep-planting pole cuttings of cottonwood and willow with access to lowered water tables in combination with taller 1.8-m vented plastic tree shelters provided statistically similar survival as compared to the shorter 0.9-m vented plastic tree shelters after two years while significantly reducing browsing by approximately 75% two years after planting.

Key words: browsing; drylands; Interior Columbia River Basin; *Populus*; riparian restoration; *Salix*; tree shelter.

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INTRODUCTION

Drylands are high water-stress ecosystems that account for over 41% of terrestrial environments globally, and riparian ecosystems in these environments are particularly sensitive to degradation (Davies et al. 2012). Riparian vegetation in drylands provides valuable ecosystem functions such as shading, organic inputs, large woody debris recruitment, and wildlife habitat (Wissmar 2004), and restoration of riparian ecosystems and the functions they provide is a national priority in the United States (National Research Council 1992). Dryland riparian ecosystems of the northern hemisphere are primarily cottonwood (*Populus* spp.) and willow (*Salix* spp.) dominated, and long-term sustainability and natural establishment of these communities is predicated on shallow alluvial groundwater and seasonal flooding onto floodplains (Wissmar et al. 2003). Loss and degradation of dryland riparian ecosystems in the western United States has been linked to lowered shallow alluvial groundwater tables and loss of floodplain connectivity from flow regulation, water management, and channel incision (Scott et al. 1999, McIver and Starr 2001, Stromberg et al. 2007). In addition, the impacts of lowering shallow alluvial groundwater tables may become a growing concern given the potential for increased occurrence, duration, and severity of droughts that are predicted under various climate change scenarios (Stromberg et al. 2010). Developing effective strategies for establishing cottonwood and willow in drylands has potential to greatly benefit riparian restoration efforts throughout the northern hemisphere (Beschta 1997, Beechie et al. 2007). Other regions where lowered water tables threaten the sustainability or restoration of riparian plant communities, or where water tables become lowered in the future through water management or climate change processes, may also benefit from the development of strategies for riparian planting with lowered water tables (e.g., Horner et al. 2009).

Lowered water tables and disconnected floodplains in drylands present significant water stressors that must be addressed to develop effective strategies for establishing riparian vegetation (Wissmar 2004, Stromberg et al. 2007). While establishing plants where lowered water tables have degraded riparian ecosystems has the potential to provide beneficial ecosystem functions, the long-term viability of such efforts may be dependent on whether unfavorable hydrological conditions are recovering or have stabilized (e.g., Horner et al. 2009). Supplemental irrigation is often used to counter the water stressors presented by arid climate and lowered water tables, although the effectiveness of this approach can be offset by cost and practicality in remote locations. In addition, long-term irrigation may be required to develop sufficient root structures to reach lowered water tables (Dreesen and Fenchel 2008). Deep-planting has been successfully used where flow regulation caused lowered water tables and loss of dryland riparian communities (Dreesen and Fenchel 2008). By planting at sufficient depths to reach lowered water tables, deep-planting provides direct access to water and encourages root development within hydrated soils. However, few studies have evaluated deep-planting effectiveness, especially where planting depths must exceed one-meter to reach water tables.

In addition to high water stress, dryland riparian ecosystems are frequently subject to large herbivore (e.g., elk, deer, beaver, and cattle) impacts that can limit plant establishment. Plastic tree shelters are commonly used to protect plantings from such herbivores and their effectiveness has been well documented (Potter 1988, Stange and Shea 1998, Devine and Harrington 2008). In addition to directly protecting plants, plastic tree shelters also create favorable microclimates with reduced transpiration and soil-water depletion that increases survival and growth (Bainbridge and Fidelibus 1994, Bergez and Dupraz 1997, Devine and Harrington 2008). However, elevated temperatures within plastic tree shelters in drylands can become detrimental under prolonged periods without water access (Kjelgren and Rupp 1997, Oliet and Jacobs 2007). Traditional circular fence cages and mesh tree shelters have also been shown to reduce damage from herbivores and are potential alternative designs to plastic tree shelters if climate interactions create deleterious conditions in drylands (Devine and Harrington 2008).

To support development of strategies for establishing cottonwood and willow in dryland riparian ecosystems affected by lowered water tables and high herbivore pressure, we conducted experimental plantings along a deeply incised stream within the dry Interior Columbia River basin of America's Pacific Northwest. Our plantings were designed to evaluate the effectiveness of deep-planting cottonwood and willow without supplemental irrigation in combination with common shelter designs (plastic tree shelters, mesh shelters, and circular fence cages). While we sought to develop a strategy that maximized survival and minimized browser impacts in our study area, we recognize that our results have international importance given the need to develop effective riparian planting strategies where lowered or lowering water tables threaten the sustainability and restoration of dryland riparian ecosystems.

