Warren D. Devine [1] and **Constance A. Harrington**, USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3625 93rd Ave. SW, Olympia, Washington 98512

Root System Morphology of Oregon White Oak on a Glacial Outwash Soil

Abstract

Oregon white oak is reportedly a deeply rooted species, but its rooting habit on coarse-textured soils is undocumented. In the Puget Trough of western Washington, Oregon white oak grows in coarse-textured glacial outwash soils on lowland sites. Our objective was to quantify the gross root system morphology of Oregon white oak in these soils, thereby improving our understanding of its belowground resource acquisition on these sites. Study trees were located on a Spanaway gravelly sandy loam soil near Olympia, Washington. Root systems of 27 oak trees (age 3-95 yr) were excavated and measured. Root systems of seedlings and small trees had prominent taproots, but root systems of larger trees were structurally dominated by shallow lateral roots. Vertical penetration of roots, including the taproot, was restricted by gravelly and cobbly layers within the C horizon, which began at a depth of about 70 cm. Although most roots were located in the finer-textured A horizon, some small roots penetrated to depths greater than 150 cm, where soils remain moist in summer. The predominance of shallow roots suggests that management of understory vegetation or overstory conifers, which both have a similar rooting zone, will likely influence growth and survival of oak. Activities, such as vehicular traffic, that significantly disturb surface soils may adversely affect oak trees.

Introduction

Oregon white oak (*Quercus garryana*), also called Garry oak, occurs on a wide range of sites and under varied climatic conditions from southern British Columbia, Canada to southern California, USA (Stein 1990). In the Pacific Northwest, Oregon white oak is found on diverse sites including poorly drained alluvial soils in Oregon's Willamette Valley (Thilenius 1964), rock outcrops of Vancouver Island, British Columbia (Erickson 2000), and glacial outwash plains of Washington's Puget Trough (Thysell and Carey 2001). In the southern Puget Sound region of Washington, Oregon white oak exists in several community types including an open oak woodland with a grassy understory, an oak woodland with a shrub understory, and a closed-canopy forest co-dominated by Douglas-fir (*Pseudotsuga menziesii*) (Chappell and Crawford 1997). In this region, these oak community types are often found on rapidly draining sandy and gravelly soils formed on glacial outwash plains resulting from the Vashon glaciation 14,000 years ago (Kruckeberg 1991). The Mediterranean climate of the coastal Northwest, in combination with these glacially derived soils, creates a unique set of conditions under which Oregon white oak is the only naturally occurring species of oak.

A fire-tolerant species, Oregon white oak was maintained on these sites, often in open savannas, by the frequent, low-intensity fires set by Native Americans prior to European settlement (Agee 1993). A dramatic decrease in fire frequency since the mid-1800s has resulted in a loss of oak savannas and woodlands as fire-intolerant conifers have regenerated within oak stands and quickly overtopped the slow-growing, shade-intolerant oak trees. Many of the oak stands that exist today are small in size and ecotonal, occupying narrow margins between prairies and conifer forests (Ryan and Carey 1995).

Foremost in managing and restoring the remaining oak stands is control of the invading conifers, the most prevalent of which is Douglas-fir. Although the shade created by the much taller conifers is a significant deterrent to oak's survival (Barnhart et al. 1996), the degree of belowground competition for water and nutrients is largely unquantified. Excessively drained soils combined with low growing-season precipitation may provide conditions that promote competition for water and nutrients during the months that the oak trees are foliated. An understanding of this competition requires basic knowledge of the root systems of both of these species. Root system morphology of Douglas-fir on coarse-textured, glacial outwash soils was described previously (Eis 1974), but the rooting habit of Oregon white oak on these soils has not been reported.

[1] Author to whom correspondence should be addressed. E-mail: wdevine@fs.fed.us

Ugolini and Schlichte (1973) hypothesized that Oregon white oak trees growing on sandy, well-drained soils tolerate droughty summer conditions because they have a long taproot. The limited amount of information that exists on the root morphology of Oregon white oak seems to support this hypothesis. Stein (1990) described the morphology as a deep taproot and extensive lateral roots. Oregon white oak seedlings growing on a silt loam soil in Oregon's Willamette Valley had taproot-dominated root systems with small lateral roots (Hibbs and Yoder 1993).

However, all of the previous data on Oregon white oak root system morphology were for trees growing in finer textured soils. As an initial step in understanding Oregon white oak's below-ground resource acquisition in coarse-textured glacial soils, we assessed whether root systems of Oregon white oak in these soils were similar to those described in previous studies for other soil conditions. We examined trees from a range of ages to document age-related changes in root morphology. Our specific objectives were to: *i*) determine whether root systems were taprooted, and if so, document the size of the taproot, and *ii*) assess the size, vertical distribution, orientation, and radial symmetry of lateral roots.

Methods

Study Site and Trees

The study took place on Fort Lewis Military Reservation, east of Olympia, WA. Study trees were located near the northeastern edge of Upper Weir Prairie (Thurston County; 46° 55' N, 122° 42' W). Mean annual temperature is 10.0° C; mean temperatures in January and July are 3.3° C and 17.3° C, respectively (Western Regional Climate Center 2004). Mean annual precipitation is 1293 mm, of which an average of only 189 mm occurs between May 1 and September 30. The study area was an ecotonal oak woodland, about 800 m in length and 100 m in width, bordered on one side by prairie and on the other side by a forest with a Douglas-fir canopy. Common understory species consisted of long-stolon sedge (*Carex inops*), Scots broom (*Cytisus scoparius*), kinnikinnick (*Arctostaphylos uva-ursi*), Oregon white oak, and snowberry (*Symphoricarpos albus*).

