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Effects of planting spacing and site quality on 25-year growth and mortality relationships of Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*)

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ABSTRACT

Growth and mortality of coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) were studied for 25 years after planting seedlings at 1–6-m spacings on a site of moderate quality in the western Cascade Mountains of Washington. Responses were compared to those from two other studies representing high and low site qualities. Third-year height did not differ among spacings ($P = 0.80$), providing no evidence that close spacing stimulated early growth. Piecewise regression identified the onset of competition-induced mortality when stand density index (SDI [Reineke, L.H. 1933. Perfecting a stand density index for even-aged forests. Journal of Agricultural Research 46, 627–638]) exceeded 52% (S.E. = 4.6) of the species' maximum or when average crown ratio (CR) declined below 52% (S.E. = 0.9). For a range of SDI values, CR averaged 2–7% points greater at the high-quality site than at the moderate-quality site. In a regression analysis of combined data from the moderate- and high-quality sites, relative values of average stem diameter and stand volume (% of maximum values observed per site) 23–25 years after planting increased and decreased with planting spacing, respectively ($R^2 = 0.97$ and 0.91, respectively). Intersection of these relationships at 3-m spacing indicated a point of equivalent relative development of tree size and stand yield. For a range of site qualities, stands planted at 3-m spacing: (1) maintained tree vigor ($CR \geq 50\%$) and stability (average height:dbh ratio <90), (2) experienced little or no competition-induced mortality through age 25 years, and (3) allocated 25-year growth equitably to development of tree size and stand yield, thereby providing a desirable starting point for subsequent management.

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1. Introduction

Spacing is a critical feature to consider when establishing forest plantations because it determines the timing and intensity of resource competition among individual trees. Given the limited pool of resources available to support tree growth on a forest site, competition among individual trees intensifies as they grow in size and their resource requirements increase. Trees become dominant within a stand when their initial size, genetic characteristics, or resource availability enable them to grow faster, suppress their neighbors, and occupy additional growing space. Spacing affects the timing, and therefore tree size, at which these competitive interactions occur (Long et al., 2004). In this way, spacing directly influences stand dynamics associated with differentiation in tree size and onset of competition-induced mortality.

Typical planting spacings for coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) are based on a variety of criteria, including forecasts of tree survival, growth, and stability (Talbert and Marshall, 2005). These criteria often are viewed as components of stand vigor, and one goal of selecting the proper spacing is to enable crop trees to maintain their vigor until a subsequent thinning or other treatment. Maintaining crown ratio (live crown length:tree height ratio) at 40% or greater is considered desirable for sustaining vigorous growth (Smith, 1986, p. 83), although few studies have experimentally manipulated this variable or related it to stand density to identify critical values for stand management (Young and Kramer, 1952; Long, 1985; Dean and Baldwin, 1996a). Likewise, maintaining the ratio of height:stem diameter (i.e., slenderness ratio) below 80–100 is considered desirable for reducing susceptibility to wind-throw and stem breakage, especially when stand height exceeds 25 m (Cremer et al., 1982; Lohmander and Helles, 1987; Wilson and Oliver, 2000). As initial spacing decreases, risk of declining vigor from accelerated crown recession (i.e., mortality of lower branches) or loss of stability from development of a high slenderness ratio occurs earlier in stand development. Declining vigor from intense competition increases the probability that an individual tree will die. The onset of competition-induced mortality in stands of coast Douglas-fir has been estimated to occur when stand density index (SDI; Reineke, 1933) exceeds a

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threshold of 55% of the species' maximum value (Drew and Flewelling, 1979).

Although resource competition characterizes many of the interactions that occur among trees, variable-density studies of coast Douglas-fir (Scott et al., 1998; Woodruff et al., 2002), red alder (*Alnus rubra* Bong.) (Knowe and Hibbs, 1996; Hurd and DeBell, 2001), and cottonwood (*Populus* spp.) (Krinard, 1985; DeBell et al., 1996) have demonstrated that peak growth of individual trees occurs at close spacings early in stand development (<10 years old) and at progressively wider spacings as the stand develops. Potential explanations for this phenomenon are related to characteristics of high-density stands: greater probability of seedlings occurring on superior micro-sites, reduced abundance of competing vegetation, reduced browsing pressure, and changes in light quality that affect seedling allometry (Ritchie, 1997).

To facilitate selection of appropriate initial spacings for forest plantations given specific management objectives, an improved understanding is needed that accounts for effects of site quality and planting spacing on subsequent stand dynamics. In general, site quality does not influence the maximum size-density limit of conifer species, but rather it has a positive influence on the rate of increase in average tree size as stands develop, and subsequently, the rate of decrease in stem density as they undergo competition-induced mortality (Harms et al., 2000; Pittman and Turnblom, 2003; VanderSchaaf and Burkhart, 2008). Although stand dynamics of Douglas-fir have been the subject of considerable research (Oliver and Larson, 1996), and prominent growth and yield models for the Pacific Northwest region (e.g., ORGANON, FVS, and CONIFERS) include empirical functions for predicting growth and mortality of individual trees from variables such as crown ratio and SDI (Ritchie, 1999; Ritchie and Hamann, 2008), several fundamental relationships have yet to be quantified. For example, the relationship of mortality rate to crown ratio could be analyzed for a potential threshold response that signals the onset of competition-induced mortality. Likewise, the relationship of crown ratio to SDI could be investigated to see if it varies with site quality. Relationships of relative tree size and relative stand volume (i.e., % of maximum values observed on a given site) to planting spacing could be analyzed jointly to identify a compromise spacing that supports equivalent development of both variables.