METHODS

Study area

All plantings occurred along a 4.5-km section of Bridge Creek within the Painted Hills Unit of the John Day Fossil Beds National Monument in eastern Oregon, USA (44.6492° N, 120.2455° W) and adjoining property. Bridge Creek is a semi-arid 710-km^2 watershed that drains into the John Day River. Riparian vegetation is dominated by narrowleaf willow (*Salix exigua*) and rushes (*Juncus balticus* and *Scirpus validus*) that are confined to a narrow band along the stream due to deep channel incision (Lowry 1993). Vegetation on disconnected floodplains is dominated by big sagebrush (*Artemisia tridentata*) and cheatgrass (*Bromus tectorum*; Lowry 1993). The surface geology within the study area is cohesive, fine-grained quaternary alluvium, with lenses of alluvial gravels and cobble. Soils on the site are diverse and range in field texture from silty clay loam near the present stream to coarse loamy sand on the lower terraces. Soil bulk density values range from 1.4 to 1.5 g/cm^3, while porosities range from 52% to 57% (Lowry 1993). Average annual rainfall in Bridge Creek is 35.5 cm (1981–2010), with an average of 11.6 cm in spring (March–May), 6.6 cm in summer (June–August), 9.2 cm in fall (September–November), and 8.1 cm in winter (December–February). Average daily temperatures are 18.0°C in summer and 1.4°C in winter (National Climatic Data Center 2012).

Planting and experimental design

We conducted three phases of experimental plantings over four years (2008–2011) in an adaptively managed study design. In the first phase of our study (2008 planting year), we designed our experimental plantings to evaluate water table penetration with deep-planting in combination with three shelter treatments. To evaluate deep-planting, we used a 1.9 m long and 0.2 m diameter motorized auger attached to a backhoe (Fig. 1A) to drill into terraces that were up to 2.5 m above the adjacent streambed elevation, which was the maximum terrace elevation at which we could penetrate water tables in our study area using this equipment. We established 36 experimental plots (167 m^2 average, 11 m^2 SE) in our 4.5 km long study area that were within 30 m of the bankfull channel edge, within 2.5 m elevation of the streambed (1.1 m average elevation, 0.1 m SE), were primarily vegetated with grasses (>75% grasses), and lacked establish shrubs or trees over 1 m tall (e.g., *Artemisia*, *Populus*, or *Salix* spp.). Each plot was drilled without surface preparation using the motorized auger at a density of approximately one hole per 5 m^2, with each hole being drilled until the water table was penetrated, the maximum depth of the auger was reached, or at the point of refusal. An average of 73% (6% SE) of auger holes penetrated the water table by plot. Four groundwater monitoring wells were also installed approximately 300 m apart along a one kilometer section in the middle of the study area, and were positioned within or adjacent to planted plots that had terraces elevations of 0.57, 1.30, 1.57, and 1.80 m above the adjacent streambed elevation. Not all planted terraces had groundwater monitoring wells installed, thus these wells were designed to monitor general water table trends within the study area. Each well was equipped with sensors positioned approximately one meter below the streambed elevation that recorded water table elevations every hour.

All holes drilled in the first phase of planting were planted in the spring (March–April) with an equal mix of dormant pole cuttings of black cottonwood (*Populus trichocarpa*) and willow (mix of *Salix monochroma*, *S. lucida* var *lasiandra* and *caudata*, *S. prolix*, *S. lasioleps*, and *S. amygoides*), which were obtained from native eastern

Fig. 1. Backhoe used to auger into floodplain terraces that were primarily vegetated with grasses (A). Shelter treatments used throughout the study included unprotected (B), 0.9-m vented plastic tree shelter (C), 1.8-m circular fence cage (D), 1.5-m mesh shelter over a 0.9-m vented plastic tree shelter (E), and 1.8-m vented plastic tree shelter (F). Cropping of plants protected with a 0.9-m vented plastic tree shelter from frequent herbivore damage (G) and failure of the mesh shelter attachment and subsequent bending of the main shoot (H) are also shown.

