Forest Ecology and Management 261 (2011) 1876–1884

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Establishment and growth of container seedlings for reforestation: A function of stocktype and edaphic conditions

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ARTICLE INFO

Article history:
Received 4 November 2010
Received in revised form 13 January 2011
Accepted 8 February 2011
Available online 12 March 2011

Keywords:
Ponderosa pine
Volumetric soil moisture content
Morphology
Container seedlings
Seedling establishment and growth

ABSTRACT

A properly selected stocktype can greatly enhance reforestation success through increased survival and growth following outplanting. Implementing a robust stocktype trial using stocktypes of equal quality can ensure results lead to the best choice. Six container types, differing primarily in depth and volume, were used to evaluate the performance of ponderosa pine (*Pinus ponderosa* Laws. var. *ponderosa*) seedlings outplanted on two sites that varied in volumetric soil moisture content (θ), average temperature, and total precipitation (mesic and xeric). Seedlings in each container type were cultured specifically to achieve uniform seedling quality. After two growing seasons, seedlings planted at the mesic site showed high survival (>99%) and incremental growth gains of 147, 100, and 794% for height, root-collar diameter (RCD), and stem volume, respectively; container types exhibited differences in total height, RCD, and stem volume with larger containers generally yielding the largest seedlings. Seedlings planted at the xeric site experienced 83% survival, smaller growth gains (25, 46, and 220% for height, RCD, and stem volume, respectively), and also exhibited differences in height, RCD, and stem volume. Regression analysis revealed that for each site, initial seedling morphological characteristics were better at predicting absolute height, RCD and stem volume after the first year than after the second year, with initial seedling height offering the best predictive power ($R^2 = 0.66$, mesic site; and $R^2 = 0.70$, xeric site). Second-year absolute growth prediction was poorest on the mesic site ($R^2 < 0.21$). Regression analysis indicates that initial seedling characteristics lost predictive value with time, especially on the mesic site, as seedlings grew out of their initial, container-induced characteristics and become more limited by current environmental and genetic factors. Conversely, on a xeric site, where absolute growth was reduced, traits determined by the container type persisted longer. Selecting stocktypes for mesic site conditions may only be limited by the minimum growth gains desired. Conversely, xeric sites may benefit from deep-planted quality seedlings or carefully planted long-rooted, large container seedlings.

Published by Elsevier B.V.

1. Introduction

Reforestation using nursery-produced seedlings can be an effective means of ensuring successful establishment and rapid growth following outplanting. Plantation establishment success often hinges on decisions and considerations made prior to planting, such as seedling stocktype, seedling morphology, genetics, site limiting factors, site preparation, the outplanting window, and planting technique (Scagel et al., 1998). The best seedling stocktype for a particular site may differ depending on how these decisions and considerations are made. To simplify this complex situation, the Target Plant Concept was proposed. This concept provides a means of overcoming the critical variables of forest establishment by focusing on morphological and physiological seedling characteristics that are linked to outplanting success (Rose et al., 1990; Landis and Dumroese, 2006). The premise behind the Target Plant Concept is that it identifies seedling characteristics that increase outplanting survival and growth under a particular set of site conditions (Rose et al., 1990).

Over the years, the number of available seedling stocktypes has increased dramatically, especially for container seedlings. It is well known that varying container volume, which usually also causes changes in seedling density, modifies seedling phenotype; this occurs even among seedlings of the same seed source grown the same year (Scarratt, 1972; Landis et al., 1990; Scagel et al., 1998). If a larger phenotype is desired, seedlings are grown in larger containers. Whether these larger containers are deeper or wider, they require more medium, more fertilizer, and more grow-

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0378-1127/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.foreco.2011.02.010

Table 1
Styrofoam® container specifications used to produce *P. ponderosa* seedlings.

Container[a]	Cavities				
	Cavities per container	Volume (cm^3)	Top diameter (cm)	Depth (cm)	Cavities per m^2
60	160	54	3.0	10.3	756
80	112	80	3.6	10.3	530
90	160	90	3.0	15.1	756
105	112	103	3.6	15.2	530
120	160	120	3.0	22.7	756
166	112	164	3.6	20.3	530

[a] 60, 90, and 120 Styroblock® containers manufactured by Beaver Plastics Ltd. (Acheson, Alberta, Canada). 80, 105, and 166 containers manufactured by Mansonville Plastics Ltd. (Surrey, British Columbia, Canada).

ing space than smaller containers, which increases production cost (Bowden, 1993). Reforestation projects are often limited by budget constraints, so the cost of a larger, more specialized, seedling may be justified only on sites where they yield a clear survival or growth benefit (Bowden, 1993; Wenny, 1995; Scagel et al., 1998).

The Target Plant Concept depends on empirical knowledge of which container types are best for certain site conditions. Studies have examined this question in terms of survival and growth in drought situations (Amidon et al., 1982; Bainbridge, 1994; Rose et al., 1997), with vegetative competition (Newton et al., 1993; Hunt, 2002), for cost effectiveness (Miller and Schaefer, 1985), and by other criteria, such as seedling density and supplemental fertilization (Arnott, 1975; Sutherland and Newsome, 1988; Simpson, 1991; Bowden, 1993; Paterson, 1997; South et al., 2005). These studies suggest that seedlings with larger height and root-collar diameter (RCD) outperform smaller seedlings after outplanting. Likewise, Rose et al. (1997) found that stocktypes with larger root volumes may have a survival and/or growth advantage after outplanting. But the question remains: what amount of height, RCD, and root volume is needed for a particular species at a particular location?

