

Root Morphology and Growth of Bare-Root Seedlings of Oregon White Oak

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Abstract

Root morphology and stem size were evaluated as predictors of height and basal-area growth (measured at groundline) of 1-1 Oregon white oak (*Quercus garryana* Dougl. ex Hook.) seedlings planted in raised beds with or without an additional irrigation treatment. Seedlings were classified into three root classes based on a visual assessment of the fibrosity of their root systems. Early-season and late-season height and basal-area growth differed significantly among root classes after accounting for initial seedling size. Irrigation significantly increased late-season height growth, but not the other growth increments. Recommendations are made for grading seedlings to increase the growth of those that are outplanted.

Introduction

Interest has been increasing in recent years in restoring or recreating Oregon white oak (*Quercus garryana* Dougl. ex Hook.) savannas and woodlands in the Pacific Northwest. Oak savannas and woodlands were an important part of the historical landscape, especially in the Willamette Valley of Oregon (Sprague and Hansen 1946, Habeck 1962, Thilenius 1968), the Puget Lowlands of Washington (Crawford and Hall 1997, Thysell and Carey 2001, Foster and Shaff 2003), and eastern Vancouver Island, British Columbia (Gedalof and others 2006). Much of the area that was historically occupied by oak has been altered by agricultural and urban development and by succession to dense, conifer-dominated forests.

In some cases, land managers are planting oak to replace trees that have been lost or to create new stands in areas that were not historically occupied by oak. Planting often requires a significant investment in labor, browse protection, and control of competing vegetation (Devine and others 2007). High-quality seedlings are needed to ensure a high rate of survival and acceptable growth. Oak species in general are known for their high degree of variation in morphology and growth rates (Long and Jones 1996, Dey and Parker 1997). Grading seedlings so that only those

with a high growth potential are planted can improve the success of restoration projects.

Although little information is currently available on the production of Oregon white oak seedlings, studies of other species have shown that root morphology strongly affects growth and survival after outplanting. Seedlings with fibrous root systems generally have the best growth and survival (Davis and Jacobs 2005). The number of first-order lateral roots (FOLR) >1 mm (0.04 in) diameter at the junction with the taproot has proven a useful quantitative measurement for predicting growth in many studies (Ruehle and Kormanik 1986, Thompson and Schultz 1995, Dey and Parker 1997, Schultz and Thompson 1997). Qualitative visual assessments of root morphology have also proven effective for identifying seedlings with high growth potential. An advantage of this approach is that seedlings can also be graded quickly on the basis of root morphology, sometimes in combination with measurements of stem height and diameter (Clark and others 2000, Oswalt and others 2006).

Nursery practices such as undercutting and root-wrenching encourage lateral root development and discourage the development of deep roots that are lost when the seedlings are lifted (Schultz and Thompson 1997, Andersen 2004). These nursery practices are important to oaks and other species that otherwise have a strong tendency to form a deep taproot.

The purpose of this study was to evaluate how root morphology, seedling size, and the growing environment affect the growth of bare-root Oregon white oak seedlings. Root morphology was qualitatively assessed on 2-yr-old seedlings that were then outplanted into raised beds. Growth was measured over one growing season; subsets of seedlings were destructively sampled for biomass measurements and determination of the initial timing of root growth. Because the ability of roots to adequately move water and nutrients from the soil into the stem is a primary factor affecting the success of recently planted seedlings (Grossnickle 2005, Jacobs and others 2005), an irrigation

treatment was imposed to create conditions of high and low soil moisture. Seedling growth in the nursery during the growing season before outplanting and growth after outplanting were also summarized in order to evaluate strategies for culling seedlings with low growth potential.