Oregon stocks propagated at a Bureau of Land Management nursery in Clarno, Oregon. Poles from coppiced trees were pruned to remove all branches (preformed buds were not removed), stored in the dark at near freezing temperature until transported to the study area, and soaked on-site in Bridge Creek for at least 24-hours prior to planting. At the time of planting, pole cuttings were cut at a 45° angle at the distal end, inserted into the drilled hole, and trimmed at a 90° angle on the proximal end 22 cm above the ground. The holes were then filled with lightly compacted soil from the auger tailings. The planted length of each pole, including the above ground portion following planting, ranged from 0.5 to 2.3 m (1.2 m average) and varied based on the terrace elevation above the streambed, hole depth, and elevation of water tables within the terrace. Above ground diameters of planted poles averaged 0.9 cm for both willow and cottonwood cuttings, and ranged from 0.5 to 3.8 cm for willow and from 0.5 to 6.0 cm for cottonwood. After planting, three shelter treatments were randomly assigned to the experimental plots such that all planted pole cuttings received the same shelter treatment within each plot with an equal number of plots assigned to each shelter treatment. Shelter treatments included unprotected controls without a shelter (Fig. 1B), 0.9 m vented Miracle Tube Tree Shelters (Fig. 1C), and circular cages of 1.8 m tall by 1.0 m diameter galvanized field fence (Fig. 1D). Each pole cutting received the prescribed shelter treatment within one week of planting, with a total of 358 pole cuttings planted with a 0.9 m vented plastic tree shelter, 440 with the 1.8 m circular fence cage, and 290 with the unprotected treatment.

For the second phase of experimental plantings, we planted in the spring of 2009–2010 to evaluate taller shelter designs in combination with deep-planting pole cuttings with access to water tables. Shelter treatments in this second phase included 0.9-m vented Miracle Tube Tree Shelters (Fig. 1C), 1.5-m Freegro open mesh tree shelters installed over 0.9-m vented Miracle Tube Tree Shelters (Fig. 1E), and 1.8-m vented Miracle Tube Tree Shelters (Fig. 1F). These plantings occurred along the 4.5-km stretch of our study area and were also restricted to terraces within 2.5 m of the streambed elevation that were primarily vegetated with grasses as described for the first planting phase. However, auger holes were drilled at a density of about one per 10 m^2 and only holes that penetrated the water table were planted with pole cuttings. Shelter treatments were randomly assigned to individual holes as opposed to being organized in plots, and all pole cuttings were acquired, handled, and planted as described for the first phase. Pole cuttings were trimmed to 0.5–2.3 m overall length in depending on the hole depth during the second phase of planting, although diameters and overall lengths were not measured at the time of planting. During the second phase of planting, approximately 14,000 m^2 of terrace were planted with a total of 367 pole cuttings protected with a 0.9-m vented plastic tree shelter, 696 with a 1.5-m mesh and 0.9-m vented plastic tree shelter, and 439 with a 1.8-m vented plastic tree shelter.

The third and final phase of experimental plantings included one year of spring planting (2011) and was designed as a test of the planting strategy that provided the best survival and browser protection as determined from our study results. A total of 1086 pole cuttings were planted with 1.8-m vented Miracle Tube Tree Shelters (Fig. 1F) in this final phase that included a 1:1 mix of cottonwood and willow planted only in holes that penetrated the water table. Pole cuttings were handled the same as previous planting years and were planted in the same terraces as used for the second phase of plantings, with pole cuttings only being planted in holes that penetrated the water table. Initial pole length and diameters were not recorded in the final phase, but all poles were trimmed to 0.5–2.3 m overall length based on the hole depth.

Monitoring and evaluation

Monitoring occurred in the spring of each year from 2009 to 2012 for all planting phases to determine survival (alive or dead), browsing (terminal bud loss from browsing, yes or no), and total plant height (tallest primary shoot on living plants). Plants were classified as alive if they had signs of active growth (live shoots, buds, or leaves). Living plants were classified as browsed only if terminal buds of the primary shoot had been damaged by herbivores (deer, elk, or beaver) while damage to lateral branches or leaves was not considered. Given the adaptive nature of our multi-year study and binary response variables for survival and browsing, we analyzed survival and browsing data within each planting phase using binary logistic regressions with R (version 3.0.2). In the first planting phase, three years of monitoring were completed with binary logistic regressions for main effects that included water table penetration (wet and dry), shelter treatment (0.9-m vented plastic tree shelter, 1.8-m circular fence cage, and unprotected), genus (cottonwood and willow), and planting plot as categorical variables; and initial pole cutting length and diameter as continuous variables. For the second planting phase, we completed two years of monitoring from each planting year and used planting year (2009 and 2010), shelter treatment (0.9-m vented plastic tree shelter, 1.5-m mesh with a 0.9-m vented plastic tree shelter, and 1.8-m vented plastic tree shelter), and genus (cottonwood and willow) as categorical variables in a main effects binary logistic regression model. In the final planting phase, only genus (cottonwood and willow) was used as a categorical variable with monitoring being limited to only the first year after planting in a main effects binary logistic regression model. All browsing binary logistic regression models were restricted to surviving plants. Confidence intervals for survival and browse rates were computed using the exact method, or Clopper-Pearson interval (Clopper and Pearson 1934), and were calculated using the gmodels and binom packages for R (version 3.0.2). We also analyzed median plant heights using Kruskal-Wallis rank sum tests and 95% confidence intervals with R (version 3.0.2) for each planting phase.

