Chapter 12

Effects of Fertilization on Wood Quality and Tree Value

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ABSTRACT. The goal of fertilization is to increase tree volume production per unit of land. There is little doubt that this objective is fully met when nitrogen and other elements are applied to Pacific Northwest coniferous forests in prudent regimes. This chapter looks beyond volume production and examines the research record for the impact fertilization has on key wood quality attributes. In general, research in this area has not been extensive and what is known has not been incorporated into usable tools for forest managers.

An assumption implicit in most economic analyses examining fertilization is that wood quality and hence product yields are not affected. However, studies on Douglas-fir indicate that several changes in basic wood properties result from this management practice. Wood density is lowered between 5 and 16% due to changes in the type of tracheids produced. Density begins to decrease immediately after fertilization and gradually returns to prefertilization values in four to six years. Changes in microfibril angle and basic wood chemistry have been noted, but seem to be small and would not significantly affect typical products manufactured today. Ring widths should definitely increase, perhaps to an extreme degree on high sites that are fertilized and kept at low stocking levels. Branch size and juvenile wood are important characteristics that affect the quality of many products, yet there is little information on the effects of fertilization on these attributes.

The research relating fertilization to product yields is limited. What is available suggests that a fertilized young-growth resource should present no major problems to the pulp and paper industry, the pole industry, and certain segments of the lumber and panel industry. Sawn and peeled products that require high strength for engineered uses, however, could suffer due to decreased wood density and perhaps an extended juvenile period and larger knots. Under current guidelines, logs cut from fast-grown, coarse-grained young-growth trees would be classified as a low grade resource in the export market. Recent forecasts indicate that supply of low grade logs from several world sources will increase, resulting in suppressed prices for this kind of material. Logs cut from a slower-grown, higher quality resource will be in demand for the coming decades and prices are expected to rise. The current domestic log grades are poor indexes of quality in the young-growth resource, thus meaningful trends in log quality related to fertilization are difficult to identify. Since research linking management activities such as fertilization to wood quality and product yields is lacking, assessing the magnitude of potential problems is difficult.

Fertilization of commercial forest lands in the Pacific Northwest is a common forest management practice; both public and private timberland owners apply nitrogen and other elements to large areas each year to increase tree growth. While the exact fertilizer treatments vary from landowner to landowner, the reasons for engaging in this practice are fairly uniform; fertilization temporarily raises site quality and increases the volume of merchantable wood compared to unfertilized sites. Economic justification of fertilization as a management practice has centered on two issues—the costs of fertilizer application and the additional value associated with increased timber volume production. An assumption implicit in most economic analyses is that wood quality is not changed as a result of fertilization. If, however, fertilization affects key wood quality attributes such as wood density (specific gravity), knot size, fibril angle, ring width, and fiber length, then the quality of products that can be manufactured from a fertilized resource may be affected. Ultimately, log and tree values are closely tied to the quality and quantity of products that can be produced from the forest. To fully evaluate fertilization as a management practice, the potential impacts on wood quality and product yield should be integrated into the discussions.

The objectives of this chapter are (1) to review what is known about the interaction between fertilization and the anatomical development of stem or bole wood, especially in regard to Douglas-fir, (2) to comment on

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how these changes might affect typical products manufactured in today's forest products industry, and (3) to point out how information on wood quality can be integrated into discussions of fertilization as a management tool for Pacific Northwest forests.

Anatomical Changes Related to Fertilization

Basic Patterns in Douglas-fir

Before discussing the effects of fertilization, a brief review of the fundamentals of wood anatomy and wood properties is necessary. We have limited the discussion to Douglas-fir because most research on West Coast conifers has concentrated on this species. Our discussion is brief; a more complete review is given in Haygreen and Bowyer (1989) or Megraw (1986*b*).

About 95% of Douglas-fir wood is composed of long, skinny, tubular cells with the ends pinched shut, called longitudinal tracheids. These tracheids have their long axis parallel to the long axis of the stem, branch, or root in which they are found. The remaining 5% of the wood is composed of short, brick-shaped cells of ray tissue, oriented in the radial direction, that lie perpendicular to the longitudinal tracheids and allow lateral flow and storage. Our discussion will focus on the longitudinal tracheids.

The tracheid wall is a complex multilayered structure composed of cellulose, hemicellulose, and lignin. The walls also have numerous structures called pits that permit transfer of fluids. The cellulose in the wall is organized into aggregate threads called microfibrils. Microfibrils are strongest along their long axis and exhibit shrinkage and swelling perpendicular to this axis. Within the cell wall, microfibrils are laid down in various layers with different angles of repose from the long axis of the tracheid. One wall layer, called the S_2, is thickest and dominates the wall. In mature wood tracheids, developed in annual rings away from the pith, the S_2 microfibrils have a small angle of repose and thus the wood is strong along the grain and has little longitudinal shrinkage. In contrast, tracheids in rings near the pith, which were formed within the live crown, have a large S_2 microfibril angle; wood comprised of these tracheids is typically weaker and exhibits much higher longitudinal shrinkage relative to mature wood.

Tracheids are produced by cell division of the cambium, a layer of living, dividing cells between the wood and bark that covers the entire tree. The processes of division and subsequent development of offspring tracheids are regulated by growth hormones produced by the crown. Thus the health and vigor of the crown and the distance from the crown to any point in the cambium play a strong role in the nature of the tracheid produced; forest management activities that modify either crown health or this distance can affect important wood quality attributes in young-growth trees. In the early part of the growing season, large diameter, thin-walled tracheids (earlywood) are produced. Smaller diameter, thick-walled tracheids (latewood) are produced later in the growing season when crown activity and levels of hormones decrease. Earlywood tracheids are also shorter (about 10%) than latewood and have a greater S_2 microfibril angle. Since wood density is primarily a function of the amount of cell wall material present, density varies greatly between earlywood and latewood. Density is low in earlywood and rises abruptly, about threefold, to a latewood maximum. Average ring density depends on the densities of these two zones and on the relative amount of latewood.

There is a distinct pattern in the transition from earlywood to latewood up and down the stem of a tree because of different amounts of crown-produced hormones present. At the onset of the growing season, growth begins first at the top of the tree and proceeds downward. The transition to latewood is thought to start when height growth ceases and when the needles developed that year mature (Larson 1969). The transition to latewood first occurs at the base of the stem (farthest from the crown), where the level of hormones is the lowest, and last occurs where the stem is within the active crown. Typically, this results in an increase in the proportion of latewood within an annual ring at lower heights in a tree.

Juvenile wood has attracted a lot of attention in recent years, and rightfully so. It is generally thought of as the inner region of the stem surrounding the pith (Megraw 1986*b*). Since this wood is formed within close proximity to the apical meristem and vigorous crown branches, it is also called crown-formed wood. Juvenile wood is known to have characteristics that affect wood strength and stability in a negative way; these include lower wood strength, shorter tracheid lengths, and higher fibril angles. In Douglas-fir these properties change, or mature, gradually over time. If average ring density is plotted, along with tracheid dimensions, and microfibril angle for rings from the pith to the bark, trends such as those shown in Figure 1 occur. Rings next to the pith, formed in close proximity to the live crown, exhibit a rapid change in these properties and then flatten out after a number of years. The region of rapid change is commonly referred to as juvenile wood and is thought

