ASSESSING AND MANAGING STANDS TO MEET QUALITY OBJECTIVES

David Briggs[1]

ABSTRACT

Process capability analysis (PCA) is a statistical quality control technique which managers can use to assess the degree of nonconformance of individual timber stands to specifications for quality properties such as knot diameter, rings per inch, and wood stiffness (MOE). Examples from Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) plantations demonstrate application of PCA to a single property or a combination and show how PCA can be used to monitor nonconformance over time. Managers can use the PCA information to assist in harvest planning and marketing mature stands and to assist in planning silvicultural planning in immature stands. Purchasers can use PCA to assist in determining if a stand has sufficient conformance to their log quality requirements to justify a bid.

KEYWORDS: Log quality, tree quality, silviculture, statistical quality control, process capability analysis.

INTRODUCTION

For a long time relatively simple, economical field tools have allowed forest managers to measure geometric properties of trees in a stand for inventory, and growth and yield analysis. This has also led to the development and use of growth and yield, harvest scheduling and other forest planning models. Unfortunately, counterparts for measuring quality properties of trees have lagged, hence quality has not received as detailed treatment in inventories, analyses, and models. If quality is treated at all, it is often through assuming an implied relationship of increasing quality with increasing tree diameter. Although a general association of higher quality with increasing tree diameter may have been reasonable for natural stands and minimally managed plantations, it breaks down in intensively managed plantations where different cultural regimes can produce similar size trees with great differences in knot size, percentage of juvenile wood, ring width, and other characteristics. An alternative to the diameter association is to estimate the log grade composition or tree grade of trees in a stand. Unfortunately, these grading systems provide only broad, generalized indications of quality and may not be consistent with, or at the resolution needed by, current and emerging markets. For example the official log grades for Douglas-fir in the Pacific Northwest do not discriminate knot size until knot diameter is at least 2.5 inches (NWLRAG 1998). Furthermore, these grades have sometimes been found to produce illogical results when applied to managed plantations. For example, Sonne et al (2004) found that No. 3 Sawlogs from a 70-year-old Douglas-fir stand that had been thinned and treated with biosolids had greater yield of high grade lumber than from No. 2 Sawlogs; a reversal of customary expectations from these grades. Forest product manufacturers have become more specialized in their log quality preferences as evidenced by an unofficial system of logs sorts (Bowers 1997) that largely replaced the official system. The principal feature of the log sorts is use of a finer resolution of log properties present in the official rules; primarily log diameter; rings per inch, knot diameter, and number of knots per log face. Manufacturer concerns with juvenile wood, wood strength and stiffness, dimensional stability, and other properties are not addressed by the current log grading systems and little has been done to formally translate desired log characteristics into counterparts that can be assessed in trees and stands.

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[1] David Briggs is professor and director, Stand Management Cooperative; College of Forest Resources Box 352100; University of Washington; Seattle, WA. 98195.

Forest managers need improved approaches for quantifying relevant quality characteristics both for marketing and managing quality in intensively managed plantations. Techniques for rapid and economical field measurement of key tree quality properties exist, including tools that use acoustic wave transmission to non-destructively assess potential modulus of elasticity (MOE) of products from logs and trees (Carter et al. 2004). Techniques of statistical quality control have been successfully implemented in many industries and manufacturing settings where properties of the product from a process are measured and monitored with the objective of maximizing conformance of properties to specifications supplied by a customer, product designer, or management. Combining these field and statistical techniques provides an opportunity to develop analytic methods for assessing quality of trees and stands that can assist silviculturists, managers and planners with silvicultural and marketing decisions.

This paper reviews a statistical quality control technique, process capability analysis (PCA), useful for assessing the degree of conformance of product properties to specifications issued by a customer or stated as quality objectives. Next, some important log quality properties that can be readily measured or estimated in standing trees for application of PCA are discussed. Several examples illustrating the use of PCA on some of these properties, singly and in combination, are presented for some intensively managed Douglas-fir plantations. Finally, management implications of applying PCA to quality of timber stands are discussed.

PROCESS CAPABILITY ANALYSIS

Process capability analysis refers to techniques for studying "process capability" or the uniformity of a process at either a single point in time or over time through repeated sampling (Montgomery 2001). More specifically, a sample of product from the process is measured for a specific property and process capability is usually estimated by using a probability distribution with the shape, center (mean, μ) and spread (standard deviation, σ) appropriate for the property. If no suitable probability distribution model can be found, process capability can be estimated from the actual frequency histogram. Two contexts for expressing process capability are presented in the following paragraphs.

First, process capability can be stated without reference to external specifications for the property of interest. In this case, process capability is stated as the six-standard-deviation spread of the distribution of the product property, expressed as the upper and lower natural tolerance limits (UNTL, LNTL);

$$UNTL, LNTL = \mu \pm 3\sigma$$

If a normal distribution is assumed for the property, process capability can be stated by noting that 0.27% of the product, or 2700 product items per million, will be outside the UNTL – LNTL range for the property.

Second, process capability can be stated as the percentage of product falling outside, or not conforming to, external specifications for the property. Upper and lower specification limits (USL, LSL) may be one sided or two sided and may originate from product designers and engineers, management directives, product standards, or customers. A manager can compare USL and LSL with the probability distribution of the product property. Nonconformance is the percentage of the distribution outside the bounds defined by USL and LSL. Assuming that the property is normally distributed, that the process is in statistical control as evidenced by control charts for the process, and that the mean is centered between USL and LSL, process capability can be expressed as a process capability ratio (C_p), formed from the external specification limits and the natural limits of the process as follows:

$$C_p = \frac{USL, LSL}{6\sigma}$$

Correct use and interpretation of C_p is dependent on the validity of the assumptions. C_p will not be used here; more experience with the distributions of timber quality properties and the effect of cultural practices on these distributions will be needed to determine if the assumptions underlying C_p are valid.

If the assumptions underlying Cp are not met, an alternative is to compare USL and LSL directly with the probability distribution or frequency histogram of the property. Process capability can be stated as the percent non-conforming as estimated from the portions of the distribution or histogram outside the specification limits. This approach, using actual frequency histograms based on sampling trees from the stand of interest, will be used in the following examples. Future research will be needed to discover probability distribution models that are adequate for quality properties of interest and can reflect impacts of cultural practices that could radically alter the distribution of the property. Developing the frequency histogram of a quality property requires sampling a sufficient number of trees from the stand. In constructing histograms, Montgomery (2001) suggests using between 4 and 20 bins, "choosing the number of bins approximately equal to the square root of the sample size." Thus to have six bins describing a quality property of trees in a stand, one should measure the property on at least 36 trees from the stand. This seems reasonable considering the typical number and size of plots one would place in a stand for inventory or appraisal.

WHAT IMPORTANT LOG PROPERTIES CAN BE EASILY MEASURED IN TREES FOR USE IN PCA?

Consider a mill peeling logs into veneer for plywood and laminated veneer lumber (LVL). Its log specifications may include a maximum and minimum diameter, a growth rate limit expressed as a lower bound on rings per inch, and an upper bound on knot diameter. It may also pay a premium for logs exceeding a lower bound on modulus of elasticity (MOE), a measure of stiffness and a key characteristic for veneer to qualify for LVL manufacture. Can these log quality properties be easily translated into measurements that can be easily obtained from standing trees and subsequently used in PCA?

Log Diameter Range

The dbh of the sample trees, combined with a taper curve to predict diameters inside bark, can be used to estimate log diameters. Since dbh is customarily measured in an inventory, measuring this property adds no new cost. If forest growth models are used, most project the dbh of individual trees and some produce log stock tables that would provide a means for finding nonconformance to log diameter range specifications. Additional accounting may be necessary before a model could automate calculation of nonconformance to user-defined log diameter specifications.

Rings Per Inch (Rpi)

On permanent plots where trees are tagged and periodically measured for dbh, the change in dbh can be used to estimate periodic rpi without new cost. One can expect that rpi at breast height (bh) is highly correlated with rpi of the first log in the tree, since bh is within that log, and should be well correlated with rpi of upper stem logs. Increment cores could be used as an alternative but this would add expense in collecting the cores and measuring the rpi. If forest growth models are used, rpi can be readily inferred from dbh changes between projection periods. It may be necessary to add some accounting procedures in the models to automate and report rpi and to produce log stock tables according to user-defined rpi specifications.

Knot Diameter

Typically, each log grade or log sort has a maximum knot diameter (Bowers 1997) and product recovery researchers have found that largest limb average diameter (LLAD, Fahey et al. 1991) also known as branch index (bix, Barbour & Parry 2001), defined as the average of the largest diameter knot in each of the four quadrants or faces of the log surface, is a good predictor of product grade recovery from a log. One can hypothesize that the diameter of the largest knot or LLAD, measured with a caliper on the lower bole, would be highly correlated with the largest knot diameter or LLAD of logs within the tree. The Stand Management Cooperative and others (Ingaramo 2003) have measured diameter of branches within a region centered on BH and have found that this adds little to field time and cost. Examination of the hypothesized relationship between BH and log knot diameter measures will be presented later in this paper. Some growth models can estimate the diameter of branches at each whorl position along the boles of trees (Hann et al. 1997, Mitchell 1975). With some further accounting, this information could be used to estimate nonconformance to a knot diameter specification.

Modulus of Elasticity (MOE)

The relationship between the MOE of a material, its density and the speed of an acoustic wave through the material forms the basis for a method of nondestructive testing of logs for MOE (Wang et al. 2000). This acoustic method measures the “dynamic” MOE in contrast with the MOE obtained by static bending. Researchers have demonstrated excellent relationships between the dynamic and static bending MOE of logs, and between the average static bending MOE of products obtained from a log and the dynamic and static bending MOE of the parent log (Ross et al. 1999, Wang et al. 2004). This research has led to commercial tools for nondestructive testing and sorting logs using acoustic signals and a related tool for nondestructive testing in standing trees has just become available (Carter et al. 2005; this proceedings). This new tool, which is used on the lower bole of a tree, provides the opportunity for assessing the degree to which trees in a stand conform to a specification for MOE. Further research is underway to develop relationships along the chain from tree to product and to optimize use of these tools in the field.

This review indicates that properties important to product and log quality and value can be readily measured on standing trees and many can be inferred from growth and yield models, although this may require some refinements in summary programming. During a stand inventory, sufficient trees are likely to be present on plots to gather these data and pooled if necessary to develop frequency histograms for use in PCA.

PCA OF DOUGLAS-FIR STANDS AT A SINGLE POINT IN TIME

A spacing trial located on the Pilchuck Tree Farm near Stanwood, Washington will be used as an example. In May of 1983, six acres of former cattle pasture was divided into fifty square plots, each 73 ft x 73 ft covering 0.08 acres. Site index is medium to high: 140 ft at 50 years (King 1966), corresponding to 98 ft at 30 years, using the new curves for planted Douglas-fir stands (Flewelling et al. 2001). The plots were planted with two-year-old, unimproved, local origin Douglas-fir seedlings over six densities ranging from 194 to 681 trees per acre; two densities had a rectangular spacing, while the rest were square. The outermost row of trees in each plot was regarded as a buffer to avoid edge effects from contiguous plots. On each plot, trees inside the buffer were tagged and measured for DBH in 1990 and 1998. In the winter of 2001-2002, six plots, chosen at random from each spacing, forming a completely randomized design with six replications of six stocking treatments, were measured for detailed growth, yield, and quality attributes (Ingaramo 2003). Using the 1998 DBH distribution, 12 trees were sampled on each plot; the smallest, the largest, and 10 others selected at random. All sample trees were measured for dbh and divided into N, S, E and W quadrants or faces. In each quadrant, the diameter of all branches greater than or equal to 1/3 inch, located within one-foot above and below breast height (4.5 ft), was measured with a caliper. Branch diameter was measured perpendicular to the branch axis, in the direction of stemcircum ference, just beyond the branch collar. Restricting branch measurement to those that were at least 1/3 inch diameter excluded many small ‘whiskers’ that tend to self-prune very rapidly, and have little, if any, effect on grading. A random sample of four of the study trees was measured for total height and height to the live crown defined as the average of the height to live branches in the four quadrants. Table 1 summarizes the tree characteristics according to stand density; at age 18 (20 years from seed).

In May 2003, the four height trees were climbed to 17.5 feet using a ladder and the largest diameter branch in each of the N, S, E and W faces of the 16-foot butt log was measured. It was assumed that the stump was 1 foot high and that the log had 0.5 feet of trim allowance. The 16-foot butt log was chosen since it is a preferred length for lumber, closely approximates two peeler bocks for making veneer, and is relatively fast and easy to measure with the ladder method; a crew of five located and measured 136 trees in about four hours. The owner had initiated thinning in some plots and if the sample tree had been removed in the thinning, the standing tree most similar in DBH was used as a replacement. Two plots had been heavily thinned and were inaccessible for sampling due to the amount of felled material on the ground. With the exception of a single branch on the southern aspect of one tree at the lowest density, all branches in the BH region of the sample trees were dead. Furthermore, live crowns had receded above the top of the log and during climbing it was noted that there were only a very small number of living but severely suppressed branches within the 16-foot butt log. It is assumed that there will be negligible additional growth on these few branches.

