Effects of Plant Date and Nursery Dormancy Induction on Field Performance of Douglas-Fir Seedlings in Western Oregon

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Abstract

The effects of nursery dormancy-induction treatments and planting date on growth and survival of Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* [Mirb.] Franco) seedlings were tested on six sites in western Oregon, selected across a geographic moisture gradient. Seedlings were outplanted on eight dates between mid-August 2005 and mid-January 2006 and four dates between August 2006 and January 2007. Two dormancy-induction treatments were tested: shortened daylength and moisture stress. Seedlings exposed to a shortened daylength had earlier bud primordia production and less lammas growth than the moisture-stressed seedlings. Few differences existed in seedling height, root-collar diameter, height:root-collar diameter, and survival between the two dormancy-induction treatments 3 years after outplanting. Plant date had a strong effect on seedling growth and survival. Seedlings planted in early fall, when roots were still elongating, were up to 39 percent taller than winter-planted seedlings 3 years after outplanting. Survival was lowest for trees planted in August, particularly at the two driest sites. If timed correctly to avoid late summer drought, fall planting is a viable alternative to winter planting in western Oregon.

Introduction

Fall planting has been perceived to be a risky, but viable alternative to the normal winter and early spring planting season in western Oregon. Because fall weather is sometimes hot and droughty, planting in this region most commonly occurs between mid-December and March, after the cold rains have arrived and seedlings are most stress resistant. At the beginning of this planting period, air and soil temperatures are cold and daylength is at a minimum. As the planting season progresses, soils begin to warm and daylength increases; trees planted too late in the spring are unable to complete primary growth before soil moisture deficits and high evaporative demands occur (Hunt 2004).

Interest is increasing to extend the operational planting window for Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* [Mirb.] Franco) seedlings planted on the west side of the Oregon Cascade Range to include the fall. Fall planting allows access to high elevation sites before winter snows accumulate and block roads and reduces the need for costly long-term cold storage (Adams and others 1991). The rationale behind fall planting is that seedlings are phenologically poised for rapid establishment when soil temperatures are still in the optimum range (10 to 20 °C [50 to 68 °F]) for root elongation (Lopushinsky and Max 1990) but shoot growth has ceased. Seedlings are, therefore, likely to establish root-to-soil contact immediately after planting. In addition, daylength is still long enough to allow continued photosynthesis, thereby increasing stored carbohydrates available for root growth in spring (van den Driessche 1987). This early establishment allows for two cycles of field root growth before initiation of shoot growth the following spring, resulting in increased growth, survival, and competitive ability relative to noncrop vegetation.

Some organizations have attempted operational fall planting with mixed success. The timing of fall planting has always presented a significant risk to seedling survival. Early fall planting in dry soils with no assurance of forthcoming rain can be an expensive gamble. Planting early in the fall also means risking whether the seedlings possess the proper morphological and physiological conditioning to survive. Seedling dormancy status (quiescence, in which dormancy is imposed by environment, or rest, when a shoot will not elongate even under favorable environments) is particularly important, not only because it is directly related to the stress resistance of the seedlings, but also because it affects growth and survival after outplanting (Lavender 1985). Planting success benefits from matching the plant growth cycle with the growing season (Turner and Mitchell 2003). Key concerns include knowing when it is safe to plant in the fall, determining the optimal physiological condition of seedlings, and understanding how to best match seedlings with the site conditions to ensure seedling survival into the following spring.

Beginning around July, most nurseries in western Oregon and Washington use moisture stress and changes in fertilization to induce terminal bud dormancy in Douglas-fir seedlings. Reducing water and shifting nutrients are techniques used to mimic natural Mediterranean seasonal changes that cause seedlings to set a terminal bud and enter into quiescence (Lavender 1990). After this stage of dormancy has been achieved, a new fertilization regime is resumed at a reduced rate to encourage stem diameter and root growth and to increase whole plant nutrition to move the seedlings into rest (Lavender and Cleary 1974). Water and nutrition must be carefully monitored in the nursery from midsummer into fall to prevent lammas growth (fall bud break) from occurring (Hahn 1984).

Canadian nurseries at higher latitude sites have successfully used photoperiod manipulation using artificially induced short-day treatments to achieve the quiescent dormant state in container seedlings (Hawkins and Draper 1991). Nursery managers refer to this manipulation as "blackout" because greenhouse interiors or seedling benches are covered with black cloth or curtains for up to 16 hours to simulate short days. During long nights (or induced periods of darkness), phytochrome is inactivated and bud formation is promoted (Colombo and others 2001).

The evidence concerning the pros and cons of fall planting is largely anecdotal; therefore, this study was initiated to quantify Douglas-fir container seedling performance as influenced by planting date, nursery dormancy-induction treatment, and environmental conditions. The null hypotheses were that the dormancy-induction method is unrelated to subsequent growth and survival and that no relationship exists between the planting date and subsequent growth and survival rates.

Materials and Methods

Planting Sites and Planting Stock

Douglas-fir seedlings were grown at the PRT (Pacific Regeneration Technologies, Inc.) nursery in Hubbard, OR. Seedlings for the moderate moisture sites (described in the following section) were grown in 615A Styroblock® containers (213 cavities per m^2, 336 ml/cavity) and those for the low- and high-moisture sites were grown in 515A Styroblock® containers (284 cavities per m^2, 250 ml/cavity). The growing medium was 100 percent Sphagnum peat moss. Before each plant date, seedlings were hand lifted and graded according to contract specifications (615A stocktype: 30 to 50 cm [12 to 20 in] height and a minimum 3.5 mm [0.14 in] root-collar diameter [RCD]; 515A stocktype: 18 to 45 cm [7 to 18 in] height and a minimum of 3.2 mm [0.13 in] RCD). Any seedlings with deformities or undesirable traits were excluded from the study.

Six western Oregon sites were selected across a geographic moisture gradient to maximize the climatic variability among sites (table 1). Operational site preparation (e.g., aerial herbicide spraying and/or slash piling) was carried out as required for each site. Three sites were planted in the 2005–06 planting season (Series 1) and three were planted in the 2006–07 planting season (Series 2). Mean annual precipitation differs among the sites, but seasonal patterns are similar to low-precipitation inputs during summer months and high-precipitation inputs through fall and winter months.

A randomized complete block design was used at each study site, with five blocks per site (with the exception of Southern Comfort, which had only four blocks because of space limitations). Each block consisted of 16 (Series 1) or 8 (Series 2) factorial treatment plots (plant dates times two dormancy-induction treatments). Each treatment plot consisted of 20 to 25 seedlings planted at a 3 m by 3 m (10 ft by 10 ft) spacing. In addition, 10 seedlings were interplanted within each plot (Series 1 only) and designated for excavation to assess the first season's fall and spring root development.

At the Series 1 dry site, Pedee Guppy 2005, three of the five blocks were situated on an extremely dry sandy slope and the other two were located in a flat area with seasonal drainage. At the Series 1 moderate site, South Red Fir, one block was on a steep slope with a condensed block design because of space constraints. The Series 1 wet site, Southern Comfort, is a productive site with well-drained soils and high organic matter content.