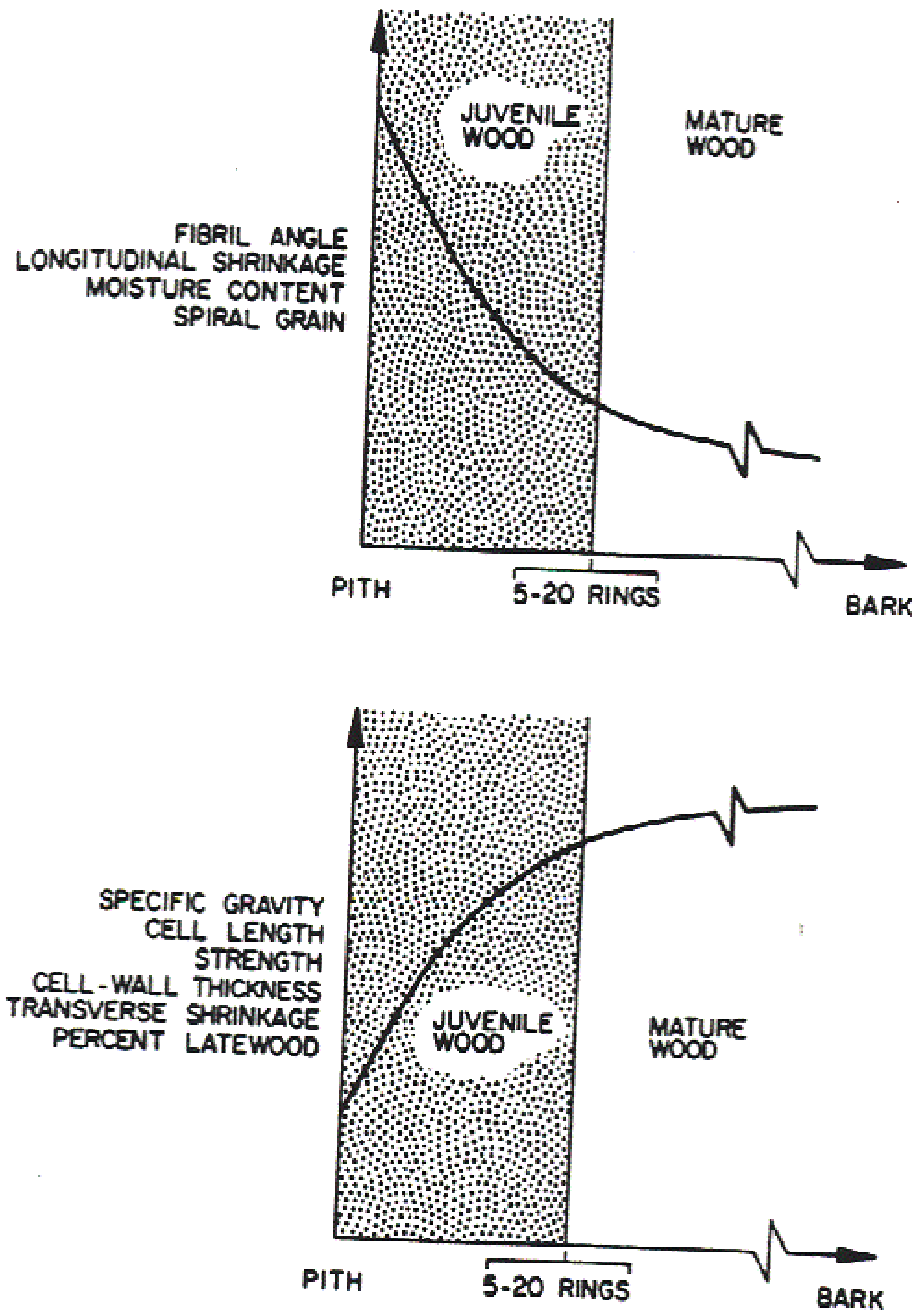

Figure 1. General trends of wood properties from juvenile to mature wood. From Senft et al. (1985).

to last about 20 years in Douglas-fir before mature wood begins (Fahey et al. 1991). These properties do not all change at the same rate, so a precise definition for where juvenile wood ends and mature wood begins depends on the properties critical to a particular industry or product.

In comparing patterns of ring density of various trees and stands, there is a common misconception that wide rings associated with fast growth translates into low density, weak wood. This misconception arises when products from trees of similar size but different age are compared. Logs cut from young trees may have wide growth rings, but they also have a large juvenile wood component. The low density and poor properties are related primarily to the presence of juvenile wood and not the wide rings. Many studies have demonstrated that when age of wood formation is taken into account, there is almost no correlation between wood density and growth rate—they are independent traits (Megraw 1986*b*).

Effects of Fertilization on Wood Quality

With this background, let's review what has been found or can be expected with respect to the effects of fertilization on some important wood quality attributes. Research on Douglas-fir is scanty, and generalizing from the results is sometimes difficult for several reasons. First, many stand conditions vary from study to study; important factors such as site class, stand age, stocking history, and fertilization regime differ greatly. The issue of stocking, especially if thinning has been conducted in conjunction with fertilization, can confuse the issue of what is a fertilization effect and what is a stocking or thinning effect. Also, most studies have examined changes that occurred at breast height or in the lower bole; more needs to be learned about the distribution of effects along the entire stem. Finally, researchers do not all investigate the same wood properties. In spite of these limitations, there are areas of agreement concerning the general direction of change, and we can speculate on what should happen to some properties when the status of the crown is modified by fertilization regimes. Obviously, more research is needed to provide a comprehensive understanding and to quantify the effects of fertilization in Douglas-fir over a broad range of treatment regimes and stand and site conditions.

Research shows that changes produced by a single fertilization are usually no longer in effect within four to six years. The period of return to prefertilization conditions after repeated treatments is not as well documented but seems to be delayed. This is another area requiring more comprehensive research.

Tracheid Geometry. Several studies have examined how fertilization affects the rate of tracheid formation, number of tracheids produced, earlywood-latewood proportions, and tracheid dimensions (Brix and Mitchell 1980; Erickson and Lambert 1958; Erickson and Harrison 1974; Mecifi 1985; Megraw and Munk 1974; Parker et al. 1976; Siddiqui et al. 1972). Although none of these studies investigated all features and there are a few inconsistencies, the following general model can be proposed: (1) Fertilization does not change the duration of the season over which tracheids are formed, but does change the rate of cambial division and number of tracheids across a ring. (2) Fertilization seems to reduce the proportion of cells classified as latewood, and definitely reduces latewood as a percentage of ring width. (3) Fertilization modifies tracheid cross section dimensions. In earlywood cells, radial diameter and wall thickness increase and the tangential diameter decreases. In latewood cells, diameters seem to decrease or not change and the cell wall thickness decreases. (4) Fertilization may decrease tracheid length 7 to 8% or slightly increase it.

These subtle shifts within the cell cross section may seem unimportant but they have two key features. First, fertilization appears to create a tendency for more uniformity of cell geometry within a ring; some have suggested that more cells are intermediate between true earlywood and latewood (Megraw 1986*b*). Second, as will be discussed later, these shifts translate into shifts in the profile of wood density across a ring, which in turn could modify overall average ring density.

Microfibril Angle. Erickson and Arima (1974) reported that fertilization of 20-year-old trees interrupted a trend toward smaller S_2 microfibril angles and increased them by 2 to 3 degrees. Mecifi (1985) found a 9% increase in microfibril angle associated with sludge treatment.

Chemistry. Siddiqui et al. (1972) found that fertilization increased cellulose content in earlywood and lowered it in latewood. Examining whole ring averages following fertilization, Erickson and Arima (1974) found little change in extractives, a small increase in lignin percentage, and a corresponding decrease in cellulose. While these changes appear small, even a one percentage point shift can have a large effect on the economics of chemical pulping processes.

Wood Density. Using X-ray densitometry, Megraw and Nearn (1972) studied the changes of density patterns within the eight rings following fertilization of a 10-year-old stand. They found that treatment did not affect the minimum density in the earlywood but did reduce the maximum latewood density. They noted a wider region of intermediate density. These shifts reflect the changes in tracheid dimensions: less thick latewood walls and thicker earlywood walls. Parker et al. (1976), working with trees fertilized at age 25, found a decrease in both earlywood and latewood densities and some of the intermediate density wood reported by Megraw and Nearn. They also sampled at four positions along the bole and found different patterns at different heights. Jozsa and Brix (1989), who also sampled different locations along the bole in trees fertilized at age 24, found overall decreases in the density of earlywood and latewood and a decrease in latewood percentage. They noted that the patterns were not the same at different heights. Presumably, these variations associated with height are related to modifications in crown activity that alter hormone distribution along the bole.

Examining whole ring density, Megraw and Nearn (1972) found no change in spite of the shifts of the within-ring profile. Since trees in their sample were only 10 years old when treated, they were still in the juvenile wood period and normal factors influencing juvenility may have dominated or masked treatment effects. Others working with trees at least 20 years old when fertilized found a decrease in density ranging from about 5 to 16% (Erickson and Lambert 1958; Erickson and Harrison 1974; Jozsa and Brix 1989; Mecifi 1985; Megraw and Munk 1974; Parker et al. 1976; Siddiqui et al. 1972).

Ring Width. Obviously, ring width should increase or the trend in declining widths should moderate following fertilization. This change can have an effect on wood machining, the acceptability of products in certain grades and markets, and the variability in strength of small lumber sizes due to a more variable earlywood-latewood content range.

Knot Diameter. When a tree responds to fertilizer, it is likely that live branches will respond with increased diameter growth. This, together with a tendency for the more vigorous crown to recede more slowly, can significantly increase knot sizes, thus producing adverse effects for many forest products. The critical determinations at the time of treatment are where the base of the live crown is relative to eventual logs and whether pruning will be done.