The site was a level glacial outwash terrace with soils of the Spanaway series (sandy-skeletal, mixed, mesic Typic Melanoxerands) (Pringle 1990). During the root system excavations in this study, we examined the soil profile at 13 locations within the study area. At each of these locations we recorded the depths of the soil horizon boundaries and made a brief description of each horizon including estimates of coarse fragment content (gravel, cobbles, and stones). A typical soil profile at the study site (Table 1) consisted of a thin organic horizon over a dark, gravelly sandy loam A horizon that contained volcanic ash as well as charcoal from the frequent, pre-settlement prairie fires ignited by Native Americans (Ugolini and Schlichte 1973, Pringle 1990). This horizon was underlain by a Bw horizon of very gravelly sand and a C horizon (70 to >200 cm) that consisted of numerous layers of glacial outwash sand with a gravel content ranging from 75% to 85%. Although the C horizon described in Table 1 was typical, the stratified layers of glacial outwash within this horizon varied from 0 to >99% coarse fragments

TABLE 1. Typical soil profile description for the study site on Upper Weir Prairie, Fort Lewis Military Reservation, Washington, USA.

Horizon	Depth (cm)	Munsell color (moist)	Texture	Structure	Coarse Fragments (% vol.) Gravel	Cobbles	Stones	Roots[1] <1 mm	1-2 mm	2-5 mm	5-10 mm
O	2-0	10YR 2/1		weak very fine granular	5	0	0	M	M	C	F
A	0-50	10YR 2/2	SL	weak fine granular	35	1	1	M	M	C	F
Bw	50-70	10YR 5/4	S	weak fine granular to single grain	55	5	1	M	M	F	F
2C1	70-105	10YR 4/2	S	single grain	75	5	1	C	F	F	F
2C2	105-185	10YR 4/2	S	single grain	80	5	1	C	F	F	F
2C3	185-200+	10YR 5/3	S	single grain	85	5	1	F	-	-	-

[1] By diameter class; M=many, C=common, F=few.

TABLE 2. Aboveground characteristics of the 27 Oregon white oak study trees (mean with standard deviation in parentheses).

Size Class	n	Stem age (years)	Diameter at 15 cm (cm)	dbh (cm)	Height (m)	Crown diameter (m)
Seedlings	14	7 (2)	1.2 (0.8)	-	1.0 (0.5)	-
Small trees	8	22 (6)	12.3 (3.6)	8.4 (2.6)	5.1 (1.0)	2.7 (0.6)
Large trees	5	93 (2)	-	39.6 (10.8)	16.1 (1.9)	10.0 (2.6)

(gravel and cobbles). The depth, thickness, and coarse fragment content of the soil horizons varied by microsite, but we observed no broad spatial trends in the soil profile across the study site.

In June 2003, we selected 27 Oregon white oak study trees ranging in height from 0.4 to 18.5 m (Table 2). Selection criteria were no crown contact with trees of other species, no overtopping by other trees, and a minimum distance between study trees of 5 m for seedlings and 20 m for trees. For each study tree we recorded height and diameter [diameter at breast height (dbh) for trees >1.3 m in height; diameter at 15 cm above groundline (D15) for trees ≤1.3 m]. Using an increment borer, we extracted a stem core at 15 cm above groundline to determine tree age.

Root System Excavation

We extracted the root systems of 14 seedlings (D15 <5.0 cm) from the soil using a combination of hand tools (shovel, pry-bar, hand spade) and an Air-Spade® Series 2000 supersonic excavator (Concept Engineering Group, Inc., Verona, Pennsylvania). The Air-Spade® was powered by a Sullair 185 air compressor (Sullair Corp., Michigan City, Indiana) capable of delivering 5.24 m^3 of air min^{-1} at 7.03 kg cm^{-3}. The Air-Spade® directs a supersonic jet of air that displaces soil and small rocks while leaving tree roots ≥1 mm diameter intact. We excavated seedling root systems to a mean depth of 1.0 m. Any deeper roots were severed (mean taproot diameter at the point of severance was 6.5 mm). We extracted at least the first 50 cm of all first-order lateral roots (FOLR; i.e., all roots originating from the taproot). Ten of these seedling FOLR were extracted beyond 50 cm to the maximum length possible which was typically until their diameter became less than 1 mm. Following extraction, seedling root systems were transported to the laboratory for measurement.

We partially excavated the root systems of eight small trees (D15 ≥5.0 cm and dbh <20.0 cm) and five large trees (dbh ≥20.0 cm) to facilitate root measurements *in situ*. Excavations were made with a mini-excavator [Takeuchi TB016 and TB135 (Takeuchi U.S., Buford, Georgia) and Bobcat 331 (Bobcat Company, West Fargo, North Dakota)], an Air-Spade®, and hand tools. We used the mini-excavator to dig one to three radially oriented trenches near each tree and then used the Air-Spade® to blow the soil away from the central root system and into the trenches, exposing the taproot to a depth of up to 1.8 m and exposing at least the first 50 cm of all FOLR. Although we excavated most trees to the maximum rooting depth (the point at which the taproot and the FOLR no longer grew downward), we were unable to reach the maximum rooting depth for two large trees due to mechanical limitations.

Root System Measurements

For seedlings and trees, we began our measurement of the root system with the taproot (defined as the primary root descending from the base of the stem) and then measured the FOLR. We defined the origin of the taproot as the root collar. Where the taproot branched, we designated the largest of the root branches as the taproot and all others as FOLR. We measured taproot diameter at 20-cm intervals beginning at the root collar and terminating at the tip or farthest exposed point. At points where the root was not round, we measured the largest diameter and the diameter perpendicular to the largest. For each of the 20-cm segments between diameter measurements, we measured the segment's vertical angle (e.g., 90 degrees = horizontal; 180 degrees = downward) to the nearest 5 degrees.