Methods

Planting regime and seedling measurements. Seedlings were grown from acorns collected from two trees in Thurston and Mason Counties, Washington. Small and unsound acorns were discarded. The large and sound acorns were sown by hand in October 2004 at the Washington Department of Natural Resources Webster Nursery (lat 46.95° N, long 122.96° W) near Olympia, WA. Initial sowing densities ranged between 29 and 86 seedlings/rtf (between 3 and 8 seedlings/ft²); sowing density did not affect seedling size at the end of the first growing season (data not shown). Seedlings were undercut June 2, 2005, lifted in January 2006, and held in cold storage until they were transplanted into different nursery beds at a density of 29 seedlings/rtf (3 seedlings/ft²) in April 2006. A sample of seedlings (n=70) was selected for destructive sampling for biomass measurements at the end of the 2005 growing season. Seedlings were irrigated and fertilized while in the nursery beds during the 2005 and 2006 growing seasons.

Lifting and transplanting were not planned cultural treatments; rather, they were done because the original nursery beds were not going to be irrigated in 2006. Transplanting did provide an opportunity to impose an additional root treatment with the intention of increasing the range of root morphologies. Tap roots were pruned to a length of 15 cm (6 in) on approximately one-half of the seedlings right

before they were transplanted in April 2006. About one-half of the pruned seedlings and all unpruned seedlings were root-wrenched in August 2006 to encourage the development of fibrous root systems. Seedling height and basal diameter were measured once monthly during the 2006 growing season. Seedlings were lifted in January 2007 and placed in cold storage.

Between March 14 and 16, 2007, seedlings (n=273) were removed from storage, gently rinsed with water, tagged, photographed, and planted. Seedlings were assigned to one of three classes based on their root morphology (figure 1); those with the most fibrous root systems were assigned to root class 1, and those with the least fibrous systems, to root class 3. Six of the 273 seedlings died during the growing season: 5 in root class 3 and 1 in root class 2. All mortality occurred during the first half of the growing season.

Seedlings were planted at a density of 11 seedlings/m² (1 seedling/ft²) in eight raised beds [4.9 m (16 ft) long x 1.2 m (4 ft) wide x 0.6 m (2 ft) deep] located adjacent to the Webster Nursery at the Olympia Forestry Sciences Laboratory, Forest Service. The raised beds were used so that roots could easily be extracted for future sampling. The raised beds were constructed in early 2007 and filled with a well-drained sandy-loam soil. Four of the eight raised beds were assigned to the irrigation treatment; a drip irrigation system maintained high soil moisture throughout the growing season.

Another 29 seedlings were planted in large pots filled with the same soil and buried in two adjacent raised beds. These seedlings were excavated between April 30 and May 25 (i.e., 6-10 weeks after planting) to quantify new root growth at the beginning of the growing season. After