Taper, Crookedness, and Compression Wood. If the crown mass is suddenly increased by fertilization, the stem may become unstable. This could worsen if fertilization is combined with thinning and thus effects of wind sway are increased. The trees may respond in two ways. First, they may redistribute growth toward the stem base, increasing taper. It has been shown that fertilization alone typically results in little change in taper, that thinning increases taper, and that the combination of fertilization and thinning will result in increased taper (Brix 1983; Jozsa and Brix 1989; Parker et al. 1976). Second, trees may also respond to the increased stress by producing more compression wood (an abnormal form generally found in leaning trees or the underside of branches). This increase in compression wood may also occur in the stems below larger limbs. Compression wood is undesirable due to its poorer strength and dimensional instability.

Although one would not expect fertilization to affect stem crookedness, an increased incidence of damage may occur in regions where trees susceptible to stress from winds, snow, and ice loads will be vulnerable because of the greater crown mass produced by fertilization.

Sapwood. Brix and Mitchell (1983) found that sapwood width in Douglas-fir is relatively constant in the portion of the stem where heartwood is present and that the number of rings within the sapwood decreases with height. They also found that sapwood width at breast height tends to increase with stem diameter and that thinning and fertilization had little effect on the percentage of sapwood area at breast height.

Juvenile Wood. With few exceptions, studies of fertilized Douglas-fir involved trees that were at least 20 years old before treatment and hence the breast height region most commonly sampled was near or beyond the period typically thought to produce juvenile wood. It is not clear, with the base of information currently available, if fertilization of young trees delays the transition to mature wood. One can hypothesize that if the crown is stimulated and its rate of recession is reduced, the juvenile period for that part of the stem covered by the crown may be prolonged. Also, it is not clear whether fertilization modifies properties in the juvenile region in the same way that mature wood characteristics have been shown to be altered. The potential for a prolonged juvenile period raises some questions regarding the stand age at which fertilization is done. Extension of the juvenile period in trees less than 20 years old, for example, could mean that the highest valued logs (the bottom logs) will contain higher proportions of juvenile wood. More information is needed concerning the effects of fertilization on juvenility in young-growth conifers.

At this time, the principal effect of fertilization on juvenile wood may be indirect. If foresters fertilize with the objective of growing trees to a given size in less time, they are reducing the time these trees will have to form mature wood. In this management scenario, fertilization could become a mechanism that increases the percentage of juvenile wood in logs harvested from the young-growth forests.

Interaction of Fertilization with Thinning

Several of the studies previously cited also examined the combined effects of thinning and fertilization. When thinning is combined with fertilization, one can anticipate generally faster growth than with either alone. One would expect the combination to magnify the effects previously discussed on wood properties; however, research often shows mixed results. Cell dimensions and wood density usually do shift after a thinning alone, but not always in the direction or magnitude we might expect. For example, most would probably expect a thinning to reduce the density of Douglas-fir, but some research has found that it increased (Erickson and Lambert 1958; Mecifi 1985). This is probably associated with sites that become moisture deficient in summer, prematurely truncating production of latewood. Apparently thinning can stretch the moisture supply so that more latewood is produced in the residual stand with an increase in density (Megraw 1986*a*). On such sites, thinning combined with fertilization may produce less of a density change than fertilizing alone. In other cases, the combination produces a greater density decrease than just fertilizing. More research is needed to better understand how different types and levels of thinning interact with fertilization.

Potential Impacts of Fertilization on Forest Products

While there is some research (mostly on Douglas-fir and loblolly pine) linking fertilization to changes in wood properties, few studies have examined the impact fertilization might have on forest products. Because of this, we emphasize the word *potential* in the title of this section and note that our discussions are, for the most part, limited to speculation and hypotheses. We currently have a poor understanding of how fertilization interacts with external indicators of quality in trees and logs and how the anatomical changes noted previously might affect the performance of typical products manufactured today. We choose to focus initially on domestic and export log grades as general indicators of wood quality and then examine the following specific products: poles, pulp and paper, sawn lumber, plywood, and composite panels.

Domestic Log Grades

Certainly, logs are a product of our forests, and log grades are used to stratify quality. This has been true of the old-growth resource and probably will continue for young-growth production. Daily transactions in many segments of the forest products industry are conducted using regional and local log grading rules as the "yardstick" by which quality is determined. Although there are many local conditions and specifications that buyers and sellers of timber use to help guide business decisions, we thought it would be most useful to comment on three of the major log grading systems currently used in the Pacific Northwest. Douglas-fir and hem-fir (a category commonly used to market a combination of several species of West Coast lumber) are, for the most part, graded by rules established by the Northwest Log Rules Advisory Group (1982); ponderosa and sugar pine are generally graded using rules established by Gaines (1962).

For Douglas-fir and hem-fir, fertilization could have positive or negative impacts on the quality of logs as defined by current grading criteria. The size and distribution of knots, the average rings per inch (Douglas-fir only), and log size are all referenced in the grades used for these species; as mentioned previously, fertilization and other management activities can have an impact on these quality attributes. The majority of the Douglas-fir young-growth resource falls into the No. 2 or No. 3 sawlog grade (Fahey 1974; Willits and Fahey 1988). The descriptions for the same grades of hem-fir are identical, so we would expect similar patterns. The basic differences between these two grades are log diameter and knot size; the No. 2 sawlog has a minimum diameter of 12 inches and allows 2 1/2 inch knots. A No. 3 sawlog has a minimum diameter of 6 inches and allows up to 3 inch knots. Though knot size has the potential for being a degrading factor when evaluating logs, we feel that only "radical" management strategies would tend to produce trees with knots greater than the 2 1/2 inch limit set in the No. 2 sawlog grade.

Log size has been the focus of much speculation in the young-growth resource. Fertilization, in combination with other management activities, can produce large trees in a relatively short time. On paper this looks good because of the diameter limits that currently exist in the grading rules. Logs cut from young-growth could potentially meet the size requirements for higher log grades (i.e., special mill); however, the inherent quality will be lower. Log size needs to be evaluated with other quality attributes such as limb size and growth rate to assign meaningful quality levels in the young-growth resource.

Log size is not a limiting factor in the grades for ponderosa pine; logs are evaluated in 4 foot panels for primary defects (knots, visual indicators, limbs) and secondary defects (scars, forks, crook, cracks, cankers) (Gaines 1962). The higher grades attempt to identify logs that will produce clear and shop grades of lumber. The general opinion among cruisers and scalers is that the Gaines grades do not work well for the young-growth resource. Work at the USDA Forestry Sciences Laboratory in Portland, Oregon (Parry 1989), is evaluating new specifications that will improve the ability of the grades to identify quality in the young-growth resource. We do not anticipate that fertilization would lower quality as defined in the current or future grades for pine.

In general, log grades used in the Pacific Northwest were developed for use on logs cut from old-growth timber. Their usefulness in evaluating the quality of the young-growth resource is in question. Hence it is difficult to assess how fertilization and other management activities might affect quality as defined by current log grades. In some cases, "misinformation" may be fed back to managers, as in the case of diameter limits in the Douglas-fir and hem-fir rules.

Log Exports

Given today's political climate in the Pacific Northwest, the log export business is a controversial one. The wisdom of exporting logs is being questioned because the forest products industry faces shortages of raw material in many situations. However, exports provide jobs in both the logging and shipping industries. Beyond the political uncertainties, log exports are currently a major activity in the forest products industry. For example, in 1989 over 3.6 billion board feet of timber worth more than $1.7 billion was exported from Oregon and Washington ports (Warren 1990). The primary customers in order of consumption have been Japan, South Korea, and the People's Republic of China. Douglas-fir and western hemlock make up the majority of exports.

The log surface and wood quality attributes each customer looks for in export logs vary. This results in many log "quality sorts" that make tracking production and price statistics difficult. Flora et al. (1991) analyzed price and volume data for two general categories of export logs: construction grade and performance grade. Construction grades (the lower quality category) were Coast Grade No. 3 sawlogs cut from second-growth trees with scaling diameters of 6 to 12 inches; performance grades were Coast and Cascade Grade No. 2 sawlogs cut from either old- or second-growth timber with scaling diameters of 12 to 24 inches. They note that the majority of U.S. exports have been in the higher quality grades (78% performance grade versus 22% construction grade) and that the Japanese and Chinese buy mostly performance grades whereas the Koreans buy exclusively the construction grades. Projections (Flora et al. 1991) indicate that prices for construction grade logs are expected to remain flat through the mid-1990s and then to decline in the next century. Prices for performance grade logs are expected to rise over time. These trends reflect the increased supply of low quality wood available from other sources such as Chile and New Zealand, and the lack of high quality logs from any source.