RESULTS

Climate and water table

Average cumulative annual and season precipitation during the study period (2008–2011) was lower than long-term (1981–2010) averages measured for the study area (National Climatic Data Center 2012). Total annual rainfall (March–February) was 7.0 cm less than long-term averages with 28.5 cm (6.5 cm SE) across planting years (2008–2011). Seasonally, average total spring (March–May), summer (June–August), fall (September–November), and winter (December–February) precipitation during our study was 9.5 cm (2.8 cm SE), 6.0 cm (2.2 cm SE), 5.5 cm (1.6 cm SE), and 7.5 cm (1.7 cm SE), respectively. These seasonal averages were 2.1, 0.6, 3.7, and 0.6 cm lower than long-term spring, summer, fall, and winter averages, respectively. The summer of 2008 was the driest with 0.8 cm of precipitation, while the summer of 2009 was the wettest with 11.1 cm of precipitation. Mean daily temperatures across planting years (2008–2011) were 17.7°C (0.8°C SE) in the summer and 1.5°C (0.3°C SE) in the winter.

Water table elevations within our study area increased an average of 0.12 m (0.02 m SE) following planting in March–April to annual maximum elevations around May of each year (Fig. 2). During this peak, water table elevations were an average of 0.19 m (0.09 m SE), 1.42 m (0.08 m SE), 0.49 m (0.11 m SE), and 0.69 m (0.09 m SE) below the surface on terraces that were 0.57, 1.30, 1.57, and 1.80 m above the streambed, respectively (Fig. 2). Following this annual peak, water tables lowered by an average of 0.41 m (0.06 m SE) at a rate of 0.3 cm (0.04 m SE) per day from May to September (Fig. 2). During this annual minimum in September, water table elevations were 0.82 m (0.05 m SE), 2.01 m (0.04 m SE), 1.48 m (0.37 m SE), and 2.04 m (0.23 m SE) below the surface on terraces that were 0.57, 1.30, 1.57, and 1.80 m above the streambed, respectively (Fig. 2).

First phase

Water table penetration (wet and dry), shelter treatment (0.9-m plastic tree shelter, 1.8-m circular fence cage, and unprotected), genus (cottonwood and willow), and pole cutting length were significant factors affecting the probability of survival three years after planting (binary logistic regression: $p < 0.05$). Plot and pole cutting diameter were not significant factors affecting the probability of survival three years after planting (binary logistic regression: $p > 0.05$). Deep-planted cottonwood and willow pole cuttings with access to the water table had higher observed survival rates regardless of shelter treatment three years after planting (Fig. 3), and water table penetration significantly increased the odds of survival by a factor of 7.0 when controlling for all other factors. Pole cuttings with a 0.9-m plastic tree shelter had higher observed survival rates three years after planting (Fig. 3), with 1.8-m circular fence cage and unprotected treatments significantly reducing the odds of survival by a factor of 0.24 and 0.10, respectively, when controlling for all other factors. The odds of survival for willow was higher by a factor of 3.69 compared to cottonwood three years after planting controlling for all other factors. Initial pole cutting length was positively related to the