The Series 2 dry site, Pedee Guppy 2006, was similar to, and located near, the Series 1 Pedee Guppy 2005 site. All blocks at Pedee Guppy 2006 were laid out on a steep sandy slope. The Series 2 moderate site, Mid Polly's View, was a productive site located on well-drained loamy soils with high organic matter. The Series 2 wet site, Mohican, was situated on flat, poorly drained ground with heavy clay soil. This site had significant standing water in the winter, and stayed wet into the spring. An elk herd lived near this site; not only was browsing a problem, but the herd also used the site as a bedding area.

Dormancy-Induction Treatment

All seedlings were grown under identical water and nutrient regimes until the initiation of dormancy-induction treatments, at which point seedlings were randomly assigned to either a short-day (SD) treatment or a moisture-stress (MS) treatment.

Table 1. Site attributes for Series 1 and Series 2.

Relative site moisture	Series 1: 2005–06 planting year		
	Dry	**Moderate**	**Wet**
Site	*Pedee Guppy 2005*	*South Red Fir*	*Southern Comfort*
Latitude	44°47’20.03”N	44°37’25.27”N	44°47’58.44”N
Longitude	123°27’52.62”W	123°34’46.44”W	123°41’55.76”W
Distance from coast (km)	48	38	29
Annual precipitation (cm)	100–150	175–230	315–355
Elevation (m)	270	230	345
Aspect	SE	N	W
Site index (m)*	32	39	38
Site preparation	aerial spray	piled, spray	piled
Stock type†	515A	615A	515A
Seed source elevation (m)	122–640	152–823	122–640
Seed source latitude	44°45’N–45°25’N	44°20’N–44°45’N	44°45’N–45°25’N
Relative site moisture	**Series 2: 2006–07 planting year**		
	Dry	**Moderate**	**Wet**
Site	*Pedee Guppy 2006*	*Mid Polly’s View*	*Mohican*
Latitude	44°47’12.75”N	44°36’20.86”N	44°49’40.68”N
Longitude	123°28’7.09”W	123°32’57.24”W	123°37’39.42”W
Distance from coast (km)	48	42	34
Annual precipitation (cm)	100–150	175–230	315–355
Elevation (m)	300	300	360
Aspect	SW	N	flat
Site index (m)*	32	39	38
Site preparation	—	piled, spray	aerial spray
Stock type†	515A	615A	515A
Seed source elevation (m)	122–640	152–823	122–640
Seed source latitude	44°45’N–45°25’N	44°20’N–44°45’N	44°45’N–45°25’N

* King’s 50-year site index (King 1966).

† 515A = Styroblock® container 515A, 250 cm^3 root volume, 60 cavities/block; 615A = Styroblock® container 615A, 336 cm^3 root volume, 45 cavities/block.

Dormancy induction was initiated in late June for seedlings scheduled for August and September plant dates, and in mid-July for seedlings scheduled for outplanting at later dates. Seedlings designated for the SD treatment were leached twice with water to remove media nutrients and then subjected to 14-hour nightlength for 21 days by covering with black cloth. Seedlings were then kept in alternating periods of 7 days with ambient photoperiod and 7 days with 14-hour nightlength until early September. Seedlings designated for the MS treatment were exposed to ambient photoperiods and leached twice with water to remove media nutrients, then allowed to dry to 65 to 70 percent of field capacity (measured gravimetrically). Seedlings of both treatments were then fertilized with Scotts Peters Conifer Finisher© (4-25-35 plus micronutrients) at 50 ppm N, and were irrigated only when crop wilting was visible.

Planting Date

Seedlings were outplanted from late summer through early winter (table 2). Dates were selected to encompass expected environmental thresholds for planting success. In the 2005–2006 season (Series 1), eight plant dates were spaced at 3-week intervals between August and January. Initial results showed little difference in performance among seedlings planted after mid-October; therefore, only four plant dates were included in the 2006–2007 season (Series 2). Plastic mesh Vexar™ tubing (15 cm by 90 cm [6 in by 36 in]) was installed at the time of planting to protect seedlings from animal browse.

Table 2. Planting dates for each planting series. For all dates, the moderate site was planted on the first day and the other two (dry and wet) sites were planted on the second day.

Series 1: 2005–06 planting year		Series 2: 2006–07 planting year	
1	*August 16 and 17*	*1*	*August 22 and 23*
2	*September 7 and 8*	*2*	*September 12 and 13*
3	*September 27 and 28*	*3*	*October 3 and 4*
4	*October 18 and 19*		
5	*November 8 and 9*		
6	*November 29 and 30*		
7	*December 20 and 21*		
8	*January 10 and 11*	*8*	*January 9 and 23*

Measurements

Bud development was evaluated on a random sample of 10 seedlings from each dormancy-induction treatment on each plant date in Series 1. Shoot tips were dissected according to the procedures described by Templeton and others (1993). The excised embryonic shoot was examined under a dissecting scope and the number of short columns and rows were counted and then multiplied together to estimate the total number of needle primordia. Buds were preserved in 100 percent ethyl alcohol and later photographed using a scanning electron microscope.

HOBO microstations (Onset Computer Corporation, Bourne, MA) were installed at each site to monitor air temperature (1.1 m [3.6 ft] above the ground), relative humidity, precipitation, soil temperature at 15-cm (6-in) depth, and soil moisture at 10- and 20-cm (4- and 8-in) depths (ECH_2O probes, Decagon Devices Inc., Pullman, WA, installed horizontally); the microstations logged measurements every 6 hours for 1 year after planting. Vapor pressure deficit was calculated according to the procedures of Murray (1967). Two soil samples, from a depth of 18 cm (7 in), were collected from each block on each planting date using a soil corer with slide hammer (101.29 cm^3 [6.2 in^3] core volume, AMS signature series, American Falls, ID). Samples were kept in zip-sealed plastic bags and weighed within 24 hours. Dry weights were determined after each soil sample was dried for 48 hours at 68 °C (154 °F). Soil samples provided metrics for bulk density and gravimetric water content in the root zone at the time of planting. Volumetric soil water content (θ) was then determined using the following formula:

$$\theta = (m_{wet} - m_{dry}) / V_b$$

Where:

m_{wet} and m_{dry} are the weight of the sample before and after drying, V_b is the volume of the cylinder. ECH_2O probe data at 20-cm depth were calibrated by linear regression for each site with the data collected from soil cores (Czarnomski and others 2005); the 10-cm (4-in) depth data was then adjusted according to its relative difference with the 20-cm (8-in) depth.