An abundance of tests have been developed to measure seedling quality and performance potential. Many grading criteria have been proposed and refined to characterize seedling quality and predict performance of outplanted seedlings (Burdett, 1987; Örlander and Rosvall-Åhnebrink, 1987; Burr et al., 1990; Binder et al., 1996; Templeton and Colombo, 1995). These tests are categorized into two areas: morphological and physiological attributes. Although many studies show good correlation between test results and field performance, the tests are often time-consuming and expensive. Consequently, nurseries tend to use morphological attributes as indicators of seedling quality; especially common are height and RCD. While some studies have shown that initial height corresponds well to subsequent growth for conifer and hardwood species (Jacobs et al., 2005; Mullin and Christl, 1981a,b), some are inconsistent (Chavasse, 1977). RCD has been correlated to root growth potential, survival, and height growth (Jacobs et al., 2005; South et al., 2005).

The variables that contribute to stocktype performance are numerous and are well known, but linking these variables together, however, in an all encompassing non-confounded study remains difficult (Pinto et al., 2011). One major source of confounding is the condition under which the seedlings are propagated. Pinto (2005) examined previous stocktype studies and found that none of them addressed stocktypes specific culturing regimes or the similarity in seedling quality between stocktypes. Container tree seedling growers know well that seedlings grown in different containers and from varying seed sources have different irrigation and nutritional requirements. By not accounting for these differences in growth pattern, previous studies have made it difficult to make unbiased selections of stocktype. In other words, one culturing regime may favor one container type; another culture regime may favor another. In an attempt to replace this bias, Pinto (2005) showed that fertilizing and irrigating seedlings according to their specific container type—versus multiple container types fertilized and irrigated under a single regime—offered more uniformity in foliar nitrogen concentration and water-use efficiency. This step is necessary for reducing bias and unexplained variation in container comparison studies.

Our study objective was to employ the culturing technique of Pinto (2005) and stocktype study recommendations of (Pinto et al., 2011) to (i) compare growth of different stocktypes on mesic and xeric site conditions in the northern mountains of the Intermountain West USA, and (ii) use initial seedling morphology (height, root-collar diameter, and stem volume) and container volume to predict seedling size after one and two growing seasons.

2. Materials and methods

2.1. Seedling preparation

In summer 2006, ponderosa pine (*Pinus ponderosa* Laws. var. *ponderosa*) seedlings were grown in a single greenhouse at the USDA Forest Service, Rocky Mountain Research Station in Moscow, Idaho (46. 7232°N, 117.0029°W; 798 m elevation). Seeds were obtained from the Confederated Tribes of the Colville Indian Reservation (Colville Tribal Forestry, Lower Stepstone: stand #1, 610 m elevation) and Potlatch Corporation (Potlatch Corporation, Lot ID#: 92-02, 915 m elevation). Six different Styrofoam® container types, differing primarily in cavity depth and volume (Table 1), were used to grow seedlings from March until December, when they were harvested and placed into freezer storage (−2 °C). Seedlings were cultured by container type, according to the methods used by Pinto (2005) and the recommendations of Pinto et al. (2011), to achieve uniform characteristics, such as foliar nitrogen and shoot-to-root ratio (Table 2).

2.2. Site description: Faeber II

Seedlings were outplanted 17 April 2007 on the Potlatch Corporation operational planting site Faeber II (F2) approximately 18 km east of Orofino, Idaho (46.4504°N, 116.0408°W; 980 m). The mixed-conifer overstory, which included ponderosa pine, was clear-cut and the site was prepared by concentrating leftover slash, burning it the fall before planting, and broadcast applying Atrazine herbicide (Syngenta, Wilmington, DE) in the spring. For each container type, 100 seedlings were hand-planted using a hoedad into 5 blocks in a randomized complete block design. To avoid confounding by planter technique, all seedlings were planted by two planters, with each planter planting half of all the stocktypes. Blocking was done to account for variability across the site. Within each block, 20 seedlings of one container type were planted in a row at 1.5 m spacing, while rows were 3 m apart. Because of browse damage on nearby reforestation sites, yellow mesh Vexar® tubes (0.13 m diameter × 0.76 m height) were installed on each seedling for protection; tubes were removed in June 2008. F2 soils belong to the

Table 2
End of growing season *P. ponderosa* seedling characteristics when grown with container-specific regimes. Standard errors are in parentheses.

Seed Source	Container	*N* (%)		Height (cm)		RCD (mm)		Shoot:Root	
Colville	60	1.97 (0.13)	a[a]	12.5 (0.44)	a	3.2 (0.09)	a	1.51 (0.06)	ab
	80	2.03 (0.07)	a	13.6 (0.57)	ab	3.6 (0.06)	ab	1.60 (0.05)	ab
	90	2.03 (0.07)	a	16.3 (0.64)	bc	3.8 (0.11)	bc	1.40 (0.04)	a
	105	2.20 (0.10)	a	17.0 (0.50)	cd	4.3 (0.16)	c	1.67 (0.10)	b
	120	2.17 (0.09)	a	19.4 (0.84)	d	3.8 (0.12)	bc	1.65 (0.05)	b
	166	2.20 (0.58)	a	19.8 (0.89)	d	3.9 (0.09)	bc	1.74 (0.05)	b
Significance		$P = 0.3330$		$P < 0.0001$		$P < 0.0001$		$P < 0.0012$	
Potlatch	60	1.90 (0.58)	a	10.3 (0.09)	a	2.5 (0.09)	a	1.82 (0.16)	a
	80	1.90 (0.58)	a	10.3 (0.87)	ab	2.9 (0.15)	a	1.59 (0.17)	a
	90	2.03 (0.07)	a	13.6 (1.02)	abc	2.6 (0.13)	a	1.53 (0.12)	a
	105	2.00 (0.58)	a	13.4 (0.70)	abc	2.8 (0.14)	a	1.98 (0.25)	a
	120	2.13 (0.07)	a	15.9 (0.94)	c	2.4 (0.11)	a	1.66 (0.09)	a
	166	2.17 (0.09)	a	14.6 (1.18)	bc	2.9 (0.13)	a	1.97 (0.15)	a
Significance		$P = 0.0627$		$P = 0.0020$		$P = 0.0605$		$P = 0.2737$	

[a] Columns with the same letter are not significantly different, Tukey adjusted ($P < 0.05$).