On seedlings we measured each FOLR ≥2.0 mm in diameter. On small and large trees we measured each FOLR ≥5.0 mm in diameter and tallied the number of FOLR between 2 and 5 mm in diameter for each 20-cm taproot section. For both seedlings and trees, we measured diameter of each FOLR as close to the origin (i.e., the junction with the taproot) as possible but beyond any significant taper associated with the junction. We measured the vertical distance between the point of origin of each FOLR and the groundline at the base of the stem as well as the location of each FOLR on the taproot relative to the taproot's origin (i.e., the distance from the root collar via the taproot). We recorded the azimuth and vertical angle (nearest 5 degrees) of the first 50 cm of each FOLR.

Data Analyses

Most analyses were based on root cross-sectional area (CSA). For non-round roots, CSA was calculated using the arithmetic mean of the two diameter measurements (Biging 1983). Our use of CSA was based on the assumptions of the pipe stem model summarized by Bengough et al. (2000). In this model the sum CSA of higher-order "daughter" roots is proportional to their "parent" root. Thus, we assumed that the functional importance of each FOLR was proportional to its CSA.

We used two-way analysis of variance to compare mean root CSA among depth intervals and angle classes (Proc Mixed; SAS Institute Inc. 2000). Data were log-transformed to meet the requisite variance assumptions (Snedecor and Cochran 1967). Protected mean separations were performed using Fisher's Least Significant Difference test. We used regression to examine the relationship between total per-tree FOLR CSA and CSA at the root collar (Proc Reg; SAS Institute Inc. 2000). We analyzed the symmetry of the radial distribution of the FOLR of each tree using the method described by Nicoll et al. (1995). In this analysis, each FOLR was treated as a vector with an azimuth of theta and a length equal to the fraction of tree's total FOLR CSA that the individual root comprised. The sum of these vectors was a single vector with a length of L and an azimuth of theta representing the deviation from a perfectly symmetrical radial distribution of FOLR CSA. A large L value indicated asymmetrical distribution (or "clustering"), while a small L value indicated radial uniformity. We then used the statistical test described by Nicholl et al. (1995) to determine whether the radial root distribution was significantly non-uniform. A significance level of $P = 0.05$ was used in all analyses.

Results

Taproot Morphology

Twenty-six of the 27 study trees had clearly defined taproots. The mean excavated length of the seedling taproots was 96 cm. The trench-based excavation procedure used for small and large trees facilitated excavation to an average length of 204 cm (Table 3). The ratio of CSA of taproots to CSA of FOLR was greater for seedlings than for small or large trees. Among seedlings, the mean CSA of the first 40 cm of the taproot was 25 times greater than that of the FOLR occurring from 0 to 40 cm; among large trees, this difference was only nine-fold. This trend resulted in seedlings having a distinctly taprooted appearance, while the root systems of large trees had relatively dominant lateral roots in addition to the taproot.

On average, seedling taproots did not begin to taper until below the 40-cm point (Figure 1). Small- and large-tree taproots tapered to averages of 59% and 18% of their respective root collar CSAs by the 40-cm point. At the 100-cm point, taproot CSA for trees of all sizes had tapered to less than 10% of that at the root collar. The taproots of 11 of the 14 seedlings and 3 of the 8 small trees thickened dramatically near the surface of the mineral soil. For both seedlings and small trees, the taproot CSA increased below the root collar due to this swelling. This feature was previously reported for Oregon white oak and described as a "knob" (Hibbs and Yoder 1993). While tree stems originated from the top or sides of this knob, we also observed lateral roots originating from the knob.

TABLE 3. Belowground characteristics of the 27 Oregon white oak study trees (mean with standard deviation in parentheses).

Size class	Excavation depth (m)	Length of excavated taproot (cm)[1]	Total number of FOLR	Number of FOLR in top 40 cm of soil
Seedlings	1.0 (0.5)	95.7 (52.8)	13.9 (6.6)	12.8 (6.7)
Small trees	1.3 (0.3)	203.1 (60.3)	39.6 (7.8)	20.9 (9.2)
Large trees	1.7 (0.1)	204.4 (20.3)	41.2 (10.2)	14.6 (10.8)

[1] Excavated length was limited by soil physical properties, particularly coarse fragments. Average taproot CSA at the distal end was 11.5%, 2.8%, and 1.0% of root collar CSA for seedlings, small trees, and large trees, respectively.

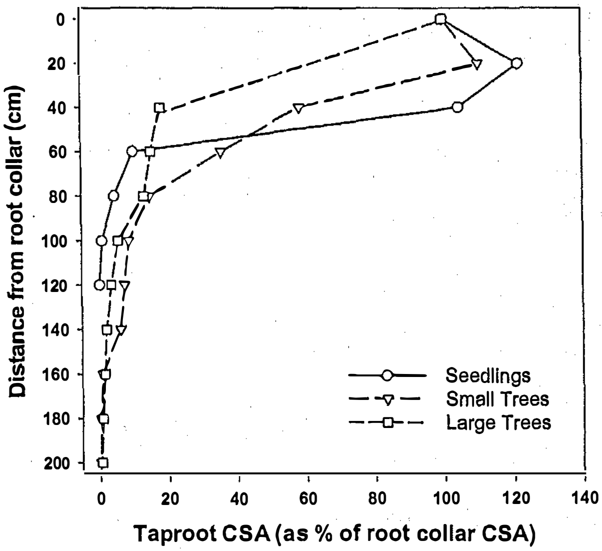

Figure 1. Mean taproot CSA (as % of root collar CSA) at 20-cm intervals (0 cm = root collar) for Oregon white oak trees in three size classes.