The hypothesis that there would be a reasonably good correlation between branch diameters in the BH region and on the 16-foot butt log was mentioned earlier. Figure 1 presents regressions between largest diameter branch and LLAD in the BH region and on the 16-foot butt log. LLAD of the 16-foot log produced a better regression than the largest diameter branch of the log. Also, the regressions were poorer using LLAD of the BH region. Over the short two-foot BH region, some quadrants had no branches (zero branch diameter), which increased variation in BH region LLAD and reduced its correlation with the log measures. This is fortunate since it is easier for field personnel to find and measure the largest branch in the BH region rather than spend time locating quadrants and measuring the largest branch in each quadrant.

Applying PCA To Knot Diameter

A timber seller or purchaser would use one of the regressions to translate a log specification for knot diameter into a counterpart BH specification for standing trees. For example, if a sawmill places a 1.5-inch upper limit on LLAD of logs, the equation in figure 1A yields a largest BH knot diameter of 1.5 inches. After translating the log specification to a tree specification, the frequency histogram of largest BH branch diameters from the trees in a stand can be compared with the translated specification. Figure 2 shows such a comparison for the 194 tpa (15 ft x 15 ft) density and shows that about 52% of the trees are nonconforming. A mill may decide to not make a purchase bid for a stand with such high nonconformance. The seller, aware of this poor non-conformance, can focus marketing efforts on those who accept trees with relatively large knots. Some may prefer to create cumulative frequency distributions that may be visually easier for comparing multiple stands with the specification limits in the same graph. Figure 3 shows cumulative frequency distributions for knot diameter for all of the densities in the 18-year-old trial; the percentage of trees nonconforming to the BH knot-diameter specification ranges from only 3% in the 681 (8 ft x 8 ft) density, to 52% for the 194 tpa (15 ft x 15 ft) density.

Table 1—Mean (and standard deviation) of tree characteristics by spacing in the Pilchuck Tree Farm spacing trial at age 18

Charachistic	Density, trees/acre Spacing ft x ft					
	194 (15 x 15)	218 (20 x 10)	302 (12 x 12)	340 (16 x 8)	435 (10 x 10)	681 (8 x 8)
Quadratic mean diameter, in	11.1 (0.56)	10.7 (0.37)	9.8 (0.36)	9.4 (0.26)	8.8 (0.21)	7.5 (0.18)
Total height, ft	52.5 (1.67)	50.8 (4.69)	53.5 (4.82)	53.2 (3.19)	56.1 (2.26)	54.1 (2.07)
Crown ratio	.68 (0.015)	.67 (0.021)	.56 (0.046)	.58 (0.054)	.52 (0.022)	.47 (0.031)
Crown base, ft (calculated)	16.8	16.8	23.5	22.3	26.9	28.7
Largest b.h. diameter, in	1.54 (0.26)	1.41 (0.23)	1.25 (0.23)	1.24 (0.21)	1.21 (0.28)	1.01 (0.22)

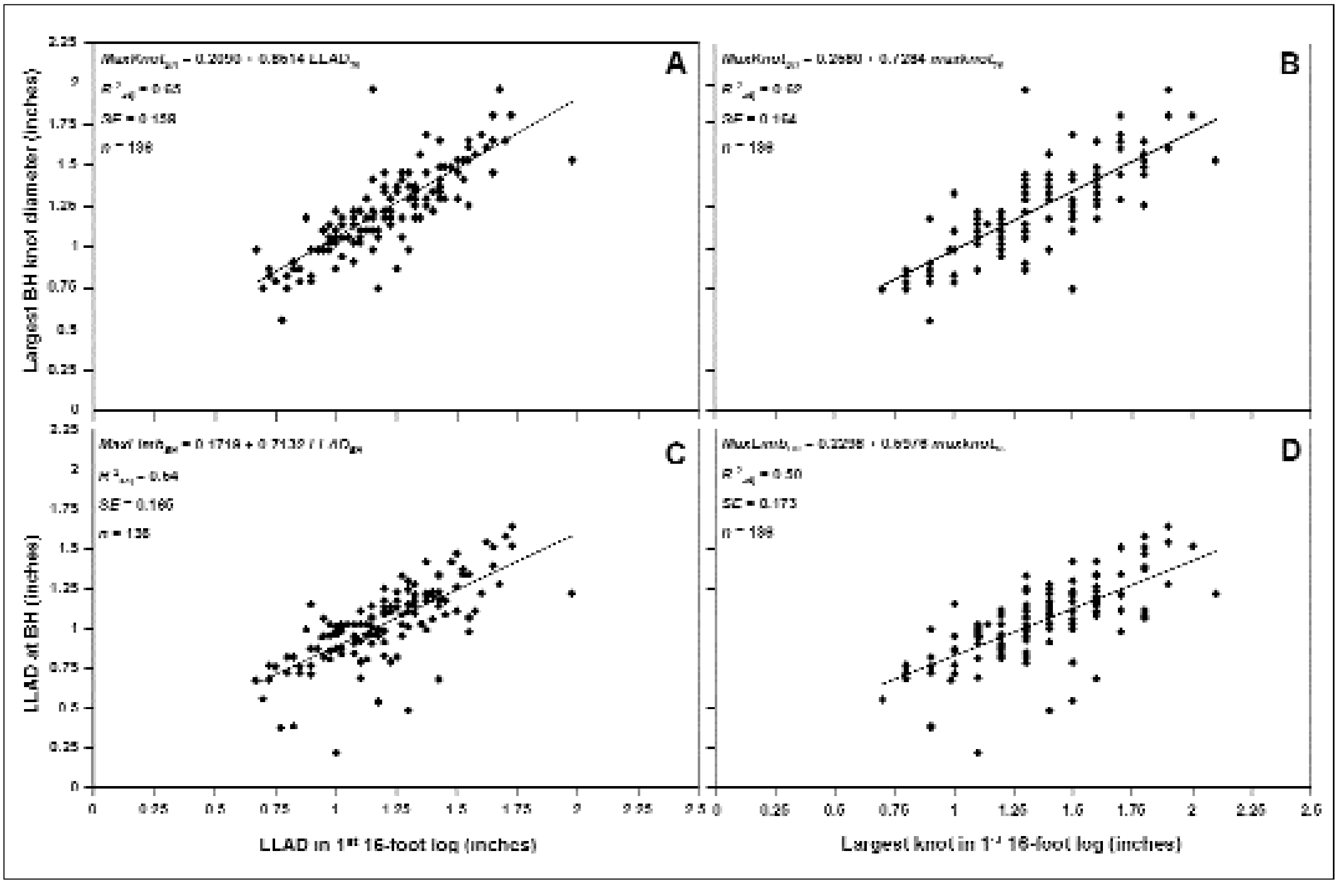

Figure 1—Knot diameter measures in the BH region of a tree verses knot diameter measures in its 1st 16-foot log.

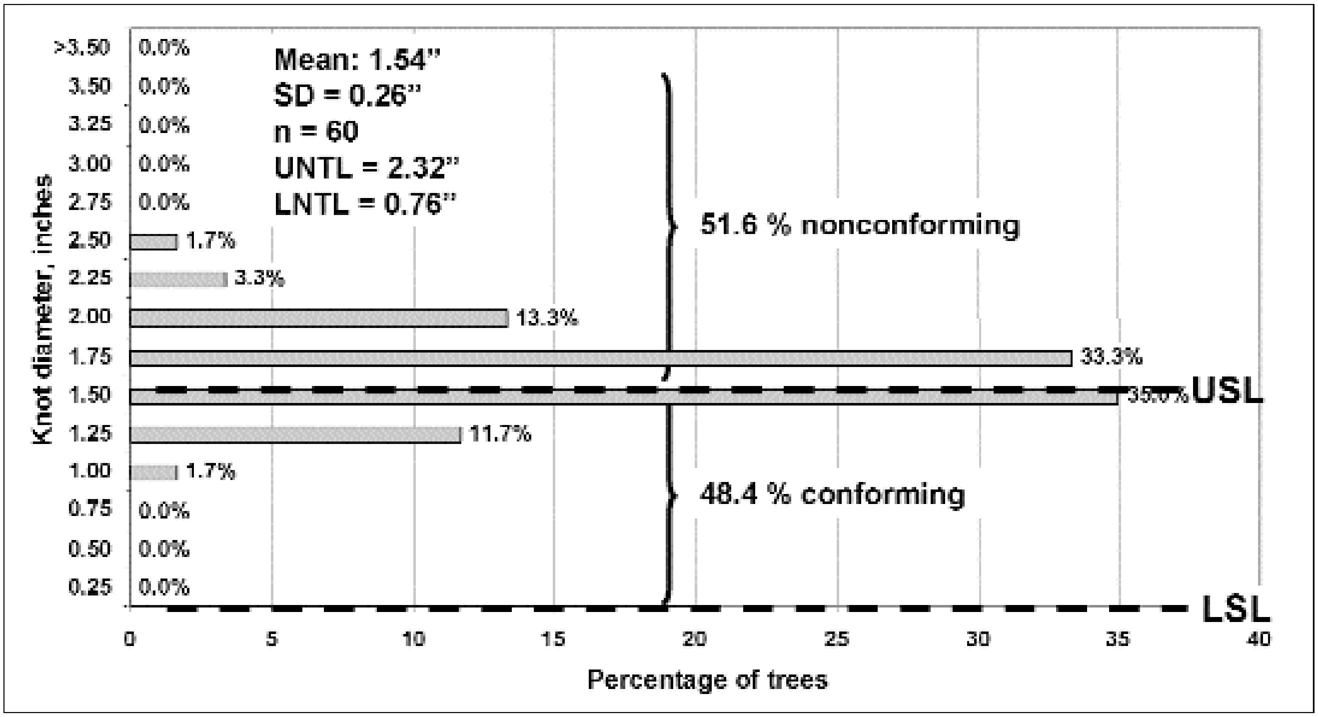

Figure 2—Distribution of the largest diameter knot in the BH region of 18-year-old trees in a plot planted at 15-ft x 15-ft spacing.

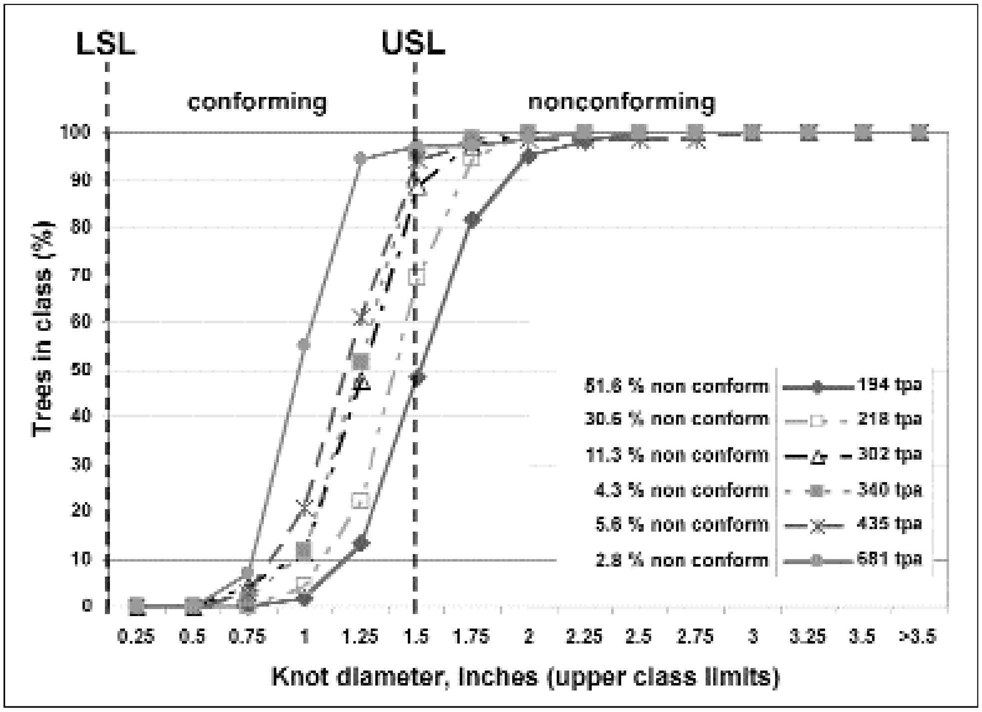

Figure 3—Cumulative distributions of the largest diameter knot in the BH region of Pilchuck Tree Farm spacing trial at age 18.