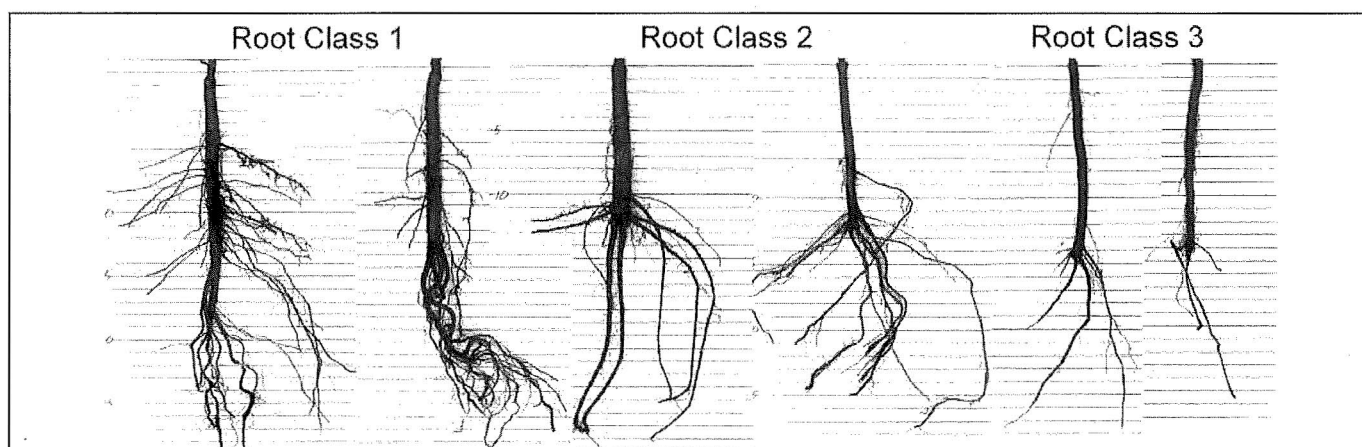


Figure 1. Examples of Oregon white oak seedlings that were classified into root class 1 (high root fibrosity; left two seedlings), root class 2 (moderate root fibrosity; middle two seedlings), and root class 3 (low root fibrosity; right two seedlings). The image is a composite of photographs of individual seedlings. Horizontal lines show 1 cm (0.4 in) gradations.

excavation and washing, the light-colored, succulent new roots were clipped from the seedlings, the remaining, older roots were divided into the small and large root categories, and all samples were oven-dried and weighed.

Seedling heights and diameter at groundline were measured shortly after planting, in the middle of the growing season, and at the end of the growing season. Basal area was calculated from diameter [basal area = $\pi (d/2)^2$] for growth comparisons. Early-season (May 1-July 31) and late-season (August 1-October 31) growth increments were calculated.

In order to quantify differences in seedling morphology among root classes, a set of seedlings was randomly selected before planting (n=56) and at the end of the growing season (n=33) for additional measurements. The number of FOLR [$>1\text{mm}$ (0.04 in) diameter] was counted and each seedling was partitioned into the shoot, small roots [$<5\text{mm}$ (0.2 in) diameter], and large roots, and then oven dried and weighed. The small and large root categories generally divided the root systems into lateral roots and the taproot, but they also provided a criterion for classifying woody roots without a simple taproot.

Data analysis. The effects of root class and irrigation on seedling height and basal-area growth were tested using the general linear model with initial height or basal area as a covariate (Neter and others 1996). Statistically significant differences for all tests are reported at $\alpha=0.05$. The Bonferroni joint-estimation procedure (Neter and others 1996) was used for multiple comparisons (e.g., among root classes) to maintain the type 1 error rate. Interactions between root class and irrigation were also tested, but these terms were not statistically significant and were dropped from the final models.

In order to examine strategies for culling seedlings with low growth potential, size-class transition rates were calculated for the 2006 growing season (when the seedlings were in nursery beds) and the 2007 growing season. Within each growing season, seedlings were classified into an initial size class (based first on height and second

on diameter at the beginning of the growing season) and a final height class (based on measurements at the end of the growing season). Transition rates among size classes were calculated as the percentage of seedlings in each initial size class that was assigned to each of the final size classes. Size classes were designated so that one-third of the seedlings fell into each class based on height and basal diameter. For example, the small size class included the shortest one-third of seedlings with ties broken first by basal diameter and then at random if basal diameters were also equal.

Results

About one-half of seedlings were assigned to root class 1, indicating a high degree of root fibrosity (table 1). The remaining seedlings were about equally divided between root classes 2 and 3. The root class assignments were not significantly associated with nursery treatments ($\chi^2=6.0$, $df=4$, $p=0.20$); however, the two wrenched treatments had greater percentages of seedlings assigned to class 1 (46 and 56 percent) than the unwrenched treatment (40 percent).

Seedlings assigned to the three root classes differed in several morphological traits (table 2). At the time of planting, seedlings in root class 1 were significantly taller than those in the other root classes and had a greater mean diameter than those in root class 3. Seedlings in root class 1 had significantly greater large root mass, small root mass, and number of FOLRs than those in the other two root classes. Differences between root classes 2 and 3 were not statistically significant for these measurements, but seedlings in root class 2 were larger in height and diameter than those in root class 3. Differences between root classes generally increased during the growing season. For example, the mean height difference between seedlings in root classes 1 and 3 was about 9 cm (3.5 in) at the beginning of the growing season and 24 cm (9.4 in) at the end.