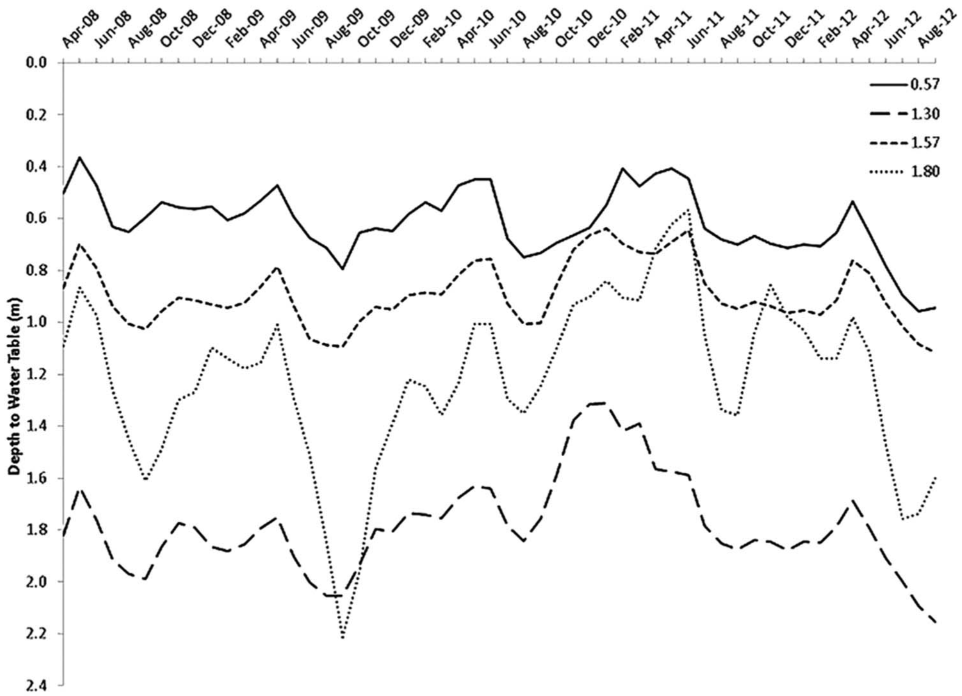

Fig. 2. Monthly water table depths over the course of the study relative to the floodplain terrace surface elevation at four monitoring wells. These four wells were located on terraces that were 0.57, 1.30, 1.57, and 1.80 m above the adjacent streambed elevation.

probability of survival, with each unit increase in initial pole cutting length (m) increasing the odds of survival by a factor of 1.76 when controlling for all other factors.

Among pole cuttings that survived three years after planting that were deep-planted with access to the water table, the probability of terminal bud loss was only significantly affected by shelter treatment (binary logistic regression: $p < 0.05$). The observed proportion of pole cuttings with browser damaged terminal buds was highest with the unprotected treatment (Fig. 4), with the odds of terminal bud loss being higher by a factor of 4.07 for unprotected pole cuttings compared to 0.9-m plastic tree shelters controlling for all other factors. Observed terminal bud loss was lowest with a 1.8-m circular fence cage (Fig. 4), and the odds of terminal bud loss was lower by a factor of 0.13 with a 1.8-m circular fence cage compared to a 0.9-m plastic tree shelter after three years controlling for all other factors. Shelter treatment also significantly affected plant height in the third year after planting among pole cuttings that survived through the first three years and were deep-planted with access to the water table. Median height after three years was significantly taller with a 0.9-m plastic tree shelter compared to both 1.8-m circular fence cage and unprotected treatments (Kruskal-Wallis rank sum test: $p < 0.01$). Median plant heights were also significantly taller with a 1.8-m circular fence cage as compared to the unprotected treatment (Kruskal-Wallis rank sum test: $p < 0.01$). Median plant height after three years was 133–153 cm (95% confidence interval, $n = 243$) with a 0.9-m plastic tree shelter, 112–133 cm (95% confidence interval, $n = 117$) with a 1.8-m circular fence cage, and 57–73 cm (95% confidence interval, $n = 53$) for unprotected.

Second phase

Based on the results of our first phase of experimental plantings, we restricted planting in the second phase to auger holes that penetrated the water table. In addition, we tested two taller plastic tree shelter designs given that plastic tree shelters significantly increased the probability of survival while the taller circular fence cage

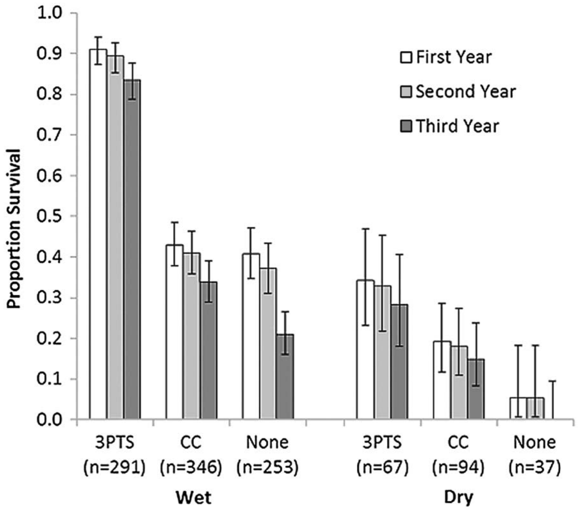

Fig. 3. Proportion of observed survival (with 95% confidence interval) for the first phase of plantings in auger holes that penetrated the water table (Wet) and did not penetrate the water table (Dry) among shelter treatment groups. Shelter treatment groups include unprotected (None), 1.8-m circular fence cages (CC), and 0.9-m vented plastic tree shelters (3PTS). Survival proportions are shown after the first, second, and third year following planting and are pooled by plot and genus. Sample sizes are shown as starting sample size for each shelter and water table penetration group.

