Growth and Water Use During Establishment of Irrigated Bare Root and Balled-Burlap Green Ash Transplanted Into A High Desert Landscape

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Abstract. We investigated growth, water relations, and water use of bare root (BR) and balled-burlapped (BB) Patmore green ash following transplanting into an irrigated landscape setting in a high desert climate. Treatments were green ash harvested as larger (40 mm caliper) BB and BR trees, and smaller BR stock (25 mm caliper). During establishment, we measured canopy growth for 3 years, and for 2 years plant water relations [predawn water potential and midday stomatal conductance (g_s)] and water depletion within the root zone. All treatments expressed varying degrees of isohydric responses to root loss by reducing g_s that maintained water potential nearly constant, but least so for the smaller BR trees. g_s was greater than that of all larger trees, meaning that for the same cost in water potential as the larger trees, BR-Small benefitted from more open stomates and presumably greater carbon gain. Greater initial conductance apparently translated into more growth. Year 1, BR-Small trees had the least total leaf area, but by Year 3 total leaf area was not different among all treatments. Also during Year 1, the ratio of water use to local reference evapotranspiration [plant factor (PF)] was 0.36 for large BR trees vs. 0.56 for BB trees, similar to the recommended PF of 0.5 for trees in dry climates. These results suggest smaller BR trees are a cheaper alternative for high desert landscapes while reaching nearly equivalent growth to BB trees after 3 years. Achieving high growth of BR trees would need careful scheduling of irrigation amount and frequency based on leaf area, root zone size, and local reference evapotranspiration.

Demand for large (>40 mm) caliper trees to create instant landscapes is greater than for smaller trees (Arnold, 2005). These larger trees are typically harvested BB from wholesale field production. Harvesting roots with soil increases weight and shipping costs and risks root system damage during handling (Koeser et al., 2009). BR trees harvested without soil are widely produced by the nursery industry, largely for use as liners in wholesale BB field production. Occasionally, BR landscape trees are sold retail and transplanted directly into the landscape as a low-cost alternative to BB trees (Buckstrup and Bassuk, 2000).

Production of BB and BR trees results in substantial root loss at harvest (Watson and Himelick, 1982), disrupting the balance between transpiring leaf area and root surface area needed for water uptake. Truncated root systems from both methods means fewer fine roots to take up water, and so increased risk

for water stress until new roots grow into surrounding ambient soil (Barton and Walsh, 2000; Kjelgren and Cleveland, 1994). Until established, transplanted trees maintain a delicate balance among leaf area necessary for photosynthesis, root regrowth into ambient soil, and rooting volume necessary for water uptake (Griffin et al., 2010; Shober et al., 2010; Watson and Kupowski, 1991). Transplanted deciduous trees balance transpiring leaf area against root loss by reducing leaf number and size (Dostalek et al., 2009; Riikonen et al., 2011), particularly BR trees with greater root loss (Abod and Webster, 1990; Gunnell et al., 2008). Leaf area can be managed to accommodate root system reduction, again particularly for BR trees, with careful pruning to reduce water stress after transplanting (Dagit and Downer, 2002; Hips et al., 2014; Ranney et al., 1989).

Transplanted BB and BR trees with truncated root systems in most climates require careful scheduling of irrigation volume and frequency to avoid stressful water deficits, reduced growth, or death (Griffin et al., 2010; Montague and Fox, 2008; Shober et al., 2010). Total leaf area largely determines irrigation volume for trees transplanted BR and BB, and irrigation frequency depends on

evaporative “pull” on water from the truncated root zone, greater on hot days for trees with more leaves, less for trees with fewer leaves and cool days (Barton and Walsh, 2000; Gilman et al., 1998; Kjelgren and Cleveland, 1994).