All three root Classes had approximately equal root-shoot ratios (range, 3.4-3.8) at the beginning of the growing season. In comparison, the mean root-shoot ratio of seed-

Table 1. Percentages of Oregon white oak seedlings assigned to each root morphology class by nursery treatment.

Treatment	Root Class		
	1	2	3
Pruned-unwrenched	40	31	29
Pruned-wrenched	46	29	25
Unpruned-wrenched	56	20	24
All seedlings	48	26	26

Table 2. Summary of morphological traits by root morphology class at the beginning and end of the 2007 growing season. Means followed by different letters indicate significant differences ($\alpha = 0.05$) among root classes at the beginning or end of the growing season.

Measurement ¹	Beginning of season			End of season		
	Root class			Root class		
	1	2	3	1	2	3
Height (cm)	23.6a	19.1b	14.8c	53.0a	36.7b	28.8c
Diameter (mm)	7.3a	6.7a	5.8b	12.4a	11.2b	9.2c
Large-root mass (g)	6.2a	3.6b	2.9b	29.8a	13.3b	8.9b
Small-root mass (g)	3.5a	1.9b	1.4b	8.6a	5.4ab	2.9b
Stem mass (g)	3.3a	1.8ab	1.4b	27.5a	10.1b	4.7b
Root-shoot ratio (g/g)	3.5a	3.4a	3.8a	1.6b	2.6ab	3.4a
FOLR (n)	8.6a	5.0b	4.4b	18.4a	11.0b	7.7b

¹ Height and diameter were measured on all seedlings (n=273, beginning of season; n=267, end of season). Large root mass [>5 mm (0.2 in) diameter], small-root mass, stem mass, root-shoot ratio, and number of first-order lateral roots (FOLR) were measured on two sets of seedlings that were destructively sampled at the beginning (n=56) or the end (n=33) of the growing season.

lings from the same crop that were sampled after their first growing season was 4.1 (n=70 seedlings sampled in 2005). Root-shoot ratios were lower in all three root classes at the end of the growing season than at the beginning. The decline in root-shoot ratio was much greater in root class 1 than in the other two root classes, and root-shoot ratio was significantly lower at the end of the growing season in root class 1 than in root class 3.

Early root growth was significantly correlated with the mass of older small roots [<5 mm (0.2 in) diameter] in seedlings that were excavated in late April and May (figure 2). Seed-

lings in root class 1 had significantly more new root mass than those in root class 3. The mass of new roots in root class 2 was intermediate between root classes 1 and 3. New root mass was not significantly correlated with sampling date. Early root growth was mostly due to the elongation of existing first- and higher-order roots, rather than the emergence of new lateral roots. Root elongation was already underway, but most seedlings had not yet broken bud, when seedlings were first sampled on April 30.

Root classes differed significantly in height and basal area growth (figure 3), but late-season height growth was the