It seems reasonable to assess how fertilization might affect the production of high quality, performance type logs from the young-growth resource. Three general characteristics are often used in evaluating export logs:

log dimensions (both length and diameter), surface characteristics such as knots and sweep, and ring characteristics such as rate of growth and ring uniformity. Fertilization, in combination with other management practices, could negatively affect these characteristics. Knot size, for example, is one of the main determinants of log grade. The performance grade logs, equivalent to a No. 2 sawlog grade, limit knot size to 2 1/2 inches. Obviously, the ability to sell logs in the export market would be seriously impacted if the young-growth resource has limbs larger than this. Rings-per-inch and ring uniformity are widely recognized as important criteria in the better grades of export logs. Six rings per inch usually represent the "swing point" between high and low quality logs. Finally, buyers of high quality logs are reluctant to purchase logs with nonuniform growth rates; fertilization could produce these types of growth patterns.

In summary, the exact impact of fertilization on the ability to export logs is difficult to quantify. Under current market conditions, fast-grown, coarse-grained wood probably would find ready buyers; however, it would not qualify as a performance or high quality resource. This has important implications for the future, because projections (Flora et al. 1991) indicate that a plentiful supply of low grade material will exist from a variety of sources. The more the resource in the Pacific Northwest begins to look and perform like other low grade wood, it is likely that opportunities to market it profitably will decrease.

Poles

The production of Douglas-fir poles is an important element of the forest products industry in the Pacific Northwest. While exact figures are difficult to find, prices for Douglas-fir poles have historically been high relative to other products. Poles usually require treating and other special handling that creates many secondary jobs in the Pacific Northwest.

We found no published research directly assessing the impact of fertilization on the pole industry, thus our comments are based on discussions with people currently involved in this segment of the industry as well as our knowledge of what fertilization does to wood quality attributes. Although wood density, or specific gravity, is decreased 5 to 16% for a few annual rings after fertilization, there is general agreement among engineers, researchers, and forest products technologists that no structural problems should be encountered if the annual rings containing the fertilized wood are not contained in the outer 2 or 3 inches of the pole. It is well known that the outside 2 to 3 inches of a structural column carry 85 to 95% of structural loads. Problems could arise if fertilizers are applied in the years just prior to harvest, for two reasons: (1) the reduction in specific gravity in the outer annual rings might result in reduced pole strength, and (2) rate-of-growth limitations specified by the national standards for wood poles may be exceeded. Current regulations specify that poles with a circumference of 37 1/2 inches or less at 6 feet from the butt shall have a ring count of not less than 6 rings per inch. Poles with 4 and 5 rings per inch are allowed if the latewood portion of the rings is 50% (ANSI 1987).

Because poles are generally treated with preservatives prior to use, the potential impacts of fertilization on the amount of sapwood present should also be evaluated. While the exact requirements vary, typically 85% of the sapwood, or from 7/8 to 1 1/2 inches of preservative penetration, is required. Some research indicates that fertilization and thinning increase sapwood widths in Douglas-fir (Brix and Mitchell 1983). Thicker sapwood has both advantages and disadvantages to the production of poles. On the plus side, meeting standard requirements might require deeper penetration of preservatives on poles cut from fertilized stands, thus increasing their in-service life. On the negative side, use of additional preservative and energy may increase the costs of treating.

We should point out that some significant advances in the grading of poles are probably not far off. The use of nondestructive evaluation (NDE) techniques is currently in the development stage (Wang and Bodig 1990). Typically, NDE relates a physical property of wood, such as wave propagation time, to wood strength. Using NDE in conjunction with visual grading will increase the accuracy of strength estimates and will allow a better match between actual pole strength and the intended use. Poles currently rejected or downgraded because of defects related to fast growth (ring widths, knot sizes, stem form) would find some uses if their actual mechanical characteristics are known.

Finally, it should be noted that recent estimates do not indicate a shortage in the supply of Douglas-fir poles. McCormick (1988) estimates that in the early 1990s, about 350,000 poles, or 45 million board feet, will be required annually to supply the pole industry in the Northwest. This volume is far below the anticipated Douglas-fir harvests in the region. While pole producers may have to search for stands that will meet their requirements, there should be enough resources to supply their needs. Availability of timber suitable for poles and the costs for this stumpage may depend in part on activity in the export market; the high quality trees normally associated with poles will be attractive to other consumers in world markets.

Pulp and Paper Products

Of the products we will comment on, there has been more research directly related to the impacts of fertilization on pulp yields from Douglas-fir, probably because the young age (small size) of fertilized trees available for products research presented no processing problems for the pulp and paper industry. Producing structural products like dimension lumber, plywood, or poles from small trees can be constrained by equipment limitations. Siddiqui et al. (1972) noted that even though wood specific gravity decreased on samples of Douglas-fir fertilized with urea, pulp yields per unit weight of wood from fertilized trees increased compared to unfertilized control trees. They attributed this to a decrease in extractives and an increase in the proportion of the S_2 cell wall layer in the earlywood tracheids. Resler et al. (1975) studied the impact of fertilization on kraft pulps and found no difference in pulp yields, kappa numbers, and strength properties of sheets manufactured from the unrefined pulps of trees felled seven and nine years after fertilization. Finally, Parker et al. (1976) found that wood specific gravity and kraft pulp yields were adversely affected by fertilization, but concluded that the losses were minor compared to the increased growth increment of the tree.

In general, there seems to be little evidence that measures of pulp yields and strength values typically used to rate paper products will be adversely impacted by commercial fertilization. We should also point out that the pulp and paper industry normally blends chips from a variety of sources in the papermaking process. Research that examines, in a laboratory sense, the impacts of fertilization on the pulp and paper industry may not directly relate to the industrial situation. Finally, it is important to note that wood chips from the young-growth forests in the Pacific Northwest are considered a secondary product, often originating as a by-product of the sawmill and veneer industries. While wood chips are an integral part of the forest products industry, forest managers probably would not make major adjustments in current practices because of perceived problems with chip utilization.

Sawn Lumber Products

Sawn lumber products are the cornerstone of the forest products industry in the Pacific Northwest. In 1989, the coastal region of Oregon and Washington produced over 9 billion board feet of lumber and the inland region over 11 billion (Warren 1990); the economic value of these products and the jobs associated with this segment of the industry are tremendous. Three general categories of lumber, based on intended use, are appearance, factory, and structural. Appearance and factory lumber is used where appearance and suitability for secondary manufacturing are the primary considerations; examples are select or clears, commons, shops, and moldings. Structural lumber is used where wood strength and performance are the important criteria; examples include the following grades: light framing, structural light framing, structural joists and planks, decking, scaffold plank, machine stress rated (MSR), and laminating stock. The majority of lumber manufactured from Douglas-fir and the hem-fir species group is in the structural category, whereas most of ponderosa pine lumber would be graded as appearance or factory. (Hem-fir includes California red fir, grand fir, noble fir, Pacific silver fir, white fir, and western hemlock.) Table 1 shows the percentage of lumber production by lumber type for Douglas-fir, hem-fir, and ponderosa pine in 1989 (Warren 1990).

Table 1—Percentage of production of Pacific Northwest lumber from Douglas-fir, hem-fir, and ponderosa pine, by lumber type, 1989. From Warren (1990).

Lumber Type	Douglas-fir	Hem-fir	Ponderosa pine
Appearance and factory	3	2	89
Structural	97	98	11

Appearance and Factory Grade Wood. Clear wood products manufactured from Pacific Northwest softwoods have traditionally been held in high esteem and are used for a variety of products worldwide. Prices for Douglas-fir and hem-fir selects and shops have typically been two to three times the prices for structural lumber; in ponderosa pine these differences can be as high as four or five times (Warren 1990). Clear and shop grade lumber feeds a large network of secondary manufacturers commonly referred to as the molding and mill work industry. Appearance and factory grade lumber manufactured in the Pacific Northwest represents a substantial portion of the raw material used by this industry.

The issue with clear wood relative to the management of young-growth forests is that unless pruning is carried out as a forest management practice, there will be no clears at harvest. Studies have documented that significant volumes of clear wood will not be produced from the young-growth resource under current rotation-length policies (Cahill et al. 1988; Ernst and Fahey 1986; Ernst and Pong 1985). In general, it is perceived that fertilization would be an integral part of management regimes that include pruning. Economic analyses have shown that fertilization tends to increase the return on an investment made in pruning young-growth Douglas-fir (Fight et al. 1987). One example estimates that the break-even investment in pruning can be increased from $8.75 to $11 per tree (Douglas-fir butt logs on site 125) if fertilization is included with pruning (Fight et al. 1987). Similar interactions between fertilization and pruning would be expected for ponderosa pine. These analyses support what we would expect: after pruning, promoting the growth of clear wood yields a better return on a pruning investment.