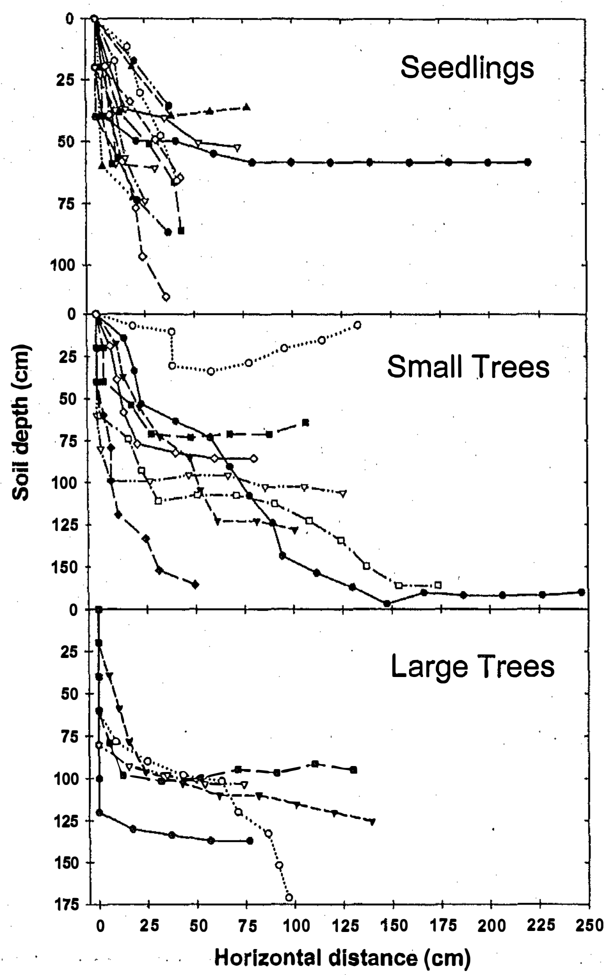

Figure 2. Horizontal distance from root collar versus depth for taproots of Oregon white oak trees in three size classes. Each line represents a separate tree.

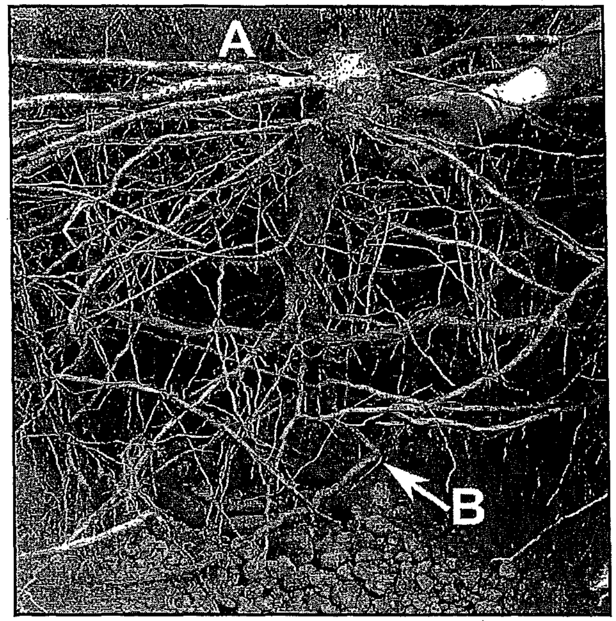

Figure 3. Root system of a small Oregon white oak (height = 4.0 m; age = 25 yr). The largest lateral roots are near the surface (A); the taproot began to grow horizontally at a soil depth of 80 cm (B).

Taproots of 12 of the 13 small and large trees and 11 of the 14 seedlings descended nearly vertically for the first 60 cm of their length below the root collar, but departed from this vertical orientation beyond 60 cm (Figure 2). The taproot of every small and large tree that we excavated grew horizontally or nearly so for part of its length. Most taproots acquired a horizontal orientation between 60 and 120 cm below the root collar (Figures 3 and 4). Only one of the large trees had a taproot that appeared likely to reach a soil depth greater than 175 cm.

First-Order Lateral Roots

The CSA of FOLR for each seedling and tree was summed within 10-cm soil depth intervals. For seedlings, an average of 92% of total FOLR CSA occurred at soil depths from 0 to 40 cm (Figure 5). For both small trees and large trees, an average of 77% of total FOLR CSA occurred at soil depths from 0 to 40 cm. Averages of 0%, 1%, and 7% of total FOLR CSA for seedlings, small trees, and large trees occurred below a soil depth of 80 cm, respectively.

Mean CSA of individual FOLR decreased with depth for small and large trees; for seedlings, this pattern was not apparent (Figure 6). While the frequency of FOLR in the largest CSA classes

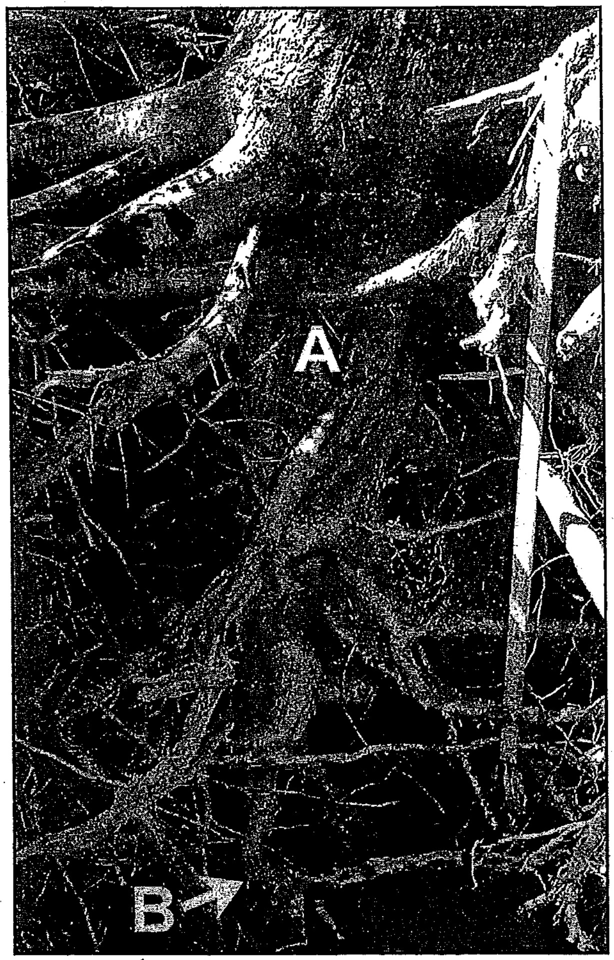

Figure 4. The taproot (A) of a large Oregon white oak (height = 14.4 m; age = 89 yr). The taproot began to grow horizontally at a soil depth of approximately 120 cm (B). Note the meter stick in the right of the photo.