At each planting date, 20 seedlings were assessed for root growth potential (RGP). In addition, during Series 1, a sample of 60 seedlings from each dormancy-induction treatment was measured for cold hardiness using the procedures of Tanaka and others (1997). Incidence of lammas growth during the fall when seedlings were planted was recorded. In Series 1, a sample of interplanted seedlings was excavated and assessed for new root growth 3 weeks after planting, in April 2006 before bud break, and in November 2006 fallowing budset. Seedling height (ht), RCD, and survival were measured in the spring after planting, before budbreak, and again at the end of the first, second, and third growing seasons. In addition, ht:RCD (mm:mm) was calculated for each seedling.

Statistical Analyses

Data were tested and examined for normality. The plot survival percentages were arcsine-transformed before analysis (Zar 1984). Survival assessments were carried out using all plots, including those with high mortality.

For field growth traits, plot means were used in all analyses. Survival after 2006 was low in some plots from both Series 1 and Series 2. Therefore, all plots with lower than 40-percent survival rate (fewer than 10 live trees from the 25 tree plots) in a particular year were eliminated before further analyses, except for the first-year (2006) measurements in Series 1. At the dry Series 2 Pedee Guppy 2006 site, survival was so low at the August and October planting dates that they were not included in the analyses, leaving only the September and January planting dates.

A mixed-model approach was used for analyses (SAS® PROC MIXED version 9.2). Because sites were confounded with seedlot and stock type, only single-site analyses were carried out. The following general linear model was fitted to the data from each site:

$$[2]\ Y_{ijk} = \mu + D_i + T_j + DT_{ij} + B_k + \varepsilon_{(ij)k}$$

where Y_{ijk} is the observed plot mean response for the ith plant date and the jth dormancy treatment in the kth block; μ is the overall mean; D_i is the fixed effect of plant date; T_j is the fixed effect of dormancy treatment, DT_{ij} is the interaction between the ith plant date and jth dormancy treatment; B_k is the random effect of block; and $\varepsilon_{(ij)k}$ is the residual error. Because block interactions with either treatment or plant date were not significant, they were not included in the final model.

Tukey-Kramer multiple comparison tests of least squared means were carried out to examine both dormancy treatment and planting date differences. Contrasts were made to compare growth of seedlings planted before root growth cessation with those planted after presumed root growth cessation. For the purposes of these contrasts, November 1 was arbitrarily designated as a reasonable date when most roots within the planting region would stop growing.

Results

Overall Site Effects

Each series had one site with superior growth. In Series 1, the best height growth occurred on the wet, productive Southern Comfort site, despite the fact that the moderate South Red Fir site was planted with a larger seedling stock type (figure 1a).

In Series 2, the best growth occurred at the moderate Mid Polly's View site which had the most productive soil and was planted with the largest stock type.

Severe ungulate browsing occurred at two sites from Series 2. After 3 years in the field, elk had browsed 48 percent of the living trees at Mohican, and deer had browsed 42 percent of the live trees at Mid Polly's View. The fast-growing trees at the latter site were able to rapidly outgrow the reach of the deer, however, but growth at Mohican was severely affected by browsing.

The ht:RCD decreased at all sites during the first 3 years after planting (figure 1b). Lower ht:RCD are desirable; ideally, this ratio will be less than 70 in young plantations (Cole and Newton 1987). By the second year after planting, ht:RCD at all sites were less than this threshold. Survival was lowest at the dry site per series (figure 1c). The wet Series 2 site, Mohican, also had low survival.

Soil temperatures during the first year after planting followed typical seasonal patterns for the western Oregon climate with soil temperature dropping below the ideal temperature range for root growth by the first week of November (figure 2). Soil moisture levels and the amount of precipitation varied considerably by site and series, especially during the earliest plant dates (figure 3). Soil moisture contents during the winter were similar at all six sites (figure 3), but summer differences were evident and reflected the dry, moderate, and wet site moisture environments. In particular, the wet Series 2 Mohican site retained high soil moisture levels during the first summer after planting, and the dry Series 2 Pedee Guppy 2006 site experienced very low volumetric soil moisture water content in late summer through mid-October. During the summer months, soil moisture content at 10-cm (4-in) depth tended to be lower than at 20-cm (8-in) depth.

Dormancy-Induction Treatment

Buds from SD-treated seedlings in Series 1 produced more needle primordia earlier in the fall than those from the MS treatment (figure 4). By December, however, trees from the MS treatment had an equivalent number of primordia as those from the SD treatment, and terminal buds of both treatments were approximately the same average diameter. Cold hardiness (Series 1 only) followed typical seasonal development, but did not differ between dormancy-induction treatments despite the early differences in bud development (data not shown). RGP of SD-treated seedlings in Series 1 was significantly lower than MS-treated seedlings on the two September plant dates (data not shown). Very little lammas growth was

