Post-Planting Treatments Increase Growth of Oregon White Oak (*Quercus garryana* Dougl. ex Hook.) Seedlings

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Abstract

The extent of Oregon white oak woodland and savanna ecosystems in the U.S. Pacific Northwest has diminished significantly during the past century due to land use changes and fire suppression. Planting Oregon white oak seedlings is often necessary when restoring these plant communities. Our objective was to determine the efficacy of post-planting treatments for establishing Oregon white oak seedlings on sites characterized by low growing season precipitation and coarse-textured soils. We evaluated the effects of control of competing vegetation, tree shelters, fertilization, irrigation, and planting date on growth of planted seedlings. Survival was generally high (90%), but growth rate varied substantially among treatments. Plastic mulch increased soil water content and increased annual seedling height growth by an average of 56% relative to one-time manual removal of competing vegetation. Solid-walled tree shelters reduced browse damage and increased mean annual height growth compared to mesh shelters and no shelter by averages of 7.5 and 10.9 cm, respectively. Controlled-release fertilizer applied at planting did not consistently increase seedling growth. Weekly irrigation (3.8 L/seedling) increased first-year seedling growth only where mulch also was applied. Seedlings planted by late February had greater root growth by summer than those planted in early April. Soil water management was necessary for best seedling growth, and the improved height growth in solid-walled tree shelters allowed the terminal shoot to grow more quickly above the height of animal browse. Our results indicate effective methods for establishing Oregon white oak seedlings, but these results may also be applicable to establishment of other tree species on similarly droughty sites.

Key words: ***Quercuo garryana*, oak savanna restoration, tree shelter, mulch, irrigation, fertilization, planting date.**

Introduction

Oregon white oak or Garry oak (*Quercus garryana* Dougl. ex Hook.) is a shade-intolerant, deciduous species, native to western North America. It occurs from southern California to British Columbia, and in the northern part of its range, it is the only native *Quercus* (oak) species (Stein 1990). Prior to European settlement in the mid-1800s, Oregon white oak savannas, woodlands, and associated prairies were maintained in the Pacific Northwest by frequent, low-intensity fires set by native peoples (Habeck 1961; Agee 1993). During the past century, the extent of Oregon white oak woodlands and savannas has been dramatically reduced and fragmented by conversion of lands to agricultural and urban uses and by the absence of fire, which has resulted in encroachment of coniferous forests (Sprague & Hansen 1946; Thilenius 1968; Crawford & Hall 1997).

Restoration of Oregon white oak savannas and woodlands in the Pacific Northwest is motivated by their cultural legacy, the number of associated plant and animal species that are at risk as they decline, and their uniqueness in a landscape dominated by conifers (Hanna & Dunn 1997; Bayrakci et al. 2001; Fuchs 2001). However, there has been little research on techniques for establishing Oregon white oak on sites from which it has been extirpated. Because sites available for restoration may have few or no trees to serve as a seed source, natural regeneration of Oregon white oak is often ineffective in these areas. Regenerating from planted acorns may be difficult due to high mortality rates from animal predation or insufficient soil moisture (Fuchs et al. 2000; Regan 2001; Regan & Agee 2004). For planted seedlings, variable survival (Bell & Papanikolas 1997; Papanikolas 1997) and low growth rates have been reported (Dunn & Grosboll 2002).

Although shade intolerant at maturity, Oregon white oak may regenerate in sun or in shade. Germination occurs in autumn, and the seedling forms a dominant taproot that elongates rapidly (Stein 1990). Because the species often occurs in a Mediterranean climate with droughty summer conditions, seedling roots must penetrate deep enough in the soil profile by midsummer to access sufficient soil water

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for survival and initial growth. Stems of naturally regenerated seedlings may die-back multiple times, but root systems continue to develop throughout the seedling stage (Hibbs & Yoder 1993). Although natural seedlings are often multistemmed, saplings typically have a single, dominant stem (Hibbs & Yoder 1993).

Post-planting treatments may be necessary to protect and promote growth of planted oak seedlings so that they will reach a height at which terminal shoots are no longer susceptible to animal browse or overtopping by competing vegetation (Potter 1988; McCreary & Tecklin 2001). A variety of post-planting treatments including tree shelters, mulching, fertilization, and irrigation have been tested on oak species other than Oregon white oak. Solid-walled tree shelters reduce animal damage to oak seedlings, create a warmer, more humid microclimate (Potter 1988; Burger et al. 1992; Peterson et al. 1995), and have increased growth rates of many oak species (Tuley 1985; Minter et al. 1992; West et al. 1999; Dubois et al. 2000; Taylor & Golden 2002). Mulching around planted seedlings limits growth of vegetative competition through physical impedance and light reduction (Teasdale & Mohler 2000) and may increase soil water availability (McDonald & Helgerson 1990; Truax & Gagnon 1993). Fertilization of oak seedlings may increase growth where soil nutrients are limiting (Foster & Farmer 1970; Johnson 1980; Tappeiner & McDonald 1980), but some studies have shown decreased survival (Adams et al. 1987) or no effect of fertilization (McCreary 1995). In regions where growing-season soil water availability is low, irrigation may increase growth of planted oak seedlings (McCreary 1990; Bernhardt & Swiecki 1991).