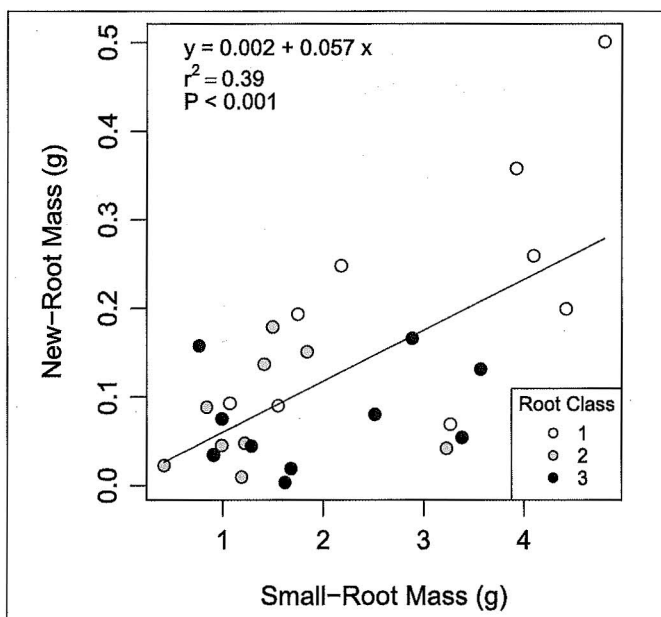


Figure 2. The growth of new roots sampled between April 30 and May 25. New-root mass (y-axis) was significantly correlated with the mass of older small roots (x-axis), but it was not correlated with sampling date. The mass of new roots differed significantly between the three root morphology classes, with the greatest mass in root class 1.

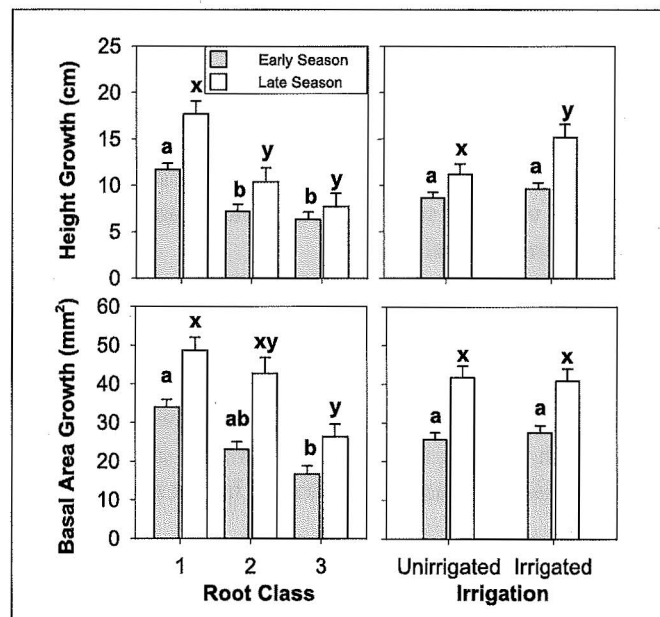


Figure 3. Mean height and basal-area growth for the three root morphology classes and the irrigation treatments. Early-season growth (grey bars) includes growth through July 31; late-season growth (white bars) includes growth from August 1 to October 31. Different letters over the bars indicate significant differences ($\alpha=0.05$) among treatments (a and b for early-season growth; x and y for late-season growth).

only growth increment that was increased by irrigation. The difference in late-season height growth between irrigation treatments [4 cm (1.6 in)] was small relative to the difference between root classes 1 and 3 [10 cm (3.9 in)]. Both height and basal area growth were greater in the second half of the growing season than in the first. Total height growth of seedlings in root classes 1, 2, and 3 averaged 29, 18, and 14 cm, respectively. Total basal area growth of seedlings in the three respective classes was 83, 66, and 43 mm² (0.12, 0.10, and 0.07 in²),

In addition to root class, initial height and basal area were statistically significant predictors of height and basal-area growth, respectively. Both predictors were positively correlated with growth. The percentage of observed variation in growth that was explained by the statistical models was low in all cases, with r^2 between 0.11-0.20.