treatment significantly reduced the probability of terminal bud loss. The second phase of experimental plantings indicated that shelter treatment (0.9-m plastic tree shelter, 1.5-m mesh shelter over a 0.9-m vented plastic tree shelter, and 1.8-m plastic tree shelter), genus (cottonwood and willow), and planting year (2009 and 2010) significantly affected the probability of survival through the first two years after planting (binary logistic regression: $p < 0.05$). Observed survival was highest with the 0.9-m plastic tree shelter two years after planting (Fig. 5), although we could not detect a statistically significant difference in the probability of survival between the 0.9-m and 1.8-m plastic tree shelter treatments (binary logistic regression: $p = 0.70$). The probability of survival with a 1.5-m mesh shelter over a 0.9-m vented plastic tree shelter was significantly lower than with a 0.9-m plastic tree shelter alone, with the odds of survival being reduced by a factor of 0.72 compared to a 0.9-m vented plastic tree shelter when controlling for all other factors.

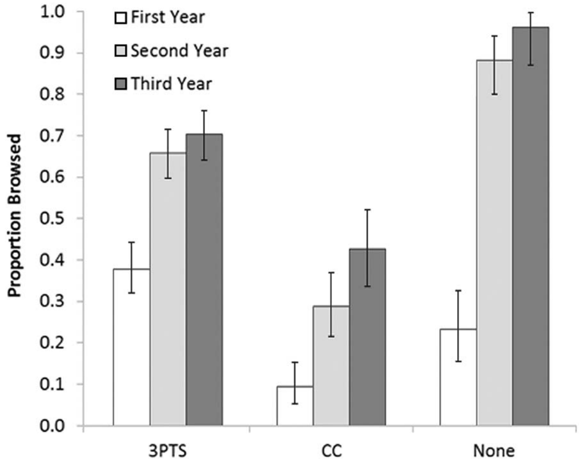

Fig. 4. Proportion of plantings with observed terminal bud loss from browsing (with 95% confidence interval) among surviving plants that were planted in auger holes that penetrated the water table among shelter treatment groups from the first phase of planting. Shelter treatment groups include 0.9-m vented plastic tree shelters (3PTS), 1.8-m circular fence cages (CC), and unprotected (None). Browsed proportions are shown after the first, second, and third year following planting for surviving plants with plot and genus pooled.

The probability of survival was lower among the 2010 plantings compared to 2009, with the odds of 2010 plantings surviving being lower by a factor of 0.42 two years after planting. This corresponds with differences in cumulative rainfall in the first summer after planting, with 11.1 cm versus 7.6 cm of cumulative precipitation in the first summer after the 2009 and 2010 planting years, respectively. The odds of survival through the first two years was higher by a factor of 1.48 for willow compared to cottonwood.

Among pole cuttings that survived through the first two years after planting, shelter treatment and planting year were the only significant factors affecting terminal bud loss (binary logistic regression: $p > 0.05$). Taller plastic tree shelter designs had consistently lower observed terminal bud loss two years after planting (Fig. 5). The odds of terminal bud loss was lower by a factor of 0.03 and 0.08 with the taller plastic tree shelter designs (1.8-m plastic tree shelter and a 1.5-m mesh shelter over a 0.9-m plastic tree shelter, respectively) as compared to a 0.9-m plastic tree

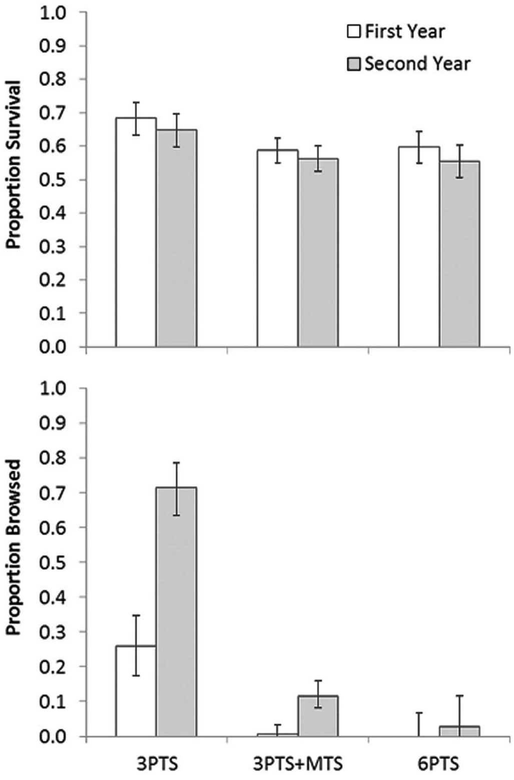

Fig. 5. Proportion observed survival (top) and browsed (bottom) for the second phase of experimental plantings with planting restricted to holes that penetrated the water table. Shelter treatments included 0.9-m plastic tree shelter (3PTS), 0.9-m vented plastic tree shelter with a 1.5-m mesh tree shelter (3PTS + MTS), and 1.8-m vented plastic tree shelter (6PTS). Browsing summaries were restricted to those plants that were alive at each year after planting. Survival and browsing proportions are shown after the first and second year following planting with genus pooled and include 95% confidence intervals.

