Planting density and tree-size relations in coast Douglas-fir[1]

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Abstract: Test plantations were established in western Washington and Oregon to compare tree growth at six initial planting densities ranging from 300 to 2960 trees/ha (120 to 1200/acre). A size–density relation was visually apparent 3 to 4 years after planting. Inventory data from the oldest 11 trials (5 or 6 years after planting) showed that initial spacing strongly influenced early growth of coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*). Average height and diameter at breast height were progressively larger as planting density increased; at the widest spacing (lowest stand density), average height was 75% and average diameter at breast height was 67% of that at the closest spacing. We have no firm explanation for the early faster tree growth at close spacings. Trees planted at 2960 trees/ha (1200 trees/acre) attained breast height (1.3 m) 2 years earlier than trees planted at a density of 300/ha (120/acre). This finding has practical significance to current efforts to achieve early establishment of plantations.

Résumé : Des plantations expérimentales ont été établies dans l'Ouest des États de Washington et d'Oregon en vue de comparer la croissance des arbres en présence de six densités initiales de plantation, allant de 300 à 2960 arbres/ha (120 à 1200/acre). Une relation taille–densité était apparente à vue d'oeil 3 à 4 ans après la plantation. Les données d'inventaire des 11 plus vieux essais (5 à 6 ans après la plantation) ont montré que l'espacement initial influençait grandement la croissance juvénile chez le douglas de Menzies typique (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*). La hauteur moyenne et le diamètre moyen à hauteur de poitrine augmentaient progressivement à mesure que diminuait la densité initiale de la plantation. Dans le cas du plus grand espacement (la plus faible densité du peuplement), la hauteur moyenne représentait 75% et le diamètre à hauteur de poitrine 67% des valeurs obtenues dans le cas du plus faible espacement. Les auteurs n'ont pas d'explication ferme pour la croissance juvénile plus rapide des arbres du plus faible espacement. Les arbres plantés à raison de 2960 tiges/ha (1200 arbres/acre) atteignaient la hauteur de poitrine (1,3 m) 2 ans plus tôt que les arbres plantés à la densité de 300/ha (120/acre). Cette constatation a une portée pratique en lien avec les efforts actuels pour réussir l'établissement rapide des plantations.

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Introduction

Capturing the full productive potential of a site for tree growth requires prompt establishment of a uniform stand of trees. To achieve this objective for coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), planting of vigorous seedlings is recommended over natural regeneration (Miller et al. 1993). Because initial spacing between trees so strongly affects subsequent growth and merchantable yields, earlier researchers (Smith and Reukema 1986; Reukema and Smith 1987) concluded that choice of initial spacing is one of the most important decisions affecting timber production. In their opinion, initial planting of Douglas-fir at 469 to 741 trees/ha (tph), or 190 to 300 trees/acre (tpa), appears to be near optimum for most regimes to produce lumber. Planting at closer spacings produces more biomass at earlier ages, however.

The effect of spacing on branch size and subsequent lumber

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quality was not considered in this recommendation or in other guides for stand density management in coast Douglas-fir. Drew and Flewelling (1979), for example, developed a graphical density management diagram to determine the potential trade-offs between maximizing average size of individual trees and stand yields. They suggest that stands be managed in the relative density range between 0.15 and 0.55. At relative densities between 0.15 and 0.40, more growth per tree will occur but less growth per unit area. At relative densities greater than 0.40, maximum stand growth will occur, but net production will decline when relative density exceeds 0.55 because of increasing mortality of trees.

Beginning in 1985, we established a series of variable-density plantations of seven commercial species over the range of soil–climate conditions common to Weyerhaeuser Company ownership in western Washington and Oregon. These test plantations are intended to provide future research sites to quantify relationships among initial spacing, thinning, wood quality, and growth and yield. At each location, test plantations were restricted to the same aspect within a narrow range of elevation and to the same soil series. Intermittent drainage channels were excluded. Local seed sources and one of various planting-stock types were used after a conventional method of site preparation (broadcast burning, piling and burning, or herbicide spray).

For example, Douglas-fir plantations were established at 60 locations. Each test plantation had widely contrasting initial spacings and included wider spacing than previously tested in

Fig. 1. Contrasting tree sizes were observed 4 years after planting to 300 tph (left) vs. 2960 tph (right).

Fig. 2. Relative size of the mean DBH and mean height of various planting densities compared with the 2960-tph density (mean and 1 SE).


