

**INCLUDING WOOD STIFFNESS IN
TREE IMPROVEMENT OF COASTAL
DOUGLAS-FIR IN THE US PACIFIC
NORTHWEST: A LITERATURE
REVIEW AND SYNTHESIS**

August 2009

by

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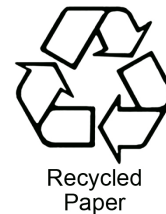
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ABSTRACT

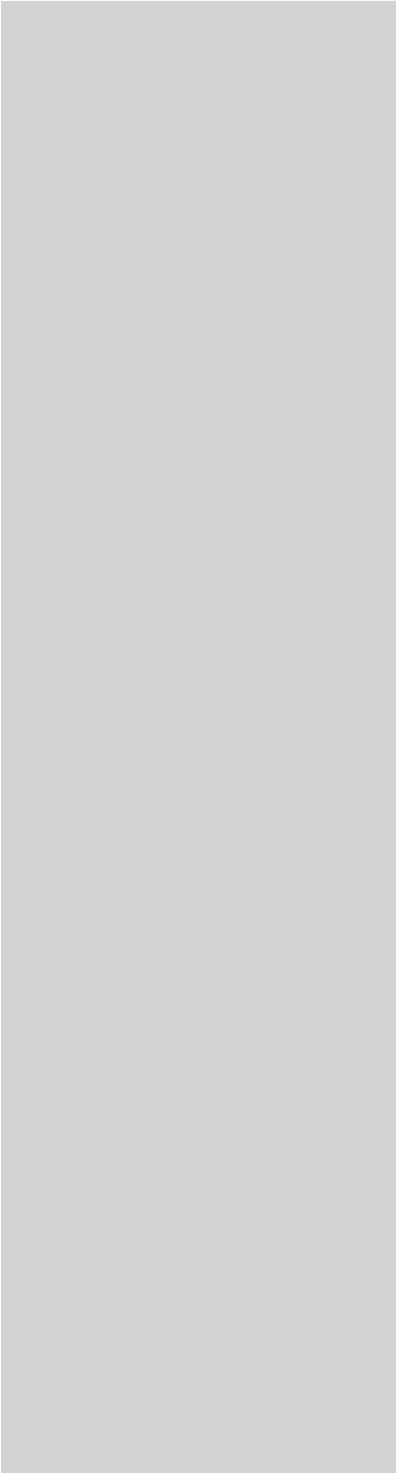
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Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] is the most important timber species in the Pacific Northwest (PNW) of the United States, and high stiffness is important for many of its products. We estimate that about 17% of Douglas-fir harvested in the PNW is used as peeler logs for plywood and 2–5% as machine-stress-rated (MSR) lumber. Stiffness is assumed as being implicit but not measured in some other products, visually graded lumber being the most prominent example. Perhaps 68% of the Douglas-fir harvested in the PNW is used as visually graded lumber.

A moderate increase in specific gravity and a much more pronounced decrease in fibril angle is observed from pith to bark in Douglas-fir. This combination results in the juvenile wood (closer to the pith) being less stiff than mature wood. It is therefore likely that current management regimes, especially rotations as short as 35 yr, will reduce average wood stiffness of Douglas-fir products. There are some nongenetic options for adjusting for reductions in average stiffness, maintaining or improving stiffness; log segregation based on acoustic velocity is the most promising and cost-effective of these and has already been adopted.

There have been many studies on the inheritance of specific gravity and stiffness in Douglas-fir and other conifers, with the stiffness studies occurring mostly in the past decade. Stiffness appears to be under stronger genetic control than height or DBH, but this control is weaker than for wood specific gravity (which is another compound trait). Methods and tools for screening stiffness in tree improvement programs are improving rapidly, becoming more reliable and easier to use. Most promising of those are acoustic tools that can be used on standing trees.