Grangemont series of Alfisols; they are deep, well-drained, fine-silty soils with a thin mantle of volcanic ash (Natural Resources Conservation Service, 2009).

2.3. Site description: Coyote Creek

The Coyote Creek planting site (CC) is located approximately 13 km northwest of Nespelem, WA (48.2376°N, 119.1272°W; 890 m) on the Confederated Tribes of the Colville Indian Reservation. Seedlings were hand-planted using hoedads on 1 May 2007 under the same experimental design as the F2 planting site. Similar to F2, planter technique confounding was avoided by having seedlings equally divided among three planters, with each planting all the stocktypes. The open-range, predominately ponderosa pine partial-cut site was prepared by concentrating leftover slash prior to planting. Slash piles were burned in early November of 2007. CC soils belong to the Bearspring series of Mollisols; they are deep, well-drained, loamy-skeletal soils formed in colluvium and residuum from granitic rock and capped with a thin mantle of volcanic ash (Natural Resources Conservation Service, 2009).

2.4. Edaphic and atmospheric monitoring and sampling

Soil moisture, air temperature, and precipitation were measured on each site. For soil moisture, three replications of volumetric moisture content (θ)—defined as the ratio of the volume of water in the soil to the total volume of soil ($m^3\,m^{-3}$)—were measured 15 cm below the soil surface. Soil moisture measurements were collected hourly using ECH_2O probes and Em50 data loggers (Decagon Devices, Inc., Pullman, WA). A single weather station (model 900ET, Spectrum Technologies, Inc., Plainfield, IL) was installed in the center of each site to collect hourly temperature and precipitation measurements 1 m above ground.

Soil was sampled where soil moisture probes were installed in order to correct and improve *in situ* soil moisture data (Starr and Paltineanu, 2002; Cobos, 2007). Raw sensor data from laboratory measurements were plotted against measured θ to generate soil-specific calibration equations. Raw data collected from the field were then inserted into each respective calibration equation for final, corrected θ values. The accuracy for each probe type with calibration is $\pm 0.02\,m^3\,m^{-3}$ (Decagon Devices, Inc., Pullman, WA).

At both sites, initial seedling height (vertical distance from ground-line to terminal leader tip) and root-collar diameter (RCD; diameter of main stem approximately 1 cm above ground-line) were measured one to two weeks after outplanting (24 April 2007 for F2; 16 May 2007 for CC); first season height, RCD, and survival were measured 14 and 24 October 2007 (CC and F2, respectively). The same variables were reassessed 14 and 15 October 2008 (F2 and CC, respectively). Fall measurements for 2007 and 2008 are defined as first- and second-year absolute growth (height and RCD), respectively. Height and RCD measurements were used to calculate seedling stem volume, which was approximated using the formula for an elliptical cone:

$$V = \frac{\pi d^2 h}{6}$$

where d is the stem diameter at ground level (cm), and h is shoot height (cm). Incremental growth was calculated for each season as the difference of spring and fall morphological measurements.

2.5. Statistical analysis

Data were analyzed using SAS (v 9.1.3, SAS Institute, Cary, NC, USA). The analysis of variance (using PROC MIXED) was performed for a randomized complete block design to identify differences in soil moisture and absolute and incremental growth differences among containers for seedling height, RCD, and stem volume. Statistical analyses were performed on soil moisture data from early spring (5 May 2007) and during the season's driest period (27 September 2007). When site by soil moisture interactions were detected, analyses were separated by location. For each site, three separate analyses were done for post planting (spring, 2007), first growing season (fall, 2007), and second growing season (fall, 2008). To correct for experiment-wise error rates, multiple comparisons among container types were calculated using Tukey's mean separation test.

Regression analyses were performed to determine which initial seedling characteristics (height, RCD and stem volume), container volume (60, 80, 90, 105, 120, and 166 cm^3), or any combination of seedling characteristics and container volume offered the best prediction on subsequent first- and second-year seedling growth. Analyses plotted container volume and spring morphological measurements (independent variables) against individual corresponding first and second season morphological measurements (dependent variables). The full model included container volume, seedling morphological characteristics, and the two-way interactions for each variable (regression model: $y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_1 x_2 + \beta_6 x_1 x_3 + \beta_7 x_1 x_4 + \beta_8 x_2 x_3 + \beta_9 x_3 x_4 + \varepsilon$). The Akaike Information Criterion (AIC; Akaike, 1974) model selection procedure was then used to select the final model (Burnham and Anderson, 2002); the use of AIC best explained the data with a minimum of free parameters (independent variables) and did so without overfitting. When assumptions for equal variances and normality were not met, data were transformed to meet the required assumptions for analysis (noted in tables and figures where applicable). All results were tested at a significance level of $\alpha = 0.05$.