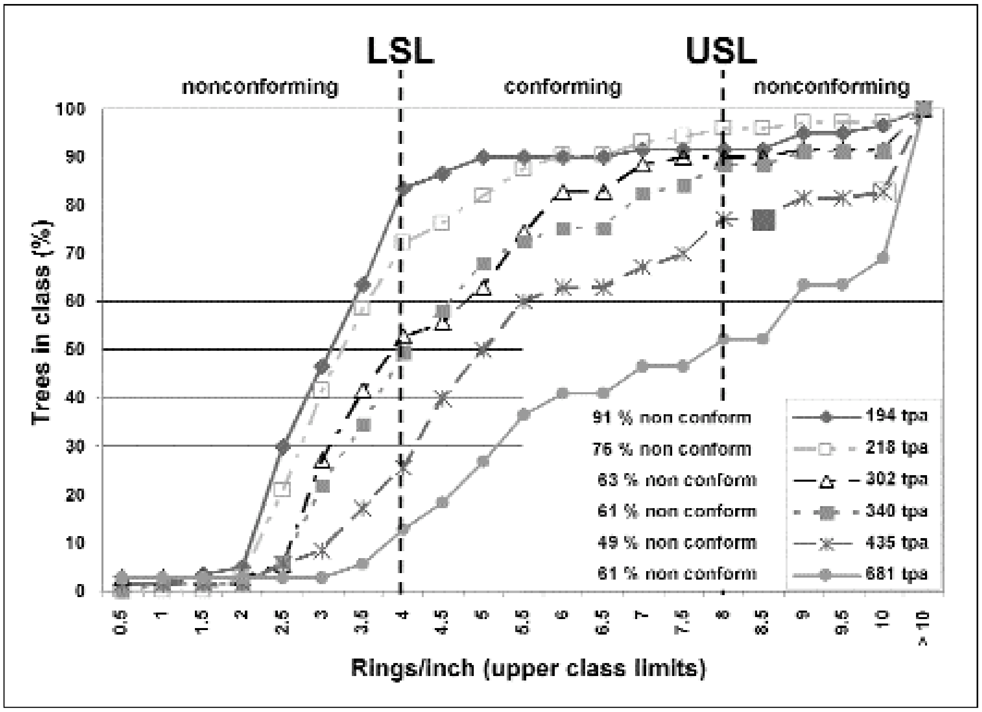

Figure 4—Cumulative distributions of rings/inch of the Pilchuck Tree Farm spacing trial at age 18.

Applying PCA To Rings Per Inch

Mills often find that extremely fast growth is an undesirable characteristic for their products while tree growers find that extremely slow growth is undesirable from a financial perspective. Suppose a mill's log specification excludes growth rates faster than four rpi while a landowner does not wish growth slower than eight rpi. Figure 4 shows an LSL of four rpi and a USL of eight rpi overlaid on the cumulative frequency distributions of rpi for the 18-year-old spacing trial, calculated from the 1998 and 2001 dbh measurements; nonconformance ranges from 49% at 435 tpa (10 ft x 10 ft) to 91% at 194 tpa (15 ft x 15 ft).

Applying PCA To Knot Diameter and Rings Per Inch Simultaneously

Specifications must usually be considered jointly rather than independently; trees must simultaneously satisfy having the largest BH branch diameter not greater than 1.5 inches and rpi not less than four and not greater than eight. Joint specifications can be readily treated by a data plot or two-variable histogram. Figure 5 plots largest BH branch diameter vs rpi for the 194 tpa (15 ft x15 ft) density along with specification limits for both quality characteristics; 98.3% of the trees are nonconforming to both specifications. Figure 6 summarizes the results across all densities. Nonconformance to the joint specification ranges from 98% at 194 tpa (15 ft x 15 ft) to 56% at 435 tpa (10 ft x 10 ft).

PCA OF DOUGLAS-FIR STANDS AT MULTIPLE TIME POINTS

Consider a 0.5-acre plot planted at 100 trees per acre (21 ft x 21ft), one of the spacings in Stand Management Cooperative (SMC) Type I Installations. This plot is part of Installation 925 located near Belfast, WA on a moderately poor site (SI 107). The installation was planted in 1990 with 2-0 Douglas-fir seedlings and has been measured every two years starting in 1997. The SMC developed a BH branch/knot assessment protocol that was first applied to the installation in 1999 hence this is one of few that has been measured with this procedure three times. The SMC BH knot protocol for Douglas fir locates the first whorl of branches above BH and the region from the point midway to the next lower and next higher whorl. In this region, the diameter of the largest branch is measured and the number of branches that are at least 50% of this largest diameter are counted. This procedure is applied to those trees on the plot that are measured for crown and total heights. Table 2 summarizes the plot at ages 9, 11, and 13. The base of the live crown is below BH hence branches at BH are alive and growing in

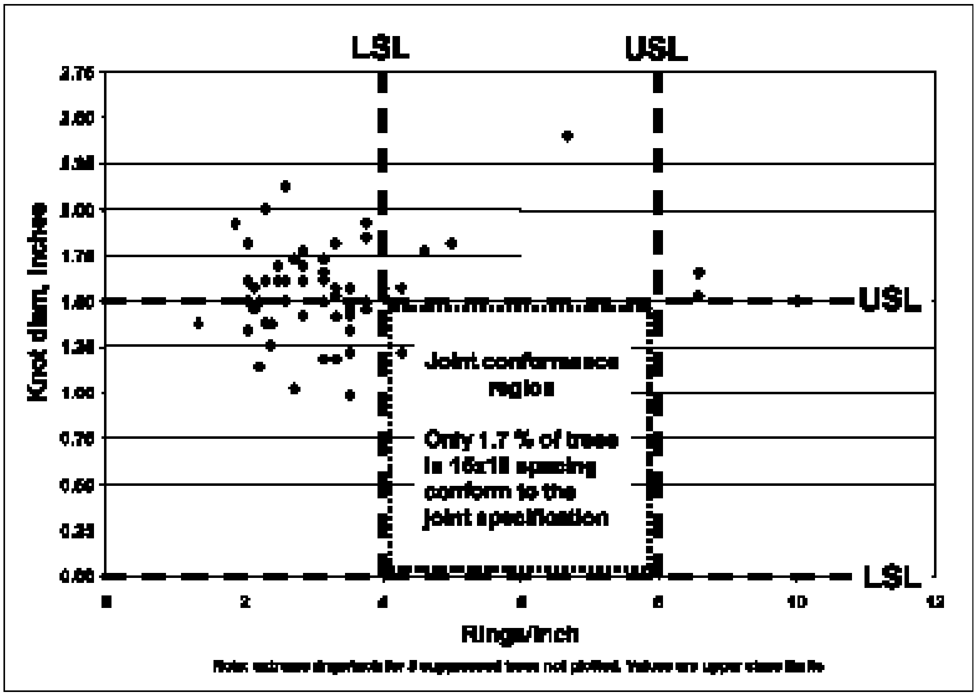

Figure 5—Largest diameter knot in the BH region at age 18 verses rings/inch of the 15-ft x 15-ft (194 tree/acre) spacing at the Pilchuck Tree Farm.

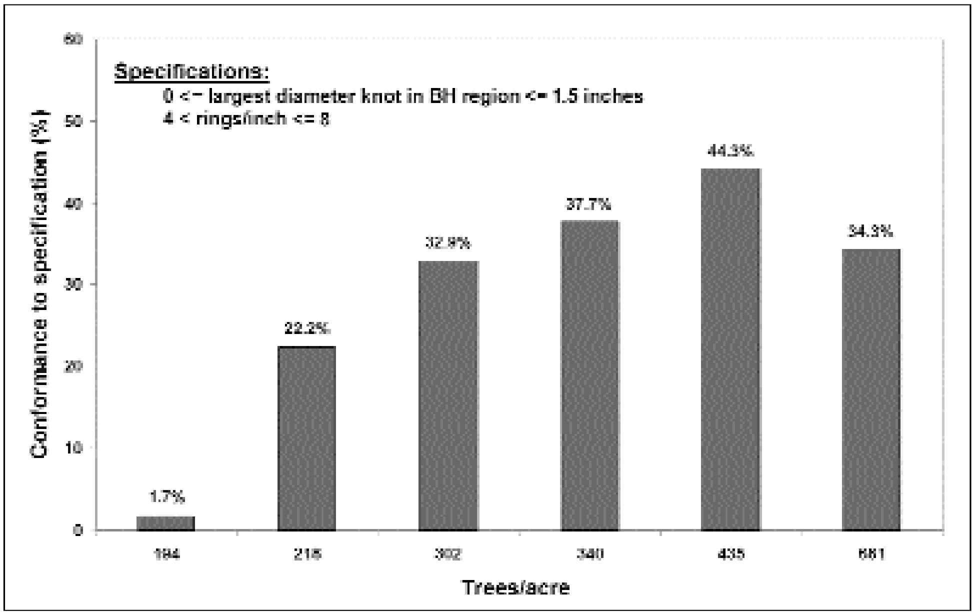

Figure 6—Conformance of Pilchuck Tree Farm spacing trials to joint specifications at age 18 .

Table 2—Trees charasteristics by stand age at SMC installation 925, 21 ft x 21 ft (100 tpa) planting

	Stand age		
Charasteristics	**9**	**11**	**13**
D.b.h., in.	1.6 (0.54) N=49	2.6 (0.82) N=49	3.8 (0.89) N=49
Total height, ft	12.0 (2.72) N=49	15.6 (5.81) N=49	20.8 (7.31) N=49
Height to crown, ft	1.2 (0.54) N=49	1.2 (0.62) N=49	1.3 (0.91) N=49
Largest b.h. branch diameter, in	0.51(0.14) N=47	0.63(0.17) N=45	0.80(0.18) N=45

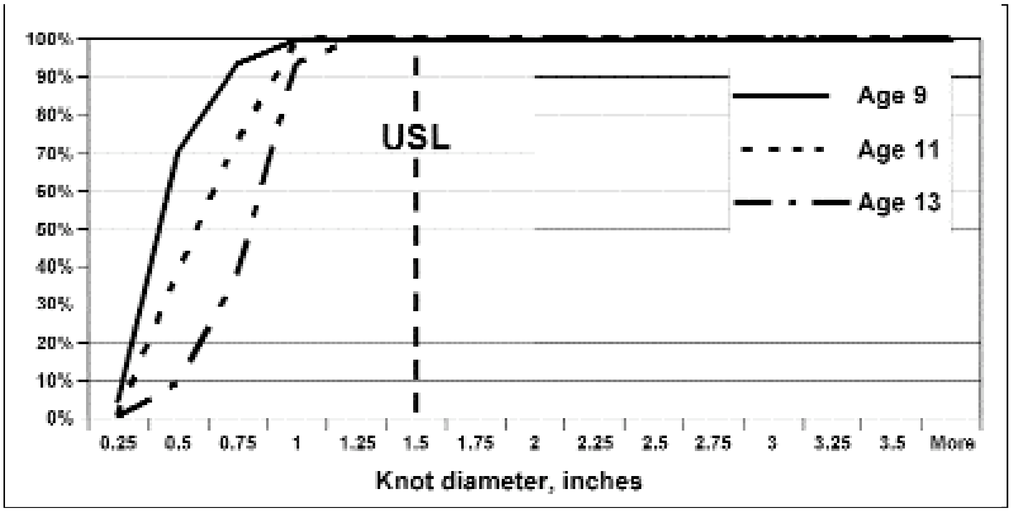

Figure 7—Cumulative distributions of largest diameter BH knot verses age for 21-ft x 21-ft (100 tree/acre) spacing at Stand Management Cooperarative Installation 925.

diameter. Figure 7 presents cumulative distributions of largest BH branch diameter as this plot has aged. It is easy for management to monitor the progression of the stand relative to a target specification for largest BH knot diameter and consider actions that may be taken to prevent excessive nonconformance.

Discussion and Management Implications

The examples presented above illustrate how producer and consumer desires for quality properties can be converted into specifications for trees. For some properties such as rings per inch, developing an acceptable tree specification may involve trade-offs between the desires of the parties that define a range of mutually acceptable values. PCA allows managers to combine these specifications with sample-based frequency distributions from stands of interest to estimate nonconformance. This provides important information on marketability of a stand and information that can assist in choosing future management actions. Process capability and conformance to specifications can be improved by taking actions to shift the process mean and/or reduce variation. Managers can monitor changes in process capability and the effectiveness of actions taken over time through repeated sampling. The following paragraphs provide two examples.