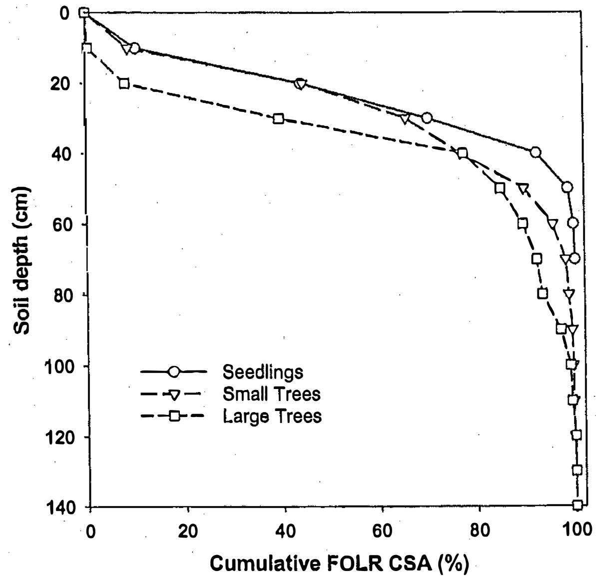

Figure 5. Cumulative (with increasing soil depth) FOLR CSA by soil depth increments of 10-cm for three size classes of Oregon white oak trees.

increased with tree size (Figure 7), trees of all size classes had FOLR in the smallest CSA class (<0.2 cm^2). Although the large FOLR of small and large trees were located primarily within 40 cm of the root collar, the smaller FOLR were distributed throughout the length of these trees' taproots (data not shown).

The majority of FOLR CSA was comprised of roots oriented horizontally or obliquely (Table 4). Roots oriented upward or downward were rare, especially among small and large trees. Roots of six of the 14 seedlings, three of the eight small trees, and one of the five large trees had asymmetrical distributions. The mean L values were 0.41 (seedlings), 0.27 (small trees), and 0.20 (large trees).

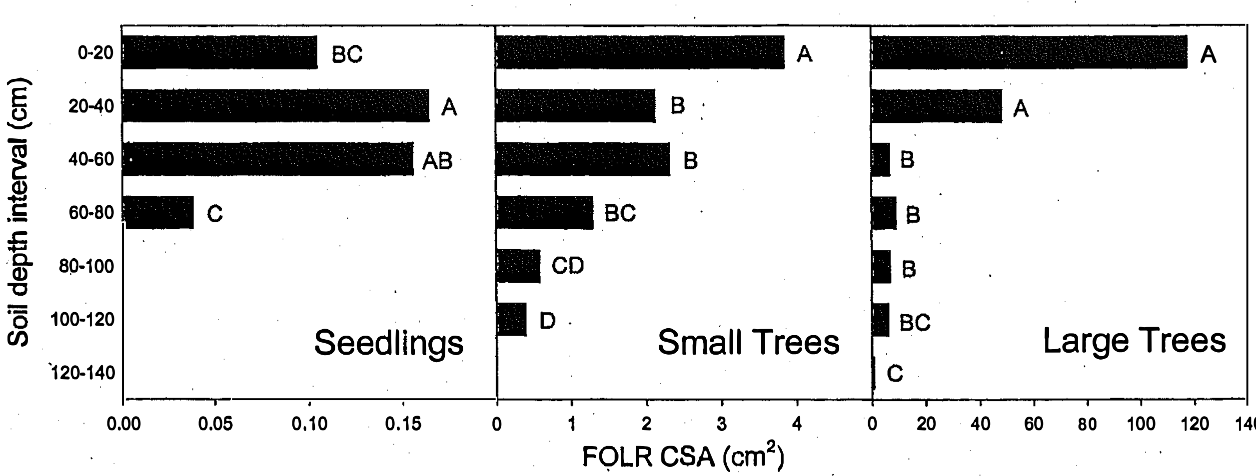

Figure 6. Mean FOLR CSA for each depth interval within three size classes of Oregon white oak trees. Same letter denotes no significant difference ($P \geq 0.05$) within each tree size class.