Landscape trees are routinely irrigated in the U.S. Intermountain West (IMW) high desert. Routine irrigation means that properly handled BR trees could be just as easy to establish (Gunnell et al., 2008) as BB trees. Previous work has shown that BR trees transplanted into landscapes often establish as well as BB trees in humid climates (Buckstrup and Bassuk, 2000; Hensley, 1993). In the arid IMW, hot, dry air (high vapor pressure deficits) translates into high evaporative pull that may trigger stomatal closure in many tree species (Montague et al., 2004). Stomatal closure reduces transpiration—at potential cost of less carbon uptake—and slows root zone water depletion and irrigation frequency (Kjelgren et al., 2016). Hot, dry conditions may increase stress on BR trees through greater stomata closure than those harvested with more roots (BB), thus delaying establishment (Anella et al., 2008). In a dry climate, such as the IMW with routine irrigation, how water use and establishment of BR vs. BB has not been studied. Here we compared during establishment first year water use, 2 years of g_s and water potential, and 3 years of total leaf area and shoot elongation of *Fraxinus pennsylvanica* ‘Patmore’ transplanted as BB and two BR sizes in a high desert climate.

Materials and Methods

Climate and weather. We characterized the high desert climate of northern Utah from the Utah State University (USU) Global Historical Climate Network (GHCN) weather station (lat. 41.7, long. -111.8, 1460 m elevation, station no. USC00425186). We plotted 30-year (1981–2010) daily probability of precipitation and 30-year average daily reference evapotranspiration using the Hargreaves max/min temperature equation (Hargreaves and Allen, 2003). We measured weather during the study period (1996–97) with an automated weather station located at the study site incoming shortwave radiation (LI-COR 200 pyranometer; LI-COR Inc., Lincoln NE), wind speed (RM Young 3-cup anemometer; R.M. Young, Traverse City, MI), relative humidity, and air temperature (Vaisala HMP3 temperature-humidity sensor in a radiation shield; Vaisala Corp., Louisville, CO). Sensors were controlled and data stored with a CR-100 datalogger (Campbell Scientific, Logan, UT). These data were used to calculate for the study period cool season turfgrass reference evapotranspiration (ET_c) using the Penman-Monteith American Society Civil Engineers equation (Allen et al., 2005).

Experimental setup. This study was conducted at the USU research farm on a well-drained Millville silt loam soil over 2 years (1996, Year 1 and 1997, Year 2). Growth was compared for 3 years, and water relations and water use for 2 years, during post-transplant

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establishment for three harvest techniques. Treatments were 'Patmore' green ash (*Fraxinus pennsylvanica*) harvested BB (40 mm caliper) or BR at two sizes (25 and 40 mm caliper). Plant material was sized according to industry standards (caliper measured at 160 mm aboveground level; ANLA 2004). BR plants were purchased from a wholesale nursery in Oregon, and BB trees purchased from a local field production nursery. Root system diameters were sized to ANLA standards (ANLA 2004), 260 and 560 mm for the BR-Small and BR-Large, respectively, and 510 mm for BB trees. Trees crowns were not pruned before planting, and only broken and long, small (<1 mm) roots were pruned on BR trees (Bellet-Travers et al., 2004). Trees were planted in holes 50–70 mm larger than the root ball diameter for the different root ball sizes, and ≈0.75 m deep. Each treatment consisted of four single-tree replicates laid out in a 3 × 4 row of rectangular grid spaced 2 m apart on center to minimize competition between root zones and irrigation overlap. Trees were randomly assigned to location within the experimental layout, and surface soil between plants was kept weed free.

Plants were installed in mid-May Year 1 and watered immediately after planting. A drip-line irrigation system was installed with a separate irrigation line for each treatment. Three 8 L/h drip emitters were installed at each tree and watered every 3 d with 10 L/tree for 2 weeks following transplanting to ensure a thoroughly wetted root zone (Gilman et al., 1998). Starting 1 June Year 1, trees were irrigated weekly, unless 10 mm or more rainfall was received, until mid-August. At that point, irrigation ceased and water stress was monitored, then re-watered the first week in September (a 16 d dry-down). After initial 2 weeks of high frequency irrigation, trees were irrigated seven times in Year 1. Year 2 the growing season was much wetter, where trees only needed two irrigations (mid-June and mid-July).