First, consider nearly mature or mature stands that are being considered for harvest scheduling or are already scheduled for sale. A producer, aware of the log specifications of potential consumers, can use PCA as part of sale development to assess which consumers are more likely to be interested in a stand and focus marketing efforts accordingly. Similarly, consumers can use PCA when they assess a stand to decide if it is worthy of a bid. Organizations with large timberland holdings may use PCA as a method for assessing conformance of stands to alternative market specification sets. These market conformance options could be included in harvest planning models to improve decisions as to which stands should be harvested and when in order to meet mill and other customer demands. For example, if a company has a laminated veneer lumber (LVL) plant, it

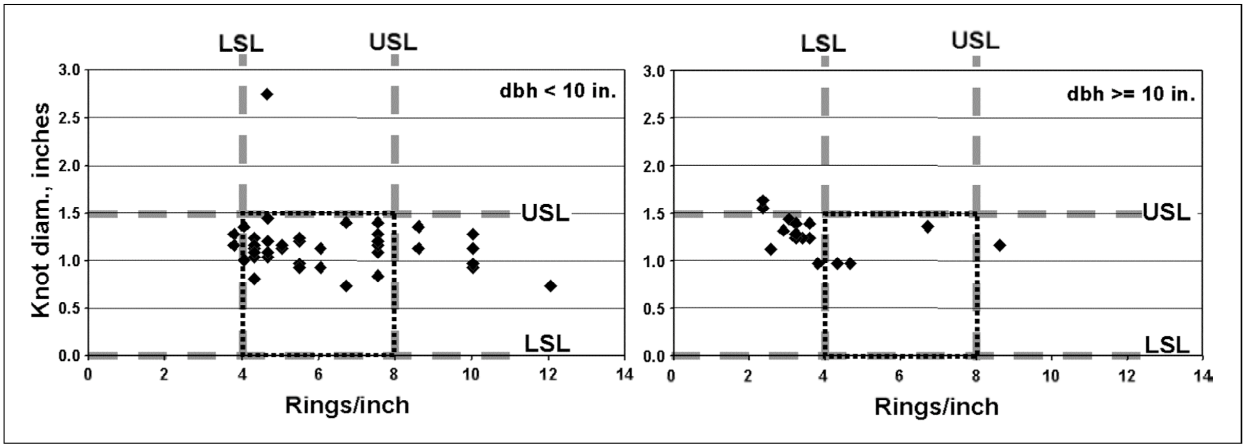

Figure 8—Largest diameter knot in the BH region at age 18 verses rings/inch by DBH of the 10-ft x 10-ft (435 tree/acre) spacing at the Pilchuck Tree Farm.

would like assurance that it's harvest plan provides an adequate supply of timber with high potential to meet the needs of the LVL plant product line.

Second, in immature stands, there are many ways that PCA could assist in silvicultural planning. For example, consider figure 8 where the plot of largest-diameter BH knot and rings per inch has been segregated for trees larger and smaller than 10 inches in dbh. This new detail shows how well larger and smaller trees conform to the joint specification. This could assist in planning future silvicultural activities such as deciding if a thinning should be done and, if so, which trees to remove. A goal might be to try to identify, retain and manage trees that maximize conformance of the final stand. As a different example, figure 7 showed the progression of largest diameter BH knot with age in the SMC 100-tree-per-acre plot. Since the crown base is very low on these trees, will the crown recede before too many trees develop large branches and become nonconforming? If this is likely, is pruning justified? These examples imply the need for a mechanism for projecting the results of such actions and providing feedback. If growth and yield models are being used to project the effects of alternative actions, are they capable of tracking quality properties and providing feedback in a PCA format? Silviculturists could use such models to simulate various options and eliminate those with poor conformance with anticipated future market specifications.

Although the applications of PCA presented in the examples focused on knot diameter and rings per inch, the techniques could be easily extended to other properties such as data gathered with the new Director ST-300™ technology for non-destructive testing trees for MOE (Carter et al. 2005; this proceedings). Figure 9 presents frequency histograms of acoustic velocities obtained from an unthinned (n = 63 trees) and a thinned (n = 50 trees) plot in SMC Type II Installation 803 at bh age 43 (Carter et al. 2005; this proceedings). If a mill specification stated that it prefers stands with trees with velocities exceeding 4.3 km/sec, the thinned stand, with 48% of trees above this threshold, is preferable to the unthinned stand with only 27% exceeding this threshold. Furthermore, the mill may pay a premium for trees exceeding 4.5 km/sec; 25% of trees in the thinned stand meet this premium whereas only 12% of the unthinned trees qualify. Combining tools such as the Director ST 300™ with PCA can provide landowners and mills with an improved and more flexible method for matching timber quality with market needs.

When using regression models to translate log values to tree values as done earlier with the conversion of LLAD of logs to largest BH knot diameter, a consumer would note that using the direct equation prediction of largest diameter BH knot would result in a tree specification where some trees with an acceptable largest diameter BH knot would contain logs with an excessive LLAD (fig. 10). The consumer's risk can be reduced by calculating a lower prediction limit, say 95%, which would reduce the largest diameter BH knot specification from 1.5 to about 1.25 inches. The use of lower limits is used in setting grades for machine-stress-rated lumber. Note that this lower limit increases the producer's risk, as more trees with acceptable logs will be rejected. Ultimately, the parties involved would negotiate a solution that strikes a balance between producer and consumer risks.

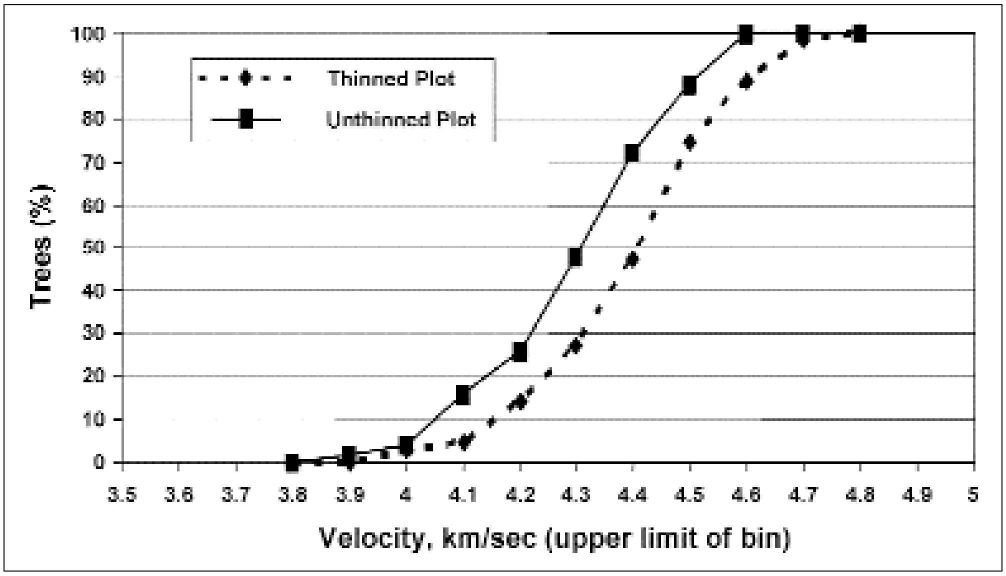

Figure 9—Cumulative frequencies of acoustic velocities measured by the Director ST-300™ in thinned and unthinned plots at Stand Management Cooperative Installation 803.

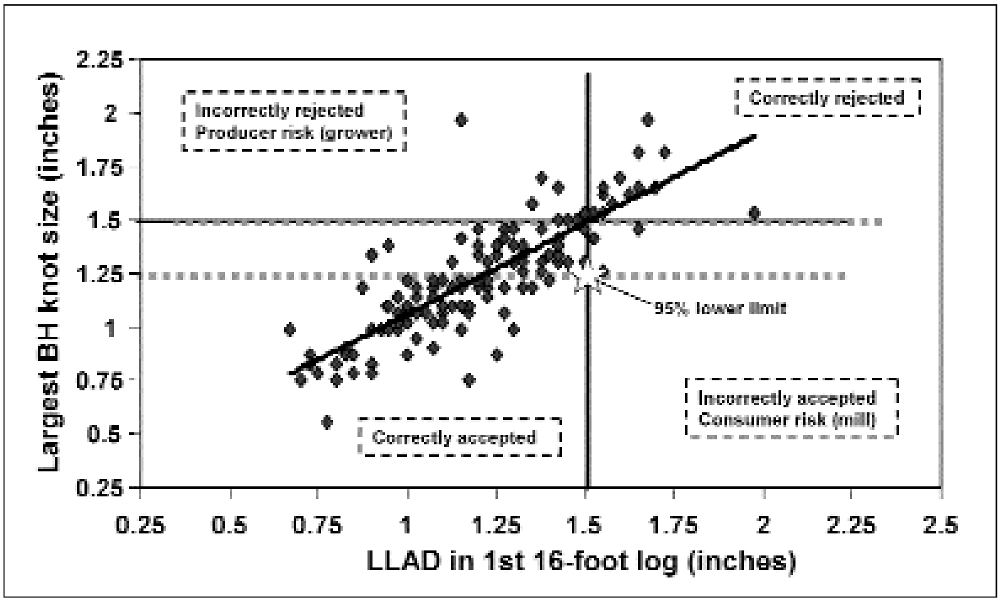

Figure 10—Producer (grower) and consumer (mill) risks as influenced by maximum BH knot size and the largest-limb average diameter in the 16-ft butt log.

CONCLUSIONS

Process capability analysis has been shown to be a useful technique for quantifying conformance of a variety of quality properties of trees that are important to log consumers. Several important properties can be easily estimated at or near BH with little additional cost. Requirements for many log properties specified by consumers can be translated into counterpart values that can be easily measured on the lower bole of trees in the field; these values appear to be well correlated with the butt log. Sample size requirements appear to fit reasonably within the number of trees that would be found in commonly used inventory plots.

Given specifications for one or more tree properties, management can use a suitable individual tree growth model to make projections and estimate the degree of nonconformance when the stand becomes ready to harvest. Armed with this information, cultural options such as density management, fertilization, and pruning can be forecast and evaluated in the context of how these options would influence the proportion of the stand that would be nonconforming. These projections would provide management planners and harvest schedulers with improved insights concerning the potential marketability of developing stands in their portfolio and provide feedback with respect to the degree to which remedial silvicultural options can reduce nonconformance.

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PAPERS BASED ON POSTERS

CARBON SEQUESTRATION IN DOUGLAS-FIR STANDS OF THE COASTAL CONIFEROUS FOREST REGION OF WASHINGTON STATE

A.B. Adams, R.B. Harrison, M.M. Amoroso, D.G. Briggs, R. Collier,
R. Gonyea, B. Hasselberg, J. Haukaas, and M.O. O'Shea[1]

ABSTRACT

Quantifying the effects of urea fertilization on carbon (C) in the solid and solution phases of soils can aid forest management. We evaluated the effect of urea fertilization on pure second-growth Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] stands growing in four soil series of the coastal coniferous forest region of Washington State. Our major objective was to determine the range of carbon flux and sequestration for this region. This paper covers our results for soil organic carbon (SOC) sequestration. Our soils were selected to give a range of texture from coarse-grained glacial to fine-textured volcanic. We compared soil types, soil depths and fertilization treatments over 20-year intervals. There was no difference in soil C in a coarse glacial outwash soil. By contrast, in a glacial sandy outwash soil all mineral horizons had more soil C and the forest floor less C compared with the paired unfertilized plot. In two volcanic soils our results provide evidence that DOC from the forest floor and A horizons was sequestered in both the epipedon and lower horizons. Differences between glacial and volcanic soils suggest that mechanisms of C were different in the coarse-textured materials than the fine-textured volcanic material. Urea fertilization added nitrogen to soils at all installations with differences ranging from 1-3 Mg N ha^{-1}. The 2 glacial soils had lower site indices. They had less SOC (mean of 87 versus 348 Mg ha^{-1}) but greater increases in aboveground C (mean increase of 41 versus 8 Mg ha^{-1}). Although fine-textured sites were more productive overall, the aboveground response to urea was limited in comparison to differences found in fertilized plots of the glacial sites. In contrast, SOC did increase with urea applications in fine-textured sites in excess of increases solely attributable to DOC.

KEYWORDS: Carbon sequestration, urea fertilization, managed Douglas-fir stands.

INTRODUCTION

There exist several ecosystem management strategies directed toward enhancing carbon (C) sequestration through forest management: 1) to partition C into longer-lived pools; 2) to increase the physical, chemical and biochemical protection of soil C; and, 3) to enhance C storage in living tree biomass. The overall theme of our work is to relate management practices to soil organic carbon (SOC) partitioning among alternative pools including dissolved organic carbon (DOC) production and transport. Specifically, in this paper we report on the storage of soil organic carbon (SOC) based on texture, horizon, depth and fertilization with urea. Gains in forest productivity have been shown with Douglas-fir stands in the Pacific Northwest (Stegemoeller and Chappell 1990). Increased aboveground biomass may (Johnson 1992) or may not (Harding and Jokela 1994, Canary et al. 2001) be accompanied by a gain in soil C. Urea fertilizer can increase the movement of SOM (Kelly 1981). Our initial hypothesis was that total C accumulation would exceed C accumulation in wood plus roots in response to nutrient management of fine-textured soil, but not on coarse-textured soils. This paper includes sequestration of SOC and aboveground C, but does not cover root C.