3. Results

3.1. Soil moisture

Soil moisture analysis between F2 and CC indicated a significant site × date interaction ($P = 0.0038$). In general, soil moisture conditions were similar between sites soon after planting (5 May 2007) but they became significantly drier for CC during the peak of the drought season. Separate site analyses indicated, as expected, that each site had significantly different soil moisture contents from early spring to the peak of the drought ($P = 0.0415$, $P = 0.0002$ for F2 and CC, respectively).

3.2. Faeber II: survival, growth, and site conditions

The Faeber II site provided mesic growing conditions that were conducive to high survival and absolute growth. Seedling survival exceeded 99% and growth was rapid after two growing seasons. First growing season absolute height, RCD, and stem volume increased (65, 118, and 702%, respectively) across all container types; second season increases were similar (98, 108, and 781%, respectively). Container type significantly affected absolute height and RCD after the first and second growing seasons ($P \leq 0.0002$; Fig. 1A and B). In general, larger container volumes yielded taller seedlings after two growing seasons. Differences in RCD were, however, less distinct. The largest and smallest mean RCDs tracked the largest and smallest containers throughout the two seasons, while the remaining container types had similar means. Accordingly, because stem volumes were calculated using height and RCDs, mean differences among container types (significant at $P \leq 0.0001$) tracked those of both height and RCD but show larger amplification in the difference between the smallest and largest volume containers; this is especially evident at the end of the second growing season (Fig. 1C).

On average, second season incremental growth increased 147, 100, and 794% for height, RCD, and stem volume, respectively (Fig. 1D–F). Although mean incremental height growth differences were observed among container types after the first growing season ($P < 0.0001$), the differences were no longer apparent after year two ($P = 0.16$). Conversely, mean incremental RCD growth showed no differences after one season ($P = 0.48$), while a second season of growth yielded differences between the largest and smallest container types ($P = 0.007$). Mean incremental stem volume growth was different among container types for each growing season ($P < 0.0001$) and generally increased with container volume.

Temperature, precipitation, and soil moisture data were collected from mid-April through late October 2007. Total growing season precipitation measured 237 mm, and with the exception of a large rainfall event occurring in late July (18 mm), most of the precipitation fell before July and after September (Fig. 2A). Volumetric soil moisture content (θ) was highest in early June and lowest in late September. Mean daily temperatures averaged 14.5 °C from mid April to mid October with a low of −3.6 °C (4 April 2007) and a high of 37.9 °C (5 July 2007; Fig. 2B).

3.3. Coyote Creek: survival, growth, and site conditions

At CC, survival was lower and growth was slower than at F2. Survival averaged 85% after the first growing season and 83% after the second, with no significant differences or trends among container types for either year ($P = 0.75$ and $P = 0.94$, respectively). Absolute height, RCD, and stem volume increased 46, 36, and 182%, respectively, after the first growing season; second-season totals for the same variables were similar, at 40, 39, and 210%, respectively (Fig. 3A–C). Container type significantly affected height, RCD, and stem volume for each measurement period ($P \leq 0.0001$). Absolute height generally increased with container volume at the end of the first growing season, but by the end of the growing season, most container types yielded seedlings with similar height, except for the largest and smallest container volumes (Fig. 3A). Seedlings grown in containers configured at low density (80, 105, 166 containers; see Table 1) tended to have larger RCDs throughout the measurement period (Fig. 3B). Stem volume was significantly affected by container type for each measurement period and became increasingly variable by the final measurement.

Second-season, mean incremental growth measurements increased 25, 46, and 220% for height, RCD, and stem volume, respectively (Fig. 3D–F). Incremental height growth was significantly different among container types for each growing season ($P \leq 0.002$), although no discernable trend with container volume was observed. The largest incremental height growth increase was observed by the second largest container in year two (C80). Similar results were seen with incremental RCD and stem volume. Differences were detected among container types for each growing season ($P \leq 0.0001$), but the largest percentage increases were observed in C166 and C80 container types (Fig. 3E and F). For RCD and stem volume growth, the smallest container exhibited the smallest amount of growth; however, for first and second year height growth, the C90 and C120 containers grew the least.

Temperature, precipitation, and soil moisture data were collected from early May through mid-October 2007. Total precipitation measured 135 mm and mostly occurred before July and after late September; one large precipitation event occurred during mid-July and measured 10 mm (Fig. 2C and D). Soil moisture at 15 cm decreased from 0.34 to 0.08 $m^3\ m^{-3}$ from early May (shortly after planting) to the end of September before recovering to 0.25 $m^3\ m^{-3}$ (after several precipitation events; Fig. 2C). Mean temperature was 16.2 °C with a low of 0.1 °C (4 May, 29 September, and 4 October 2007) and a high of 35.8 °C (12 July 2007; Fig. 2D).

3.4. Predicting outplanting performance

Initial height, RCD, stem volume, and container volume were investigated as simple predictor variables for one- and two-year absolute field growth measures. All regression analyses, for both sites, showed positive relationships and were significant ($P \leq 0.001$). In most cases, more of the variation (coefficient of determination, R^2) was explained in the first year than in the second year, although nearly all values tended to be low (Table 3). For both sites, initial outplanting height alone explained 66 and 70% of the variation for first-year absolute height growth. AIC analysis showed that adding more parameters to the model increased predictive power, but only minimally when compared to the best single parameter models (data not shown). The greatest gain in multi-parameter modeling came from using initial stem volume and height to predict first-year absolute height growth at the F2 site. In this case, a gain of 8% was observed boosting the predictive power from 66 to 74%. All second-year absolute height models yielded low R^2 values for both sites ($R^2 \leq 0.33$). At F2, no suitable RCD prediction models were observed with single- or multi-parameter models ($R^2 \leq 0.08$). Results for CC were similar, although R^2 values were higher ($R^2 \leq 0.38$). According to AIC analyses, the best first-year stem volume predictions came from single-parameter models; initial stem volume explained 54% of the variability at the CC site, while only 28% was explained at the F2 site. Second-