Tree water use was calculated from measured changes in soil water content in tree root zones using a time-domain-reflectometer (TDR) system (Griffin et al., 2010). At planting, eight single-diode TDR wave guides (150 mm long) constructed at USU were installed at each tree. Wave guides were calibrated during late summer the year before the study at a nearby location with identical soil. A dry reading was taken by installing each wave guide into undisturbed side wall soil in a pit dug into a harvested barley crop at 200-mm depth, and in adjacent bare soil at the same depth that had been saturated and allowed to drain to field capacity. Calibration was based on gravimetric water content from physical soil samples collected during installation under barley (dry) and after drainage (wet) and then corrected to volume using previously characterized soil bulk density. We assumed the calibration was applicable to the similarly textured (ostensibly silt loam) BB root zone soil. Eight wave guides were installed in soil around each of the four large BR and BB (but no BR-Small trees) trees to compare water uptake of trees with similar

trunk sizes but potentially different total leaf areas. Four wave guides were inserted at the edge of the root zones pointing into the root ball (one each at 150- and 300-mm depths on the north and south side of each tree), and another four were inserted at the same depths but pointed outward into the undisturbed ambient soil (Griffin et al., 2010). The 50–70 mm of backfill soil between the edge of the root size and ambient soil sidewalls was not instrumented. Wave-guides were read with a soil moisture meter (Environmental Sensors Moisture Point Model MP-917, Vancouver, BC, Canada).

Data collection. Soil water content was measured weekly Year 1 starting in mid-July before and after each irrigation (if no rain), and measured twice during wetter Year 2. Soil water data were converted to percent soil moisture (mm water/mm soil). Average daily change in soil water content was calculated over the period between irrigations for a given sensor placement (root ball inward and ambient soil outward). Soil moisture data were averaged across the two depths and two orientations for wave guides pointing into the root ball or outward into ambient soil, and then summed over the 300-mm depth to calculate millimeters of water use per day.

Plant water status was measured every 7–10 d Year 1 following transplanting. Predawn leaf water potential (LWP) was measured with a pressure chamber (model 3000; Soil Moisture Inc., Santa Barbara, CA). One leaf per tree was excised at predawn, tightly sealed in a plastic bag, and stored in an insulated plastic cooler with cold packs until measurement, typically within 15 min of excision. Late summer midday water potential was measured once in Year 1 and twice in Year 2 to determine if, under greater afternoon evaporative demand, treatment differences were detectable. g_s was measured at midday on six mature sunlit leaves per tree with a steady-state porometer (Model 1600; LICOR Inc., Lincoln, NE). During the 16-d dry down in Year 1, g_s was measured every other day. In Year 2, midday g_s was measured twice during the dry-down cycle.

Growth data were taken for 3 years by measuring terminal bud elongation of five randomly selected main branches from each tree after fall dormancy. Total leaf area was measured by harvesting all leaves from each tree mid-September each year before seasonal senescence. A 25-leaf subsample was removed, average area per leaf was measured (Model CI-203 leaf area meter; CID Inc., Vancouver, WA), and then subsample leaves were oven dried and weighed to obtain specific leaf area (cm^2/g). The bulk sample of the leaves was also oven dried and weighed. Total tree leaf area was calculated as the product of specific leaf area (cm^2/g) determined from the subsample and bulk leaf weight.

Data analysis. Local historical climate was characterized from the GHCN data by plotting the 30-d running average probability of precipitation each day of the regional Apr. 1 to Oct. 31 growing season, then 30-d running average depth of precipitation for those

days with precipitation over the 100-year period. Further, we plotted daily average and 3-d running average Hargreaves ET_o (cool season grass reference). Soil water depletion was compared in the root ball or in ambient soil for each treatment using two-way analysis of variance (ANOVA) (Sigma-Stat 2.1; Systat Inc., Chicago, IL). Total leaf area and shoot elongation differences were analyzed with the same software using one-way ANOVA with three treatments. Variation in water relations data was characterized by error bars in plotted graphs.