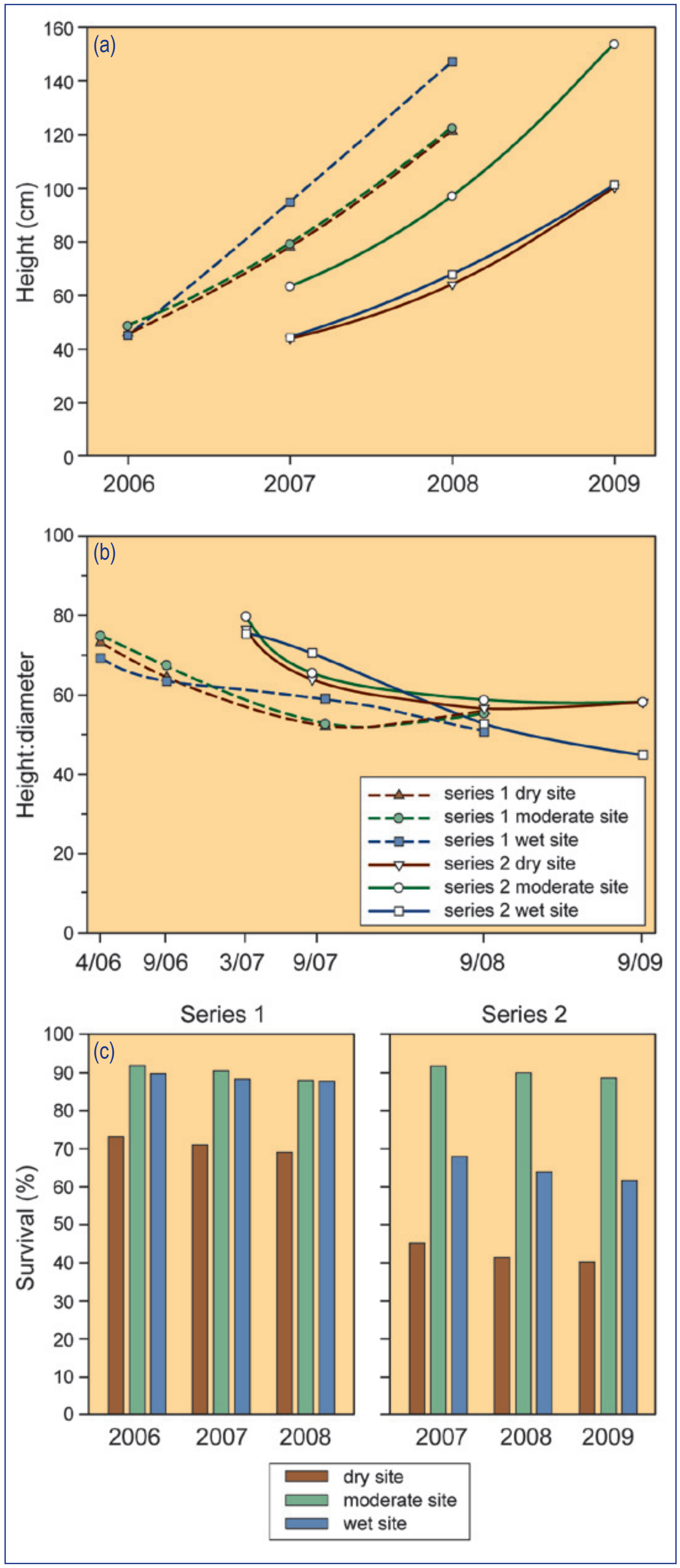

Figure 1. Overall mean height (a), height:diameter ratio (b), and survival (c) for the two series, where ▲ denotes the dry site, ● denotes the moderate site, and ■ denotes the wet site per series.

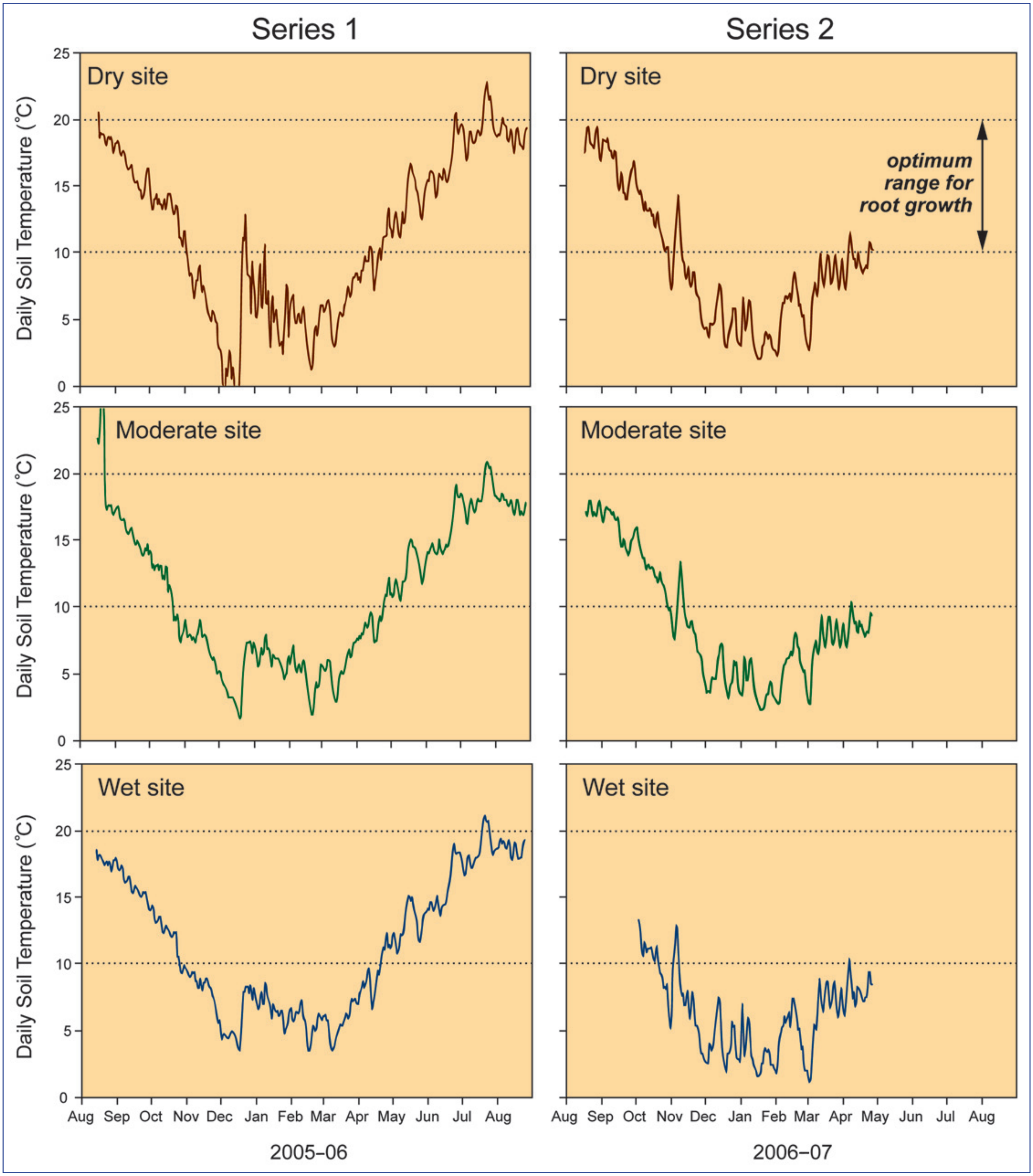

Figure 2. Average daily soil temperature at a 15-cm depth for each of the three sites planted in Series 1 and Series 2.