In this study (hereafter referred to as the 1981 study), growth and mortality rates were monitored for 25 years on Douglas-fir planted at 1–6-m spacings on a site of moderate quality in the western Cascade Mountains of Washington. Study objectives were to characterize relationships of growth and mortality rate to planting spacing and SDI and to compare these responses to those observed on a low-quality site (1925 Wind River study; Eversole, 1955) and a high-quality site (Maple Ridge study, 49-tree-plot trial; Reukema and Smith, 1987). The research also tested the following null hypotheses: (1) early growth in height does not differ among planting spacings, and (2) average top height does not differ among planting spacings.

2. Methods

2.1. Study site and treatments

The 1981 study was conducted in the Trout Creek Unit (T4N R7E S18) of the Wind River Experimental Forest, Gifford Pinchot National Forest, about 20 km north and slightly west of Carson, WA (lat. 45°50′N, long. 122°0′W). The soil is classified as a dark brown loam of the Stabler series, a medial, amorphic, mesic, Vitric Hapludand with a solum thickness of 76–127 cm. Vegetation is intermediate between the western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Pacific silver fir (*Abies amabilis* Dougl. ex Forbes) zones (Franklin and Dyrness, 1973). Elevation ranges from 512 to 557 m, slopes are less than 10%, and aspect is south. The average frost-free growing season is 120 days and average annual precipitation for the study period (1981–2005) is estimated to be 2748 mm (Daly et al., 1994).

The pre-harvest old-growth stand was dominated by Douglas-fir (site class III–IV, McArdle et al., 1961) and western hemlock, with occasional western redcedar (*Thuja plicata* Donn ex D. Don) and Pacific silver fir. The understory was dominated by vine maple (*Acer circinatum* Pursh), salal (*Gaultheria shallon* Pursh), Oregon-grape (*Mahonia nervosa* Pursh), vanilla-leaf (*Achlys triphylla* (Smith) DC.), beargrass (*Xerophyllum tenax* (Pursh) Nut.), red huckleberry (*Vaccinium parvifolium* Smith), spreading dogbane (*Apocynum androsaemifolium* L.), and saplings of western hemlock and Pacific silver fir. The site was clearcut harvested in 1977 and woody debris was piled and burned in summer 1978. Remaining debris was scattered and areas dominated by residual understory vegetation were scarified with a brush rake in 1979.

In summer 1980, 34 plots of dimension 63.2 m × 63.2 m (0.4 ha) were located on the 26-ha study site. Four plots were randomly assigned for planting Douglas-fir seedlings at 1-m spacing and six plots were randomly assigned for planting at each of 2-, 3-, 4-, 5-, and 6-m spacings resulting in a completely randomized experimental design. Because costs for establishing the closest spacing (1-m) were very high and the area available for plot location was finite, only four replications of the 1-m spacing were installed. Individual planting spots were marked with stake flags, and in March 1981, 2 + 0 bare-root Douglas-fir seedlings were hand planted. A 5% solution of Roundup® (glyphosate) herbicide in water was applied as a directed application in August 1981 to suppress beargrass and salal. Seedling mortality surveys were performed several times during the first few years, and seedlings that died or had poor vigor were replaced to ensure that assigned spacings were maintained. Volunteer seedlings of Douglas-fir and other tree species were removed in 1986, 1990, and 1998.

2.2. Measurements and statistical analyses

In July 1984, third-year height (nearest 0.01 m) was measured on 10–30% of seedlings per plot located in systematically selected rows. In 1989 (year 9), measurement trees were assigned and tagged within each plot. The 1- and 2-m spacings each had 200 measurement trees per replication, and the 3-, 4-, 5-, and 6-m spacings had 196, 100, 64, and 49 measurement trees per replication, respectively. In 2001 (year 21) and 2005 (year 25), dbh (stem diameter at 1.3-m height; nearest 0.1 cm) was measured on each tagged tree and height (nearest 0.1 m) was measured on a systematic sample of 48–50 tagged trees per plot for the 1-, 2-, 3- and 4-m spacings and on each tagged tree in the 5- and 6-m spacings. Crown base height (i.e., defined as the height at which whorl branches are present on at least three of four cardinal-direction quadrants of the crown; nearest 0.1 m) was measured on each height measurement tree. Average crown width (nearest 0.1 m; average of two directions perpendicular to each other) was measured on a systematic sample of 10–22 height measurement trees per plot.

All statistical analyses were conducted in SAS (SAS Institute Inc., 2005) with a significance level of α = 0.05. Specific responses in the 1981 study, the 1925 study, and the Maple Ridge study refer to years since planting 2-year-old seedlings. Plot averages for year 25 were calculated for the following variables: height, quadratic mean diameter (square root of the mean squared dbh, hereafter referred to as average dbh), slenderness ratio (height:dbh, expressed in the same units for both variables), crown base height, crown width,