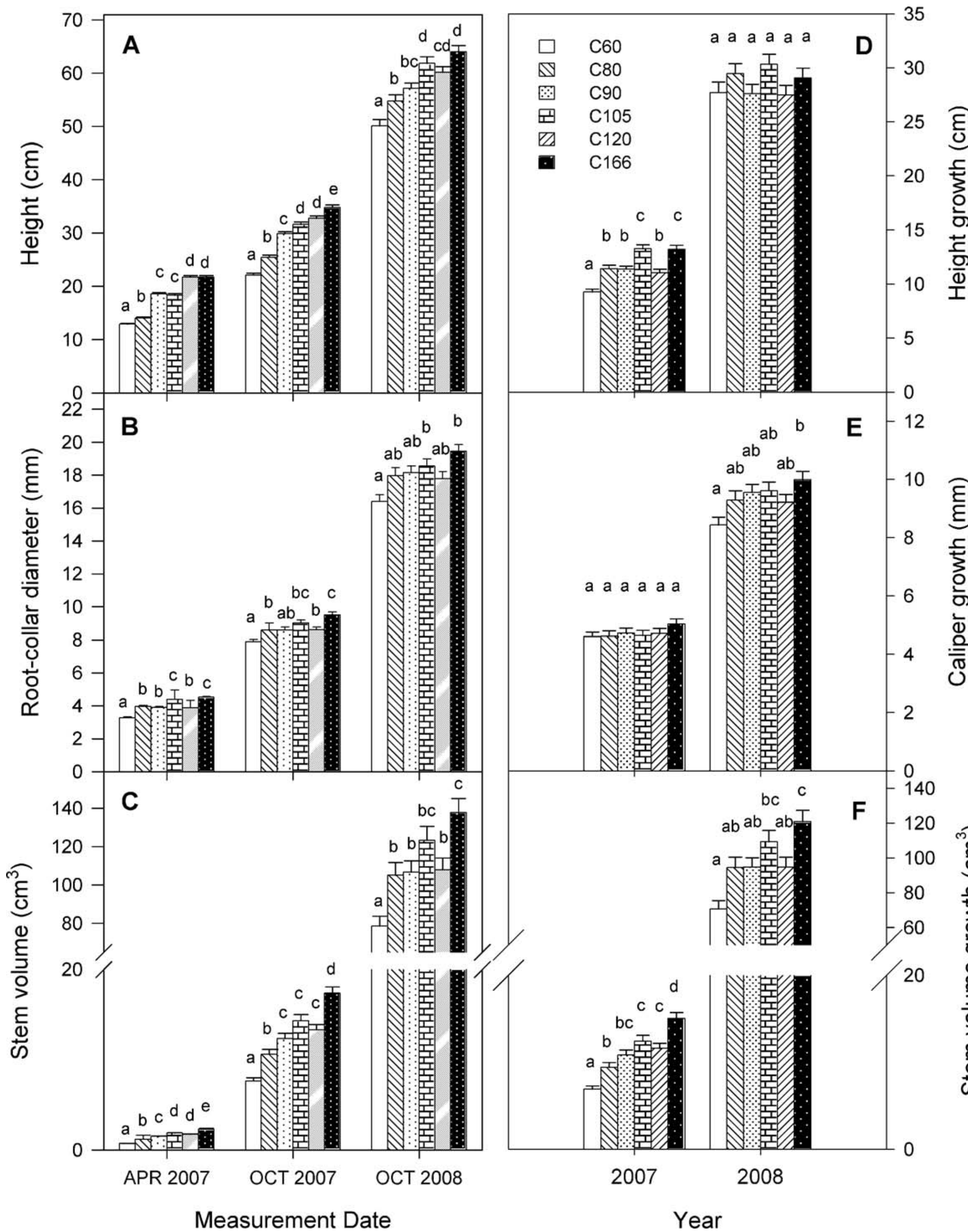

Fig. 1. (A–C) Absolute and incremental seasonal growth of *Pinus ponderosa* seedlings on a mesic site in Idaho (Faeber II). Morphological measurements were done after planting and after first and second growing seasons (n = 476–600). (D–F) Incremental growth for height, root-collar diameter, and stem volume were calculated for the first growing season and second year's growth; the first growing season (2007) was 6.25 months (n = 477–507). Bars show least square means + SE. For each measurement period, bars with the same letter are not significantly different for each measurement date, Tukey adjusted (P < 0.05). Stem volume was log transformed for spring and fall 2007 analyses and for 2007 growth. Container volumes were 60, 80, 90, 105, 120 and 166 cm^3.

year models explained 27% and 10% of the variability at CC and F2, respectively.