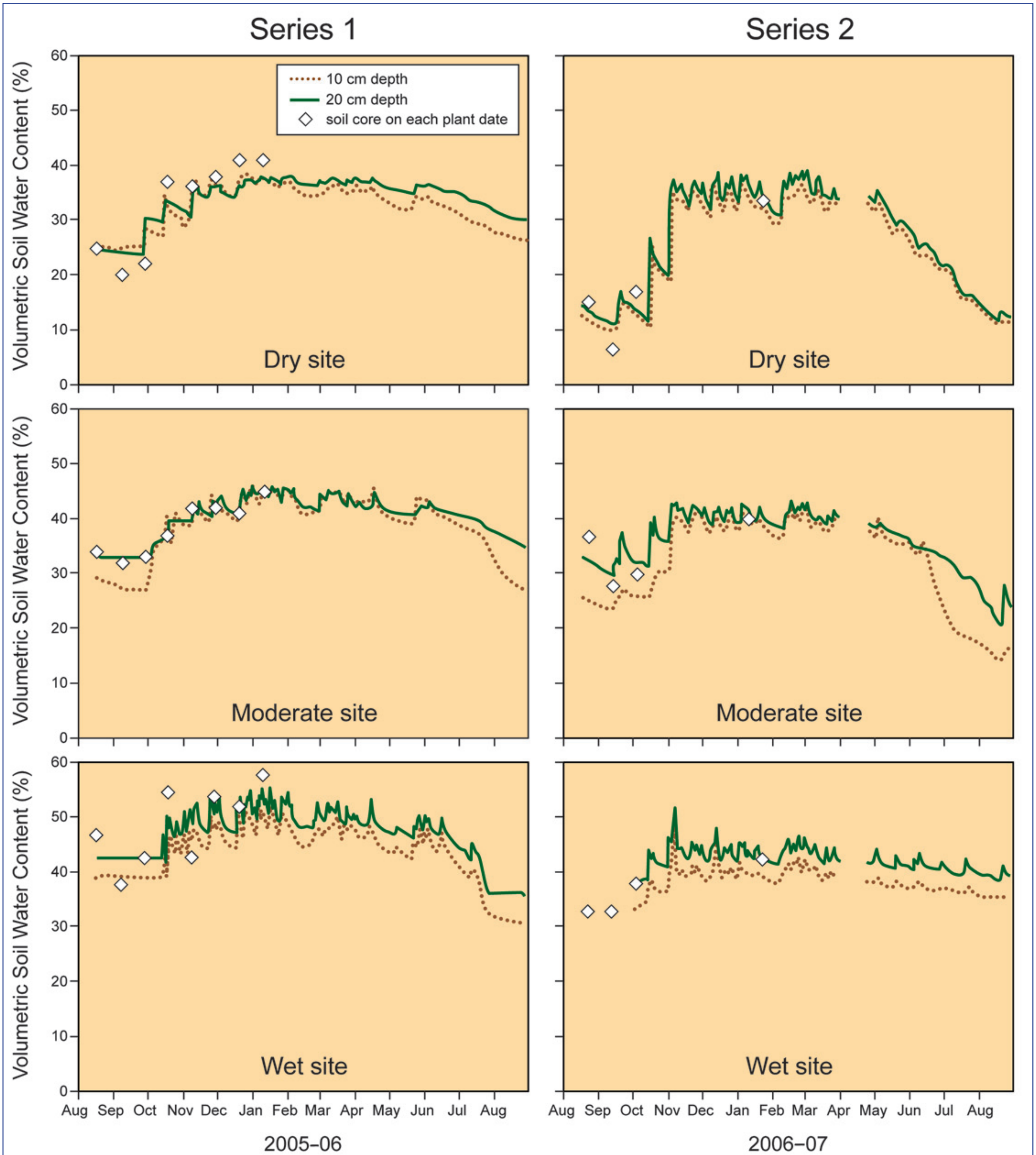

Figure 3. Average daily volumetric soil water content measured at two depths via ECH_20 probes during the first year after planting for each of the three sites planted in Series 1 and Series 2.

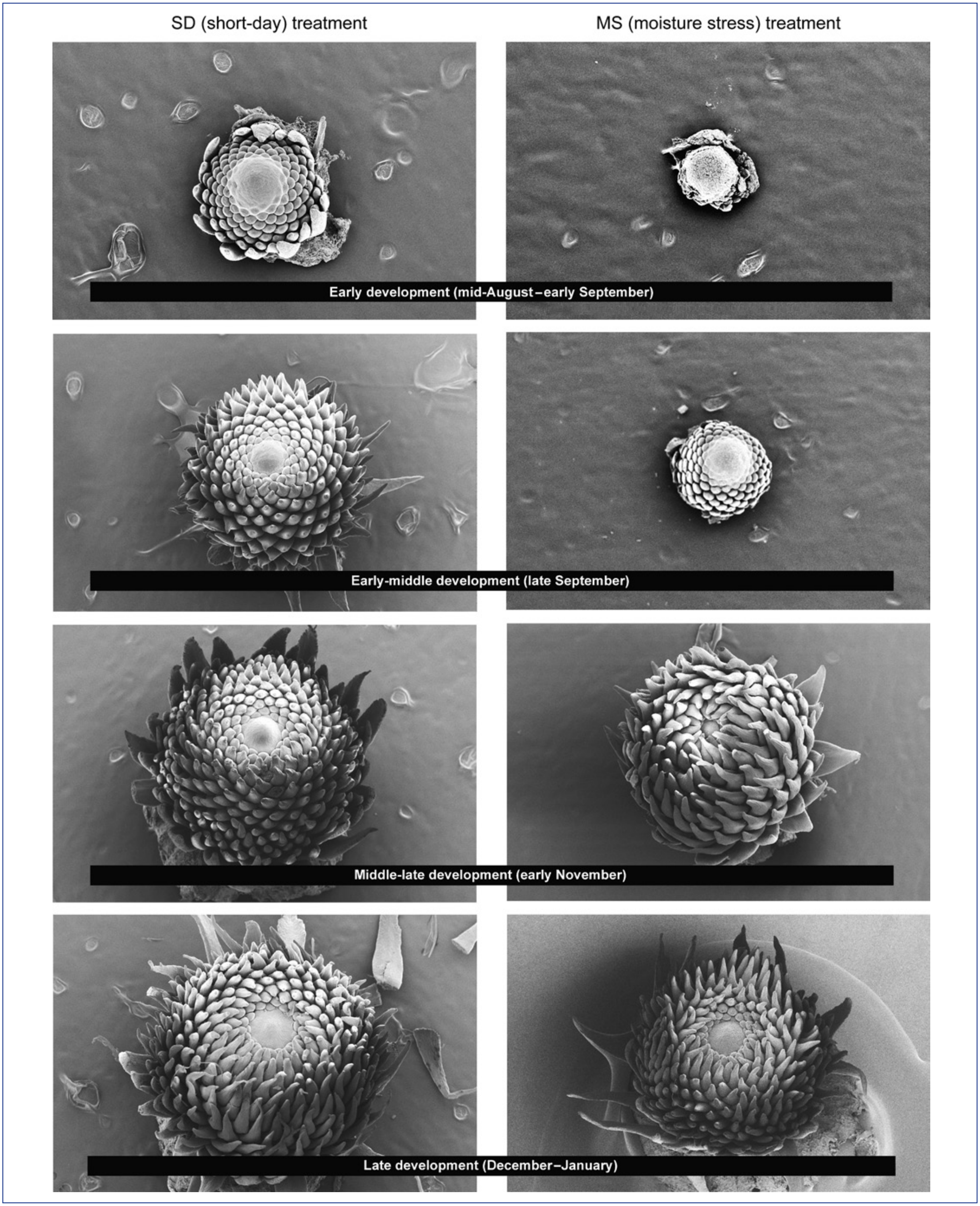

Figure 4. Scanning electron microscopy photos, taken at the time of planting, of typical terminal buds in both dormancy-induction treatments for seedlings planted in Series 1.

observed in Series 1, but in Series 2, lammas growth after planting was 7.5 times more prevalent in MS-treated trees (323 trees across three sites) than in SD-treated trees (43 trees across three sites). Most of the lammas growth occurred for trees planted in either mid-September or early October (plant dates 2 and 3).

After three field growing seasons, height, RCD, ht:RCD, and survival showed few differences between dormancy-induction treatments (Tukey-Kramer multiple comparison test; $p < 0.05$) (table 3). In Series 2, the MS treatment yielded significantly better survival than the SD treatment at the dry Pedee Guppy 2006 site, which had the lowest survival of all six sites (figure 1c). Height and RCD means for MS seedlings were significantly larger than those for the SD treatment at the dry (Pedee Guppy 2005) and wet (Southern Comfort) sites from Series 1. Mixed-model analyses (table 4) and repeated measures analyses generally concurred with the Tukey-Kramer means separations test (table 3).