Our goal was to ascertain the most effective treatments for establishing Oregon white oak seedlings on sites where the species existed historically. No research thus far has evaluated a broad range of establishment techniques for this species. In this study, our primary hypothesis was that growth and survival of planted Oregon white oak seedlings can be increased by (1) control of competing vegetation; (2) tree shelters; (3) fertilization; and (4) irrigation. We further hypothesized that planting date affects early first-year root growth of seedlings.

Methods

Study Area

This study took place at seven sites in southwestern Washington, U.S.A., all within 30 km of the city of Olympia (lat 46°58′N, long 122°54′W) in the Puget Trough physiographic province (Table 1). Sites were selected in or near areas where Oregon white oak savanna or woodland stands likely existed prior to European settlement; most of the sites were in areas undergoing restoration. All sites had sandy soils of glacial origin, with varying gravel content. Soils were all moderately to somewhat excessively drained, and slopes were less than 2%. The VSF1 trial was on the Spanaway soil series (Typic Melanoxerand); the VI trial was on the Nisqually series (Vitrandic Dystroxerept); the FI trial was on the Everett series (Vitrandic Dystroxerept); the SF trial was on a Spanaway–Nisqually complex; and the VS and VSF2 trials were on Spanaway and Nisqually soils. In the DAT trial, seedlings were in pots containing artificial growing media (see below), and roots did not contact soil.

The VS, VSF1, VSF2, SF, and VI sites were originally prairie. The VSF1 and VSF2 sites were used for grazing after European settlement in the mid-1800s and later for military training during much of the 1900s. The VS, SF, and VI sites were converted from prairie to cropland prior

Table 1. Descriptions of seven Oregon white oak planting trials.

			Seedling Size at Planting		*Treatments*[a]			
Trial	*Established on (month/yr)*	*Trees (n)*	*Height (in cm)*	*Diameter (in mm)*	*Vegetation control*	*Tree shelter*	*Fertilizer*	*Irrigation*
VS	01/2001	80	11.5 (3.7)	3.6 (1.2)	91-cm plastic mulch/scalping	Tubex 91 cm/ wire mesh	None	None
VSF1	04/2002	224	22.9 (6.7)	5.3 (0.9)	91-cm plastic mulch/scalping	Protex 91 cm/none	14 g/none	None
VSF2	01/2003	152	21.6 (7.2)	4.9 (1.2)	91-/122-cm plastic mulch	Protex 91 cm/none	14 g/none	None
SF	02/2003	80	22.3 (7.5)	5.7 (1.4)	122-cm plastic mulch	Protex 91 cm/ plastic mesh	14 g/none	None
VI	02/2004	48	25.5 (5.8)	4.6 (0.9)	122-cm plastic mulch/none	Protex 91 cm	None	4 L per week/none
FI	02/2004	40	33.1 (6.2)	6.0 (1.6)	122-cm plastic mulch	Protex 122 cm	14/28 g	4 L per week/none
DAT	Varied	140	14.7 (4.2)	4.5 (1.5)	None	None	None	None

Trial names consist of letters denoting treatment comparisons within each trial (V, vegetation control; S, tree shelter; F, fertilization; I, irrigation; DAT, planting date). Mean seedling sizes are followed by standard deviation in parentheses.
[a]A single treatment listed within each cell indicates that treatment was applied to all seedlings; multiple treatments per cell indicate an experimental comparison.

to recent restoration activities. At all of these sites, native vegetation was likely similar to the Roemer's fescue (*Festuca roemeri* (Pavlick) Alexeev)–white-top aster (*Sericocarpus rigidus* Lindl.) plant association (Chappell & Crawford 1997), although non-native grasses including Colonial bentgrass (*Agrostis capillaris* L.), Common velvetgrass (*Holcus lanatus* L.), and Kentucky bluegrass (*Poa pratensis* L.) are now present in varying amounts. The FI and DAT sites were originally Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forest, although soils and topography are similar to the other sites. Non-native grasses predominated at the FI and DAT sites.

Mean annual air temperature in Olympia, Washington, is 10.0°C (WRCC 2005). Mean air temperatures in January and July are 3.3 and 17.3°C, respectively. Mean annual precipitation is 1,293 mm, although mean precipitation for the months of June, July, and August is only 40, 18, and 30 mm, respectively (WRCC 2005).

Study Design and Installation

The study consisted of seven trials, six of which tested two or three treatments (two levels each) in factorial arrangement (Table 1). The seventh trial (DAT) had one treatment with seven levels. The SF trial followed a completely randomized design, and all other trials followed randomized block designs, with 2–10 replicates of each treatment combination per block. In the block design trials, blocking was used to control for random variation in site due to topography, soil variation, or proximity to forest edge.

Seedling stock consisted of containerized Oregon white oak seedlings from a local seed source grown in a 1:1:1 mixture of peat, perlite, and vermiculite. Seedlings in the VS trial were grown in 21-cm-tall, 3.8-L round pots; seedlings in all other trials were grown in 36-cm-tall, 2.8-L square pots. Seedlings were irrigated during the growing season and fertilized with water-soluble 20-20-20 fertilizer (The Scotts Company, Marysville, OH, U.S.A.) on a monthly basis. Seedling age at planting was 2–3 years. Seedlings were planted into 40- to 45-cm-deep holes that were dug with posthole diggers and shovels, except for the VSF1, VSF2, and FI trials in which a motorized auger was used. At planting, seedling taproots were pruned at 30 cm to remove any root-bound portion. Seedlings were planted at spacings of 1.5 m or greater; seedling root excavations confirmed that there was no root competition between seedlings at this spacing.