Results and Discussion

Regional IMW climate is a high desert, marked by 30% to 50% probability of rainfall on any given spring day (May through early June) that falls to 10% to 20% probability by early July (Fig. 1A). On wet spring days, depth of rainfall ranges from 2.5 to 7 mm, but after July 1, rain depth ranges from 1 to 5 mm (data not shown). Reference (potential) evapotranspiration is closely linked to rainfall and temperature in a dry climate, as it increases steeply from spring to a July maximum average of 6 mm/d when rain probability is lowest (Fig. 1B). Weather conditions differed between the 2 years. Only 30 mm fell during Year 1 season—June, July, and August—compared with an average 71 mm (Fig. 1A) and ET_o was greater at 572 mm vs. 515 mm average (Fig. 1B). Year 2 was cooler and wetter, as seasonal rainfall was 139 mm and ET_o 522 mm.

Under hot and dry high desert conditions, irrigated, smaller BR stock appeared more successful than the larger trees in balancing root loss; less leaf area (and less overall evaporative pull) ostensibly allowed greater gas exchange during the first 2 years of establishment. Year 1, BR-Small trees had ≈80% the leaf area of BR-Large trees, and one-third that of the BB trees (Table 1). By Year 3, all trees appeared well established based on leaf area and shoot elongation that was not different among treatments. Yearly shoot elongation was relatively high among all treatments of Year 1, but BB shoot elongation remained relatively constant while BR-Small almost tripled by Year 2. By Year 3, shoot elongation was the same among the treatments. Year 3 leaf area was not different among treatments, partially due to high BB tree-to-tree variability. Over the 3-year establishment period, BR-Small trees grew the fastest; leaf area increased 13.5 fold, BR-Large 10-fold, and BB trees increased leaf area 5-fold. The story these data tell is that irrigated BR-Small trees achieved nearly the same crown size (total leaf area) and the same crown growth rate (shoot elongation) as the BB trees that were larger and with more intact roots at planting. Near parity growth of BR trees compared with BB trees after 3–4 years has been reported in several other species (Buckstrup and Bassuk, 2000; Hensley, 1993; Levinsson et al., 2014).

g_s was a more representative indicator of water stress and establishment than pre-dawn

LWP under irrigated conditions (Figs. 2 and 3). While having less initial leaf area, BR-Small trees maintained $\approx 50\%$ higher g_s (Fig. 2), and so likely higher carbon gain, from mid-July to mid-August compared with the larger trees. Conductance levels of the BR treatments largely converged during the Year 1 dry down. Not so for BB trees, as over most of the dry down period BB g_s was much lower than even BR-Large trees. The two measurement dates for Year 2 indicated g_s levels had nearly converged for all three treatments around 200 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Relative g_s patterns among the

three treatments were consistent with vigorous growth responses of BR treatments, particularly BR-Small, as compared with BB trees.

Predawn LWP did not effectively represent stress levels among the three treatments (Fig. 3). Apart from BR-Small levels, much less negative than the other two treatments in early July and again early August, predawn LWP differed little among treatments of Year 1 and not at all during Year 2. Afternoon LWP was also not different when measured once during the dry-down Year 1 and on 2 d Year 2. Absence of LWP differences among

treatments in the high desert climate is different from other studies of establishment in more humid climates, where LWP is a more definitive measure of establishment (Beeson and Gilman 1992; Gilman et al., 1998; Griffin et al., 2010; Shober et al., 2010).

Conductance differences combined with the absence of consistent water potentials describe an isohydric response to root loss. Isohydric behavior is stomatal closure under high ETo (high temperatures, dry air) to reduce water use to moderate the risk of more negative LWP that could lead to damaging cavitation (Schultz, 2003). This isohydric response was least in BR-Small trees. A possible mechanism explaining an isohydric response is less leaf area reducing whole-plant evaporative “pull” on root water uptake that allowed, in turn, greater g_s and carbon uptake. By contrast, greater leaf area of BB and BR-Large trees in proportion to their truncated root systems may have increased whole-plant evaporative “pull” enough to trigger a greater isohydric response that reduced g_s to maintain similar pre-dawn water potential.