The Regional Forest Nutritional Research Project (RFNRP) (Stegemoeller et al., 1990) established installations in the Pacific Northwest to evaluate the response of coastal Douglas-fir to urea-N fertilization. In 1991, this project was combined with the Stand Management

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[1] A.B. Adams, R.B. Harrison, M.M. Amoroso, D.G. Briggs, R. Collier, R. Gonyea, B. Hasselberg, J. Haukaas, and M.O. O'Shea are faculty and staff of the College of Forest Resources, University of Washington, Box 352100, Bloedel Hall 292, Seattle, WA 98195.

Cooperative (SMC) in order to include research on integrated studies (SMC 1999). For this study we utilized the stand database created by RFNRP and currently maintained by the SMC at the University of Washington. The sites [arranged in order from coarsest textured soil (Site 1) to finest textured soil (Site 4)] used were Cedar River [RFNRP #159 (a coarse glacial outwash soil)], Port Gamble [#196 (sandy outwash)], Radio Hill [#247 (coarse silty loam over a compacted duripan)] and Mud Mountain [#235 (deep, silty loam)]. These soils represent a regional association of parent material types from a very coarse skeletal matrix, to outwash sand and then to deep, silty loam. The skeletal matrices of Sites 1 and 2 were derived predominantly from glacial parent material and Sites 3 and 4 from tephra. The RFNRP permanent plots revealed that following fertilization, the periodic increment increased due to the N treatment, resulting in 49.9, 31.3, 6.4, and 9.7 Mg ha^{-1} additional C in the four sites, respectively, for an average of 24.3 Mg ha^{-1} additional C from a 16-year growth period (Adams et al., submitted). The largest aboveground tree responses were in the glacial soils. This paper focuses specifically on the SOC in relation to the aboveground live tree C compartments of these stands.

METHODS

When the four installations were established (1972 to 1980), 224 kg ha^{-1} elemental N as urea fertilizer was added to treatment plots. The same amount of fertilizer was then again added at 8 and 16 years. In addition, Sites 1 and 2 received 224 kg ha^{-1} urea 12 years after installation. One pit was dug and soils collected at each 0.1 ha plot (2 pits per installation). Soil collections were made from the face of pits using a hand trowel. Sampled layers were delineated and measured based on color, texture and structure breaks. All soils with texture < 25 mm and rocks ≥ 25 mm were weighed as two separate components in the field. A 1 kg sub-sample of the < 25 mm component was taken from each field identified layer and used to determine field moisture, particle size distribution (standard sieve procedures with dried samples), C and N content and pH. Mineral soil was air-dried to constant weight. Forest floor material was dried for 7 days at 70°C. The amount of C and N (in Megagrams ha^{-1}) were calculated for each layer based on thickness, percent soil C or N, and bulk density (Db); then, values for all layers were summed within each horizon. Adams et al. (in prep.) contains a more detailed explanation of the sites and methods.

RESULTS

The range of soil textures present was a function of parent material. Although volcanic and glacial activity both impact soils in the Pacific Northwest, the soil skeletal matrix of the parent material is usually dominated by one of the two processes. Our study found (fig. 1) that the two coarse-textured installations (Sites 1 and 2) were dominated by glacial outwash with mixed mineralogy, whereas Sites 3 and 4 were volcanic in nature (ashy, silty loam). Rocks dominated Site 1, while sand dominated Site 2. Tephra dominated Sites 3 and 4. Clay (which can play a role in C stabilization and sequestration) (Brady and Weil 2002) was almost absent from Site 1, but present on the other three sites where it ranged from 5% to 9% by dry weight.

There was a marginally significant difference in total SOC between unfertilized and fertilized paired plots ($p < 0.1$, paired Student’s t-test analysis, $n = 4$ (fig. 2). There was a significant difference in N between fertilized and unfertilized plots ($p < 0.05$) and both N and C in glacial soil were significantly less than N and C of volcanic soils ($p < 0.05$, ANOVA, $n = 8$). A regression of the means of soil C from the two pits at each site compared with percent silt was significant ($R^2 = 0.91$, $F = 19.2$, $P < 0.05$; $Y = 4.3X + 20.2$, $n = 8$).

When profiles for these soils are compared with respect to C (fig. 3), forest floor C is less in fertilized compared to unfertilized plots. In the sandy glacial outwash plots (Site 2), C is higher in all horizons; interestingly, the E and B horizons show two or three times as much C as the same horizons in the unfertilized plot. In the volcanic installations, the higher soil C content is due to larger amounts of C in the A and AB (Site 3) or just the AB (Site 4) horizons. Much of the SOC is found below the A horizon. This difference is due to larger volumes of soil included in the calculations to a one m depth as well as the increase in Db of the < 2 mm fraction that was measured.

At all installations fertilized plots have less C in the forest floor than paired unfertilized plots (fig. 4), but this difference was negligible (< 1 Mg ha^{-1}) at Site 1. In contrast, mineral soil of fertilized plots at Sites 2, 3, and 4 had more soil C relative to paired unfertilized controls. The differences in C sequestration between paired plots were mainly attributable to larger amounts of soil C in fertilized plots between 10 and 60 cm depths (Adams et al. in prep.). The three sites with greater mineral soil C were more acidic and had higher C/N ratios than paired unfertilized plots. The greatest increases in C sequestration occurred between 5 and 60 cm and at C/N ratios between 20 and 35.

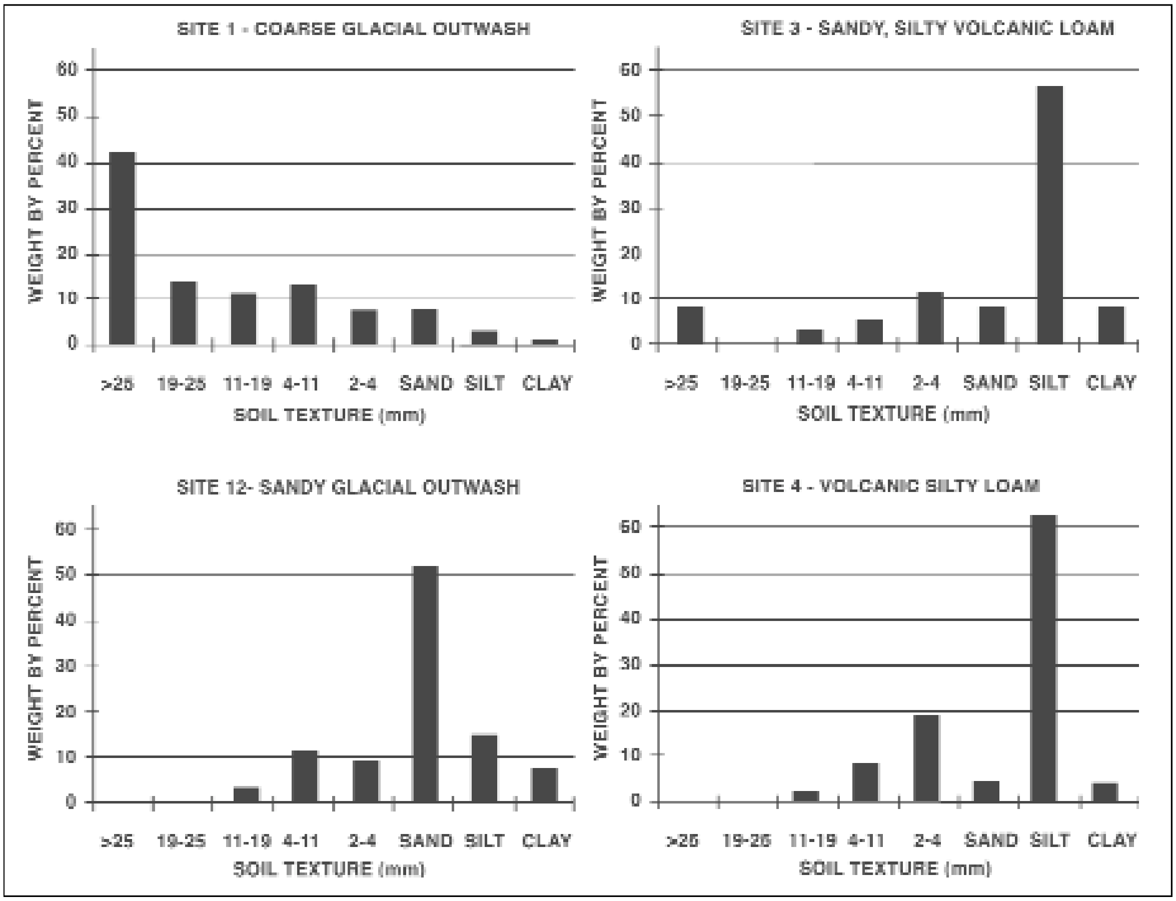

Figure 1—Particle size distribution taken at 25 cm mineral soil depth for each site. Site 1 (Cedar River) had many large rocks and gravel with only 12% < 2mm. Site 2 (Port Gamble) was mostly sandy outwash. Site 3 (Radio Hill) was coarse loamy silt with some rocks and Site 4 (Mud Mountain) was mostly silty loam with no rocks.

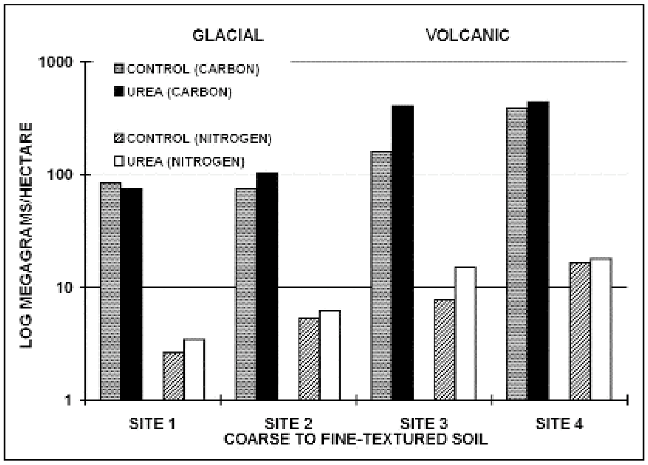

Figure 2—Distribution of C and N by site and treatment in 2001. All previously fertilized plots still had more nitrogen several years after cessation of urea applications. Volcanic soils and treated soils had more carbon, but this difference was only significant with volcanic versus glacial soils. Please note that the Y axis is a log scale.

DISCUSSION AND CONCLUSIONS

Our results provide evidence that in fertilized coarse-textured soils (as manifested in glacial parent materials) C sequestration is mostly in aboveground living trees, whereas fine-textured soils (in this case, products of volcanic parent materials) have more C sequestered in soils. The mechanisms for coarse-textured soils appear to be different than those of fine-textured ones. The idea of mechanistic differences is supported by lower pH values, higher C/N ratios and solubilization of fertilized forest floors. In the Central Puget Sound, the proportion of silt in soil may play a major role in the amount and nature of C sequestered. Besides texture, mineralogy is undoubtedly playing a role in shaping the results because the silt source in our study area is volcanic as opposed to the mixed mineralogy from the glacial parent material. The benefit to using texture as a criterion of C sequestration and forest productivity is that it can be easily and quickly determined in the field. Mineralogy, on the

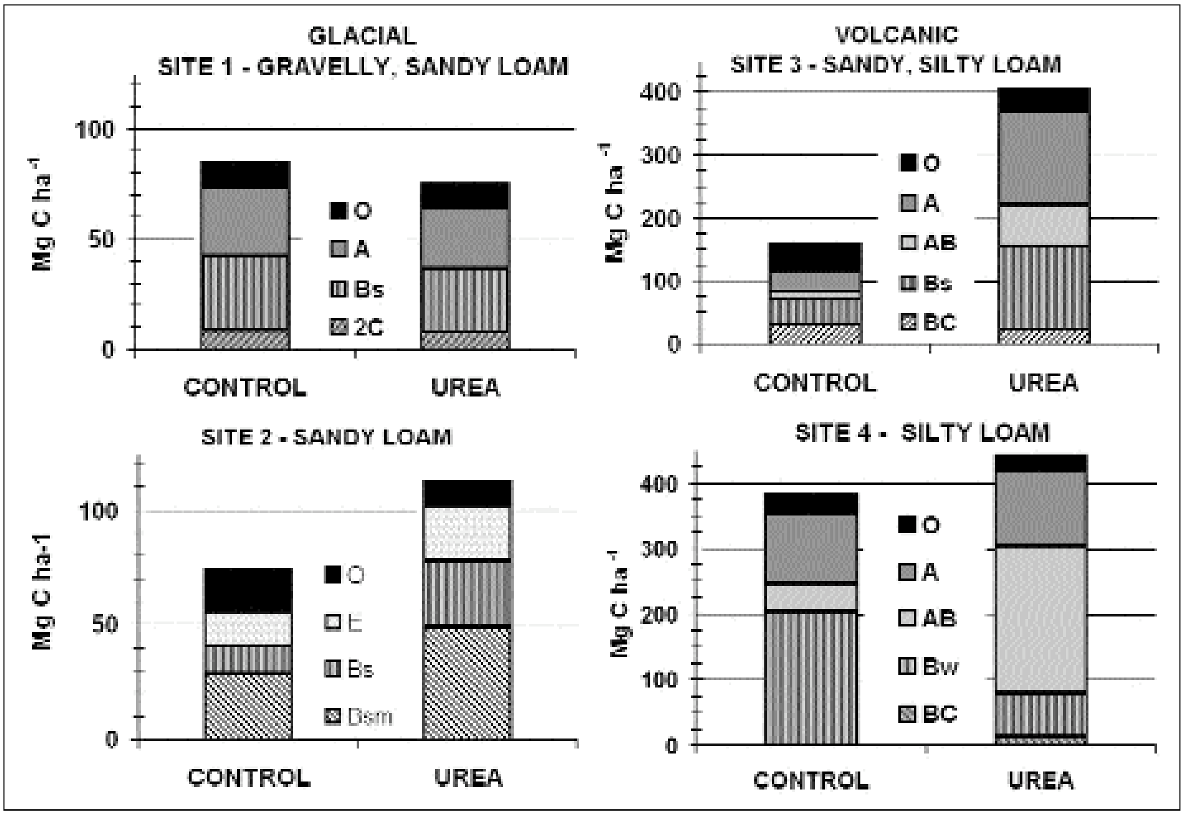

Figure 3—Distribution of C by site and soil profile. In all cases the fertilized O horizon had less C than did the unfertilized plot. There was no difference between treated and control of Site 1, but the A, E and B fertilized horizons of Sites 2, 3 and 4 had much more C than did their respective controls.