Treatments included combinations of tree shelters, competing vegetation control, fertilization, irrigation, and planting date (Table 1). Solid-walled and mesh tree shelters were tested. Solid-walled shelters were single-walled, blue Protex Pro/Gro shelters (Norplex Incorporated, Auburn, WA, U.S.A.), except in the VS trial where twin-walled, polypropylene Tubex shelters (Tubex Limited, South Wales, UK) were used. Shelters were supported with either bamboo or wooden stakes, although many bamboo stakes were replaced due to decay. Mesh shelters were 30 cm in diameter and constructed from wire mesh (VS trial; 2.5-cm openings; 122 cm tall) or plastic mesh (SF trial; 1.2-cm openings; 91 cm tall).

Competing vegetation control treatments were: (1) squares of perforated plastic mulch applied at planting (91- or 122-cm-wide Brush Blankets; Arbortec Industries, Mission, British Columbia, Canada) and secured with 15-cm landscape staples or (2) one-time manual removal of the sod layer at planting (so-called scalping) to a radius of 50 cm. Tears and gaps in plastic mulch were repaired with waterproof tape.

Fertilizer was added at 14 or 28 g per seedling (100 and 200% of manufacturer's recommendation) as controlled release (12–14 months at 21°C) Osmocote Plus (15-9-12 plus micronutrients; The Scotts Company) placed in the bottom of the planting hole, with a layer of soil 3–5 cm deep between fertilizer and seedling roots. The irrigation treatment was 3.8 L of water per seedling applied once per week for 7 weeks (June to mid-July) in 2004 in the VI trial and in 2004 and 2005 in the FI trial.

The DAT trial was conducted to examine the influence of planting date on the development of seedling root systems prior to the dry summer months when first-year seedlings would be most likely to suffer water stress. Twenty Oregon white oak seedlings were planted on each of seven dates (2003–2004): 26 September, 29 October, 26 November, 23 December, 30 January, 27 February, and 1 April. Prior to planting at each date, the base of each pot was removed and the seedling therein was subsequently root pruned at 30 cm below groundline. The still-potted, root-pruned seedling was then placed partway inside a second pot already containing 15 cm of growing media. The base of the second pot was permeable to water but not to roots. The pots were securely taped together and then placed in the ground. Soil temperature (depth = 30 cm) was monitored with four Ibutton sensors (Maxim Integrated Products Incorporated, Sunnyvale, CA, U.S.A.). Seedlings were irrigated to maintain moist growing media. On 21 June 2004, pots planted at all dates were removed from the ground, and all roots growing in the 15 cm of media in the lower pot (i.e., new downward root growth since planting) were extracted from the media by washing. These roots were dried to constant weight at 65°C and weighed. Although new root growth did not occur solely in the lower pot, this measurable portion was used as an index of root growth.

Data Collection and Analysis

Height and stem diameter at 3 cm above groundline were measured for all seedlings at the time of planting and remeasured after each subsequent growing season through 2004 (SF, VI, and FI trials measured through 2005). Browse damage, survival, and cause of mortality, when evident, were recorded for each seedling at remeasurement.

To measure the effects of irrigation and mulch on volumetric soil water content (Θ) near the planted seedlings, ECH_2O EC-20 soil water probes (Decagon Devices, Pullman, WA, U.S.A.) were installed near 12 seedlings (three replicates of four treatment combinations) in the VI trial and 6 in the FI trial (three irrigated and three non-irrigated) at the time of planting. The 20-cm-long probes were installed vertically from a 10–30 cm soil depth at a distance of approximately 5 cm from the taproot. The Θ measurements in the VI trial were made weekly, immediately prior to irrigation and were made at 240-minute intervals in the FI trial using EM5 dataloggers (Decagon Devices). To remove bias of different initial Θ values among probes due to apparent variability in soil and soil–probe contact, soil water data collected during the 2004 growing season were analyzed as relative values (i.e., as a fraction of the initial, seasonal high Θ reading for each probe on 29 April 2004).

A separate analysis of variance (ANOVA) model was used for each trial, with treatments analyzed as fixed effects and blocking as a random effect. Repeated measures ANOVA was used to analyze annual height growth in all trials and weekly Θ values in the VI trial (Proc Mixed; SAS Institute Incorporated 2005). Stem diameter growth was analyzed as the basal area growth increment for the entire duration of the trial. In analyses of seedling growth, basal area at planting was used as a covariate when significant ($p < 0.05$). Orthogonal contrasts were used to compare treatment combinations. Statistical significance was judged at an alpha level of 0.05.

Results

Survival

Survival rates among trials were greater than 92%, with two exceptions. In the VS trial, 4-year survival averaged 84%, with similar rates among treatments. In the VSF1 trial, 3-year survival averaged 86%, with survival rates of 89% or higher for all tree shelter/vegetation control treatment combinations, except the no-shelter/scalping treatment (70%). Across trials, mean survival rates were similar for solid-walled tree shelters (93%), mesh shelters (90%), and no shelter (88%).

Control of Competing Vegetation

Plastic mulch increased annual height growth compared to no-vegetation control (VI trial) and increased annual height growth in one of two trials (VSF1 but not VS) in which it was compared to scalping (Tables 2 & 3; Figs. 1 & 2). Relative to scalping, the height growth advantage of plastic mulch increased over time (VSF1).