4. Discussion

Although the literature includes numerous studies that examine the effect of stocktype choice on outplanting survival and growth, most fail to include any information about nursery culturing methods related to specific container types (e.g. Amidon et al., 1982; Paterson, 1997; Hunt, 2002; South et al., 2005; Dominguez-Lerena et al., 2006). This major flaw of most container type selection studies (Burdett, 1990) can be avoided by growing seedlings with container-specific fertilizer and irrigation regimes (Pinto et al., 2011). As (Pinto, 2005) demonstrated in the production of *P. ponderosa*, seedlings produced this way have greater uniformity in foliar nitrogen status and water use efficiency than seedlings of different container volumes grown under a single culture regime. This study made use of seedlings that were cultured specifically to

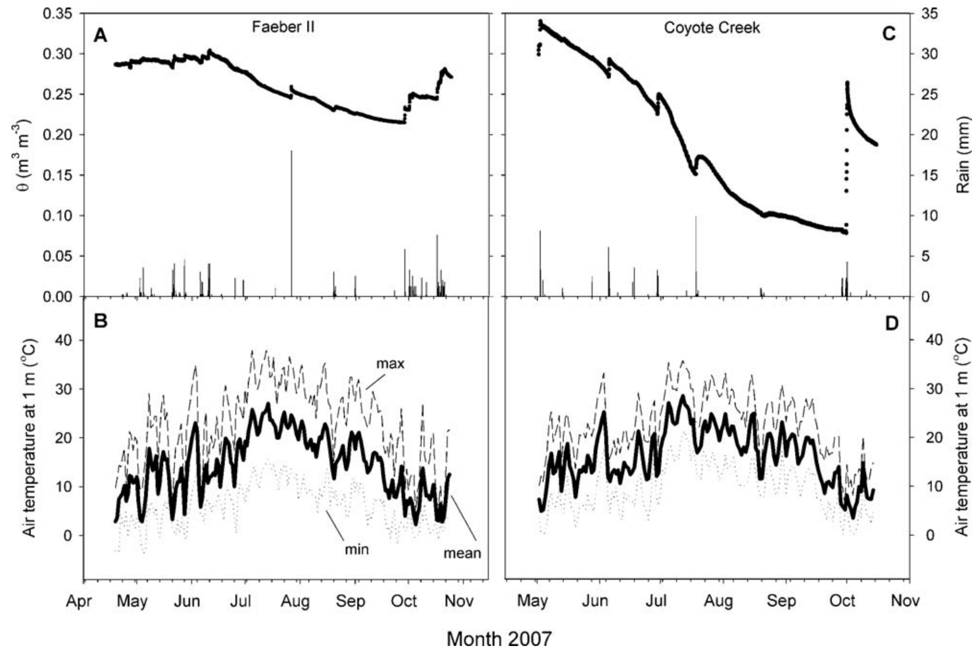

Fig. 2. Site conditions for reforestation planting units in Idaho (Faeber II; A and B) and Washington (Coyote Creek; C and D). Variables measured include θ (soil volumetric water content 15 cm below the soil surface), precipitation (represented by bars; A and C), and daily air temperatures (mean, maximum, and minimum at 1 m; B and D).

their container type to reduce the physiological variation among the seedling types and thereby yield a truer reflection of container volume influence on outplanting performance.

Few studies investigate the difference in stocktype growth in differing site conditions (Amidon et al., 1982; Racey et al., 1989; South et al., 2005). Because water availability is one of the most important variables that contribute to successful establishment and growth of seedlings (Burdett, 1990; Margolis and Brand, 1990), our study identified and used two sites that differed in this characteristic. Our objective was not, however, to statistically compare the two sites as they were expected to be different in soil texture, soil nutrition, and precipitation but rather to quantify soil moisture differences and analyze the differences in container seedling growth for these sites as two independent case-studies. This is of additional importance because variability in seedling growth has been observed among different seed sources of ponderosa pine (McMillin and Wagner, 1995; Cregg et al., 2000; Cregg and Zhang, 2001). Our use of a locally adapted seed source at each site ensured potential optimal seedling growth for the specific conditions at each site.

Data collected from F2 and CC indicate the sites were distinctly different in their precipitation and soil moisture regimes (Fig. 2A and C). F2 had fairly mesic conditions as a result of periodic precipitation and a lack of competing vegetation from site preparation, which kept θ high. Conversely, CC had more xeric conditions because of higher mean temperature, lower precipitation inputs, and no site preparation. The presence of transpiring mature trees, shrubs, and grasses in addition to well-drained, loamy-skeletal soils also likely contributed to soil moisture loss observed at the CC site (Warren et al., 2005). The large soil moisture reductions and reduced precipitation inputs observed at CC are typical of those seen in coniferous forests of the Pacific Northwest and Intermountain West, including the seasonal drought from July through the end of September. Despite the differences in θ between F2 and CC, the seedlings at both sites were planted during a period of favorable soil moisture (Rietveld, 1989). With the exception of a short warming event at the first part of June, early season site conditions remained favorable for establishment until the onset of the expected seasonal drought in July.

Table 3
Coefficient of determination (R^2) for simple linear regression models of *P. ponderosa* seedlings for two field seasons (n = 530–600). Root-collar diameter (RCD) is the diameter of the main seedling stem approximately 1 cm above ground-line.

Independent variables	Dependent variables (R^2)[a]					
Spring 2007	Fall 2007			Fall 2008		
	Height	RCD	Stem volume[b]	Height	RCD	Stem volume[b]
Faeber II						
Height	0.66***	0.02**	0.20***	0.17***	0.04***	0.07***
RCD	0.28***	0.08***	0.19***	0.12***	0.03***	0.06***
Stem volume[b]	0.63***	0.07***	0.28***	0.21***	0.05***	0.10***
Container volume	0.47***	0.05***	0.20***	0.13***	0.03***	0.06***
Coyote Creek						
Height	0.70***	0.04***	0.29***	0.27***	0.03**	0.27***
RCD	0.06***	0.34***	0.32***	0.07***	0.14***	0.07***
Stem volume[b]	0.46***	0.28***	0.54***	0.26***	0.14***	0.27***
Container volume	0.36***	0.07***	0.23***	0.16***	0.05***	0.16***

[a] Regression significance: ** P < 0.001, *** P < 0.0001. Regression slopes were positive and linear.
[b] Stem volumes were log transformed.