The size-class transition rates calculated for the 2006 and 2007 growing seasons indicated that slow-growing seedlings may be identified for culling after the first growing season (figure 4). During 2006 (the second growing season in the nursery), only 10 percent of seedlings that were initially in the small size class [<5 cm (2 in) tall] grew into the large size class [>18 cm (7 in) tall]; thus, culling these seedlings would have had little effect on the number of large seedlings

at the end of the growing season. The likelihood of seedlings transitioning between the small and large size classes diminished after outplanting. Only 3 percent of seedlings in the small size class transitioned into the large size class, while 73 percent remained in the small size class. Size-class transition rates could not be directly calculated between growing seasons because seedlings were not tagged before lifting; however, based on the transition rates for the individual years, only 19 percent of seedlings that were in the small size class after the first growing season would be expected to reach the large size class 1 yr after outplanting. About 54 percent of seedlings in the large size class at the end of the first year in the nursery would be expected to remain in the large size class 1 yr after outplanting.

Discussion

The growth of Oregon white oak seedlings is highly variable, but it is affected by initial seedling size and root morphology. Seedling size (height or basal area) and root class were significant predictors of growth in linear models that included both variables, indicating that both size and root class are separate indicators of seedling vigor. The visual assessment of root morphology was valuable for identifying seedlings that had relatively high root mass and a high number of FOLR. Seedlings in root class 1 also had relatively high new root growth in the early growing season, which is essential for successful seedling establishment (Grossnickle 2005).

Root class was not associated with nursery treatments that were imposed at the time of transplanting or late in the second growth season; however, these treatments might have been more effective if all seedlings had not already received some root management in the first season (undercutting in June) and again when they were lifted in January. Although it was not statistically significant, there was some evidence that root pruning reduced the percentage of seedlings in root class 1, possibly due to the removal of some FOLR (Kaczmarek and Pope 1993). Root pruning may not offer additional benefits in nursery regimes that already include undercutting to reduce the length of the taproot and root wrenching to increase root fibrosity.

Irrigation increased late-season height growth but did not significantly affect the other growth increments. Oregon white oak has a determinant growth habit, and early-season growth may have been more strongly affected by the number of leaf primordia in the bud at the beginning of the growing season than by soil moisture. Late-season

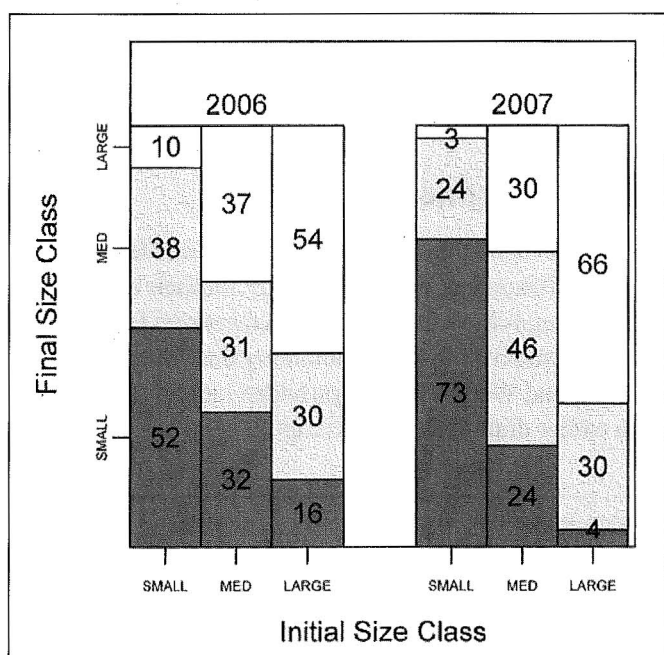


Figure 4. Size-class transition rates of Oregon white oak seedlings during the 2006 growing season (in nursery beds) and 2007 growing season (outplanted in raised beds). Size classes were designated based on seedling height and basal diameter so that each initial and final size class contained one-third of the seedlings measured during each growing season.

height growth presumably reflected additional flushes from terminal buds formed during the growing season. Nevertheless, the magnitude of the irrigation effect was small compared to growth differences among root classes. Possibly the effect of irrigation would have been greater if there had been less summer rainfall. Precipitation in May through September 2007 was 185 mm (7.3 in), which is slightly less than the long-term average [203 mm (8.0 in)]. However, several rain events during the growing season helped to maintain soil moisture. The total precipitation in July was more than twice the average due to one large rain and several smaller ones.