It would be feasible to select for and breed for higher wood



stiffness for coastal Douglas-fir. Stiffness data could be fed into the tree improvement programs in the short term through collecting open-pollinated seed from select families or producing control mass-pollinated seedlots, and in the medium-term through high-stiffness orchards, high-stiffness third-cycle crosses, or elite populations. A preliminary breeding objective of 1.6 million psi average whole-tree stiffness is proposed. The direct cost of a well-designed program would be low when translated to dollars per reforested acre, since it would make use of existing tests and seed orchards. The main cost of such a program is indirect, namely, volume gain foregone. Genetic selection for wood stiffness may be very profitable for some forest growers, and less so for others.

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EXECUTIVE SUMMARY

Improving the quality of wood produced from fast-growing, young plantations has become especially important for many advanced-generation tree-improvement programs. Currently some growers are strongly interested in improving wood stiffness through selection.

Douglas-fir is the most important timber species in the Pacific Northwest (PNW) of the United States, and high stiffness is important for many of its products. This analysis was prompted by

- the need to evaluate whether genetic selection can and should be used to counteract reduced stiffness caused by growing Douglas-fir on shortened rotations;
- the availability of robust equipment that can take meaningful indirect measures of stiffness in the field, at costs much lower than those for bending tests in laboratories;
- increased knowledge about the inheritance of stiffness in Douglas-fir and other commercially important plantation softwoods;
- a long-standing tree improvement program with many selections in progeny tests where wood stiffness could be screened, and orchards that could be redirected to produce high-stiffness seedlots; and
- interest by some cooperators in moving to a third cycle of breeding and testing and a desire to adequately factor wood stiffness into such programs.

Stiffness is explicitly required in grading some Douglas-fir products, such as structural plywood, laminated veneer lumber, and machine-stress-rated (MSR) lumber. We estimate that about 17% of Douglas-fir harvested in the PNW is used as peeler logs for plywood and 2–5% as MSR lumber. Stiffness is assumed as being implicit but not measured in some other products, visually graded lumber being the most prominent example. Perhaps 68% of the Douglas-fir harvested in the PNW is used as visually graded lumber. Another 12% of softwood harvest (predominantly Douglas-fir) is for pulpwood, fuel, posts, and such where, again, stiffness is not measured. It is hard to predict whether the current situation—in which 100% of Douglas-fir logs are sold and nearly 80% are processed without reference to stiffness—will continue.

A moderate increase in specific gravity and a much more pronounced decrease in fibril angle is observed from pith to bark in Douglas-fir. This combination results in juvenile wood (closer to the pith) being less stiff than mature wood. It is therefore likely that current management regimes, especially rotations

as short as 35 yr, will reduce average wood stiffness of Douglas-fir products. Wood quality concerns were raised almost 50 yr ago, as harvest from old-growth Douglas-fir gave way to harvests from naturally regenerated second-growth; the industry survived that transition. We can predict some variation in wood stiffness associated with latitude and elevation, and perhaps with aspect and rainfall distribution. Douglas-fir in North America also appears to have a weak trend of decreasing stiffness with increasing height in the tree. Contrary to popular belief (arising mostly from comparing fast-grown juvenile with slow-grown mature wood) that fast growth inevitably results in weak wood, the correlation between tree size and stiffness for a given location, ring number from pith, and vertical position can be negative or zero.

There are some nongenetic options for dealing with changes in stiffness and maintaining or improving stiffness: rotations of 60 yr or longer; knot size control through tight spacing, pruning, or both; identifying and possibly relocating to geographic areas that promote higher stiffness; segregating logs, boards, and veneers by nondestructive stiffness evaluation; developing manufacturing technologies to make high-stiffness products from average quality material; and modifying building designs. Log segregation based on acoustic velocity is the most promising and cost-effective of these and has already been adopted. Much greater use of MSR is technically possible, which would improve efficiency of use of the raw material considerably. (Visual grading is only moderately effective in segregating boards based on stiffness and tends to undervalue lumber overall.) Pruning is prohibitively expensive and affects only the pruned part of the stem. Minor ($\leq 5\%$) reductions in Douglas-fir wood stiffness would have little effect on the integrity of structures, given the large safety margins and redundancy in building design and building codes.