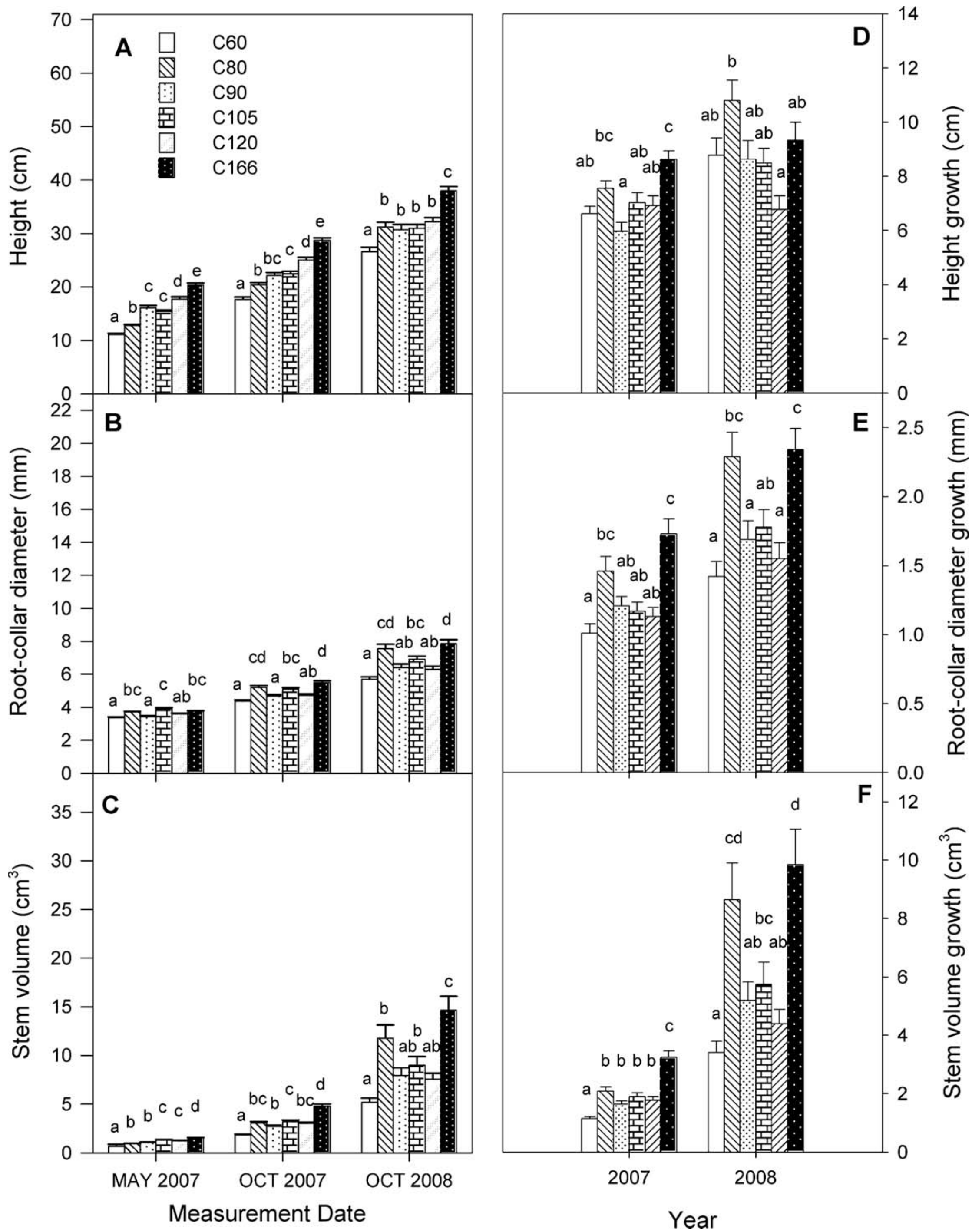

Fig. 3. (A–C) Absolute and incremental growth measurements of *P. ponderosa* seedlings on a xeric site in Washington (Coyote Creek). Morphological measurements were done after planting and after first and second growing seasons (n = 476–600). (D–F) Incremental growth for height, root-collar diameter, and stem volume were calculated for the first growing season and second year's growth; the first growing season (2007) was 5.5 months (n = 477–507). Bars show least square means + SE (n = 477–507). For each measurement period, bars with the same letter are not significantly different for each date, Tukey adjusted (P < 0.05). Stem volume was log transformed for spring and fall 2007 analyses and for 2007 and 2008 growth. Stem volume was square root transformed for fall 2008 analysis. Container volumes were 60, 80, 90, 105, 120 and 166 cm^3.