Douglas-fir. These variable-density plantations included six stocking levels: 300, 590, 890, 1360, 1850, and 2960 tph (120, 240, 360, 550, 750, and 1200 tpa) each in 2-ha plots. At some locations, however, planting was limited to four or five densities because of limitations of homogeneous planting area or available planting stock. A few locations had two replications of some planting densities. The original planting densities were maintained by periodically felling volunteer trees and potentially overtopping vegetation; our intent was to avoid compromising future interpretations of data. Unexpectedly, visually apparent differences in tree size were observed by the third or fourth growing season after planting (Fig. 1). These observations triggered earlier measurements than originally scheduled. The results from the 11 oldest locations are reported here.

Methods

Sample trees were measured at the 11 oldest trials in Douglas-fir after the 1990 growing season (5 or 6 years after planting). Ten of these trials were located in Washington; only one trial was located in Oregon (coastal). Eight were in coastal areas and three in the Cascade Ranges. Average 50-year site index among the 11 locations ranged from 34 to 43 m (110 to 140 ft).

Nine of the 11 installations were broadcast burned, one installation received a site-preparation spray with herbicide, and one was scarified and the piles burned. Site preparation occurred in the late summer – fall and was effective at all locations. Essentially no vegetation existed when the units were planted the following spring. Each planting was sampled and controlled by counting recently planted seedlings in systematically spaced, temporary plots that sampled 5% of the area. The plots were 0.0081 ha (0.02 acre) in size. In year 5 or 6 after planting, each planting density was sampled again with a systematic square grid. The intent was to measure the size of 100 live trees representing each planting density. From a random starting point, 20 or more circular subplots were centered at 30-m intervals. Our target sample was 100 trees per planting density or 5 trees per subplot;
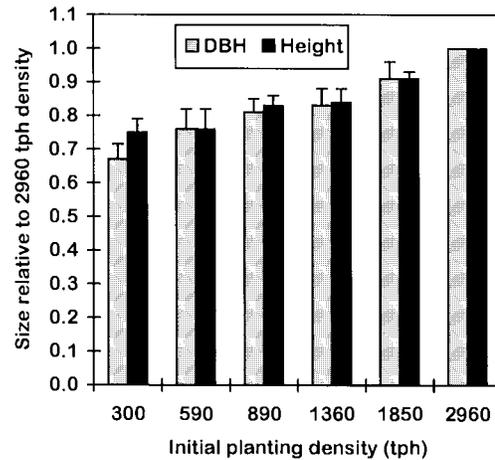
hence, subplot size differed with planting density. Because of stumps, other planting obstructions, and some seedling mortality, the actual number of seedlings measured in each stand density varied slightly from the 100-tree target. This second sampling provided a second estimate of average density of live trees in each plantation. The difference between these two samplings was considered the mortality loss since planting. The following data were collected from each live tree: diameter at breast height (DBH in mm), total height (in cm), and height (cm) to each whorl above breast height (1.3 m).

Results

Survival
Five or 6 years after planting, seedling survival at the 11 locations averaged 95, 91, 86, 83, 79, and 82% for the 2960-, 1850-, 1360-, 890-, 590-, and 300-tph densities, respectively. The two highest densities averaged better percent survival than lower densities.
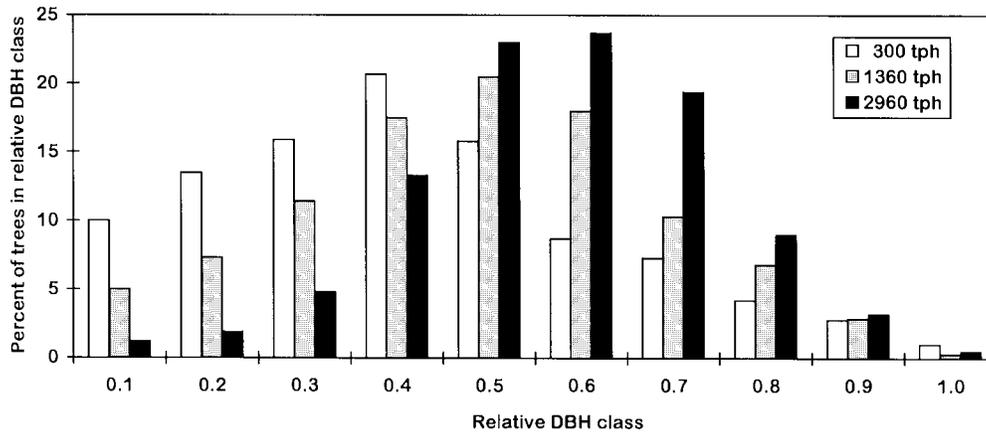
Tree height and current growth
Mean height increased as planting density increased (Fig. 2). Note that the x-axis in this conventionally presented bar graph is misleading because the densities are not plotted at their correct positions. Regression relationships will be presented later. To adjust for differences among the 11 plantations in age and site quality, we calculated relative comparisons. Compared with average height in the closest spacing (2960 tph), relative heights declined with progressively wider spacings (91, 84, 83, 76, and 75% for the 1850-, 1360-, 890-, 590-, and 300-tph plantings, respectively). Moreover, current 1-year height growth at tree ages 7, 8, or 9 was greater on plots with closest spacing between trees (Table 1). On average, trees reached breast height 2 years sooner at 2960 than at 300 tph.