One potential problem with "pushing" the growth of clear wood after pruning by fertilization regimes is that growth rates in the clear shell may be excessive. Currently there are no ring width limitations in the lumber grading rules for selects and shops; however, consumers of clear wood manufactured from old-growth fir and pine are used to dealing with fairly tight-grained wood. In Douglas-fir, for example, there is always a ready market for tight, vertical-grain selects—typically sold under the category vertical grain (VG). Selects from a young-growth resource will, for the most part, not be sawn on the vertical grain because the log size will be too small, and the clears that are produced will generally be regarded as coarser-grained wood. In general, clears from a fast-grown, young-growth resource will not look like clears that come from the old-growth resource. It is impossible to predict what markets will accept this material and what prices they will pay.

Structural Lumber. Douglas-fir and hem-fir structural lumber products from the Pacific Northwest have long been recognized nationally and internationally as high quality products with high strength-to-weight ratios. All structural grades of Douglas-fir and hem-fir lumber have a complete range of design properties for various measures of strength and stiffness. These values are estimated from tests on actual lumber samples and are periodically updated (Green 1983). The design values for structural lumber grades are an important part of using wood safely and efficiently in structures and other engineered applications. The design values take into account many strength-related characteristics that we typically see in lumber. These characteristics include knot size and placement, grain separations (check, shake, and split), stain and decay, wane, manufacturing defects such as warp or planer skip, and growth rate.

Assessing the impact of fertilization on specific grades of structural lumber is impossible without first compressing the wide array of grades currently recognized into a manageable number. This has been done recently for Douglas-fir (Haynes et al. 1988); these grade groups also apply to hem-fir lumber. Haynes recognizes seven general lumber grade groups (Table 2).

Table 2—Selected grade groups of Douglas-fir lumber.

Haynes Group	Actual Lumber Grades Included
C select	C select, export clears
D select and shop	D select, D and better, all shop grades
Structural items	All laminating stock, machine stress rated lumber, 2 inch select structural, 2 inch No. 1, 3 inch and thicker select structural, crossarms, scaffold planks, export commons
Heavy framing	2 by 10 and wider No. 2 and better, 3 inch and thicker No. 2 and better, ties
Light framing	All studs, standard and better light framing, 2 by 6 and 2 by 8 No. 2 and better, 1 by 4 and 1 by 6 utility and better, 4 by 4 utility and better, 4 by 4 standard and better
Utility	All utility, all No. 3 lumber
Economy	All economy lumber

Figure 2 shows the historical trends of lumber production for each of the Haynes lumber groups for Douglas-fir and hem-fir lumber in the Pacific Northwest (coast mills only). Of interest to us are the three groups that contain all of the structural lumber: structural items, heavy framing, and light framing.

Structural items. Historically, lumber in this grade group has accounted for between 12 and 16% of Douglas-fir lumber and between 4 and 7% of hem-fir lumber (Figure 2). Lumber in this group represents the "best in the West" relative to wood strength; typical applications are in "glulam" (glued-laminated) beams, scaffold planks, crossarms, and other engineered uses that require certifiable wood strength and performance. Lumber items in this grade group can be graded either visually or by machines (machine stress rated, or MSR). Under the visual grading rules there are two potential problems related to fertilization. First, the visual grading rules have requirements specifying minimum annual rings per inch. "Medium grain," or at least 4 rings per inch, is required for select structural grades; "dense grain," or at least 6 rings per inch, is required for the higher grades used in laminating stock (WWPA 1988). Ring counts of less than 4 and 6 rings per inch are allowed if the latewood band of the annual ring is at least one-third for medium grain and at least 50% for dense grain (WWPA 1988). Fertilization, particularly on

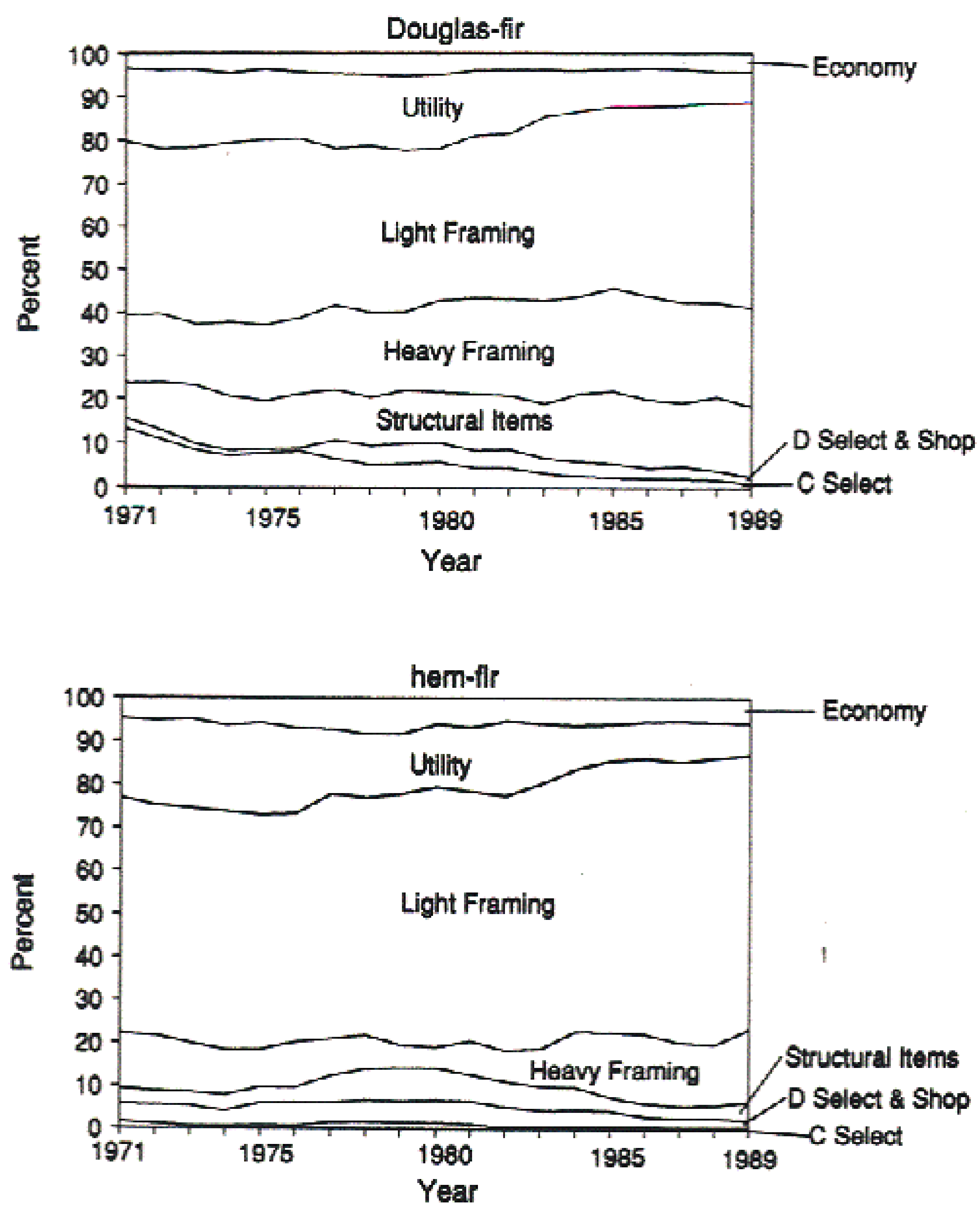

Figure 2. Cumulative proportions of selected lumber grade groups for Douglas-fir and hem-fir coastal mills. From Warren (1990).

higher sites, could produce wood that has excessive growth according to current grading standards. This could be a problem in that our "future" forests may not produce adequate supplies of medium- and dense-grained lumber needed for a variety of engineered uses.

Loss of wood strength resulting from fertilization is probably the most serious potential problem in visually graded structural lumber items. As we stated previously, a decrease in wood density for a number of years after fertilization has been observed in Douglas-fir; estimates of this loss vary but are in the 5 to 16% range. Wood strength is highly correlated with wood density (Haygreen and Bowyer 1989); when density increases, more of the three-dimensional volume occupied by wood is in cell wall material and not air space. In clear wood testing, higher density equates with greater strength. A potential problem with lumber containing fertilized fiber is that it may be overgraded for the actual strength it contains. These products may grade out as select structural under the visual rules, for instance, but in reality the piece will not meet the design requirements set forth by the grading standards for that species and lumber grade. The end result may be strength-related failures during product manufacture or, worse yet, failures of engineered products in service. It should be emphasized that the actual impact of fertilization on the performance of structural lumber is a complex issue. It is reasonable to assume that relatively few pieces of lumber will contain only fertilized fiber (two ends of a board are rarely made up of the same annual rings), and the number of boards containing fertilized fiber will depend on the number of times the stand was fertilized. Megraw (1986*b*) notes that the importance of temporary wood density reductions caused by fertilization will depend on the age of material harvested and whether or not it is already marginal in strength or above the requirements of the intended product mix.