Planting Date

RGP of seedlings potted in the greenhouse and root growth of seedlings excavated 3 weeks after planting (Series 1 only) tended to be greatest in the August and September plant dates (data not shown). Although little difference in initial height existed among trees from the different plant dates, by the end of three seasons, mean height differences were significant at four of the six sites (Tukey-Kramer multiple comparison test; $p < 0.05$) (figure 5). On the best sites, these growth differences after three growing seasons were striking (figure 6). On the two moderate sites, height increased by 39 (South Red Fir) and 32 percent (Mid Polly's View) between the best performing fall planting dates and the winter (January) plant date after three growing seasons. Fall planting also resulted in greater height growth than winter planting at the other Series 1 sites (23- and 15-percent increases at the wet Southern Comfort and dry Pedee Guppy 2005 sites, respectively), but these differences were less evident at the other Series 2 sites (wet Mohican: 11 percent; dry Pedee Guppy 2006: 4 percent).
At the dry Pedee Guppy 2006 site, growth differences between planting dates was likely influenced by low survival attributed to extreme late summer soil moisture deficit, which led to only two of four plant dates (September 12 and January 9) remaining in the dataset for analysis of growth traits. At the wet Mohican site, seedling height was most likely compromised by both flooding and high browsing. Interestingly, although planting date effects were not observed for height at Mohican,

Table 3. Third-year dormancy-induction treatment measurement means (± s.e.) of growth traits. For each column within a site, means followed by the same letter are not significantly different according to the Tukey-Kramer multiple comparison test of least squared means (α = 0.05).

Treatment	Series 1: 2005–06 planting year				
	n	Height 2008 (cm)	RCD† 2008 (mm)	Ht:RCD† ratio 2008	Survival 2008 (cm)
	Pedee Guppy 2005, dry site				
SD	37	115.9 (3.62) b	21.8 (0.88) b	56.2 (1.48) a	69.7 (3.00) a
MS	36	127.4 (4.03) a	23.8 (0.95) a	55.8 (1.12) a	68.3 (3.45) a
	South Red Fir, moderate site				
SD	40	121.8 (4.85) a	24.1 (1.13) a	54.0 (1.15) b	88.1 (1.82) a
MS	40	119.4 (5.11) a	22.8 (1.11) a	56.3 (0.81) a	87.6 (1.67) a
	Southern Comfort, wet site				
SD	32	136.1 (3.67) b	28.3 (0.95) b	50.7 (0.96) a	85.2 (2.27) a
MS	32	157.0 (3.91) a	32.4 (0.88) a	50.7 (0.99) a	90.0 (1.57) a
Treatment	**Series 2: 2006–07 planting year**				
	n	**Height 2009 (cm)**	**RCD† 2009 (mm)**	**Ht:RCD† ratio 2009**	**Survival 2009 (cm)**
	Pedee Guppy 2006, dry site				
SD	9	91.8 (4.59) a	15.9 (0.94) a	58.7 (0.85) a	28.0 (6.68) b
MS	11	100.1 (3.48) a	17.8 (0.69) a	57.8 (1.44) a	40.0 (6.95) a
	Mid Polly's View, moderate site				
SD	19	144.7 (6.41) a	26.3 (1.36) a	58.0 (2.13) a	83.6 (3.89)a
MS	20	152.5 (6.79) a	27.4 (1.56) a	59.6 (2.12) a	88.8 (2.04) a
	Mohican, wet site				
SD	16	97.2 (4.80) a	22.3 (1.41) a	46.1 (1.81) a	61.2 (5.45) a
MS	15	99.7 (4.29) a	23.5 (1.18) a	44.0 (0.93) a	58.3 (6.62) a

Notes: Means are based on plot averages. Statistical tests of survival are based on arcsine square root transformed data.

SD = short-day dormancy treatment. MS = moisture and nutrient stress dormancy treatment.

† RCD = root-collar diameter, stem diameter at ground level; Ht:RCD is the ratio of height to RCD.

Table 4. Mixed-model analyses p-values for third-season field data for Series 1 and Series 2 (data collected in 2008 and 2009, respectively). Values in **bold** are significant at α = 0.05.

Source of variation	Series 1: 2005–06 planting year				Series 2: 2006–07 planting year			
	Height 2008	RCD 2008	Ht:RCD 2008	Survival 2008	Height 2009	RCD 2009	Ht:RCD 2009	Survival 2009
	Pedee Guppy 2005, dry site				Pedee Guppy 2006, dry site			
Date planted	**0.0025**	**0.0002**	0.4678	**< 0.0001**	0.5147	0.5330	0.6368	**< 0.0001**
Treatment	**0.0013**	**0.0008**	0.5227	0.7698	0.0767	0.1467	0.8905	**0.0016**
Date × treatment	0.1960	0.3281	0.1693	0.1597	0.9980	0.8257	0.3823	**0.0132**
Block	0.0925	0.0839	0.1013	0.1213	0.1585	0.2565	0.2340	0
Contrast†	**0.0003**	**< 0.0001**	0.1132	**< 0.0001**				
	South Red Fir, moderate site				Mid Polly's View, moderate site			
Date planted	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.5000	**< 0.0001**	**< 0.0001**	0.9452	**0.0040**
Treatment	0.5580	0.1370	**0.0354**	0.6713	0.1600	0.3669	0.6010	0.3718
Date × treatment	0.2497	0.1433	0.0524	0.8774	0.1940	0.8688	0.8408	0.4488
Block	0.1003	0.1069	0.1604	0.2121	0.1802	0.1257	0.1263	0
Contrast†	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.5809	**< 0.0001**	**< 0.0001**	0.5595	0.9905
	Southern Comfort, wet site				Mohican, wet site			
Date planted	**< 0.0001**	**< 0.0001**	0.1075	0.0791	0.4029	**0.0209**	**0.0403**	**0.0342**
Treatment	**< 0.0001**	**< 0.0001**	1.0000	0.0976	0.9808	0.8101	0.8491	0.5989
Date × treatment	0.6853	0.5600	0.5165	0.1309	0.0738	0.4049	0.2303	0.2233
Block	0.2375	0.3492	0.1886	0	0.2365	0.1278	0.1347	0.2093
Contrast†	**< 0.0001**	**< 0.0001**	0.2043	0.7776	0.1244	**0.0156**	**0.0435**	0.3133

Note: Block is a random effect; all other effects are fixed. Statistical tests of survival are based on arcsine square root transformed data. Analyses were carried out using SAS PROC MIXED.

RCD = root-collar diameter, stem diameter at ground level. Ht:RCD is the ratio of height to RCD.

† Contrast = contrast of four plant dates before root growth cessation (defined as before November 1) versus four plant dates after root growth cessation (after November 1).

significant differences in RCD growth did occur at this site. The ht:RCD was not significantly different among plant dates in most cases.