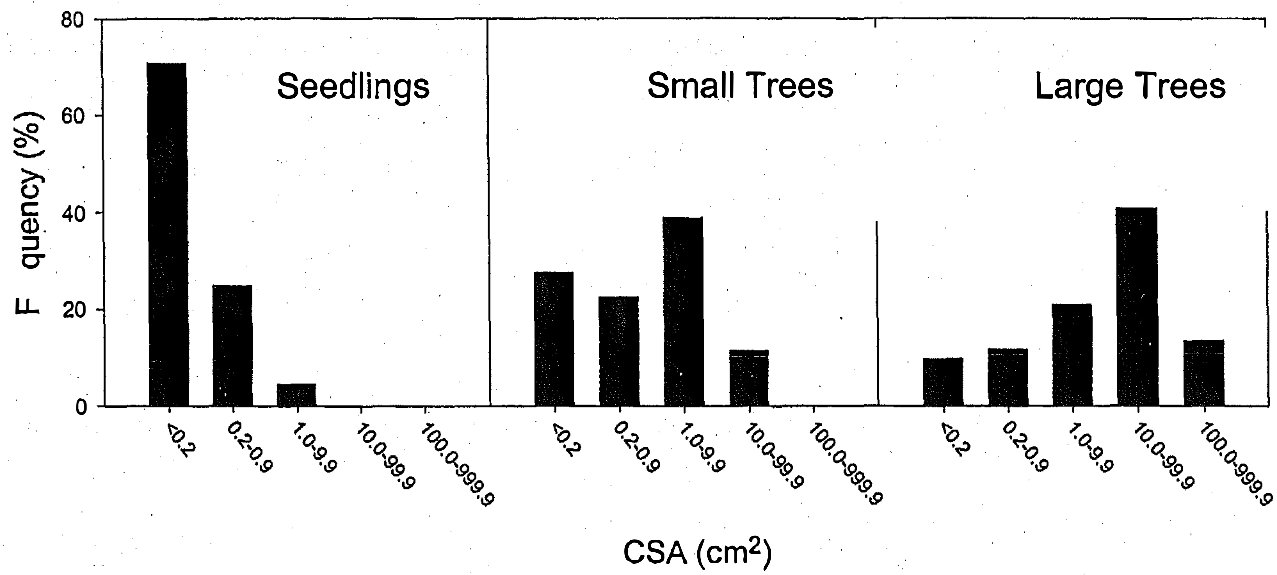

Figure 7. Frequency of FOLR in five CSA classes for three size classes of Oregon white oak trees.

TABLE 4. Distribution of FOLR CSA per tree among four vertical-angle categories within three tree-size classes of Oregon white oak (mean %).

Size class	Upward (≤75°)	Horizontal (76-105°)	Oblique (106-150°)	Downward (151-180°)
Seedlings	11.8b[1]	32.4a	47.0a	8.8b
Small trees	3.6c	64.1a	30.2b	2.1c
Large trees	2.6b	38.2a	57.5a	1.7b

[1]Same letter denotes no significant difference ($P \geq 0.05$) within each tree size class. Statistical analysis was performed on measured values; percentages are presented here to facilitate interpretation.

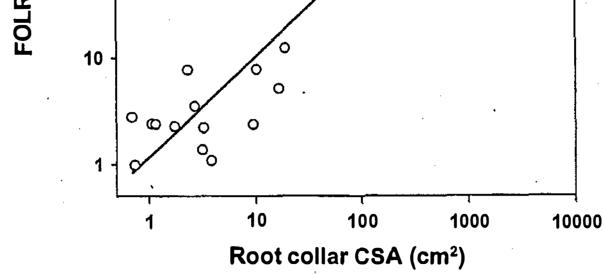

Figure 8. Relationship between total per-tree FOLR CSA and root collar CSA for 27 Oregon white oak trees.

CSA of the stem at the root collar was significantly related to total FOLR CSA per tree ($R^2 = 0.94$; $P < 0.001$). The slope of the regression line was 0.99 (Figure 8).

Discussion

Taproot Morphology

Oregon white oak seedlings and most of the small trees in our study had dominant taproots with FOLR that were comparatively small in diameter. In large trees, the rapidly-tapering taproots were less prominent relative to the large, shallow FOLR. Hibbs and Yoder (1993) reported Oregon white oak seedlings and saplings growing on a finer-textured soil had taproot-dominated root systems similar to those we observed. The decline in taproot dominance with increasing age has been reported for root systems of other species. While young northern red oak (*Q. rubra*) had a prominent taproot, mature trees did not (Lyford 1980). The root systems of the older trees were dominated by large FOLR originating near the groundline. Prominent taproots were uncommon among holm oak (*Q. ilex*) with an estimated age of 60-90 years; instead, root systems were composed primarily of shallow, horizontal FOLR (Canadell and Rodà 1991). On soils similar to those in our study, Douglas-fir, western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*) had a rapidly developing taproot when young (≤8 years), while older trees had root systems that were dominated by oblique lateral roots (Eis 1974).

The relatively rapid tapering of taproots that we observed among large trees has been reported for other species growing in adverse soil conditions. Taproots of blue oak (*Q. douglasii*) trees tapered abruptly in a dense argillic horizon (Millikin and Bledsoe 1999), as did bur oak (*Q. macrocarpa*) in a soil horizon with massive structure (Weaver and Kramer 1932) and holm oak growing on a shallow, stony soil (Canadell and Rodà 1991).

The depth to which taproots penetrated was influenced by soil properties, particularly coarse fragment content. We observed that layers in the C horizon with very high coarse fragment content (>80%) were restrictive to downward root growth. This was evidenced by the fact that the taproots of seven small and four large trees assumed horizontal growth immediately above such soil layers. Although roots of *Quercus* spp. are capable of reaching great depths under a variety of conditions (Lewis and Burgy 1964, Stone and Kalisz 1991), layers of gravelly glacial materials inhibit deep rooting (Lyford 1980). Under a coniferous forest near our study site, no roots were found in the C horizon of a similar soil (Everett series; sandy-skeletal, isotic, mesic Vitrandic Dystroxerept) (Ugolini and Schlichte 1973).

Once taproots penetrated the C horizon, they became highly contorted and followed tortuous routes among the coarse fragments. These roots were often flattened between and against the edges of rocks, similar in appearance to roots in rock fissures (Zwieniecki and Newton 1995). The taproots commonly made abrupt turns (>45°), sometimes several in rapid succession, due to cobbles and stones. Taproots of all 27 trees made at least one abrupt turn with an angle >45°, and occasionally abrupt turns were >90°.

First-order Lateral Roots

The large trees in our study had many large, shallow FOLR. The presence of very small FOLR (CSA <0.2 cm^2) on these trees indicates that new FOLR continue to initiate as trees approach 100 years of age, even though large, and likely extensive, FOLR already exist. Well-developed shallow lateral root systems have been reported for other *Quercus* spp. in Mediterranean climates, likely a result of limiting soil layers or a need for wind stability (Canadell and Rodà 1991, Millikin and Bledsoe 1999). The shallow vertical distribution of FOLR in our study was likely due in part to the location of nutrients and water within the soil profile and the difficulty of penetrating layers of gravel and cobbles in the C horizon.