Plastic mulch significantly increased basal area growth relative to scalping (177% increase in VS and 124% increase in VSF1) and no mulch (107% increase in VI trial). There was a significant interaction between vegetation control and tree shelter treatment in the VSF1 trial: for sheltered seedlings, basal area growth was similar for plastic mulch (5.3 mm^2) and scalping (5.1 mm^2), but for unsheltered seedlings, basal area growth was greater for plastic mulch than for scalping (8.5 vs. 1.1 mm^2).

The rate of browse damage was similar for plastic mulch and scalping treatments.

Tree Shelters

In all four shelter trials, annual height growth of seedlings in solid-walled shelters was significantly greater than that of seedlings in mesh shelters or no shelter (Tables 2 & 3; Fig. 1). There were also significant shelter × year interactions in all four trials; generally, the height growth

Table 2. ANOVA results for fixed effects on annual height and total BA growth for three trials.

			Annual Height Growth		*Total BA Growth*	
Trial	*Effect*	*df*	*F Value*	*p > F*	*F Value*	*p > F*
VS	V	1	1.56	0.212	5.59	**0.021**
	S	1	37.65	**<0.001**	3.80	0.056
	V × S	1	0.03	0.863	0.59	0.446
	Y	3	5.07	**0.002**	—	—
	V × Y	3	0.73	0.537	—	—
	S × Y	3	4.48	**0.004**	—	—
	V × S × Y	3	0.26	0.858	—	—
VSF1	V	1	16.75	**<0.001**	4.96	**0.028**
	S	1	134.03	**<0.001**	0.06	0.800
	V × S	1	3.54	0.060	4.51	**0.036**
	F	1	0.00	0.949	3.15	0.078
	V × F	1	0.00	0.948	2.18	0.142
	S × F	1	0.37	0.541	0.16	0.688
	V × S × F	1	0.02	0.895	1.26	0.263
	Y	2	13.65	**<0.001**	—	—
	V × Y	2	4.54	**0.011**	—	—
	S × Y	2	12.05	**<0.001**	—	—
	V × S × Y	2	0.20	0.820	—	—
	F × Y	2	2.23	0.109	—	—
	V × F × Y	2	0.20	0.820	—	—
	S × F × Y	2	0.78	0.458	—	—
	V × S × F × Y	2	0.18	0.832	—	—
VSF2	V	1	10.62	**0.001**	6.45	**0.012**
	S	1	86.92	**<0.001**	0.10	0.756
	V × S	1	7.00	**0.009**	0.58	0.449
	F	1	0.75	0.389	0.63	0.429
	V × F	1	3.12	0.078	7.37	**0.008**
	S × F	1	0.02	0.892	0.64	0.425
	V × S × F	1	0.01	0.913	2.23	0.138
	Y	1	10.02	**0.002**	—	—
	V × Y	1	2.72	0.101	—	—
	S × Y	1	28.13	**<0.001**	—	—
	V × S × Y	1	1.92	0.167	—	—
	F × Y	1	0.00	0.947	—	—
	V × F × Y	1	0.19	0.661	—	—
	S × F × Y	1	0.45	0.502	—	—
	V × S × F × Y	1	0.24	0.628	—	—

Significant p values ($\alpha = 0.05$) are given in bold face. Treatments are shown in Table 1. BA, basal area; df, degrees of freedom; F, fertilization; S, shelter; V, vegetation control; Y, year.

Table 3. ANOVA results for fixed effects on annual height and total BA growth for three trials.

			Annual Height Growth		Total BA Growth	
Trial	*Effect*	*df*	*F Value*	*p > F*	*F Value*	*p > F*
SF	S	1	68.80	**<0.001**	0.35	0.554
	F	1	13.28	0.074	0.50	0.482
	S × F	1	0.45	0.506	1.02	0.315
	Y	2	19.32	**<0.001**	—	—
	S × Y	2	7.95	**<0.001**	—	—
	F × Y	2	1.67	0.192	—	—
	S × F × Y	2	0.70	0.497	—	—
VI	V	1	37.43	**<0.001**	**13.29**	**<0.001**
	I	1	1.99	0.166	1.71	0.199
	V × I	1	0.23	0.636	0.62	0.435
	Y	1	6.06	**0.018**	—	—
	V × Y	1	2.81	0.101	—	—
	I × Y	1	1.29	0.262	—	—
	V × I × Y	1	4.43	**0.041**	—	—
FI	I04	1	0.56	0.458	2.13	0.155
	I05	1	0.10	0.750	0.53	0.473
	I04 × I05	1	0.06	0.803	0.11	0.746
	F	1	1.42	0.242	0.99	0.327
	I04 × F	1	0.27	0.610	0.00	0.959
	I05 × F	1	0.41	0.527	0.03	0.867
	I04 × I05 × F	1	2.84	0.102	0.11	0.744
	Y	1	21.53	**<0.001**	—	—
	I04 × Y	1	13.64	**<0.001**	—	—
	I05 × Y	1	0.08	0.783	—	—
	I04 × I05 × Y	1	0.09	0.766	—	—
	F × Y	1	0.04	0.846	—	—
	I04 × F × Y	1	0.27	0.606	—	—
	I05 × F × Y	1	0.01	0.925	—	—
	I04 × I05 × F × Y	1	4.15	0.051	—	—

Significant p values ($\alpha = 0.05$) are given in bold face. Treatments are shown in Table 1. BA, basal area; df, degrees of freedom; F, fertilization; I, irrigation; I04, irrigation 2004; I05, irrigation 2005; S, shelter; V, vegetation control; Y, year.

advantage of solid shelters, relative to mesh shelters or no shelter, increased over time. In the VSF2 trial, there was an interaction between shelter and mulch size: height growth of unsheltered seedlings was not affected by mulch size, whereas that of sheltered seedlings was greater with 122-cm mulch than with 91-cm mulch. Basal area growth was not affected by tree shelter treatment in any trial; but by the end of the first or the second growing season, solid-walled shelters increased seedling height–diameter ratio (H:D) relative to mesh shelters or no shelter (Table 4).