Fertilization would seem to be less of threat in structural lumber graded by machines. Typical MSR techniques use a measure of stiffness (modulus of elasticity, or MOE) as an indicator of actual lumber strength. MOE, coupled with a visual inspection for knots and other defects, can be used to determine the actual strength properties for populations of boards. Lumber weakened because of fertilized fiber should be detected by the MSR machine and downgraded accordingly. Measurement of ring counts, or rings per inch, is not directly required, as in the visual grading process, because dense material is identified during the MSR grading process. A final thought on this subject is that grade yields in the highest MSR strength categories might be reduced because of fertilization.

Heavy framing. Lumber production in the heavy framing category has ranged between 18 and 23% for Douglas-fir and 5 and 15% for hem-fir in recent years (Figure 2). As the grade name implies, this lumber is generally "big stuff" intended for uses such as heavy construction, and bridge and pier construction. Heavy framing has been an excellent market for Douglas-fir and hem-fir because of their high strength values and large log sizes suitable for producing large dimensional products. Fertilization should not have a negative impact on the production of these products. In fact, we would guess that it would increase opportunities to continue in this product line because of the increased tree sizes. The only negative attribute caused by fertilization might be rings-per-inch violations; medium grain is required in the higher grades of heavy framing.

Light framing. More light framing material has been produced from West Coast conifers than any other product category. About 40% of Douglas-fir production and over 60% of hem-fir has been light framing (Figure 2). Fertilization should not significantly affect light framing lumber because it is intended for uses (the housing industry) where straightness and dimensional stability are the primary requirements.

While fertilization should not affect the production of light framing lumber from the young-growth resource, there may be other problems ahead for this category. Ernst and Fahey (1986) note that the Pacific Northwest has some disadvantages compared to other regions in North America that also can produce light framing lumber. Higher logging costs in the Pacific Northwest and the distance to markets in the Midwest and East may tend to favor other species of wood for these types of products. Light framing lumber will always be produced in the Northwest, but its dominance in the future is in question.

Knots. Knots in the young-growth resource are an overriding consideration for all the structural products discussed above. The size and position of knots occurring in structural lumber products are the most common defect related to the softwood resource. In effect, a knot is similar to a hole: the lack of continuous fiber reduces many properties that are important to using wood in structural applications. Grain distortions around knots also contribute to lower strength properties. Figure 3 shows the impact of knots on visually graded lumber yields from young-growth Douglas-fir logs (Fahey et al. 1991). The impact of large limbs on lumber recovery is dramatic. Lumber in the select structural grade, for instance, was not produced in this study when the limb index (LLAD) was larger than 1.5 inches. Beyond strength losses, knots also cause difficulties in drying, woodworking, gluing, and finishing.

Knots in lumber will vary according to the size of the branches, or limbs, from which they were formed in trees. Limb size in the forests of the Northwest has been thought to be mainly a function of stand stocking: widely spaced trees have vigorous persistent limbs that will, on the average, be larger than those on trees of similar age growing in denser conditions (Smith 1961). More recent work (Maguire et al. 1988) indicates that limb size in young-growth Douglas-fir is a function of site index, depth into crown, and relative stand density. As we have indicated, little is known about the quantitative impacts of fertilization on limb growth; however, the trends in Figure 3 show that small shifts in average limb sizes can have a major impact on the yield of structural lumber products. More information is needed relating fertilization and other management activities to branch and tree growth.

Juvenile Wood. Numerous studies have shown that juvenile wood has a negative impact on structural lum-

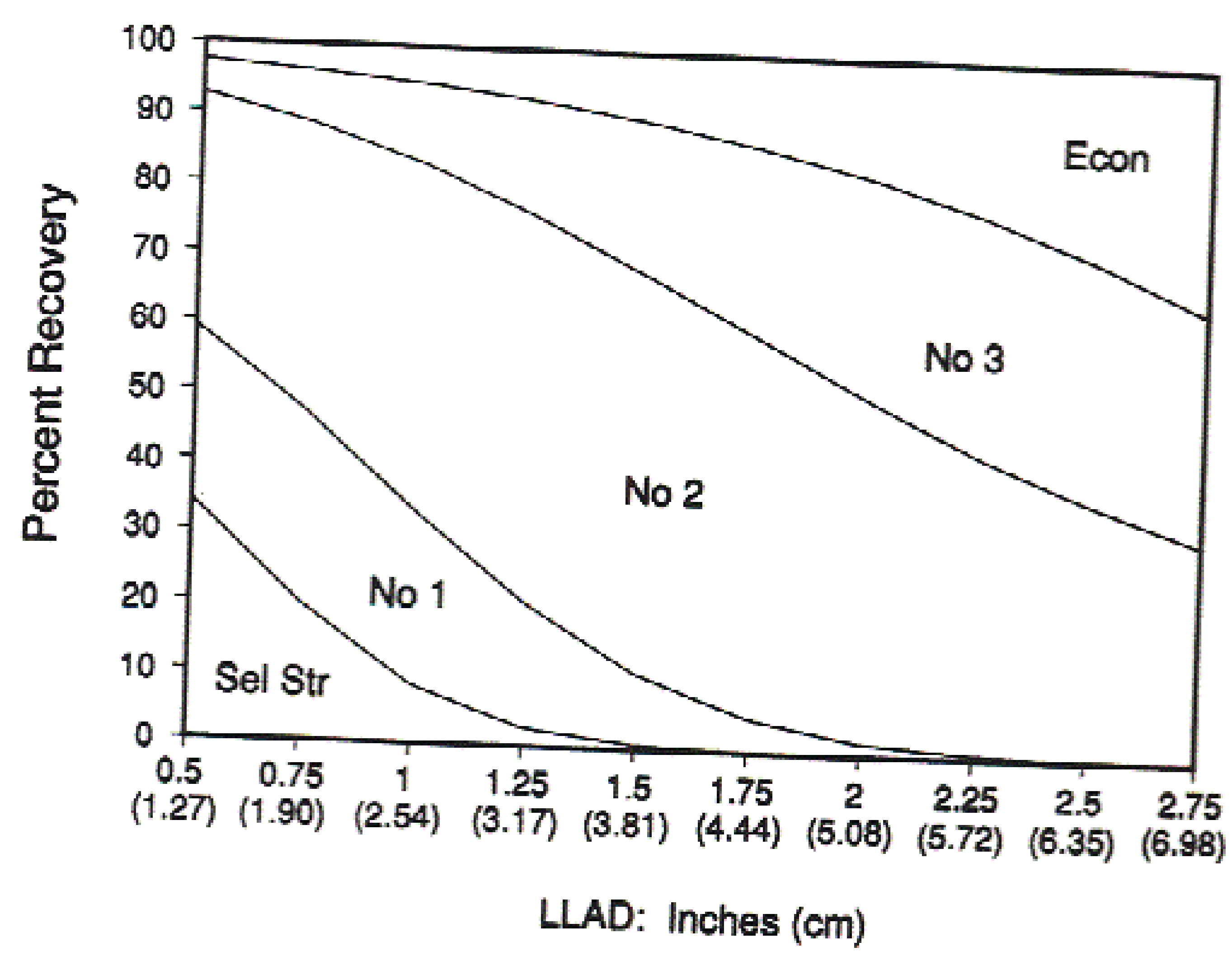

Figure 3. Cumulative visual lumber grade yields for young-growth Douglas-fir logs. Data based on actual mill recovery from 694 logs sawn into 2 by 4 and 2 by 6 lumber (Fahey et al. 1991). LLAD is the average of the largest limb diameter in each log quadrant.

ber products (Fahey et al. 1991; Bendtsen et al. 1988; Barrett and Kellogg 1989; Senft et a1. 1985). There is little doubt that the anatomical characteristics associated with juvenile wood add up to real problems for many forest products. Dimensional stability and product strength are two key concerns in all lumber groups. A few findings from recent research linking juvenile wood to product performance in Douglas-fir help make this point. Barrett and Kellogg (1989) found that strength decreased for 2 by 4 select structural Douglas-fir lumber as the percentage of juvenile wood increased. Lumber containing 40 to 60% juvenile wood decreased 15% in modulus of rupture (MOR); lumber with 90-100% juvenile wood decreased in MOR by 29%. Bendtsen et al. (1988) found that the tensile strength of Douglas-fir 2 by 4s cut from the juvenile portion of the log was only 59% the tensile strength of lumber cut from the outer, or mature, wood. As stated previously, the concern with fertilization is that it may tend to extend what we would consider the juvenile period of growth in young-growth trees. Currently there are few studies that allow us to evaluate this potential problem.