Most FOLR of our study trees (on average, 86% of total FOLR CSA) were oriented at a vertical angle of less than 120°. Few FOLR grew upward, particularly among the small and large trees. Roots that did grow upward originated from the taproot at apparently random locations. It has been suggested that some lateral roots have an inherent tendancy for upward growth (Coutts and Nicoll 1991). The large fraction of FOLR CSA in the oblique root class among large trees may have been a function of our angle measurement protocol. We measured the angle from root-center at the origin to root-center at the 50-cm point; however, root-center at the origin was often artificially elevated due to taper or slight buttressing of large FOLR, resulting in a greater vertical angle measurement. If we had measured these root angles from the 25- to the 50-cm point, they would have been closer to 90°. For the 10 seedling FOLR that we excavated as far as possible (≤226 cm), vertical angle remained relatively constant throughout their length. These roots typically grew between 15 and 30 cm below the soil surface. We did not measure second- and higher-order roots but assumed that they occupied the same layers within the soil profile.

The radial distribution of roots became more symmetrical with increasing tree size. Similarly, among 55 sessile oak (*Q. petraea*) trees, only the smaller trees had asymmetrical root distributions (Drexhage et al. 1999). The seedlings in our study with asymmetrical radial root distributions typically had one or two major FOLR that comprised a large portion of the total FOLR CSA and thus were heavily weighted in the radial analysis. FOLR CSA of small and large trees was distributed more evenly among many roots, resulting in a lower likelihood of asymmetrical distribution. Among the trees with significantly asymmetrical root distributions, there was no consistent pattern in the direction in which roots were clustered. The symmetrical root distribution among large trees may result from a necessity for wind-firmness due to their larger crowns.

Although the root systems of all but one of the large trees were clearly restricted to some extent by the C horizon, all of the large trees penetrated it with at least one FOLR. At depths ≥150 cm, we found fans of fine roots within thin lenses of moist sand that were isolated by layers of coarser materials. Similar phenomena have been reported in other soils of glacial origin (Eis 1974, Lyford 1980). The ability of tree roots to reach the C horizon suggests that they may be important in providing water during the typically dry growing season, a phenomenon also found in *Quercus* spp. in California (Lewis and Burgy 1964, Griffin 1973) and in other tree species in the region (Zwieniecki and Newton 1994, Wang et al. 1995).

The significant 1:1 relationship (i.e., the regression line slope of 0.99 in Figure 8) that we observed between FOLR CSA and root collar CSA confirms the applicability of the pipe stem model assumptions on which our use of CSA for root analysis was based. Similarly, 1:1 ratios between root CSA and groundline CSA were observed for loblolly pine (*Pinus taeda*) and shortleaf pine (*Pinus echinata*) ranging in diameter from 1.7 to 12.3 cm (Carlson and Harrington 1987). For Douglas-fir <7.0 cm in diameter, a 1:1 relationship between root CSA and stem basal area was calculated (Kuiper and Coutts 1992). For larger Douglas-fir, this ratio increased, a pattern that the authors attributed to an increased influence of taper on measurements made near the origins of the roots. Root taper did not influence our analysis because we measured each root at a point beyond its initial taper.

Conclusions and Management Implications

Root systems of Oregon white oak growing on a coarse-textured glacial soil are taproot-based when young, but with age, become structurally dominated by shallow lateral roots. While these observations agree with previous descriptions of Oregon white oak on other soil types (Krygier 1971, Stein 1990, Hibbs and Yoder 1993), the deep taproot suggested elsewhere (Ugolini and Schlichte 1973, Stein 1990, Phillips et al. 2003) was not a common characteristic of trees on our site. This suggests that the majority of belowground resource acquisition occurs in the upper soil horizons. Shallow roots may be advantageous in acquiring water during summer months when precipitation events are infrequent and often wet only the surface soil. Because roots of Oregon white oak are primarily limited to the upper horizons of these coarse soils, they are susceptible to damage if timber harvesting or other vehicle traffic creates deep rutting.

Oregon white oak's primary competitor in the region is Douglas-fir, which has invaded many stands that once contained pure oak. The rooting habit of Douglas-fir on glacially derived soils is similar to what we observed for oak (Eis 1974). Thus, in stands that have been invaded by Douglas-fir, belowground competition is probably a significant component of the overall competition between these species. Oak's shallow rooting also is likely to result in a high level of competition with understory vegetation roots. Therefore, treatments such as prescribed fire that alter the understory will likely influence the availability of resources to oak trees. Consideration of rooting habits in terms of belowground competition and susceptibility to damage will improve management of Oregon white oak on glacial outwash soils.

Acknowledgements

We thank the Fort Lewis Forestry Program, especially Gary McCausland (retired), for funding this project and providing permission for destructive sampling. We thank the members of the Silviculture and Forest Models Team who assisted with field and office work, and Dave Peter for providing soil profile descriptions.

Literature Cited

Agee, J. K. 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, D.C.

Barnhart, S. J., J. R. McBride, and P. Warner. 1996. Invasion of northern oak woodlands by *Pseudotsuga menziesii* (Mirb.) Franco in the Sonoma Mountains of California. Madroño 43:28-45.

Bengough, A. G., A. Castrignano, L. Pagès, and M. van Noordwijk. 2000. Sampling strategies, scaling, and statistics. Pages 147-173 *In* A. L. Smit, A. G. Bengough, C. Engels, M. van Noordwijk, S. Pellerin, and S. C. van de Geijn (editors), Root Methods: A Handbook. Springer-Verlag, Berlin.