The dry Pedee Guppy 2006 site was excluded from contrast analyses investigating growth and survival differences of seedlings planted before or after the assumed date of root elongation cessation, because only two planting dates remained in that dataset (table 4). At the five sites where growth of seedlings planted before November 1 were contrasted with seedlings planted after this date, growth for the earlier plant dates was significantly higher than for seedlings planted late at all sites except for wet Mohican (table 4). Average height after three field seasons at Mohican was lowest for the January planting (figure 5), however, despite no statistically significant difference.

At three of the six sites (wet Southern Comfort, moderate South Red Fir, and moderate Mid Polly's View), survival by plant date after three growing seasons ranged between 75 and 96 percent (data not shown). Survival was lowest on the earliest (August) planting date for all sites, except the moderate South Red Fir (with uniformly high survival across all plant dates) and the wet Mohican sites (August survival = 56 percent). Survival for trees planted during August at the two dry sites was particularly low (Pedee Guppy 2005: 38 percent; Pedee Guppy 2006: 0 percent), with mortality occurring immediately after planting on these dry sites.

Survival was also low for two of the Series 2 sites on the October 3 plant date (dry Pedee Guppy 2006: survival = 16 percent; wet Mohican: survival = 43 percent). Although soil temperature in early October of the planting year was similar for the two series (figure 2), volumetric soil water content was lower at the beginning of October 2006 than for the same time period in 2005, most notably for the wet and dry sites (figure 3).

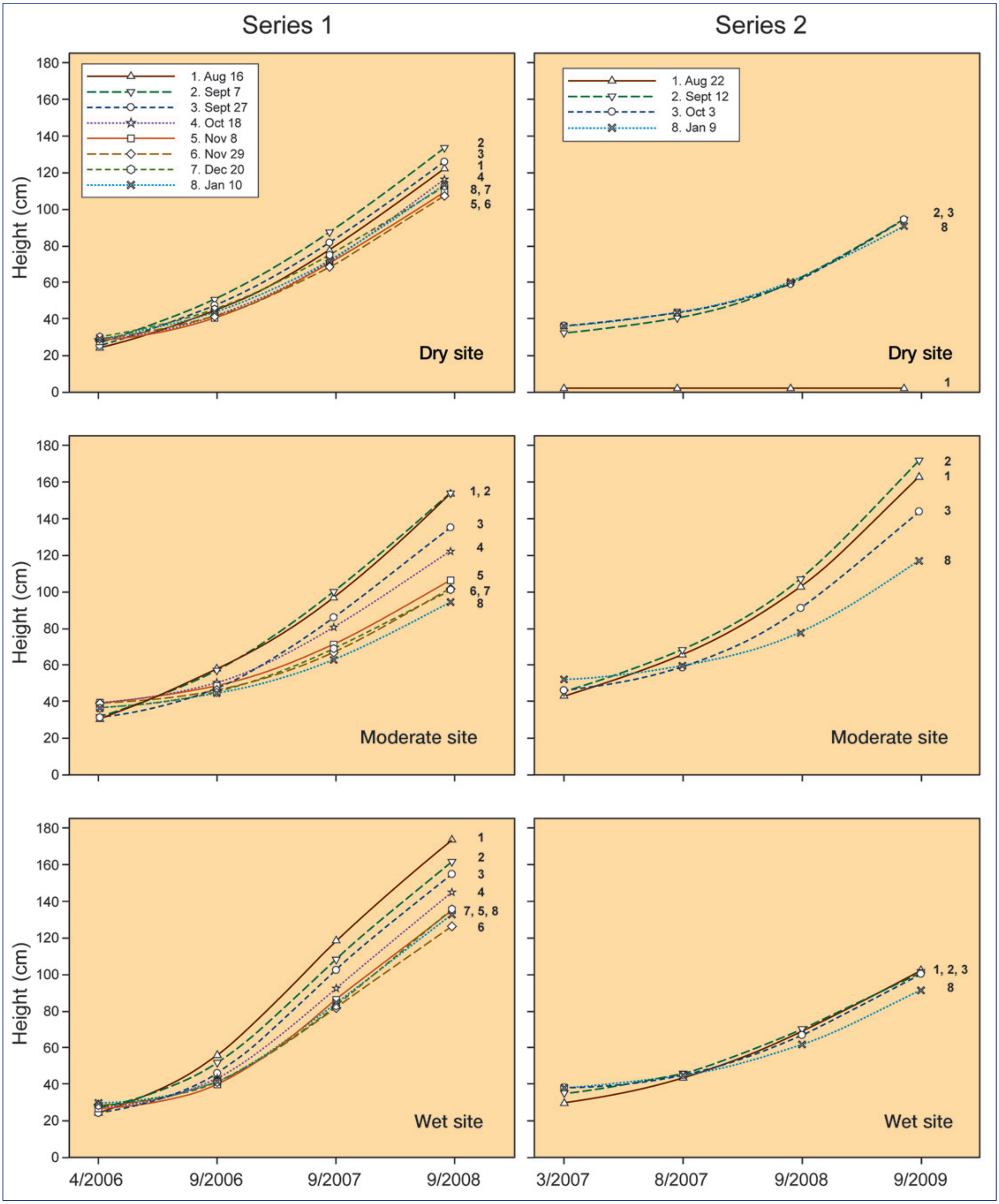

Figure 5. Mean seedling height by planting date per site for the two series.

Figure 6. Seedlings planted during the fall were notably taller than those planted in the winter on favorable sites. Shown here are seedlings planted September 7 (left) and December 21 (right) after two growing seasons (August 2007) at the Series 1 wet Southern Comfort site (Photos source: Diane L. Haase).

Discussion

Dormancy-Induction Treatment Effects Are Minimal

Seedling physiological condition at outplanting is vitally important to subsequent field performance. In particular, seedling dormancy status can affect seedling stress resistance and influence growth and survival after outplanting (van den Driessche 1991). Short-day regimes have been used in forest nurseries for more than 20 years to control seedling morphology and physiology. These treatments have resulted in earlier budset (MacDonald and Owens 2006) and reduced seedling height (Jacobs and others 2008) in previous Douglas-fir studies. Accordingly, shortened photoperiods have been used to manipulate ht:RCD, control lammas growth, and maintain seedlings within target nursery specifications (Turner and Mitchell 2003). Short-day treatments have also been shown to increase fall cold hardiness (Jacobs and others 2008), decrease late fall root growth capacity, and cause earlier spring dormancy release (Turner and Mitchell 2003). However, Jacobs and others (2008) found that short day-treated seedlings had greater new root proliferation at cold soil temperatures, but less new root growth at warm temperatures, than seedlings grown under ambient photoperiods.