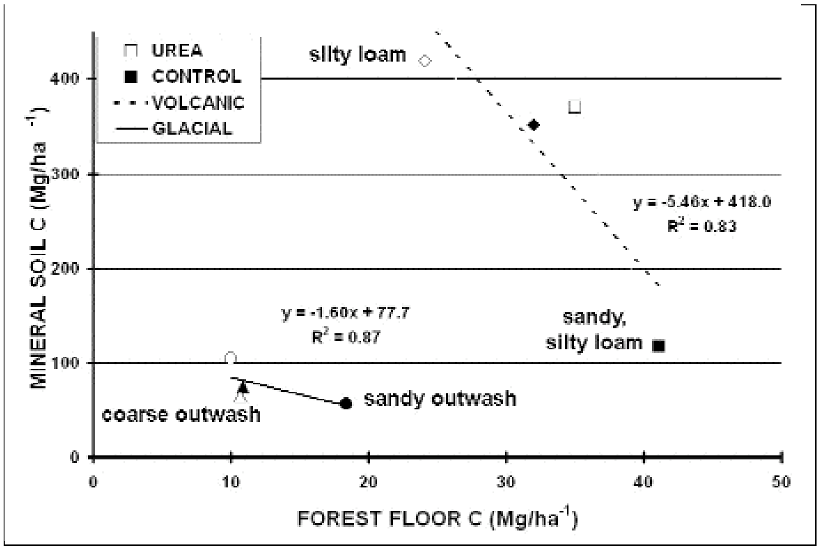

Figure 4—Forest floor (O horizon) C versus mineral soil C. Fertilized plots have more C in the mineral soil, but less C in the forest floor relative to paired controls.

other hand, requires complicated analyses that are expensive in terms of time and money. The fact that volcanic soil holds more C is not surprising. What is interesting is the idea that C sequestered above ground varies with soil type; in particular, the less productive sites sequester more C in trees when N fertilizer is applied.

ACKNOWLEDGMENTS

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VOLUMETRIC SOIL WATER CONTENT IN A 4-YEAR-OLD AND A 50-YEAR-OLD DOUGLAS-FIR STAND

Warren D. Devine[1], Constance A. Harrington[1], and Thomas A. Terry[2]

ABSTRACT

We compared growing-season soil water content in a young Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] plantation (established in 2000 with no vegetation control) to that of an adjacent 50-year-old conifer stand on a highly productive site in southwestern WA. Soil water content in the older stand was slightly greater than that of the younger stand at soil depths of 10 and 30 cm during the 2003 and 2004 growing seasons. At 100 cm, soil water content was similar between stands. During the 2003 growing season, when precipitation was below average, soil water content declined by a similar amount in both stands.

KEYWORDS: Soil water, Douglas-fir, regeneration, evaporation, transpiration.

INTRODUCTION

Silvicultural practices can influence soil water in forest stands (Langdon and Trousdell 1972). For example, modification of the forest canopy affects stand evapotranspiration rates, which in turn may affect soil water content. In the Pacific Northwest, removal of overstory conifers will quickly result in increases in soil water (Keppeler and Ziemer 1990; Adams et al. 1991; Gray et al. 2002). Thus, in compared to that available in an unharvested area, clearcutting will increase the amount of soil water available to the subsequently regenerated stand. Our objective in this study was to compare growing-season volumetric soil water content (VSWC) in two conifer stands: a young Douglas-fir plantation established after a clearcut and an adjacent 50-year-old Douglas-fir/western hemlock [*Tsuga heterophylla* (Raf.) Sarg.] stand.

METHODS

We investigated two adjacent stands, one established in 1953 and one in 2000, on a highly productive site in the Coast Range of southwestern WA, USA. Mean annual precipitation is 2260 mm, but an average of only 241 mm occurs from 1 June through 30 September (USDA 1999). Topography is gently sloping, and soil is of the Boistfort series (medial over clayey, ferrihydritic over parasesquic, mesic Typic Fulvudands), with a silt loam A horizon (12- to 17-cm thick) underlain by a silt loam AB horizon (19- to 24-cm thick) and a silty clay loam Bw horizon (to >140 cm)[3]. Soils are derived from basalt, with volcanic ash influence, and are well drained, low in bulk density, and high in available water capacity.

Until 1999, the entire study area was occupied by Douglas-fir planted in 1953 and western hemlock that established naturally (Terry et al. 2001). In 1999, a portion of this stand was harvested, removing a volume of 914 m^3 ha^{-1} (55% Douglas-fir; 45% western hemlock). In the harvested area, the Fall River Long-Term Site Productivity study (LTSP) was established, and 1+1 Douglas-fir seedlings were planted at a 2.5- x 2.5-m spacing in March 2000. Although the LTSP study examines a range of treatments, we collected data from a single treatment: a bole-only harvest of the previous stand and no vegetation control. We

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[1] Warren D. Devine and Constance A. Harrington are research foresters, USDA Forest Service PNW Research Station, Olympia Forestry Sciences Laboratory, 3625 93rd Ave SW, Olympia, WA 985122.

[2] Thomas A. Terry is senior scientist, Weyerhaeuser Co., PO Box 420, Centralia, WA 98531.

[3] Textures are apparent field textures as assessed by Darlene Zabowski, University of Washington.

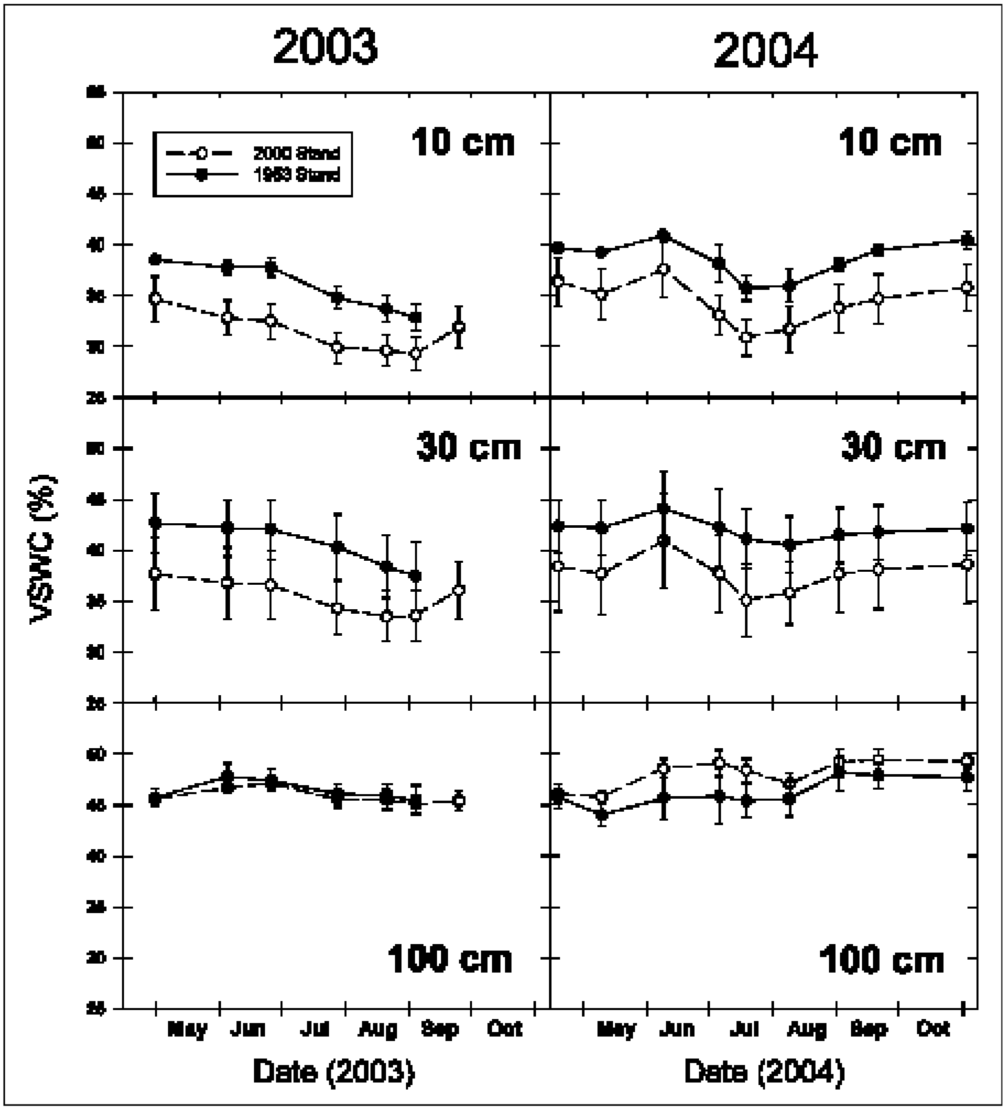

Figure 1—Volumetric soil water content (VSWC, ± standard deviation) at 10-, 30-, and 100-cm soil depths during 2003 and 2004 in two forest stands. Data missing for 25 September 2003 in the 1953 stand.

chose the treatment without vegetation control because we considered it analogous to the understory conditions of the stand established in 1953.

Using a Profile Probe® (Delta-T Devices Ltd., Cambridge, UK), we measured volumetric soil water content (VSWC) at six depths (10-100 cm) at 3- to 4-week intervals during the 2003 and 2004 growing seasons. In 2003, we sampled 12 locations in the 2000 stand and 4 locations in the 1953 stand; in 2004, the number of locations was increased to 21 and 6 in the 2000 and 1953 stands, respectively. Data were recorded in millivolts (mv) and subsequently converted to VSWC using a soil-specific calibration [% VSWC = (0.057 * mv) + 21.67]. We calculated VSWC loss during the 2003 growing season by subtracting values recorded on 4 September from those recorded on 1 May. Because data presented here were not part of the randomized block design of the LTSP study, we did not use analysis of variance.

RESULTS AND DISCUSSION

Growing-season fluctuations in VSWC varied between 2003 and 2004 due to large differences in precipitation (fig. 1). Precipitation during the 2003 growing season was 50% of the long-term average, while in 2004 it was 134% of

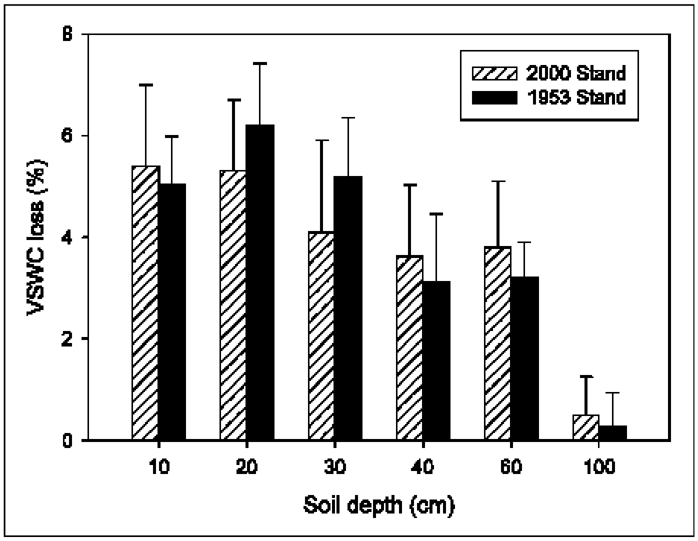

Figure 2—The loss in volumetric soil water content (VSWC, ± standard deviation) from 1 May to 4 September 2003 in two forest stands.

average. In 2003, VSWC decreased from May through early September in both stands at 10- and 30-cm depths. In 2004, VSWC decreased only from June through July at these depths because of above-average precipitation earlier and later in the growing season.