Biging, G. S. 1983. Accurate determination at breast height of cross-sectional area and growth of eccentric stems. Pages 686-689 *In* J. F. Bell and T. Atterbury (editors), Proceedings of an International Conference: Renewable Resources Inventories for Monitoring Changes and Trends. Oregon State University, Corvallis, Oregon.

Canadell, J., and F. Rodà. 1991. Root biomass of *Quercus ilex* in a montane Mediterranean forest. Canadian Journal of Forest Research 21:1771-1778.

Carlson, W. C., and C. A. Harrington. 1987. Cross-sectional area relationships in root systems of loblolly and shortleaf pine. Canadian Journal of Forest Research 17:556-558.

Chappell, C. B., and R. C. Crawford. 1997. Native vegetation of the South Puget Sound prairie landscape. Pages 107-122 *In* P. Dunn and K. Ewing (editors), Ecology and Conservation of the South Puget Sound Prairie Landscape. The Nature Conservancy of Washington, Seattle.

Coutts, M. P., and B. C. Nicoll. 1991. Orientation of the lateral roots of trees. I. Upward growth of surface roots and deflection near the soil surface. New Phytologist 119:227-234.

Drexhage, M., M. Chauvière, F. Colin, and C. N. N. Nielsen. 1999. Development of structural root architecture and allometry of *Quercus petraea*. Canadian Journal of Forest Research 29:600-608.

Eis, S. 1974. Root system morphology of western hemlock, western red cedar, and Douglas-fir. Canadian Journal of Forest Research 4:28-38.

Erickson, W. R. 2000. Garry oak communities in Canada: classification, characterization and conservation. International Oaks 10:40-54.

Griffin, J. R. 1973. Xylem sap tension in three woodland oaks of central California. Ecology 54:152-159.

Hibbs, D. E., and B. J. Yoder. 1993. Development of Oregon white oak seedlings. Northwest Science 67:30-36.

Kruckeberg, A. R. 1991. The Natural History of Puget Sound Country. The University of Washington Press, Seattle, Washington.

Krygier, J. T. 1971. Comparative water loss of Douglas-fir and Oregon white oak: project completion report. Water Resources Research Institute and School of Forestry, Oregon State University, Corvallis, Oregon.

Kuiper, L. C., and M. P. Coutts. 1992. Spatial disposition and extension of the structural root system of Douglas-fir. Forest Ecology and Management 47:111-125.

Lewis, D. C., and R. H. Burgy. 1964. The relationship between oak tree roots and groundwater in fractured rock as determined by tritium tracing. Journal of Geophysical Research 69:2579-2588.

Lyford, W. H. 1980. Development of the root system of northern red oak (*Quercus rubra* L.). Harvard Forest Paper 21:1-30.

Millikin, C. S., and C. S. Bledsoe. 1999. Biomass and distribution of fine and coarse roots from blue oak (*Quercus douglasii*) trees in the northern Sierra Nevada foothills of California. Plant and Soil 214:27-38.

Nicoll, B. C., E. P. Easton, A. D. Milner, C. Walker, and M. P. Coutts. 1995. Wind stability factors in tree selection: distribution of biomass within root systems of Sitka spruce clones. Pages 276-292 *In* M. P. Coutts and J. Grace (editors), Wind and Trees. Cambridge University Press, Cambridge, United Kingdom.

Phillips, N., B. J. Bond, N. G. McDowell, M. G. Ryan, and A. Schauer. 2003. Leaf area compounds height-related hydraulic costs of water transport in Oregon white oak trees. Functional Ecology 17:832-840.

Pringle, R. F. 1990. Soil survey of Thurston County, Washington. USDA Soil Conservation Service, Olympia, Washington.

Ryan, L. A., and A. B. Carey. 1995. Distribution and habitat of the western gray squirrel (*Sciurus griseus*) on Ft. Lewis, Washington. Northwest Science 69:204-216.

SAS Institute Inc. 2000. The SAS System for Windows. Version 8.01. Cary, North Carolina.

Snedecor, G. W., and W. G. Cochran. 1967. Statistical Methods, 6th edition. The Iowa State University Press, Ames, Iowa.

Stein, W. I. 1990. Oregon white oak. Pages 650-660 *In* R. M. Burns and B. H. Honkala (technical coordinators), Silvics of North America: Hardwoods. USDA Agricultural Handbook No. 654. USDA Forest Service, Washington, D.C.

Stone, E. L., and P. J. Kalisz. 1991. On the maximum extent of tree roots. Forest Ecology and Management 46:59-102.

Thilenius, J. F. 1964. Synecology of the white-oak (*Quercus garryana* Douglas) woodlands of the Willamette Valley, Oregon. Ph.D. Dissertation, Oregon State University, Corvallis, Oregon.

Thysell, D. R., and A. B. Carey. 2001. *Quercus garryana* communities in the Puget Trough, Washington. Northwest Science 75:219-235.

Ugolini, F. C., and A. K. Schlichte. 1973. The effect of Holocene environmental changes on selected western Washington soils. Soil Science 116:218-227.

Wang, Z. Q., M. Newton, and J. C. Tappeiner. 1995. Competitive relations between Douglas-fir and Pacific madrone on shallow soils in a Mediterranean climate. Forest Science 41:744-757.

Weaver, J. E., and J. Kramer. 1932. Root system of *Quercus macrocarpa* in relation to the invasion of prairie. Botanical Gazette 94:51-85.

Western Regional Climate Center. 2004. Washington climate summaries. Available online at www.wrcc.dri.edu/summary/climsmwa.html.

Zwieniecki, M. A., and M. Newton. 1994. Root distribution of 12-year-old forests at rocky sites in southwestern Oregon: effects of rock physical properties. Canadian Journal of Forest Research 24:1791-1796.

Zwieniecki, M. A., and M. Newton. 1995. Roots growing in rock fissures: their morphological adaptation. Plant and Soil 172:181-187.

Received 10 February 2005
Accepted for publication 17 June 2005