DBH and diameter distribution
Surprisingly, mean DBH also increased with closer planting density (Fig. 2). Compared with average DBH of the closest spacing, relative DBH declined at wider spacings (91, 83, 81, 76, and 67% for the 1850-, 1360-, 890-, 590-, and 300-tph densities, respectively).

Fig. 3. Average percentage of trees in relative DBH classes for the 300-, 1360-, and 2960-tph planting densities across all locations.

Table 1. Average height growth (m/year) in the current year (tree age was 7, 8, or 9 years), by planting density and stand component.

Item	Planting density (stems/ha)					
	2960	1850	1360	890	590	300
Largest 198 trees/ha	1.12	1.06	0.99	0.98	0.90	0.84
Largest 741 trees/ha	1.09	1.03	0.88	0.86	0.79	0.79
All trees	0.98	0.91	0.82	0.85	0.79	0.79
No. of test locations	8	11	9	9	11	11

Note: 198 tph = 80 tpa and 741 tph = 300 tpa.

The proportion of large trees was greater in the denser spacings. At each location, relative diameter was calculated for each tree across all densities from the formula

$$[1] \quad RELDBH = \frac{DBH - MINDBH}{MAXDBH - MINDBH}$$

where RELDBH is relative DBH for each tree at a location, DBH is diameter at breast height for each tree, MINDBH is minimum diameter at a location, regardless of stocking, and MAXDBH is maximum diameter at a location, regardless of stocking.

This calculation normalizes diameter on a scale from 0 to 1.0 and enables comparison of the relative diameter distributions across all locations regardless of site index or age (Fig. 3). Although trees are found in all classes (0.1 through 1.0) at all stockings, there is a dramatic shift to the larger relative diameter classes in the 1360- and 2960-tph plantings as compared with the 300-tph plantings. This shift accounts for the larger mean diameters found in the closer spacings.

Tree size

Trees in denser spaced plots averaged greater DBH and height than those in plots of lower density. A linear regression effectively models the relationship of the average relative size in each of the lower density spacings to that in the 2960 -tpa density for both DBH and height (Fig. 4). Mean values plotted for each spacing are based only on the data from the eight locations, where all six spacing were tested. The equations for both relative DBH and height as a function of initial planting density are

$$[2] \quad RELDBH = 0.683\ 747 + 0.000\ 278 TPH$$

$$[3] \quad RELHT = 0.721\ 392 + 0.000\ 236 TPH$$

where RELDBH is relative DBH of wider spacings as compared with the closest spacing (2960 tph) set to 100, RELHT is relative height of wider spacings as compared with the closest spacing (2960 tph) set to 100, and TPH is initial planting spacing (tph).

The R^2 values are 0.9412 and 0.9823 and the root mean squared errors are 0.030 69 and 0.013 99 for relative DBH and height, respectively. These equations represent data for Douglas-fir stands 5 or 6 years after planting at 300 through 2960 tph.

Discussion

The early and consistent expression of differences in Douglas-fir size among the various initial planting densities was unexpected. Height growth of dominant and codominant trees is usually assumed to be independent of stand density and strongly related to site quality (Wenger 1984). Some planting densities in our study were tested earlier in Douglas-fir plantings at Wind River near Carson, Wash. (1925), and at Haney, B.C. (1957). Densities tested by Oregon State University at three locations in or near the Oregon Coast Range (1978), however, are far beyond those of this and other studies. Cole and Newton (1987) used a Nelder design to systematically compare planting densities of 6557 to 330 000 tph. An early height advantage at denser spacings was reported by Isaac (1937) for the infertile site at Wind River and by Reukema and Smith (1987) for the more fertile site near Haney, B.C. Early height–density trends at Wind River are unclear, but those at Haney are similar to those for our 11 locations.