The percentage of unsheltered seedlings suffering damage from herbivory (attributed primarily to Black-tailed deer [*Odocoileus hemionus columbianus*]) averaged 20% per year, compared with less than 1 and 5% of seedlings in solid-walled and mesh shelters, respectively. Browse damage to sheltered seedlings occurred when seedlings grew above the top of the shelter or through the mesh. For unsheltered seedlings, browse damage varied by location. During the first year of the VSF1 trial, the fraction of unsheltered seedlings browsed ranged from 2 of 16 to 11 of 16 seedlings per block.

Fertilization and Irrigation

The only significant effect involving fertilization (14 g fertilizer vs. none) occurred as an interaction between vegetation control and fertilization in the VSF2 trial (Table 2): with fertilization, basal area growth was similar for 122-cm and 91-cm mulch (16.1 and 16.5 mm^2), but without fertilization, basal area growth was greater for 122-cm mulch than for 91-cm mulch (23.8 vs. 12.3 mm^2). There were no differences in height or basal area growth between 14- and 28-g fertilizer treatments.

In the first year after planting, irrigation significantly increased seedling height growth only when mulch also was applied (VI trial; Fig. 2). After no irrigation in year 2, this effect was no longer significant. With all treatments receiving mulch, first-year irrigation increased height growth in that year (FI trial; Fig. 2), but second-year growth was greater for seedlings not irrigated in the first year. Second-year irrigation had no effect on growth.

Mean Θ was relatively low (11%) at the first reading on 29 April 2004. During the month of April, the VI study site had received 41 mm of precipitation; from 1 May until 18 June, precipitation totaled 85 mm, and from 18 June through 30 July, precipitation totaled 1 mm. In all treatments, Θ declined consistently during the latter period. Mean Θ across treatments was 6% on 30 July. Figure 3a shows relative soil water content, measured weekly from May through July 2004. In the nonirrigated treatment, relative soil water content was significantly lower ($p = 0.049$) in the absence of plastic mulch for the period of 18 June to 30 July (Fig. 3a). In the irrigated treatment, relative soil water content was not significantly affected by plastic mulch. Short-interval measurements showed that approximately 5 days after irrigation, relative soil water content had returned to the level prior to irrigation (Fig. 3b).

Planting Date

Planting date significantly affected the amount of new root growth between the time of planting and June of the first growing season ($p = 0.019$; degrees of freedom $= 6$). When contrasted with all six prior planting dates, root growth of seedlings planted on 1 April (0.97 g) was significantly less ($p = 0.008$) than that on the other dates (mean $= 1.47$ g). Root growth of seedlings planted on 27 February (1.28 g) did not differ from that on earlier planting dates, nor were there differences in root growth among the earlier planting dates.

Discussion

Although Oregon white oak can regenerate naturally on droughty sites, shoot growth during the seedling stage is