Although the pattern of decreasing soil moisture during the growing season that is typical of the Pacific Northwest did not occur over the course of this study, Oregon white oak are often planted in dry and nutrient-poor soils and typically must compete with other vegetation for soil moisture and growing space (Devine and Hanington 2007; Devine and others 2007). The survival and early growth of seedlings depend on their ability to quickly recover from the stress caused by lifting, storage, and planting and their ability to develop a root system that can adequately supply the seedling with water and nutrients (Rietveld 1989; Grossnickle 2005). Seedlings in root class 1 likely benefited from their high initial root area and the high root growth potential that was observed among those seedlings that were excavated at the beginning of the growing season.

Seedlings in root class 1 had a lower root-shoot ratio at the end of the growing season than those in root classes 2 and 3; however, root-shoot ratio should not necessarily be viewed in this case in terms of a trade-off between root and shoot growth. Seedlings in root class 1 had considerably greater above- and below-ground growth after outplanting than those in the other root classes. These seedlings were clearly vigorous, and the decrease in root-shoot ratio was the result of the normal changes in morphology (e.g., greater above-ground biomass) that occurs as trees grow larger (Monk 1966).

Culling may be an important tool for improving the vigor of Oregon white oak seedlings at the time of outplanting. Oregon white oak is a slow-growing species in general (Hibbs and Yoder 1993), and some of the seedlings used in this study grew particularly slowly. Growing conditions over the life of the seedling were generally very favorable; however, at the end of this study approximately 25 percent of the 3-yr-old seedlings were still <24 cm (9.4 in) tall. In this study and related nursery trials, we have observed that

the growth of some seedlings appears to stagnate early and the seedlings remain small over multiple growing seasons. Identifying and removing slow-growing seedlings at an early age may help to reduce losses later.

Conclusions

As is the case with many other tree species, root morphology is an important factor in determining the quality of Oregon white oak seedlings. Although growth was not tested across the same range of growing conditions that seedlings encounter in operational outplantings, seedlings with fibrous root systems should have the best growth and survival under most growing conditions. Nursery managers should consider applying root-management treatments to encourage development of fibrous root systems. When practical, Oregon white oak seedlings should be graded based on a combination of height, diameter, and root morphology to increase the percentage of outplanted planted seedlings that have a high growth potential. It may also be effective to sow acorns at very high densities [e.g., >100 acorns/m² (9 acorn/ft²) and then heavily cull seedlings during or after the first growing season. Land managers should likewise select large seedlings with fibrous root systems, when available, for outplanting.

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REFERENCES

- Andersen, L. 2004. Field performance of *Quercus petraea* seedlings grown under competitive conditions: influence of prior undercutting in the seedbed. *New Forests*. 28: 37-47.
- Clark, S.L.; Schlarbaum, S.E.; and Kormanik, P.P. 2000. Visual grading and quality of 1-0 northern red oak seedlings. *Southern Journal of Applied Forestry*. 24: 93-97.