On the mesic F2 site, initial seedling characteristics obtained at the nursery—in this case a true reflection of container type because of container specific culture—were poor predictors of long-term absolute growth (Table 3). Seedlings had little difficulty establishing and growing because the combination of ash cap soils, exemplary site preparation, and periodic rain inputs—55 mm during the typical drought period—kept soil moisture conditions high and allowed the seedlings to grow vigorously. While seedling morphology remained stratified for absolute height, RCD, and stem volume, with seedling size increasing with container volume, incremental height growth appeared to equilibrate among container types (Fig. 1D). These height results are contrary to two-year results observed for bareroot ponderosa pine and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) seedlings by (Rose et al., 1991a,b). Two factors may explain the differences between these studies and our results. First, variability in seedling size increased with each season making differences among container types difficult to distinguish. Secondly, seedlings that are well established within the soil profile are faced only with limitations in exploiting their environment and are less dependent on the attributes provide by initial nursery growth (Burdett et al., 1984; Nambiar and Sands, 1993). In this case, second season incremental height growth may have been more limited by the presence of vegetative competition (in the form of weeds) and the compound effects of limited soil moisture during the shoot elongation phase—typically April through July (Newton and Preest, 1988). However, RCD and stem volume, normally not limited to growth during the shoot elongation phase, were allowed further growth under the resumption of favorable growth conditions when precipitation resumed in the fall.

CC seedlings experienced soil moisture depletion, low precipitation inputs, high temperatures, and competing vegetation while trying to establish and grow after planting—all of which are known to reduce seedling growth (Larson, 1967; Rose et al., 1993; Anderson et al., 2001; Zhang et al., 1997). Under these difficult establishment conditions, differences among container types would be expected, as seen by (Amidon et al., 1982) with longleaf pine (*Pinus palustris*) in drought conditions. After the first growing season, container-type differences in absolute height, RCD, and stem volume remained relatively unchanged from planting. The second growing season illustrates, however, two interesting trends. Most of the mid-sized containers (90, 105, and 120) became similar in absolute height, RCD, and volume, while the 80 container caught up in height and exceeded them in RCD and volume (Fig. 3A–C). Our seedlings were grown to have similar physiological status, so observing seedlings grown in smaller volume containers unexpectantly outperform those grown in larger volume containers under relatively dry soil conditions may show the benefit of growing seedlings with container-specific regimes for stocktype trials. In one study, small and medium containers showed better performance than the largest stocktype under differing watering regimes, but results were confounded by reduced seedling quality (Lamhamedi et al., 1996).

One- and two-year incremental growth results were clear in the differences among container types (Fig. 3D–F), but they did not show any consistent differences by container volume. Because the site was not prepared with herbicide or burning, it may be that variation in planting microsites contributed to the large variation in growth (Gray and Spies, 1997). However, the large number of seedlings used and their distribution over five blocks should have decreased some of this variation. Despite this, these results, in combination with uniform culturing techniques, show the potential for small container seedlings to outperform larger container seedlings.

At the CC site, initial seedling height and stem volume offered the best predictive power for first year absolute seedling growth. RCD and container volume R^2 values were too low to offer any prediction of subsequent CC seedling growth, especially after the first year. The long-term predictive power of initial seedling morphology we observed are inconsistent with those reported for white spruce (*Picea glauca*; Mullin and Christl, 1981b), eastern white pine (*Pinus strobus*; Mullin and Christl, 1981a), or loblolly pine (*Pinus taeda*; McGilvray and Barnett, 1982), where initial seedling morphological characteristics correlated well with seedling growth for more than three years after outplanting. The best predictor values within each variable in our study, however, were higher than those seen at F2, especially after the second season's growth. The harsh site and slower growth of CC seedlings may be responsible. Because CC seedlings grew considerably less, the attributes attained in the nursery remained—small seedlings remained small and large seedlings remained large. For either site, adding more parameters to the regression model proved to be ineffective; predictive gains were small (<2%) and only achieved by adding only one or two parameters. This is probably a reflection of our poor initial predictive power.

This study offers unique perspective in seedling stocktype selection because it used differing stocktypes cultured to their specific container type and outplanted on divergent sites. By planting trees of common physiology, but different size, on different sites, we obtained a clearer understanding of a container type's true gains in performance in the field. As seen at F2, when quality seedlings are planted carefully, at the correct time, and under favorable (mesic) growing conditions, container selection is less important for seedling survival than it might be for overall growth. For the CC site, with more potential site limiting factors, container selection appears to be more important (Landis and Dumroese, 2006).

A larger seedling with a longer root plug might have the greatest total growth, and may do better in dry conditions (Chirino et al., 2008), but the risk of improper planting might offset any gains (Robert and Lindgren, 2006). Deep planting—placing the cotyledon scar below the soil surface—a shorter container of similar volume having equal or better growth potential might prove just as beneficial (Stroempl, 1990). Although unlikely because of our efforts to minimize the "planter effect" in this study, it may be that the long, flexible root system of C120 seedlings planted on the rockier CC site may not have been planted as well as the firm, stout, easily planted root system of the C80. Studies have shown that deep planting bareroot of seedlings increases survival and shows no differences in growth (South and Mitchell, 1999; VanderSchaaf and South, 2003).

Using simple morphological variables to predict absolute growth remains difficult and inconclusive. Simple, standard grading criteria fail to explain large proportions of variation in seedling growth in the field. However, differences in absolute growth on mesic versus drier sites illustrate how morphological traits acquired in the nursery might persist over time and how sites might influence predictability. Puttonen (1997) suggests one test cannot do it all, but provides a matrix in which morphological measurements alone provide the best test (combining research, operational feasibility, timeliness, and cost). With this in mind, research that ties the understanding of seedling physiology, ecophysiology, and environmental biophysics to morphology will provide the best seedling growth and prediction models relating to field performance.

Acknowledgements

Potlatch Corporation and the Confederated Tribes of the Colville Indian Reservation donated seed, planting sites, and planting help for the project. Ann Abbott and Scott Baggett provided statistical guidance. Funding support was provided by the USDA Forest Service. We are thankful to the editor and the anonymous reviewers for their constructive comments on a previous version of this manuscript.

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