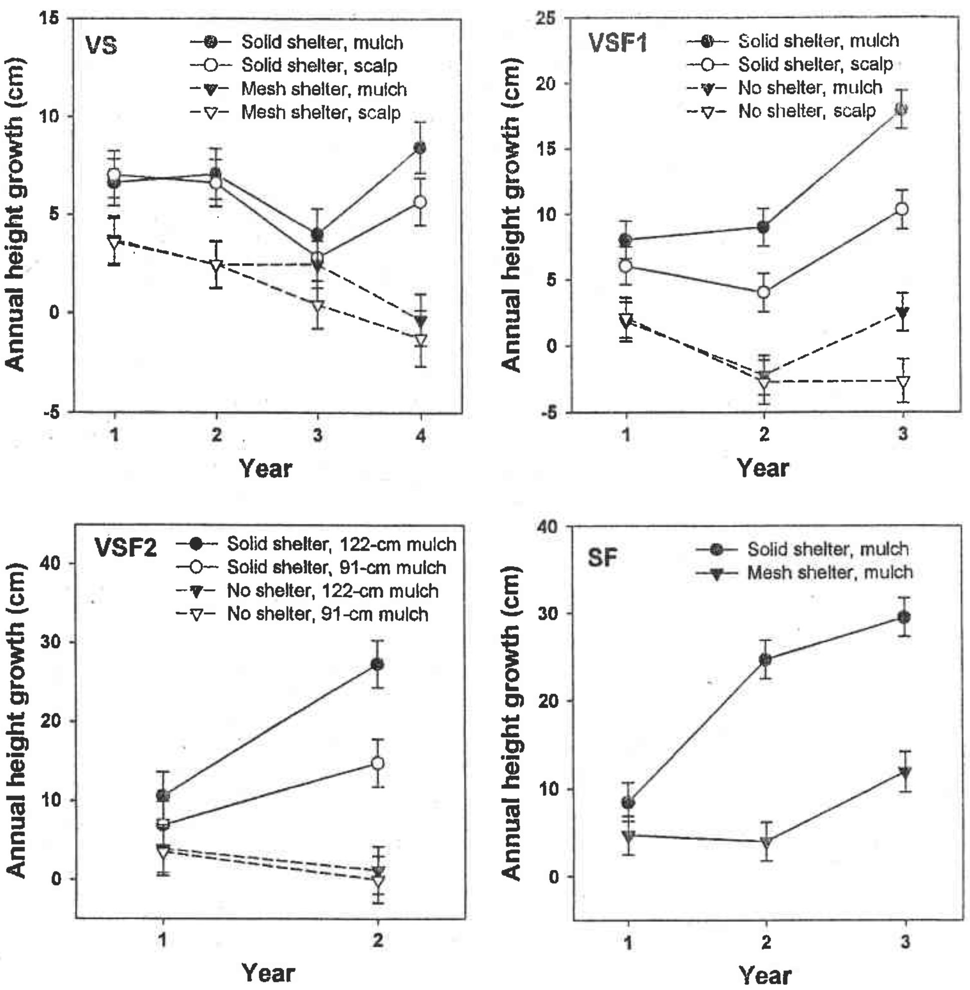

Figure 1. Annual height growth increments with standard error for various treatments in four Oregon white oak planting trials. Negative values are due to die-back or browse damage.

often very slow and shoot die-back is common (Stein 1990; Hibbs & Yoder 1993). Where lack of a seed source or severe seed predation necessitates planting of seedlings to meet restoration objectives, expectations for survival and growth of these seedlings are typically higher than for natural regeneration. In this study, we found that relatively intensive post-planting treatments were necessary to create the microsite conditions that lead to increased growth. Where these treatments were applied, growth rates were much greater than those previously reported for plantings on similar sites (Bell & Papanikolas 1997; Dunn & Grosboll 2002).

Survival rates were generally high in our study. In contrast to findings of Papanikolas (1997), Oregon white oak seedlings planted in full sun (i.e., in no-shelter and mesh shelter treatments) did not have significantly lower survival than those planted in shade (i.e., in solid-walled shelters that had approximately 30% full sun; Sharew & Hairston-Strang 2005). In a study located on soils similar to those of our study, Papanikolas (1997) attributed to drought stress the 15% first-year shoot survival of Oregon white oak seedlings planted in full sunlight. Seedlings planted under shade cloth (50% full sun) in the same study had 88% survival. Our results are more in agreement with those of Fuchs et al. (2000) who found no relationship between overstory shading and survival of 1-year-old Oregon white oak seedlings. By contrast, oak regeneration in the Mediterranean climates of Spain and California has been facilitated by shading (Callaway 1992; Espelta et al. 1995; Standiford et al. 1997; Rey Benayas & Camacho 2004). Although natural Oregon white oak regeneration is often more prevalent in shade, this may be due to proximity to seed source, patterns of seed hoarding by animals, or due to other factors not yet determined (Fuchs et al. 2000; Regan 2001).

Under a Mediterranean climate, soil moisture may limit the establishment of oak regeneration (Tyler et al. 2002). In our study, low growing-season precipitation, in combination with coarse-textured, rapidly draining soils, apparently resulted in limited soil water availability for

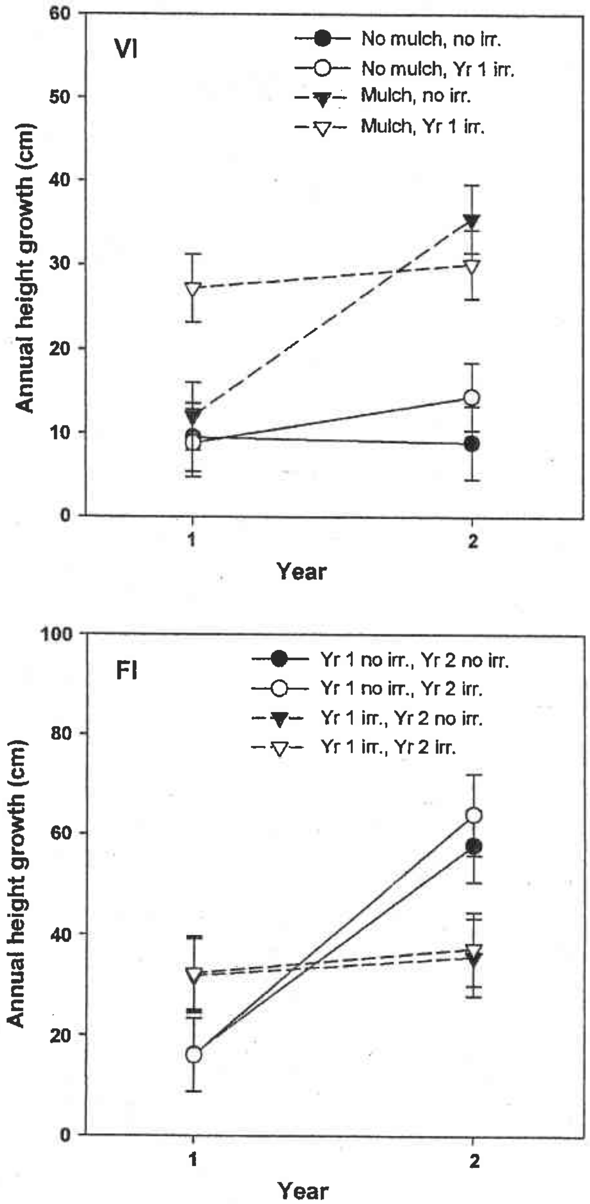

Figure 2. Annual height growth increments with standard error for various treatments in two Oregon white oak planting trials.