Change in soil water content was consistent with differences in transpiring leaf area for BB and BR-Large trees (Fig. 4). Soil water content outside the root zones showed no depletion either year during the measurement periods. Absence of water depletion may be due to a combination of root growth not penetrating through the backfill soil, wave guides blocking roots from penetrating the ambient soil around the guides, and the limited soil volume measured. Changes in soil water content inside the root zones did differ among treatments. BB trees used between 3.3 and 4 mm/d from mid-July to early August, as compared with the BR-Large trees that used 2 to 2.5 mm/d (Fig. 3). Water use as a percent of ETo is equivalent to the PF relating ETo to plant water demand as defined in the national standard for estimating landscape plant water demand (ASABE, 2015; Kjelgren et al., 2016). PF of BR-Large trees averaged 36%, whereas BB PF averaged 56%; lower BR PF was likely due to fewer leaves compared with BB trees, rather than transpiration differences as g_s was similar among the two treatments. The PF of BR-Small trees would likely fall between that of the two larger treatments due to less leaf area but greater g_s . Both PFs are reasonably close to values previously reported for green ash (Montague et al., 2004) and to recommended PF value of 0.5 for established trees in arid climates (ASABE, 2015). PF results from this study will be useful in applying the standard

Fig. 1. (A) 30-year (1980–2010) daily probability of precipitation from the Utah State University Logan, UT Global Historical Climate Network (GHCN) weather station. Daily, plus actual precipitation during the study period from an on-site weather station; (B) 30-year average daily reference evapotranspiration (ETo) also from the same GHCN weather station calculated using $Tmax/Tmin$ input into the Hargreaves equation, plus Penman-Monteith ET collected from an on-site weather station during the study.

Table 1. Mean ($n = 4$) leaf area (m^2) and yearly shoot elongation (mm) for green ash trees (*Fraxinus pennsylvanica* ‘Patmore’) 3 years following transplanting.

	Total leaf area (m^2)			Shoot elongation (mm)		
	Yr 1	Yr 2	Yr 3	Yr 1	Yr 2	Yr 3
BB	2.58 ± 0.19 a ^z	5.80 ± 0.95 a	15.6 ± 4.3 a	444 ± 10 a	506 ± 18 b	565 ± 22 a
BR-Large	1.26 ± 0.33 b	5.36 ± 0.45 a	12.5 ± 2.3 a	180 ± 3 b	725 ± 11 ab	573 ± 18 a
BR-Small	0.84 ± 0.04 c	2.74 ± 0.35 b	11.3 ± 2.3 a	383 ± 4 ab	924 ± 7 a	537 ± 13 a

BB is balled-and-burlapped harvest method, 40 mm caliper; BR-Large is bare-root 38 mm caliper; BR-Small is bare-root harvest method, 25 mm caliper.

^zTreatment means within a column with different letters are different at $P < 0.05$.

Fig. 2. Midday stomatal conductance and daily high vapor pressure deficit (VPD) in an irrigated high desert environment for green ash (*Fraxinus pennsylvanica* 'Patmore') for (A) first year following transplanting, and (B) second year following transplanting. Treatments were BB-Large (balled and burlapped, 40 mm trunk diameter), BR-Large (bare root, 40 mm trunk diameter), and BR-Small (bare root 25 mm trunk diameter). Data points represent mean plus standard error.

Fig. 3. Rainfall during study period and predawn and midday leaf water potential for green ash (*Fraxinus pennsylvanica* 'Patmore') over 2 years following transplanting in an irrigated high desert environment. Treatments were BB-Large (balled and burlapped, 40 mm trunk diameter), BR-Large (bare root, 40 mm trunk diameter), and BR-Small (bare root, 25 mm trunk diameter). Data points represent mean plus standard error.

for transplanted trees, and may encourage further related studies. Year 1 water use from mid late August was lower than the prior measurement periods, possibly due to a combination of no irrigation and greater root growth into backfill and possibly ambient soil (but not around the wave guides, evidently). Water uptake from new roots into ambient soil would diminish the contribution of root zone volume to overall tree water loss. Water use in Year 2 was again lower than Year 1, further indicating even less contribution of root ball volume to overall tree water loss.