- Crawford, R.C.; H. Hall. 1997. Changes in the South Puget Sound landscape. In: Dunn, P.; Ewing, K., eds. Ecology and Conservation of the South Puget Sound Prairie Landscape. Seattle, WA: Nature Conservancy: 11-15.
- Davis, A.S.; Jacobs, D.F. 2005. Quantifying root system quality of nursery seedlings and relationship to outplanting performance. *New Forests*. 30: 295-311.
- Devine, W.D.; Harrington, C.A. 2007. Release of Oregon white oak from overtopping Douglas-fir: effects on soil water and microclimate. *Northwest Science*. 81: 112-124.
- Devine, W.D.; Harrington, C.A.; and Leonard, L.P. 2007. Post-planting treatments increase growth of Oregon white oak (*Quercus garryana* Dougl. ex Hook.) seedlings. *Restoration Ecology*. 15: 212-222.
- Dey, D.C.; Parker, W.C. 1997. Morphological indicators of stock quality and field performance of red oak (*Quercus rubra* L.) seedlings underplanted in a central Ontario shelterwood. *New Forests*. 14: 145-156.
- Foster, J.R.; Shaff, S.E. 2003. Forest colonization of Puget Lowland grasslands at Fort Lewis, Washington. *Northwest Science*. 77: 283-296.
- Gedalof, Z.; Pellatt, M.; and Smith, D.J. 2006. From prairie to forest: three centuries of environmental change at Rocky Point, Vancouver Island, British Columbia. *Northwest Science*. 80: 34-46.
- Grossnickle, S. 2005. Importance of root growth in overcoming planting stress. *New Forests*. 30: 273-294.
- Habeck, J.R. 1962. Forest succession in Monmouth Township, Polk County, Oregon since 1850. *Proceedings of the Montana Academy of Sciences*. 21: 7-17.
- Hibbs, D.E.; Yoder, B.J. 1993. Development of Oregon white oak seedlings. *Northwest Science*. 67: 30-36.
- Jacobs, D.F.; Salifu, K.F.; and Seifert, J.R. 2005. Growth and nutritional response of hardwood seedlings to controlled-release fertilization at outplanting. *Forest Ecology and Management* 214: 28-39.
- Kaczmarek, D.J.; Pope, P.E. 1993. The effects of pruning treatments and initial seedling morphology on northern red oak seedling growth. In: *Proceedings, 9th Central Hardwood Forest Conference*; 1993 March 8-10; West Lafayette, IN. General Technical Report NC-161. St. Paul, MN: U.S. Department of Agriculture (USDA), Forest Service, North Central Forest Experiment Station: 436-446.
- Long, T.J.; Jones, R.H. 1996. Seedling growth strategies and seed size effects in fourteen oak species native to different soil moisture habitats. *Trees-Structure and Function*. 11: 1-8.
- Monk, C.D. 1966. Root-shoot dry weights in loblolly pine. *Botanical Gazette*. 127: 246-248.
- Neter, J.; Kutner, M.H.; Nachsheim, C.J.; and Wasserman, W. 1996. *Applied Linear Statistical Models*. 4th ed. Boston: WCB McGraw Hill.
- Oswalt, C.M.; Clatterbuck, W.K.; and Houston, A.E. 2006. Impacts of deer herbivory and visual grading on the early performance of high-quality oak planting stock in Tennessee, USA. *Forest Ecology and Management*. 229: 128-135.
- Rietveld, W.J. 1989. Transplant stress in bareroot conifer seedlings: its development and progression to establishment. *Northern Journal of Applied Forestry*. 6: 99-107.
- Ruehle, J.L.; Kormanik, P.P. 1986. Lateral root morphology: a potential indicator of seedling quality in northern red oak. *RN-SE-344*. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC. 6 p.
- Schultz, R.C.; Thompson, J.R. 1997. Effect of density control and undercutting on root morphology of 1+0 bareroot hardwood seedlings: five-year field performance of root-graded stock in the central USA. *New Forests*. 13: 301-314.
- Sprague, F.L.; Hansen, H.P. 1946. Forest succession in the McDonald Forest, Willamette Valley, Oregon. *Northwest Science*. 20: 89-98.
- Thilenius, J.F. 1968. The *Quercus garryana* forests of the Willamette Valley, Oregon. *Ecology*. 49: 1124-1133.
- Thompson, J.R.; Schultz, R.C. 1995. Root system morphology of *Quercus rubra* L. planting stock and 3-year field performance in Iowa. *New Forests*. 9: 225-236.
- Thysell, D.R.; AB. Carey. 2001. *Quercus garryana* communities in the Puget Trough, Washington. *Northwest Science*. 75: 219-235.