seedlings. Furthermore, herbaceous vegetation, dominated by graminoids, appeared to be a strong competitor for soil water because soil water content near seedlings was increased by the application of mulch. There was a trend in which seedling growth was greater when more intensive control of vegetation was applied (i.e., plastic mulch vs. scalping or no-vegetation control; 122-vs. 91-cm mulch). Under controlled conditions, herbaceous species, and grass in particular, significantly depleted soil water and reduced root and shoot growth of Blue oak (*Quercus douglasii* Hook. & Arn.) seedlings (Gordon et al. 1989). The competitive ability of grass was attributed to its

Table 4. Height–diameter ratio (H:D) of Oregon white oak seedlings in four trials comparing solid-walled tree shelters to mesh shelters or no shelter.

Trial	*Year*	*Solid-Walled Shelter*	*Mesh Shelter*	*No Shelter*	$p > F$
VS	At planting	34.2	33.6	—	0.801
	1	45.1	38.7	—	**0.025**
	2	56.8	42.3	—	**<0.001**
	3	66.3	50.9	—	**<0.001**
	4	73.0	42.8	—	**<0.001**
VSF1	At planting	42.5	—	44.8	0.127
	1	42.9	—	37.8	**0.002**
	2	63.1	—	39.2	**<0.001**
	3	77.8	—	43.9	**<0.001**
VSF2	At planting	45.7	—	45.6	0.992
	1	51.1	—	42.6	**0.001**
	2	74.7	—	40.0	**<0.001**
SF	At planting	40.3	41.8	—	0.556
	1	47.5	44.1	—	0.223
	2	68.0	43.9	—	**<0.001**
	3	93.2	50.3	—	**<0.001**

Significant differences between treatments ($\alpha = 0.05$) are given in bold face. Treatment comparisons (p values) are from ANOVA models of the same design as those in Tables 2 and 3; all comparisons shown have one degree of freedom.

fibrous root system. Elsewhere, control of graminoids by mulching significantly increased soil water content near planted seedlings (Bendfeldt et al. 2001).

Although first-year seedling growth was increased by irrigation, short-interval soil water measurements indicated that Θ was elevated for only 4–5 days after irrigation events. A shorter irrigation interval would be necessary to maintain increased Θ in these well-drained, sandy soils. The data collected approximately 7 days after each irrigation event showed no effect of irrigation.

We observed interactions between the effects of irrigation and other treatments. The interactive growth response to vegetation control and irrigation in year 1 of the VI trial indicated that seedlings benefited from supplemental water only when competing vegetation was controlled. Without mulch, the water was likely consumed by herbaceous vegetation. In both irrigation trials, there was a large increase in height growth from year 1 to year 2 for seedlings that were not irrigated in the first year but received mulch. This may be an indication of root development during the first year, leading to improved soil water access in the second year. In the FI trial, irrigation effects on height growth may have been influenced by tree shelter height. The fact that seedlings irrigated during year 1 grew less during their second year than those without year 1 irrigation was likely a result of the typical slowing of height growth (McCreary & Tecklin 2001) when the former group surpassed the tops of their solid-walled tree shelters earlier than the latter group.

As with other oak species (e.g., Minter et al. 1992; Mayhead & Boothman 1997; Sharpe et al. 1999; Quilhó et al. 2003), Oregon white oak responded to solid-walled

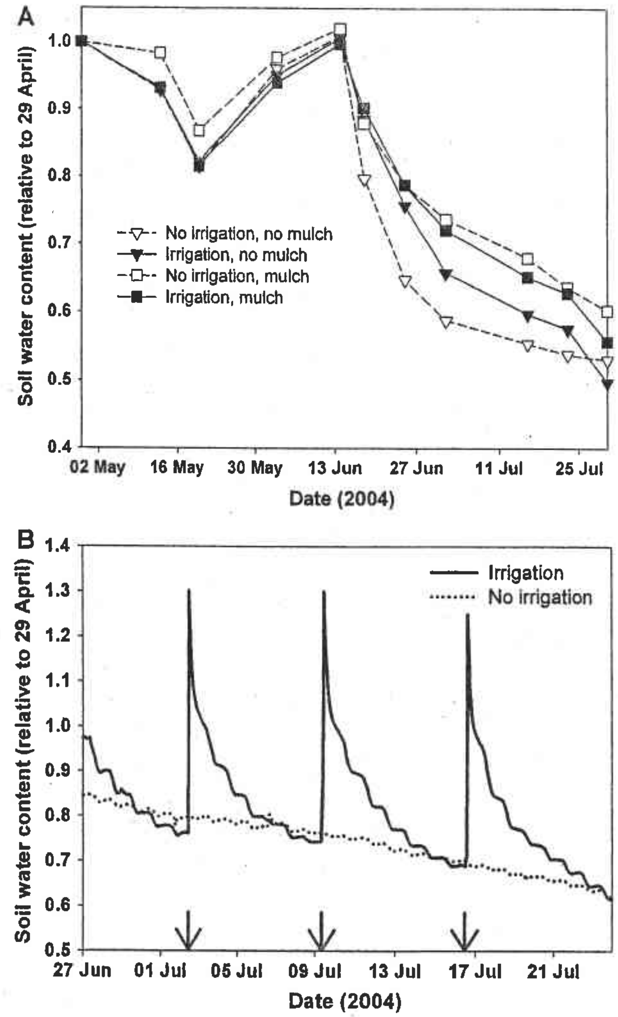

Figure 3. Volumetric soil water content (Θ), relative to the 29 April value, near planted Oregon white oak seedlings during the 2004 growing season in the VI (a) and FI (b) trials. Data were collected approximately 7 days after the last irrigation in the VI trial (a) and at 240-minute intervals in the FI trial (b). Arrows indicate time of irrigation in (b). In (a), Θ was significantly greater ($p < 0.05$) for nonirrigated seedlings with mulch than for nonirrigated seedlings without mulch.