At shallow sample depths, particularly 10 cm, VSWC was generally greater in the 1953 stand than in the 2000 stand. At greater depths, VSWC was similar between the stands. Seasonal fluctuations in VSWC also were similar between stands. There were no differences in VSWC loss between the two stands during the 2003 growing season at any of the sample depths (fig. 2).

The overall similarities in VSWC between the two stands were unanticipated. We had hypothesized that during the growing season, VSWC would decrease by a greater amount in the 1953 stand than in the 2000 stand as a result of greater transpiration by the larger trees. It has previously been shown that growing-season soil water content was lower in a closed-canopy Douglas-fir forest relative to forest openings (Gray et al. 2002; Lindh et al. 2003). However, vegetation regrowth after clearcutting can have a strong, negative effect on soil water content (Adams et al. 1991).

The contribution of understory vegetation to total transpiration was likely greater in the 2000 stand than in the 1953 stand. Total dry biomass of understory vegetation in the 2000 stand (sampled in 2004) was much greater (2940 kg ha^{-1}) than that in the 1953 stand (221 kg ha^{-1}). Much of this vegetation in the 2000 stand consisted of generally shallow-rooted herbaceous species that may have reduced VSWC near the soil surface. Furthermore, the transpiration rate of the vegetation in the 2000 stand was probably greater than that of the vegetation in the 1953 stand because of microclimate differences caused by the forest canopy. For example, from June through August 2002, the temperature at the forest floor was, on average, 4.8° C higher in the 2000 stand than in the 1953 stand. Increased air temperatures result in greater transpiration rates due to a greater vapor pressure gradient between leaves and air (Kramer and Kozlowski 1979).

Processes other than transpiration may have differently influenced the soil water content of the two stands in this study. Evaporation at the soil surface may have been lower in the 1953 stand relative to the 2000 stand due to less solar radiation reaching the ground as well as the mulching effect of the undisturbed forest floor (Hillel 1998). At a soil depth of 5 cm, summer soil temperatures averaged 4.2° C less in the 1953 stand than in the 2000 stand. Thus, cooler soil temperatures may have led to greater VSWC in the 1953 stand, especially at shallow depths. It is also possible that the soil water content in the measured profile of the 1953 stand was influenced by hydraulic redistribution from deeper soil layers. Elsewhere in the region, it has been shown that water is transported upward in the soil profile as a consequence of water uptake by overstory trees (Brooks et al. 2002; Unsworth et al. 2004); however, the soil water contents in our soils were higher than the levels at which this phenomenon is likely to be operating.

While the final harvest of the previous stand in 1999 probably caused a temporary increase in soil water, soil water content by age four in the 2000 stand was similar to or less than that in the adjacent 50-year-old stand. In the younger stand, transpiration, and possibly evaporation at the soil surface, were reducing soil water to an extent similar to that of the overstory trees in the older stand.

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FACTORS AFFECTING NITROGEN MOBILITY: ORGANIC MATTER RETENTION AND VARIABLE-CHARGE SOILS

Brian D. Strahm[1], Robert B. Harrison[1], Thomas A. Terry[2],
Barry L. Flaming[1], Christopher W. Licata[1], and Kyle S. Petersen[1]

ABSTRACT

Forest harvesting and organic matter management practices may affect the cycling of nutrients, particularly nitrogen (N), through the removal of different organic matter components (e.g., branches, foliage, coarse-woody debris) from a site, and the associated changes in carbon-source quantity and quality. Such practices may also alter microclimatic conditions that influence N cycling processes, thereby affecting the rates at which N is made available to plants or is leached through the profile. This study examined the influence of intensive harvesting and organic matter retention practices on soil N dynamics on a highly productive (Site Index I-II+) coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) site in southwestern Washington; the study results are from a time period when all competing vegetation was controlled. Additionally, this study addresses the ability of the Boistfort soil series (Typic Fulvand) to retain nitrate (NO3) as a function of soil mineralogy and solution concentration. The specific focus of this investigation was to determine the effects of bole-only (BO) harvesting and total-tree harvesting plus coarse woody debris removal (TP) on soil-solution N concentrations and leaching rates (to a depth of 1.0 m) during the third through fifth year following harvest. Additional comparisons were made between the harvested treatments and the adjacent non-harvested stand (FS) representative of the initial stand condition. Solution concentrations were then related to NO_3- sorption isotherms generated using batch equilibration techniques to determine the quantity of NO_3- retained via sorption.

Soil-solution monitoring from April 2001 through March 2004 indicated that the increased organic matter retention associated with BO harvesting treatment increased the total N concentrations and leaching flux to a depth of 1.0 m by roughly two to three times that of TP harvest treatments. Nitrate comprised a majority of the 75, 29 and 4.5 kg ha^{-1} yr^{-1} of total N leached in the BO, TP and FS observations, respectively. The annual nitrogen leaching rates to a depth of 1.0 m however, are a small percentage of the 15 Mg ha^{-1} total soil N pool to a depth of 1.0 m (0.5, 0.2 and <0.03%, respectively). Similarly, the amount of NO_3- sorbed to the mineral surface represents a small fraction of the total soil N pool, however, it comprises 41, 53 and 152% of the NO_3- leached from the BO, TP and FS observations, respectively.

KEYWORDS: Nitrogen leaching, nitrate sorption, organic matter retention, soil-solution.

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[1] Brian D. Strahm, Robert B. Harrison, Barry L. Flaming, Christopher W. Licata and Kyle S. Petersen are members of a forest soils research team, University of Washington, College of Forest Resources, Box 352100, Seattle, WA 98195.

[2] Thomas A. Terry is research forester, Western Forestry Research, Weyerhaeuser Company, Centralia, WA 98513.

OVERVIEW OF STUDY AREAS VISITED ON FIELD TRIPS

FALL RIVER LONG-TERM SITE PRODUCTIVITY STUDY

Constance A. Harrington[1], Thomas A. Terry[2], and Robert B. Harrison[3]

ABSTRACT

The Fall River Long-Term Site Productivity study is a cooperative project designed to examine factors influencing short- and long-term productivity and how management practices affect both tree growth and soil characteristics. The study was established after the existing Douglas-fir/western hemlock stand was harvested in 1999 and several levels of biomass retention were created as major treatments in the study. The study also includes fertilization, vegetation control, compaction, and tillage. Douglas-fir seedlings were planted in spring 2000 and several tree and soil assessments have been made since then. Early results indicate that biomass removals and compaction/tillage affected physical and chemical soil properties but vegetation control was the primary factor affecting tree growth.

KEYWORDS: Douglas-fir, site productivity, seedling growth, vegetation management, woody debris retention, biomass removal, compaction, soil tillage, nitrogen cycling.

INTRODUCTION

Intensive forest management practices aimed at increasing the production of wood products have raised questions regarding potential detrimental effects to sustained forest productivity. Management practices such as harvesting mechanization, harvesting intensity, and vegetation control can affect tree growth and site productivity by creating soil disturbance, removing nutrients in biomass, changing seedling microclimate, and altering plant community composition and the distribution of nutrients and biomass between trees and non-trees.

How these factors affect forest growth over the short as well as the long term (multiple rotations) is not well understood. In addition, the ameliorative potential of practices such as soil tillage and nitrogen fertilization for maintaining and enhancing forest productivity needs to be evaluated. The Fall River study will begin to fill a data gap that exists in the Pacific Northwest for the management of Douglas-fir forests. Fall River is an affiliate site in the Long-Term Soil Productivity Study coordinated by the U.S. Forest Service in several major forest production regions of the U.S. and Canada. Fall River investigators also coordinate with scientists working on other productivity studies in the Pacific Northwest.

STUDY OBJECTIVES

The overall objective of this study is to examine the impacts of a range of biomass removal/wood retention treatments and forest management practices on long-term productivity. The experiment was installed in 1999-2000 on a highly productive Douglas-fir site on Weyerhaeuser

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[1] Constance A. Harrington is research forester, USDA Forest Service, Pacific Northwest Research Station, Olympia Forestry Sciences Laboratory, 3625 93rd Ave SW, Olympia, WA 98512.

[2] Thomas A. Terry is senior scientist, Weyerhaeuser Company, PO Box 420, Centralia, WA 98531.

[3] Robert B. Harrison is professor of forest soils, University of Washington, College of Forest Resources, 218 Bloedel Hall, Box 352100, Seattle, WA 98195-2100.

Company's McDonald Tree Farm in southwestern Washington. Fertile soils such as those present at the study site cover extensive areas in western Washington and are managed intensively for Douglas-fir wood production.

Specific research objectives are:

1) Evaluate effects of four levels of biomass removal on soil and Douglas-fir growth over a 40-year rotation.

2) Develop nutrient budgets for various levels of harvest and biomass removal.

3) Determine the impact of soil compaction and tillage on soil properties and tree growth.

4) Evaluate the need for fertilization and its effects on nutrient supply and tree growth.

5) Assess the effects of vegetation control and fertilization on tree growth, plant community composition, and soil characteristics.

6) Evaluate differences in seedling physiology and microclimate associated with the treatments.

The study addresses one of the priority topics in AF&PA Agenda 2020—Achieve and Sustain the Full Productivity Potential of Forest Soils. The study also addresses the Pacific Northwest Research Station's Priority Research Area: Produce Wood within Sustainable Frameworks.

METHODS

Site Description

The study area is on a 20-ha, very productive, low-elevation (300 m), gently sloping (<10 to 15%) site in the Coast Range Mountains located 60 km southwest of Olympia, WA, USA (Terry et al. 2001). Mean annual precipitation is 2260 mm, falling mostly as rain from September through May. Temperatures are mild (9.2°C mean annual) with mean January low of only -0.1°C (USDA NRCS 1999). The soil is a deep, well-drained silt loam over silty clay loam (Typic Fulvudand in the Boistfort series) developed from highly weathered basalt with ash influences in the upper horizons (Steinbrenner and Gehrke 1973).

Study Treatments

Study treatments were designed to look at factors of interest to both scientists and managers. Some treatments were operational while others were designed to "stretch" the system, that is, to implement treatments that are not operational but would provide valuable information on long-term productivity (table 1). In addition, the study was designed to include treatments that could ameliorate problems if there was a reduction in productivity in one or more of the treatments. For example, fertilization was included to determine if fertilizer additions could compensate for organic matter removals and a compaction-followed-by-tillage treatment was included to see if tillage could eliminate any deleterious effects on soil characteristics or tree growth induced by compaction.

The overall study design is a randomized complete block with 4 blocks. Treatment plots are 30 X 80 m. Study measurements include: tree size, condition and nutrient content; cover, species composition, biomass, and nutrient content of non-tree vegetation; volumetric soil water by depth; N in soil water; soil and air microclimate; and soil physical properties. A complete meteorological station is maintained onsite (fig. 1).

RESULTS

Seedling growth and non-tree vegetation for years 1-4 (fig. 2)

- Seedling growth was markedly lower in the treatment without vegetation control
- There was no significant difference in tree size associated with amount of biomass removed
- Compaction associated with harvesting was not detrimental to seedling growth
- Cover of non-tree vegetation was negatively correlated with soil moisture content and tree growth (for more information on tree responses, see Roberts et al. 2005).

Microclimate during growing season:

- Soil moisture was a good predictor of seedling volume both across and within treatments
- Without vegetation control, soil moisture was lower (Roberts et al. 2005)
- With removal of residues, soil moisture was lower
- With compaction, soil moisture was higher
- Soil temperature during the growing season increased with intensity of residue removal
- Warmer temperatures were beneficial to tree growth when soil moisture during the growing season was high

Soil physical properties:

Soil compaction in traffic lanes affected soil properties but they did not exceed critical levels (for more information on this topic, see Ares et al. 2005)

Table 1—Plot-level treatments at the Fall River Long-Term Site Productivity study

Biomass Removal[1]	Fertilization[2]	Vegetation control	Compaction	Tillage
Total tree plus	+	+	-	-
Total tree plus	-	+	-	-
Total tree	+	+	-	-
Total tree	-	+	-	-
Bole only, 5-cm top	+	+	-	-
Bole only, 5-cm top	-	+	-	-
Bole only	+	+	-	-
Bole only	-	+	-	-
Bole only	+	-	-	-
Bole only	-	-	-	-
Bole only	+	+	+	-
Bole only	+	+	+	+

[1] Total tree plus = removal of entire tree bole and branches with foliage attached plus removal of legacy woody debris (old-growth logs); Total tree = removal of entire tree bole and branches with foliage attached; Bole only, 5-cm top = removal of the tree bole to a 5-cm top diameter (non-merchantable material that met this diameter limit was also removed); Bole only = removal of tree bole to normal merchantability standards (10-cm top, no removal of broken, rotten or otherwise defective material).

[2] Fertilization treatments have not yet been applied.