BR and BB trees must balance carbon allocation between new leaves (more carbon uptake) and roots (more water uptake) (Richardson-Calfee et al., 2007). In this study, frequent initial irrigation evidently allowed BR-Small trees starting with less leaf area to maintain higher g_s per unit leaf area. Higher g_s per unit leaf area would mean less isohydric stress, more carbon uptake that would explain the leap in growth Year 2. This growth surge highlights smaller trees being more effective in re-establishing a new root: leaf area balance than BB and BR-Large trees (Dostalek et al., 2009; Watson, 2005). BR tree root systems have the advantage of more direct root contact with ambient soil. By contrast, BB roots must cross an interface or gap between the root ball and ambient soil that may constrain root growth. During Year 1, greater leaf:root zone imbalance for BR-Large trees and BB trees may have caused a lingering suppression of g_s , and by proxy, photosynthetic assimilation and growth.

Absence of total leaf area and shoot elongation differences after 3 years indicated that BR trees can be a successful and cheaper alternative to BB trees in IMW urban landscapes. Although this study only included one species, other commonly used landscape species that transplant as BR stock may perform similarly, with smaller 25-mm caliper trees preferable to larger 40-mm caliper trees where stress is proportional to root loss (Bellett-Travers et al., 2004). Species more difficult to transplant or with coarser root systems (Kjellgren and Cleveland, 1994) should be approached more cautiously. However, BR trees require careful handling attention to avoid drying out compared with BB plants to be established successfully in urban IMW landscapes (Koeser et al., 2009). In addition, BR plant material from a wholesale nursery needs to be in optimal health, well pruned, and fertilized (Gunnel et al., 2008).

End users need enough knowledge to transplant smaller BR trees successfully. Proper handling is critical for any tree harvested with large root loss (Koeser et al., 2009). This is especially true for BR trees best planted during the narrow spring window when plants are still dormant (Richardson-Calfee and Harris, 2005; Richardson-Calfee et al., 2007) to avoid root drying, loss of vigor, and overall stress (Apostol et al., 2009). Irrigation frequency is the most critical step in establishing BR trees. Until the tree reaches the threshold of

Fig. 4. Mean water use of green ash over (*Fraxinus pennsylvanica* 'Patmore') 2 years following transplanting in an irrigated high desert environment. Treatments were BB-Large (balled and burlapped, 40 mm trunk diameter), and BR-Large (bare root, 40 mm trunk diameter). Water use measured as water depletion within root zone and in ambient soil surrounding the hole excavated for planting. Each bar is a mean of four trees, plus standard error.

sufficient new roots for into ambient soil and take more water, water application several times a week seems appropriate (Gilman et al., 1998). Irrigation scheduling (when and how much) is the critical management issue under end user control, with volume of water needed a rather straightforward calculation of $ET_o \times PF \times$ estimated leaf area. In this equation, transpiring leaf area governs total water use more than water use rate. Assuming a common summer daily ET_o value of 5 mm and a leaf area of 1 m² (Table 1), a 25-mm-diameter tree needs ≈ 2 L/d as a starting point. However, given the complexity of handling and irrigation, using BR trees in urban landscapes would likely be most successful with targeted education of the end user regarding a few simple but key procedures.

Also, this study suggests insights into irrigation scheduling of transplanted trees. Griffin et al. (2010) and Shober et al. (2010) tracked xylem water potential to determine tree establishment in a high summer rainfall climate. Here, we showed that stomatal sensitivity to root loss is amplified by high ET_o (Hipps et al., 2014) on transplanted trees with higher leaf area:root ratio (Dostalek et al., 2009; Riikonen et al., 2011). Stomatal closure mediates root loss and dry to moderate xylem water tension enough that water potential is not a good measure of root establishment following transplanting in dry climates. Instead, stomatal closure itself is a better measure of establishment, opening the possibility that water stress and time to establishment could be detectable through remote sensing (Atherton, et al., 2013). Water use of the BB trees indicate that the

ASABE S623 PF of 0.5 for established plants can also be applied to transplanted BB, and possibly to BR, trees.

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