The DBH advantage at denser spacings that we observed has not been reported previously. Because DBH was first measured at age 23 years at Wind River, Wash., and age 12 years at Haney, B.C. (Reukema and Smith 1987), initial advantages of close spacings for diameter growth could have been undetected and reversed by the time these measurements were made.

Tree size – spacing relations shift with time

If these plantations are not thinned, DBH differences and later height differences among spacing will reverse, so that trees in closer spaced stands will average shorter and smaller in diameter

Fig. 4. Relative DBH and height regressed on planting density (density means for eight locations and least-squares fitted regression line are shown).
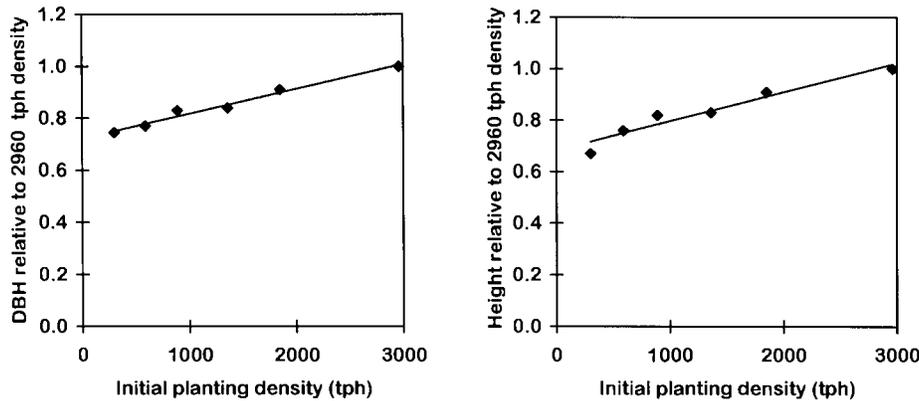
than those in wider spaced stands. For example, the height shift for the largest 247 trees/ha (100 tpa) occurred by age 23 years in the Wind River spacing study (Reukema 1979; Reukema and Smith 1987).

Explanations for early growth difference

Currently, we have no firm explanation for the early faster tree growth at close spacings. Within the range of reasonable plantation spacings that we tested, individual tree growth is initially greater at close spacing than at wide spacing. This could indicate that early tree growth is (1) stimulated at close spacing, (2) reduced at wide spacing, or (3) both. Any of these explanations could be valid at some sites, depending on the specific growth-determining climatic and competitive stresses involved. For example, closed stand conditions can moderate extremes of temperature. Hence, at sites subject to frost or drying winds, trees at close spacing would be less vulnerable than those at wide spacing. Similarly, the balance and significance of negative or positive interactions both between trees as well as between trees and other vegetation is affected by planting density and subsequent survival percentages. Cole and Newton (1987) demonstrate competitive relations in a 5-year-old Nelder design at three locations in Oregon. Mean diameter at 15-cm height was less reduced by grass competition in closer spacings than in wider spacings. Moreover, grass competition showed greatest effects at the driest site, whereas the competitive effects of taller red alder (*Alnus rubra* Bong.) were strongest at the coastal site where moisture was least limiting.

We observed no apparent difference in the vegetation among the variable-density plantations in the first three growing seasons. As the Douglas-fir crowns expanded, differences started to develop; the 1200-tpa spacing was first to close canopy. Five to 6 years after planting, crowns on the 1200 tpa were just touching, but understory vegetation was still present. Invasion by competing species at our 11 study sites was similar at most locations because 9 of these were broadcast burned. At most locations, vegetation in the first season was dominated by *Senecio*; this pioneer species was replaced later by grasses and forbs. We controlled only vegetation that could have overtopped our planted seedlings.

Some hypotheses to explain initially larger trees at closer spacings include

(1) Greater likelihood of planting favorable microsites.

(2) Improved microclimate.

(3) Less animal damage.

(4) Earlier crown closure, resulting in less interspecies competition for nutrients and water. This does not explain the differences in tree size that were apparent in years 3 or 4 after planting and before vegetative cover and vigor were reduced by crown closure.