shelter after two years controlling for all other factors. Median plant height was also significantly taller among the taller plastic tree shelter treatments after two years (Kruskal-Wallis rank sum test: $p < 0.001$), with median plant heights of 152–168 cm (95% confidence interval, $n = 392$) with a 1.5-m mesh shelter over a 0.9-m plastic tree shelter and 162–178 cm (95% confidence interval, $n = 243$) with a 1.8-m plastic tree shelter. In contrast, frequent browsing of plants with a 0.9-m plastic tree shelter resulted in coppiced growth form (Fig. 1G) and median plant heights of 98–102 cm (95% confidence interval, $n = 238$).

Third phase

Based on the results from the first and second phases of experimental plantings, we planted only in auger holes that penetrated the water table and only used 1.8-m vented plastic tree shelters in our third phase of experimental plantings. In the first year after planting, we observed 67.1–72.6% (95% confidence interval, $n = 1086$) survival with 1.8–4.4% (95% confidence interval, $n = 759$) terminal bud loss among those that survived. Median height was 97–103 cm (95% confidence interval, $n = 759$) after the first year among these surviving plants. The probability of survival was significantly higher for willow compared to cottonwood, with the odds of survival being higher by a factor of 1.52 for willow compared to cottonwood. Observed survival was 70.4–77.8% (95% confidence interval, $n = 558$) for willow and 61.1–69.4% (95% confidence interval, $n = 528$) for cottonwood. However, the probability of terminal bud loss (binary logistic regression: $p > 0.05$) and median plant height (Kruskal-Wallis rank sum test: $p > 0.05$) after one year were not statistically different between willow and cottonwood.

DISCUSSION

Our results indicate that deep-planting pole cuttings with direct access to shallow alluvial groundwater could be a promising strategy for establishing cottonwood and willow in dryland riparian ecosystems without supplemental irrigation. We were able to penetrate shallow alluvial groundwater as deep as 1.9 m below the surface using motorized augers in floodplain terraces up to 2.5 m above the incised streambed elevation. By deep-planting pole cuttings in holes that both penetrated and did not penetrate the water table in our first experimental planting phase, we were able to determine that providing pole cuttings with access to the water table significantly increased the probability of survival. While water table penetration resulted in higher survival among all shelter treatments tested in our first planting phase, combining water access with a 0.9-m vented plastic tree shelter resulted in over 5× greater increases in survival as compared to combining water table penetration with a 1.8-m circular fence cage or unprotected treatment. In addition, the 0.9-m plastic tree shelter provided higher survival regardless of water table penetration as compared to 1.8-m circular fence cage and unprotected plants. Maintenance of a beneficial microclimate within the shelter is likely the reason for higher survival with a vented plastic tree shelter (e.g., Bergez and Dupraz 1997, Kjelgren and Rupp 1997, Devine and Harrington 2008). However, plastic tree shelters can become detrimental under prolonged periods of drought if plants do not have access to water (Kjelgren and Rupp 1997, Oliet and Jacobs 2007), and it was this concern that influenced the use of circular fence cages and unprotected treatments in our initial planting phase. Our results indicate that this concern was not realized under the conditions of our study given that vented plastic tree shelters increased survival even when deep-planted without access to shallow alluvial groundwater. However, it should be noted that some holes originally classified as dry could have become wet before summer drawdown initiated due to increasing groundwater elevations that were observed following planting each year. This could have resulted in increased survival among plantings that were deep-planted without access to water at the time of planting, and could have masked effects of deep-planting without water access and explain the larger confidence intervals observed for survival of these dry plantings.