Figure 1—The weather station at the Fall River study site records information for many meteorological factors.

- Bulk density in the 0- to 30-cm depth was increased by compaction from 0.63 to 0.82 Mg m^{-3}

- Macroporosity at 10- to 20-cm depth decreased in compacted areas (0.36 to 0.19 m^3 m^{-3}) but did not drop below 0.10 m^3 m^{-3}, the level that is usually considered limiting for tree growth

- Soil strength in traffic lanes increased at all depths < 55 cm but never exceeded 1300 kPa; the critical value for impacting tree growth is usually considered to be >2000 to 3000 kPa

- Available water and early tree growth were both increased in traffic lanes

Nitrogen movement and cycling:

The adjacent uncut forest (50-year-old stand) and two of the biomass removal treatments differed in the amount of total N in soil solution at 100 cm: Bole only (BO) > Total Tree plus (TT+) > Uncut forest (for more information on soil chemistry, see Strahm et al. 2005a and Strahm et al. 2005b)

- Nitrate was the major form of N in soil solution at 100 cm.

- NO_3 accounted for 92% of N in BO, 84% in TT+, and 57% in the adjacent uncut forest.

Average annual leaching of total N to 100 cm from April 2001 through March 2004 was: 75 kg/ha/yr for BO, 29 kg/ha/yr for TT+, and 4.5 kg/ha/yr for the adjacent uncut forest.

- Percent N in Douglas-fir foliage was lowest in the treatment without vegetation control (Roberts et al. 2005)

- Percent N in Douglas-fir foliage was similar across biomass removal levels (Roberts et al. 2005)

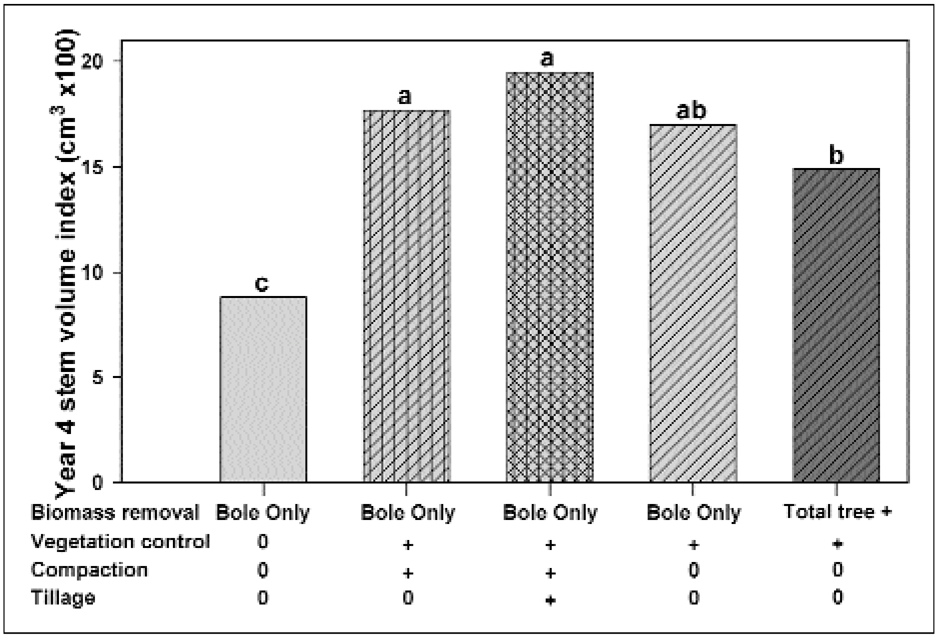

Figure 2—Effects of treatments on year-4 volume index (calculated as basal diameter squared times total height). Bars with the same letter above them do not differ at $p < 0.05$.

ACKNOWLEDGMENTS

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FOREST PRODUCTIVITY RESPONSES TO LOGGING DEBRIS AND COMPETING VEGETATION: EFFECTS OF ANNUAL PRECIPITATION AND SOIL TEXTURE

Timothy B. Harrington[1], Constance A. Harrington[1], and Stephen H. Schoenholtz[2]

ABSTRACT

Logging debris and competing vegetation are being manipulated at two sites to determine their potential influences on selected soil factors and productivity of planted Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*). The sites, located at Matlock WA and Molalla OR, were selected to differ in annual precipitation and soil texture. As part of the field tour for the Forest Productivity Conference, participants visited the Matlock site to observe the various treatments and vegetation responses in the first year since study initiation.

KEYWORDS: Long-term site productivity, soil properties, microclimate, plantations.

STUDY OBJECTIVES AND TREATMENTS

In 1998, the Fall River long-term site productivity (LTSP) study was initiated to examine effects of logging debris removal, competing vegetation control, fertilization, compaction, and tillage on soil characteristics and Douglas-fir growth (Terry et al. 2001). The study is affiliated with the national network of Long-Term Soil Productivity studies (Powers et al. 1990). In 2002, the Agenda 2020 program, members of forest industry, and the USDA Forest Service, PNW Research Station provided financial support to initiate an expansion of the Fall River research. The new research was designed to quantify potential effects of annual precipitation and soil texture on Douglas-fir responses to logging debris manipulation and competing vegetation removal. Six treatments have been replicated at two sites: Matlock WA (Olympic Peninsula) and Molalla OR (Western Cascades). The sites differ from Fall River and from each other in soil texture, precipitation, and temperature (fig. 1). Each site is an independent study.

The research will quantify stand establishment, early (1 to 5 years) and longer-term (5 to 20 years) growth of planted Douglas-fir, and long–term site productivity. A variety of pre-treatment and first-year measurements have been taken at each site, including soil nutrient content, bulk density, *in situ* net nitrogen mineralization and needle decomposition rates, logging debris mass and soil disturbance intensity, competing vegetation abundance, microclimate (air and soil temperatures and soil water content), and Douglas-fir initial size. The specific research objectives are to determine:

1. effects of logging debris abundance (retained vs. removed) and spatial distribution (dispersed vs. piled) and competing vegetation (presence vs. absence) on selected soil factors.
2. influence of soil responses on early growth and nutrition of Douglas-fir seedlings.
3. whether soil and Douglas-fir responses vary between sites differing in annual precipitation and soil texture.

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[1] Timothy B. Harrington and Constance A. Harrington are research foresters, USDA Forest Service, PNW Research Station, Forestry Sciences Laboratory, 3625 93rd Avenue, Olympia, WA 98512.

[2] Stephen H. Schoenholtz is associate professor, Department of Forest Engineering, Oregon State University, Corvallis, OR 97331.

The following experimental treatments have been replicated four times at each site in a randomized complete block design:

Logging debris treatment	Competing vegetation control	
1. <u>Stem-only harvest</u>: removal of merchantable logs only (i.e., retention of logging debris)	Absent	Present
2. <u>Stem-only harvest + piling</u>: removal of merchantable logs plus moving of tops and limbs into piles (i.e., retention and piling of logging debris).	Absent	Present
3. <u>Whole-tree harvest</u>: removal of merchantable logs plus tops and limbs (i.e., removal of logging debris)	Absent	Present

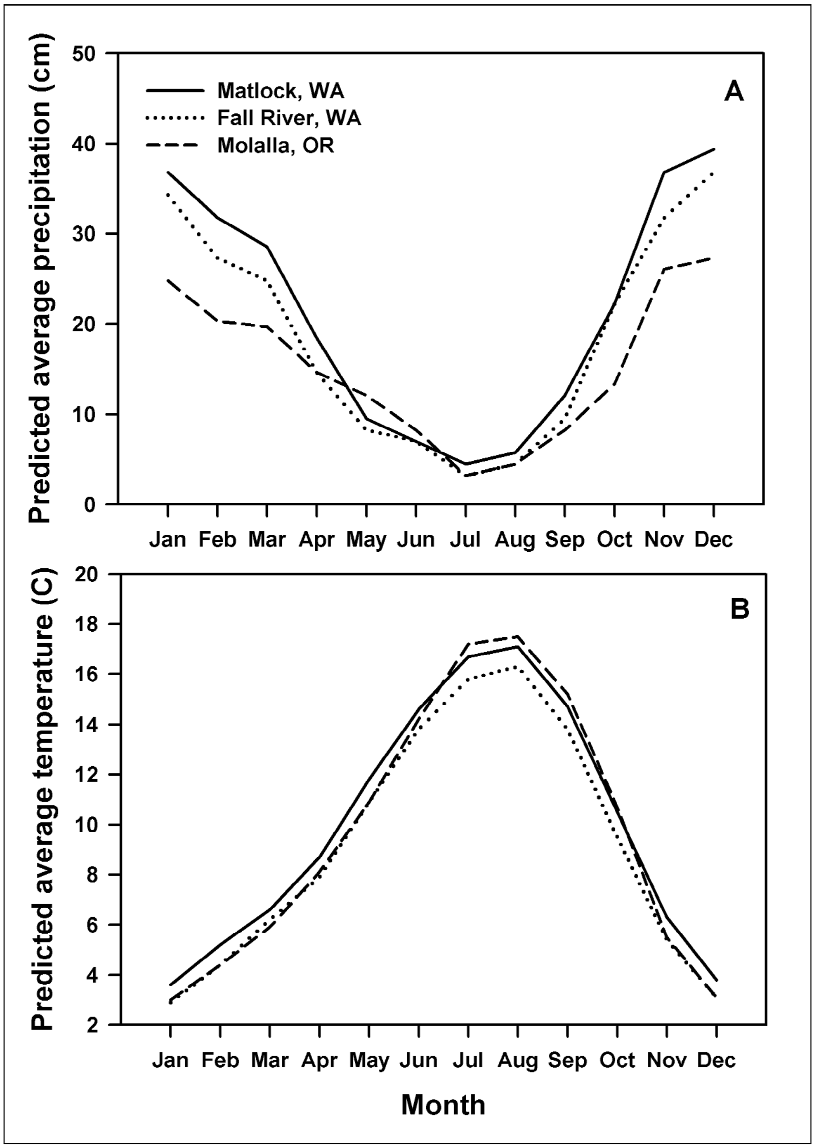

Figure 1—Predicted average monthly values for (a) precipitation and (b) air temperature at three forest productivity study sites in Washington and Oregon. Values were predicted from the PRISM model (Spatial Climate Analysis Service 2005).

CURRENT FINDINGS

In the first 3 or 4 months after treatment, mass of logging debris varied nearly two-fold between the stem-only (20.5 to 20.7 Mg ha^{-1}) and whole-tree (10.9 to 12.3 Mg ha^{-1}) harvesting treatments at each site. In August 2004, first-year cover of competing vegetation differed between herbicide-treated and non-treated plots at Matlock (12% vs. 20%, respectively) but not at Molalla (61% vs. 59%, respectively) where trailing blackberry (*Rubus ursinus* Cham. & Schlecht.) became dominant. The logging debris treatments had no detectable effect on abundance of competing vegetation at either site. Additional herbicide treatments are planned to achieve vegetation-free conditions on 80% or more of the area within treated plots. Although first-year measurements of the planted Douglas-fir have not yet been completed, field observations indicate that survival will be more than adequate for long-term monitoring of forest productivity.

FUTURE DIRECTION

In 2004, additional funding was received from the Agenda 2020 program to begin a new phase of research at Matlock and Molalla. Abundance of logging debris will be varied systematically to quantify the level at which it causes potential effects such as increased soil water conservation and thermal insulation, and shifting roles as a nitrogen source vs. a nitrogen sink. Logging debris will be applied to create 0, 40, or 80% covers (±10%) in 2- x 2-m areas around individual Douglas-fir growing either with or without competing vegetation. This new phase of research will identify some of the mechanisms by which logging debris and competing vegetation influence Douglas-fir productivity. In combination with the Fall River study, the research will contribute to a regional database that will enable forest managers to make more effective silvicultural prescriptions for maintaining or enhancing productivity of Douglas-fir plantations.

ACKNOWLEDGMENTS

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METRIC EQUIVALENTS

When you know:	Multiply by:	To find:
Degrees Fahrenheit (°F)	(F-32) x 0.556	Degrees Celsius (°C)
Inches (in)	2.54	Centimeters (cm)
Feet (ft)	.3048	Meters (m)
Acres (ac)	.4047	Hectares (ha)
Trees per acre	2.471	Trees per hectare
Square feet per acre (ft^2/ac)	.2296	Square meters per hectare (m^2/ha)
Thousand board feet (MBF)	.0024	Cubic meters (m^3)
Fluid ounces	.0296	Liters (L)
Gallons	3.78	Liters (L)

ENGLISH EQUIVALENTS

When you know:	Multiply by:	To find:
Degrees Celsius (°C)	(C*9/5) +32	Degrees Fahrenheit (°F)
Centimeters (cm)	.3937	Inches (in)
Meters (m)	3.2808	Feet (ft)
Kilometers (km)	0.6214	Miles (m)
Square meters per hectare (m^2/ha)	4.3560	Square feet per acre (ft^2/ac)

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