(5) Enhanced interactions in the rhizosphere among trees and other vegetation (Prescott et al. 1996).

(6) Favorable intraspecies interactions: more root grafting and mycorrhizal interconnections among the Douglas-fir.

(7) Earlier response to future competitors through alterations in red – far-red light reflected from foliage (Ballaré et al. 1990) or through root contact. Ritchie (1997) has recently reported evidence supporting the red – far-red signaling hypothesis.

Management implications

Planting trees at close spacing shortens "green-up" time (the time needed to reach a target height sometimes specified by forest-practice regulations). This permits earlier harvest of adjacent stands. More rapid height growth also reduces the time that seedlings are vulnerable to animal browsing of terminals and to competing vegetation.

Establishing higher density stands may improve stem quality because branch diameters will be smaller and because a greater number of trees will be available for selection at thinning. Hence, thinning would remove trees with undesirable stem characteristics, thereby retaining higher quality trees.

Future research

Future research activities in these plantations should include both silvicultural manipulations and physiological studies to determine causes for early differences in growth among planting densities. These causes may differ from site to site according to the importance of individual growth-limiting factors and the capacity of variously spaced plantations to ameliorate these factors. We have initiated studies to determine the effect of competing vegetation and animal damage on the early size–density relationship.

Thinning studies are needed to determine optimum timing of thinning to capture early gains in tree size. The benefits of

selection intensity on subsequent growth and stem quality need to be quantified over a range of site conditions.

Conclusions

Planting coast Douglas-fir seedlings at higher densities facilitates the prompt establishment of a more uniform and faster growing stand. At 5 to 6 years after planting, survival in the 2960-tph density was 13% more than that in the 300-tph density. Moreover, both DBH and height were greater in the higher stockings than in the lower stockings. Trees at higher densities, 2960 and 1850 tph, passed through breast height sooner than trees at lower densities. Increased survival and reduced time to fully occupy the site are significant considerations for forest managers. Close spacing at planting increases the likelihood of capturing the full productive potential of a site and of improving wood quality. Further studies are necessary to understand the mechanisms that explain this phenomenon.

Acknowledgements

References

Ballaré, C.L., Scopel, A.L., and Sánchez, R.A. 1990. Far-red radiation reflected from adjacent leaves: an early signal of competition in plant canopies. Science (Washington, D.C.), **247**: 329–331.

Cole, E.C., and Newton, M. 1987. Fifth-year responses of Douglas-fir to crowding and nonconiferous competition. Can. J. For. Res. **17**: 181–186.

Drew, T.J., and Flewelling, J.W. 1979. Stand density management: an alternative approach and its application to Douglas-fir plantations. For. Sci. **25**: 518–532.

Isaac, L.A. 1937. 10 years' growth of Douglas-fir spacing-test plantations. USDA For. Serv. For. Res. Notes 23.

Miller, R.E., Bigley, R.E., and Webster, S. 1993. Early development of matched planted and naturally regenerated Douglas-fir stands after slash burning in the Cascade Range. West. J. Appl. For. **8**: 5–10.

Prescott, C.E., Weetman, G.F., and Barker, J.E. 1996. Causes and amelioration of nutrient deficiencies in cutovers of cedar–hemlock forests in coastal British Columbia. For. Chron. **72**: 293–302.

Reukema, D.L. 1979. Fifty-year development of Douglas-fir stands planted at various spacings. USDA For. Serv. Res. Pap. PNW-253.

Reukema, D.L., and Smith, J.H.G. 1987. Development over 25 years of Douglas-fir, western hemlock, and western redcedar planted at various spacings on a very good site in British Columbia. USDA For. Serv. Res. Pap. PNW-RP-381.

Ritchie, G. 1997. Evidence for red:far red signaling and photomorphogenic response in Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco.) seedlings. Tree Physiol. **17**: 161–168.

Smith, J.H.G., and Reukema, D.L. 1986. Effects of plantation and juvenile spacing on tree and stand development. *In* Douglas-fir: stand management for the future. Contribution No. 55. *Edited by* C.D. Oliver, D.P. Hanley, and J.A. Johnson. Institute of Forest Resources, University of Washington, Seattle. pp. 239–245.

Wenger, K.E. 1984. Forestry handbook. 2nd ed. John Wiley & Sons, New York.