tree shelters with greater height growth but no difference in basal area growth relative to no shelter or mesh shelters. Furthermore, the effect on height growth increased over time in all the shelter trials, except the VS trial. This increased height growth produced seedlings that were significantly more slender (i.e., greater H:D). This phenomenon has been attributed to lack of stem movement inside solid-walled shelters (Kjelgren & Rupp 1997; Johansson 2004) and etiolation due to the reduction in light (Gillespie et al. 1996). Once oak seedlings grow beyond the top of tree shelters, there is a significant increase in stem diameter growth rate accompanied by a decrease in height growth rate, resulting in a sturdier stem (McCreary & Tecklin 2001). Although the height growth advantage of solid-walled tree shelters eventually disappears after saplings grow above shelter height (Clatterbuck 1999), the primary function of shelters is protection from herbivory, and solid-walled shelters reduce the length of time, relative to mesh shelters, for saplings to grow above the height of animal browse.

For the young soils of glacial origin in the Pacific Northwest, and young soils elsewhere, N is often the nutrient most limiting plant growth (Steinbrenner 1979; Chapin et al. 1994; Chadwick et al. 1999). The lack of growth response to controlled-release N fertilizer may have been due to an insufficient application rate or due to disproportionate release of nutrients during the months when trees are dormant but soils are generally much wetter. Similarly, controlled-release fertilizer did not increase growth of planted Blue oak seedlings (McCreary 1995). However, in a study of California black oak (*Q. kelloggii* Newb.) seedlings, fertilization significantly reduced moisture stress (McDonald & Tappeiner 2002). This effect was attributed to better development of root systems among fertilized seedlings. Fertilizer efficacy under climates similar to that of our study area may be improved if controlled-release fertilizer with a more rapid nutrient release is applied to oak seedlings in spring.

Rapid growth of roots, particularly that of the taproot, is one of the primary mechanisms of drought avoidance for oak seedlings (Pallardy & Rhoads 1993). We found that root growth was significantly less for the 1 April planting date relative to earlier dates. Soil temperature (30 cm depth) at the study site remained below 10°C from the end of October through the first week of April and was below 5°C for 1 month beginning in mid-December. In a growth chamber trial, we recorded little root growth for Oregon white oak seedlings when air and soil temperatures were maintained at 14°C or lower (data on file at Olympia Forestry Sciences Laboratory). Similarly, Larson (1970) reported minimal root growth for Northern red oak (*Q. rubra* L.) at 13°C. Because planting in winter (with soil temperature <10°C) resulted in greater root growth by June relative to the 1 April planting, we must conclude, as did Larson (1970), that earlier planting confers an establishment advantage other than immediate regeneration of roots. Papanikolas (1997) found no difference in survival or shoot growth for Oregon white oak seedlings among planting dates from 5 September to 1 March, but growth and survival of bareroot Blue oak seedlings were lower when planted after early March (McCreary & Tecklin 1994).

Poor height and basal area growth in the VS trial may have been due to small seedling stock or due to the fact that seedlings used in that trial were grown in shallower containers than in the other trials, which may have negatively affected taproot development. In the VS trial, mean annual growth did not improve over time, whereas in most other trials, growth increased in the second or third year after planting. We attribute this trend, at least in part, to increasing root system development. Seedling size and root system morphology at the time of planting are known to influence early growth and survival of oak seedlings (Kormanik et al. 1995; Dey & Parker 1997). Thus, the planting of larger seedlings may result in greater early growth rates, which may be especially important where risk of herbivory or competition for soil water is severe.

Conclusions

Under droughty growing season conditions, control of competing vegetation was of primary importance for increasing growth of oak seedlings, whereas irrigation was an effective supplement to vegetation control during the first year of establishment. Results from fertilization treatments did not show a nutrient limitation, but further research in this area is needed. Browse pressure necessitated tree shelters, and although solid-walled shelters reduced stem taper, the increased rate of growth in these shelters may reduce the length of time for oak seedlings to reach the sapling stage, above the height of browsing animals and competing vegetation. Although trees are only one element of the oak woodland or savanna ecosystem, they are a vital structural component and thus a primary focus in restoration of these communities. Our results indicate that planting of seedlings, in conjunction with post-planting treatments, was an effective method of regenerating Oregon white oak where the absence of a seed source precluded natural regeneration.

Implications for Practice

- Survival rates were generally high for planted Oregon white oak seedlings (90% overall); however, post-planting treatments substantially increased early growth.
- Control of competing vegetation with plastic mulch (122 cm diameter) increased soil water content and seedling growth.
- Weekly irrigation at a rate of 3.8 L/seedling increased first-year growth, but only when plastic mulch was used.
- Solid-walled and mesh tree shelters prevented most browse damage, and solid-walled shelters significantly increased seedling height growth.
- Seedlings planted by late February had greater root growth than those planted in early April.

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