While deep-planting with access to shallow alluvial groundwater in combination with a 0.9-m tall plastic tree shelter clearly provided the highest survival rates in our first planting phase, this strategy proved vulnerable to browsing. The coppiced growth form observed among a majority of the 0.9-m plastic tree shelter plantings from frequent browsing (Fig. 1G) will likely fail to provide intended ecosystem benefits (e.g., canopy formation, shading, and large woody debris inputs) given that plants may not breach the shelter top. While the taller 1.8-m circular fence cages significantly reduced terminal bud loss compared to the shorter 0.9-m plastic tree shelter, the clear survival benefits of a plastic tree shelter warranted evaluation of taller designs that incorporated a plastic tree shelter. As a result, our second phase of experimental plantings included 1.8-m vented plastic tree shelters and a combination of a 1.5-m mesh shelter and 0.9-m vented plastic tree shelter. With these designs and deep-planting only in auger holes that penetrated the water table, we found that while survival was highest with the shorter 0.9-m plastic tree shelter, the probability of survival was not significantly different between 0.9-m and 1.8-m plastic tree shelters treatments. However, the taller 1.8-m plastic tree shelter did significantly reduce the probability of terminal bud loss from browsing, with over 70% of 0.9-m plastic tree shelter plants having lost terminal buds to browsing as compared to less than 3% when protected with a 1.8-m plastic tree shelter. Combining a 1.5-m mesh shelter with a 0.9-m plastic tree shelter also significantly reduced browsing, but the probability of survival was actually significantly lower compared to the 0.9-m plastic tree shelter. In addition, 6.0% (42/696) of the mesh shelters deployed in our study collapsed causing severe bending of plants and growth of stems through the mesh (Fig. 1H). In contrast, the 1.8-m plastic tree shelters were more durable with only 0.3% (5/1525) falling over during our study.

As a result of our first two phases of experimental plantings, we selected the 1.8-m vented plastic tree shelter for our final planting phase in which we only deep-planted cottonwood and willow in auger holes that penetrated the water table. The results of this third phase of experimental plantings were encouraging, with 67.1–72.6% (95% confidence interval) survival and only 1.8–4.4% (95% confidence interval) terminal bud loss in the first year after planting. This strategy provided high survival and reduced browsing impacts under our study conditions, was the easiest to install and most durable of the taller plastic tree shelter designs evaluated, and was effective on terraces up to 2.5 m above the streambed elevation without irrigation. We hypothesize that the utility of this strategy may be further expanded by evaluation of deep-planting with longer augers and longer pole cuttings in areas where water tables are more than 2 m below the surface. However, it should be noted that our groundwater monitoring wells indicate that water table elevations increased following each spring planting and then declined approximately 0.3 cm per day from May to September. Given the rise in water table elevations we observed after planting and that cottonwood and willow can tolerate drawdown as high as 2.5 cm per day (Mahoney and Rood 1998, Amlin and Rood 2002), pole cuttings planted with access to water tables at the time of planting likely had time to develop sufficient root structure within hydrated soils and were able to keep up with the relatively low rate of drawdown observed. Higher drawdown rates may be more of a concern in areas where lowered water tables are the result of water management strategies that can cause higher drawdown rates, and this should be considered when developing riparian planting strategies in such areas (Dreesen and Harrington 1999).

We also found that willow had a significantly higher probability of survival throughout our study when controlling for all other factors (e.g., shelter treatments and water table penetration). While this indicates that higher overall survival rates would likely be achieved by using only willow pole cuttings under our experimental conditions, the taller growth and canopy forming potential provided by cottonwood are more likely to contribute more desired riparian ecosystem functions (e.g., shading, organic inputs, large woody debris recruitment, and wildlife habitat). While cottonwood and willow represent the dominant constituents of dryland riparian ecosystems in the northern hemisphere, we also encourage future studies to consider other drought tolerant species like desert willow (*Chilopsis linearis*), New Mexico olive (*Forestiera neomexicana*), indigobush (*Amorpha fruticosa*), and seepwillow (*Baccharis* spp.), which have shown promise for pole planting in arid conditions (Dreesen and Harrington 1999) and could expand the utility of deep-planting for riparian restoration to other regions with more arid climates or different plant assemblages.

In conclusion, our results provide a useful contribution to the development of effective dryland riparian planting strategies where lowered water tables and high herbivore pressure present significant challenges to plant establishment, and where supplemental irrigation is impractical. We encourage future studies evaluating deep-planting with longer pole cuttings where water tables are more than 2 m below the surface, and with higher drawdown rates and more drought tolerant species. Developing successful strategies for establishing riparian vegetation in dryland riparian ecosystems has potential to greatly benefit restoration efforts in high water-stress ecosystems that are sensitive to degradation (Davies et al. 2012) by facilitating restoration of beneficial ecosystem functions. Given that over 41% of terrestrial environments are drylands (Davies et al. 2012), effective planting strategies for dryland riparian ecosystems have potential to benefit restoration efforts on a global scale, and continued development and evaluation of such strategies are encouraged given the challenges associated with such restoration efforts. Increased risk of drought and lowering water tables under predicated climate change scenarios also point to a need for developing effective riparian planting strategies under such conditions (Horner et al. 2009, Stromberg et al. 2010).

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