Panel Products

Panel products range widely from very expensive cabinet-grade plywood to low priced sheathing products such as oriented strandboard and waferboard. Annual production figures for various products are difficult to obtain; however, over 8 billion square feet of panels (3/8 inch basis) were produced in 1989 (Warren 1990). Panel products represent a major segment of the forest products industry in the Pacific Northwest. For the sake of simplicity and to keep the discussion parallel to lumber, we have lumped panel products into the following categories: appearance grade plywood, construction grade plywood, veneers used in engineered applications, and composites.

Appearance Grade Plywood. As one might expect, appearance grade represents the best products the plywood industry has to offer. Veneers used in the construction of these products are generally the top grades (A, B, and C plugged[1] veneers), which allow few defects such as tight and loose knots. Examples of the plywood products are natural finish (used in cabinets), high and medium density overlays (used in making outdoor signs), marine grade (used in boat construction), and siding grades (used as exterior siding for housing). Appearance grade plywood is made for either interior or exterior uses; generally interior grades are less restrictive on the quality of material allowed in the inner plies. Much of the previous discussion about clear wood lumber products applies to appearance grade plywood. A pruned, young-growth resource would provide knot and defect-free veneers that would "feed" the manufacture of these products; as we mentioned earlier, fertilization would likely be a component of growing clear wood on commercial forest lands. The "look" of fast-grown clear wood in appearance grade plywood is a concern for some products, such as cabinet-grade plywood, that use Douglas-fir as the exposed surface. Once again, the fast-grown clear wood will look different from veneer manufactured from the old-growth resource. However, there are many products that require defect-free veneers that are not exposed—medium and high density overlays used for signs, for example.

Construction Grade Plywood. Although a wide variety of construction grade plywood products are available for interior and exterior uses, the majority of production has been in CD exterior plywood. This sheathing product has many uses, particularly in building construction, including subflooring, roofing, and siding. CD, and most of the other construction grade plywoods, are less stringent in requirements for veneer than are appearance products. Construction plywood is similar to light framing lumber; product strength is certainly important but it is not the overriding consideration.

Limb size and its relationship to fertilization is about the only issue we could envision as a potential problem for this category of plywood. C and D are the two most common veneer grades used in these products, and knot size and condition are the key factors separating them. C grade allows a 1 1/2 inch tight knot or a 1 inch loose or dead knot; D grade allows tight and loose knots of up to 2 1/2 inches. Studies have shown that the young-growth resource produces mostly C and D grade veneer (Fahey and Willits 1991; Ernst and Fahey 1986; Fahey 1974); however, the relative proportions of C and D recovered do vary depending on the average limb size of the log (Fahey et al. 1991). Figure 4 shows the impact of limbs on veneer grade recovery; the recovery of D grade veneer increases dramatically as limb size increases (Fahey et al. 1991).

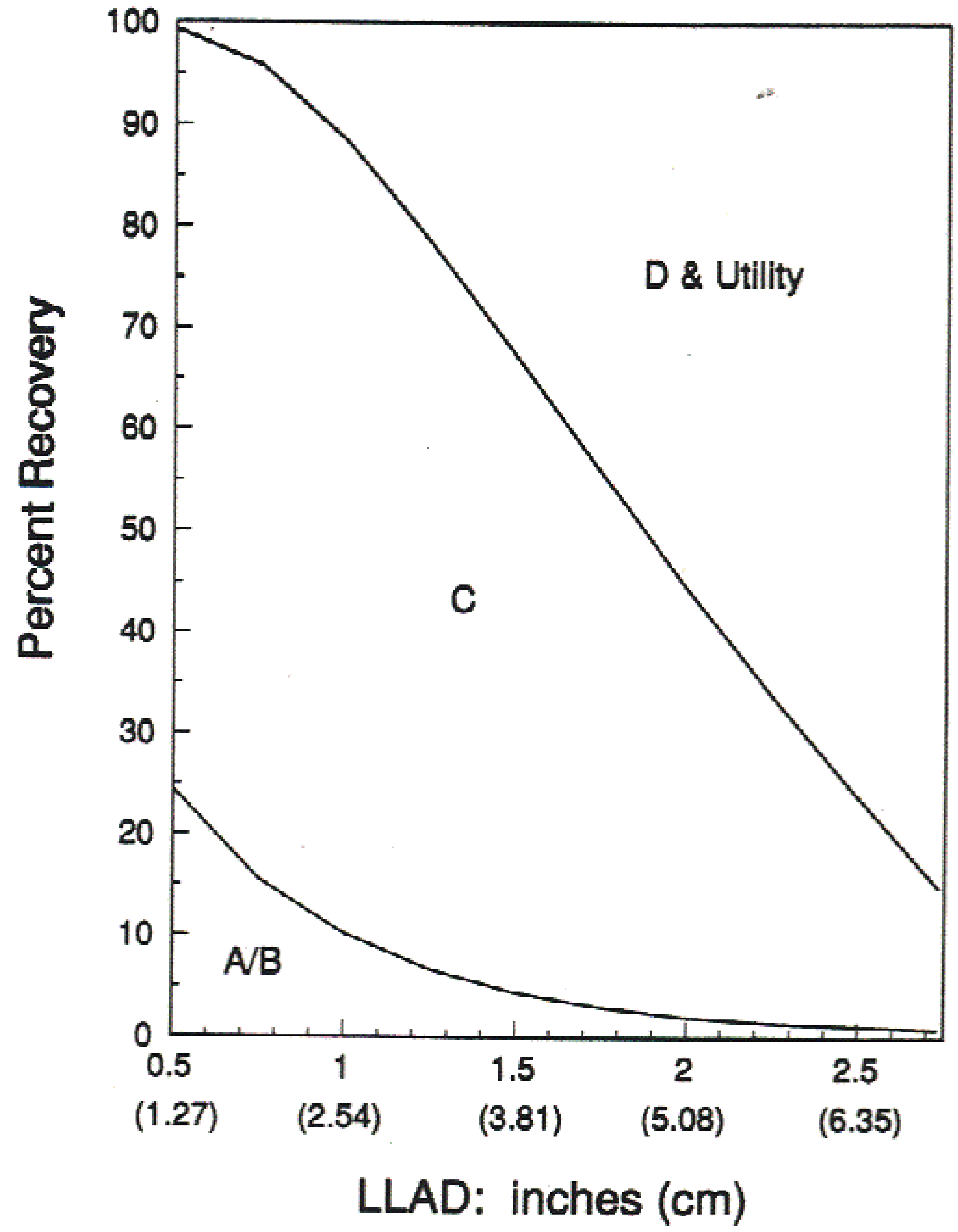

Figure 4. Cumulative veneer grade yields for young-growth Douglas-fir logs. Data based on actual mill recovery from 267 logs (Fahey et al. 1991). Veneer was peeled to 1/8-inch thickness. LLAD is the average of the largest limb diameter in each log quadrant.

Veneers Used in Engineered Products. An increasing use of softwood veneer is in the manufacture of parallel laminated veneer products (PLV). PLV typically consists of several layers of dried veneer, cured by heat and pressure in moving presses. The layering of veneer decreases the variability of strength properties by minimizing the influence of defects such as knots. PLV is used mostly in engineered applications where predict-

[1]Plugged veneer refers to the practice of punching out knots, knotholes, and other defects and replacing them with a veneer or synthetic patch.

able performance is desired. In the Northwest, industries manufacturing PVL products use Douglas-fir C and D grade veneer, mostly 1/10 inch thick. An important aspect to the successful use of this veneer in producing reliable, high strength products is that each veneer sheet is evaluated ultrasonically to estimate its actual strength. Although the physics of ultrasonic grading is complex, the underlying principle is that wood density affects the time it takes sound waves to travel through wood. The denser the wood, the faster the "wave propagation time." Ultrasonic grading allows the PLV industries to identify and sort veneer, at production rates, into high, medium, and low strength wood. Producers of PLV products mix different strength categories of veneer in precise patterns to achieve the high strength values their products now have.

It is in this industry that a fertilized resource may have some impact. Ultrasonics should "pick out" and downgrade wood that has been weakened by fertilizer applications. As we indicated earlier, wood density has been shown to be lowered as a result of fertilization. While PLV products can tolerate a certain amount of low strength material, the industry does require substantial amounts of high strength wood. Ring width is another potential problem in producing these products from a resource that is pushed to its maximum growth rate through fertilization and other silvicultural techniques. Given the relatively thin veneer used in these products, wide growth rings mean that much of the veneer will be produced from the earlywood portion of the annual ring, and earlywood density is always lower than latewood. A recent study on Douglas-fir showed that veneer peeled from a fast grown resource experienced high rates of rejection when graded by ultrasonics; the presence of earlywood was believed to be a contributing factor (Kretschmann et al. 1992).