In this study, earlier budset and initially greater primordia production were observed with the SD treatment, but this effect was only short term, and buds from both treatments were approximately the same size by December. Few differences between SD- or MS-treated trees were seen in growth or survival during this study with the exception of lammas growth after planting in Series 2. The SD treatment successfully prevented lammas growth, whereas the MS treatment did not prevent a second flushing in seedlings planted at the same time and also exhibited greater RGP on the September plant dates (Series 1, data not shown). This indicates that the MS trees were quiescent, whereas the SD trees were transitioning into the rest stage of dormancy. Where growth differences were significant, the SD trees were smaller than the MS trees. Survival at the harshest site, Series 2, dry Pedee Guppy 2006, was significantly higher for the MS treatment than for the SD treatment. Exposure to moisture stress may have decreased transplant shock in the MS seedlings, because they were more conditioned to moisture stress at the time of planting as compared with the SD seedlings, which had minimal moisture stress in the nursery.

The findings of this study concur with those of MacDonald and Owens (2006), who found no survival or morphological differences after 1 year between SD- and MS-treated seedlings of a coastal Douglas-fir seedlot from British Columbia. Although Jacobs and others (2008) suggested that Douglas-fir sources from latitudes more southerly than 45º N might show strong responses to photoperiod, little evidence was found in this study to support this suggestion.

Planting Date Affects Plantation Growth and Survival

This study demonstrates that tree height significantly increased after three field seasons for trees planted while root egress was still occurring in the fall (August through October plant dates). Presumably, the new root growth that occurred for trees planted before November 1 conferred a growth advantage that was still evident 3 years later. These growth differences were most dramatic on the sites where soil moisture levels were least limiting. Scagel and others (1990) found that root growth of excavated Engelmann spruce seedlings (*Picea engelmannii* Parry ex Engelm.) within a few months of planting was largest on seedlings from the earliest planting and decreased with later planting days. Barber (1989) found that western larch (*Larix occidentalis* Nutt.) seedlings planted in fall (October) were superior to those planted in spring (April) with respect to survival, height growth, and total height.

A true assessment of tree height could not be made at the wet Mohican site from Series 2 because of severe browsing. For the other sites, overall growth during the first 3 years related well to the volumetric soil water content at the time of planting; growth was poor on the two dry sites where 20 cm soil moisture content was less than 20 percent during August through October (figure 3). Akgul (2004) observed an increasing relationship between volumetric soil moisture content at the time of planting (September through April) and first-year survival of bareroot slash pine (*Pinus elliottii* Engelm.) seedlings planted in the flatlands of western Louisiana. The sites used in the current study had little competing vegetation. Although Grossnickle (2005) cited numerous studies where removal of vegetation cover caused soil temperatures to rise, no evidence existed in the current study of soil temperatures greater than the optimum range for Douglas-fir root growth (10 to 20 ºC) (Lopushinsky and Max 1990) were observed in the first autumn after planting.

Most of the observed lammas growth occurred for trees planted between mid-September and early October. Trees planted before this period would have been exposed to moisture stress and, therefore, be less prone to flushing. Trees planted after this time would be more dormant, and combined with the colder soil temperatures and shorter photoperiod, new shoot growth would have been unlikely. Although the autumn of 2006 (when planting of Series 2 began) was drier than the previous autumn (when Series 1 was planted), lammas growth was much higher for Series 2 seedlings planted in 2006. Seedlings grown in 2006 were assumed to be less dormant at the time of planting than those grown and planted the previous year.

Survival at the two dry sites (Pedee Guppy 2005 and 2006) was unacceptably low for the August plant dates. As this study shows, the potential benefits of late summer planting may be great on some sites, but the risks are high on drier sites. High temperature and low soil moisture levels at the time of planting may result in stresses leading to reduced growth or increased mortality. Upon planting, roots must have the ability to supply enough water to transpiring needles to maintain proper plant water balance (Grossnickle 2005). New root growth is especially critical on harsh planting sites, where the existing root system may not be adequate to supply enough water to the shoot system to meet transpirational demand (Simpson and Ritchie 1997). Although some degree of planting stress is unavoidable, a seedling on a droughty or nutrient-poor site will allocate much of its stored photosynthate to extending its root system, contributing to planting check (Lavender 1990). If soil moisture levels are too limiting, seedling survival will be severely affected. Conversely, high water tables affected survival at the wet Series 2 Mohican site. Mortality at this site was not a direct result of planting timing, because winter-planted seedlings also died due to seasonal flooding.

Little difference existed in growth and survival rates between seedlings planted late in the fall and those planted in winter because, beginning in late fall, soil temperatures were likely too low for root egress. The optimal planting window between the onset of adequate seedling dormancy at the nursery and the end of the fall planting season is relatively short. Colder soil temperatures cause an increase in plant resistance to water flow (Grossnickle 2005); after soil temperatures drop to less than 5 °C, root growth is impeded (Lopushinsky and Max 1990). If seedlings are planted too late in the fall when soil temperature is no longer favorable for growth, they may have a poorly developed root system, lower carbohydrate reserves, and the inability to promptly use water and nutrients for growth the next season compared with spring and early fall planted seedlings (Adams and others 1991).

Taking into account moisture and temperature influences on seedling growth and survival, the data suggest that the optimal planting time is mid-September through mid-October. Compared with winter-planted seedlings, the increase in growth for seedlings planted during this timeframe was impressive at four of the six sites (figure 5). Hunt (2004) observed similar, albeit less dramatic, results 7 years after planting Douglas-fir seedlings in the coast-interior transition zone of southwestern British Columbia. In his study, survival was lowest (about 40 percent) for seedlings planted at the end of August; however, growth for trees planted in late August and late September tended to be greater compared with spring-planted trees. For Douglas-fir seedlings planted on harsh, high-elevation sites in Washington between late September and late October, Taylor and others (2009) noted best growth and survival for the early October plant date, and lowest survival at the September plant date. Together, these studies indicate that throughout the Pacific Northwest, fall planting is a viable option when implemented after the cessation of summer drought.

Implications

For coastal Douglas-fir plantations in Oregon, no advantage was observed for using short-day (blackout) treatments to induce fall dormancy. Moisture-stress treatments cost less to implement, and are easier to apply. As suggested by MacDonald and Owens (2006), however, short-day-treated seedlings may be desirable for fall planting at higher elevation sites where earlier budset is advantageous. Also, if early fall planting is planned for sites that are at high risk of lammas growth, short day treatments may be warranted.

This study demonstrates that with the judicial timing of fall planting on productive sites in western Oregon, height 3 years after planting can be increased by as much as 39 percent compared with winter planting.

Success or failure of fall planting depends on both seedling physiology and environmental conditions, especially soil temperature and moisture levels. Fall planting can be a viable alternative to winter planting as long as three critical elements are present: soil temperature is favorable for root egress (at or above 10 ºC), root-to-soil contact occurs soon after planting, and soil moisture is available (greater than 20 percent) for seedling uptake. In regions such as western Oregon, however, where late summer is typically very hot and dry and soil moisture very low, planting is not recommended before September, especially on drier sites. If precipitation is adequate, mid-September to late September may be an optimal planting window for these sites. In extremely dry years, planting should be delayed until mid-October.

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