Composite Panels. This category covers a wide range of products produced by compressing small particles of wood while simultaneously bonding them with adhesives. They differ with respect to "furnish" used as the raw material, the type and amounts of adhesives used, and the density to which the panel is pressed (Haygreen and Bowyer 1989). Examples of furnish are shavings, flakes, wafers, chips, sawdust, strands, slivers, and wood wool. Final products are marketed by many names, including chipboard, flakeboard, oriented standboard, and particleboard. The composite panel industry has shown steady growth since the 1970s, when timber costs in the western United States escalated (Spelter 1988). The advantage of composites over alternative products such as plywood has been in the availability and low cost of the materials used in their production.

We were unable to find any research dealing directly with the impacts of fertilization on this class of products. Some work has assessed the properties of Douglas-fir structural particleboard made from the tops and branches of trees (Lehmann and Geimer 1974). The results showed that strength and dimensional stability were reduced, presumably due to the presence of juvenile wood. Maloney (1986) makes the point that the composite panel process lends itself to solving problems with juvenile wood, and we feel the same logic could be applied to the use of a fertilized resource in these products. Maloney states that there are many opportunities to adjust the manufacturing process so that the problems associated with juvenile wood can be minimized. For example, the furnish can be blended from a wide variety of sources, adjustments can be made in the adhesives, fibers can be oriented, and chemical treatments can be used to increase product stability. Our conclusion from all this is that use of fertilized fiber should not present any major problems to this industry.

Incorporating Consideration of Wood Quality in Forest Management Decisions

Ultimately, forest managers would like tools that allow a full evaluation of all possible management practices. The effects of practices such as fertilization on volume production, wood quality, management and logging costs, and final product and value yields should all be considered when evaluating forestry decisions. Obviously, this requires a lot of information, and computer models help considerably in storing and organizing biological and economic data relevant to forest management. At present two models exist for Northwest conifers that can be used to simulate the conversion of managed Douglas-fir stands into products and provide managers with insights on the financial trade-offs between cultural practices and their effects on wood quality and product value. These are the SYLVER model developed by the Douglas-fir Task Force in British Columbia (Mitchell et al. 1989) and the TREEVAL model (Briggs 1989; Briggs and Fight 1992). Although there are substantial differences in methods and details, both models simulate the impacts of site, stocking, and harvest age on two key wood quality attributes—limb size and the amount of juvenile wood. Outputs from these models have been used to estimate the financial return for various management assumptions based on end product values (Mitchell et al. 1989; Briggs and Fight 1992).

While these models could be readily adapted to fertilized stands, the necessary relationships to quantify the diverse effects of fertilization are lacking. While much effort has focused on predicting the tree volume response to fertilization, we have little information on how fertilization interacts with the crown to modify branch size, juvenile wood characteristics, and wood density across a range of stand conditions. Furthermore, there are no product recovery studies that link the attributes of fertilized trees to product volume and grade yields. In the absence of this information, these models ignore potential impacts of fertilization on wood quality. Hopefully, the decade of the 1990s will see the completion of the comprehensive research needed to address the effects of fertilization and other management practices on wood quality and product value.

Summary and Conclusions

The goal of fertilization, like many other young-growth management practices, is to increase volume production per unit of land. There is little doubt that this objective is fully met when nitrogen and other elements are applied in prudent regimes. In this chapter we have tried to look beyond tree volume production and assimilate from the research record how fertilization might affect wood quality. We found that research in this topic has not been very extensive and has not been incorporated into usable tools for forest managers. The key impacts on wood quality resulting from fertilization and their potential impact on products are summarized below.

Wood density is decreased for a number of years following fertilization. The specific results vary between studies, but the range in reduction is between 5 and 16%. Studies indicate that density drops immediately following fertilization and gradually increases to prefertilization values over four to six years. The decrease in density is thought to be caused by decreases in the cell wall thickness of both earlywood and latewood, and because fewer thick-walled latewood cells are present in annual rings under the influence of fertilization.

Microfibril angle has been shown to increase 2 to 3 degrees in one study and 9% in another. The magnitude of these changes would seem to be small and the impacts on lumber warpage should not be significant.

Ring widths should increase as a result of fertilization. The widest possible widths will occur on high sites that are fertilized and kept at low stocking levels. The overall importance of ring widths to the forest products industry varies depending on what product is under consideration. Currently, there is common misconception that fast-grown wood with wide growth rings is always weaker than slower-grown wood. Research has clearly shown that after age of wood is taken into account, ring width and wood strength are virtually independent traits for Douglas-fir. Current lumber grading rules, however, still have rings-per-inch limitations for certain high grades of lumber. If these limits are maintained, lumber produced from fast-grown trees (4 or less rings per inch) may experience degrade.

Juvenile wood and knot size are two important young-growth characteristics that significantly impact many forest products, but there is not much information quantifying the impact of fertilization on these two key wood quality attributes. Knots are essentially discontinuous wood, or holes, that lower the strength of many structural products and cause problems in drying, woodworking, gluing, and finishing wood products. Juvenile, or crown-formed, wood has been shown to be a problem in structural wood products because of lower wood density, greater fibril angle, and greater longitudinal shrinkage when compared to mature wood. Research has repeatedly shown that the negative traits associated with juvenile wood translate into problems for many structural products. The concern regarding fertilization is whether increased crown vigor will result in excessive branch diameter growth and extended periods of juvenility.

The research record relating yields of forest products to management activities such as fertilization is very limited. Based on the anatomical changes we found in the literature, and current product standards, we have made the following assessment. There is some direct research indicating that a fertilized, young-growth resource should not be a problem to the pulp and paper industry. The amount of fiber that may be influenced by fertilization should be small relative to the overall mix of chips used by this industry.

Use of young-growth trees for poles should not be seriously affected by fertilization. Though there are rings-per-inch and knot requirements in the rules used to grade poles, advances in grading techniques should be able to match the design properties required to the resource available. Also, the annual volume needed by the pole industry is small relative to anticipated future harvests in the region.

The key wood quality variables in the log export business are log size and straightness, limb size and frequency, and rings per inch. Recent predictions for the log export industry indicate that the supply of low grade logs from several world sources will increase, resulting in suppressed prices for this kind of material. Logs cut from fast-grown, coarse-grained trees would likely fall into this category. Logs cut from a slower-grown, higher quality resource will be in demand for the coming decades and prices are expected to rise.

The current domestic log grades were developed for the old-growth resource and are a poor index of quality in the young-growth resource. Because of this, meaningful trends in log quality related specifically to management activities such as fertilization are difficult to identify. Log size specifications in some grading rules can be a source of misinformation to land managers because they tend to conclude that "big is always better."

A wide array of lumber and panel products currently account for the majority of products manufactured in the Pacific Northwest. Commodity type products such as light framing lumber and construction grade plywood should not be seriously affected by fertilization. Reduced wood density associated with fertilization could be a problem in products that demand reliable, high strength performance. Examples of these products are "glulam" beams, machine stress rated lumber, and parallel laminated veneer products. Fertilization should increase the production of clear wood after pruning; however, clear wood from a fast-growing, young-growth resource will not look the same as clear wood from old-growth forests.

Although ring widths are currently incorporated into many of the standards for visually graded lumber, their usefulness in sorting out strength classes of lumber is in question. MSR grading techniques are more accurate in determining the actual strength properties of lumber and do not use ring counts as a requirement.

A full economic evaluation of young-growth management activities, such as fertilization, is in the beginning stage. Currently there are two computer models (SYLVER and TREEVAL) that allow foresters to incorporate the impacts of management practices on growth and yield, wood quality, management costs, and end product values for Douglas-fir. Nothing similar exists for the hem-fir species group or for pines. However, even for Douglas-fir some important links between management practices and their effects on wood quality are currently lacking—fertilization is a good example. Because of this we cannot address the actual impact that fertilization might have on the economics of various management regimes. In general, we feel that the fertilization issue will not "sink" the forest products industry in the Pacific Northwest. Certainly there are changes in wood anatomy that will affect some products, particularly those requiring high strength. These products currently are a small part of the total mix of goods produced from Pacific Northwest forests; but many think that they represent a fast-growing segment of the industry. We do feel strongly that failure to ignore wood quality in the total management of the young-growth forests would be a serious mistake. Forest managers have a variety of "tools" at their disposal and many of them can have an effect on the suitability of young-growth trees for specific forest products. We also feel that research involving issues like fertilization should take an integrated approach and include the effects and interactions of other key management activities, such as thinning. Our ultimate goal is to understand how forests "behave" in response to the full range of management conditions they are likely to be grown under. It seems reasonable to us that forest managers need to have a broad perspective when evaluating management strategies and not lose sight of the fact that forestry and the forest products industry are closely linked.

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