There have been many studies on the inheritance of specific gravity and stiffness in Douglas-fir and other conifers, with the stiffness studies occurring mostly in the past decade. The results refer to young trees and mid-rotation trees. Stiffness appears to be under stronger genetic control than height or diameter at breast height (DBH), but this control is weaker than for wood specific gravity. The number of trees assessed has varied from as few as 6 per clone to 19 per half-sib family. Genetic correlations between height growth and wood stiffness are generally close to zero or even favorable, whereas correlations between stiffness and diameter growth are typically adverse. There is an indication that Douglas-fir families that are more cylindrical will have denser and stiffer wood than families with high taper. Predicted gains ranging from 4.1% to 24% are reported in the literature for direct or indirect measures of stiffness in various conifer species.

Studies have shown that we can improve volume growth and stiffness at the same time, though maximum gains will not be possible for either. Methods

and tools for screening stiffness in tree improvement programs are improving rapidly, becoming more reliable and easier to use. Most promising of those are acoustic tools that can be used on standing trees or felled logs. Conifer tree-improvement programs have attempted to improve stiffness and strength through selection for either density or pilodyn resistance and, more recently, for acoustic velocity or other indirect measures. A production rate of 800 trees/day for a two-person crew using a standing-tree time-of-flight tool has been reported for loblolly pine, but typical production rates may be closer to 200–300 trees/day.

It would be feasible to select and breed for higher wood stiffness in coastal Douglas-fir. This follows 20 yr of work in the breeding program screening selections for specific gravity, ramicorn branches, upper stem forking, and stem sinuosity. There are several reasons to select for stiffness:

- (1) Genetic selection will be a much more cost-effective tool to maintain or improve stiffness than branch size control (tight spacing, pruning, or both) or engineering in stiffness by processing and could have fewer regulatory issues and consequences than the latter.
- (2) Although treatments that can dramatically increase plantation growth rate exist, few such techniques could be used to improve wood stiffness.
- (3) Given the potential adverse correlations of stiffness with diameter growth rate, failing to score stiffness could result in low-stiffness selections becoming significant components of breeding or production populations.
- (4) Once a Douglas-fir tree is planted, we typically have to live with its genetic strengths and weaknesses for 35 yr or longer.
- (5) Some organizations wish to use all available tools to maintain Douglas-fir's niche as a high-value species.

Several assessment issues need to be addressed, such as (1) optimal strategies to sample and combine first- and second-generation data, (2) number of trees to be sampled per family per site, (3) number of sites to sample per test series, (4) whether sampling more than one location per tree is necessary, (5) age of assessment, and (6) how to adjust for knots. On the basis of work in several species, we should need to sample no more than 25 trees per family for measures of stiffness, starting at about age 10 yr. If it is proven that knots hinder the ranking of second-cycle Douglas-fir progenies, we could prune a subset of second-cycle tests and remeasure after the formation of some knot-free wood. We could even establish one or two supplemental sites in the third cycle with perhaps 10–12 trees per cross, at wider spacing, and prune them early specifically to prepare them for acoustic velocity assessment. Stiffness

data could be fed into the tree improvement programs in the short term through collecting open-pollinated seed from select families or producing control mass-pollinated seedlots, and in the medium-term through high-stiffness orchards, high-stiffness third-cycle crosses, or elite populations. A preliminary breeding objective of 1.6 million psi (10.34 GPa) average whole-tree stiffness is proposed. This average level of stiffness is quite feasible for Douglas-fir in the PNW, since No. 2, No. 1, and Select Structural grade Douglas-fir meeting or exceeding this standard is already being produced.

The direct cost of a well-designed program, translated to dollars per reforested acre, would be low if it uses existing tests and seed orchards. The main cost of such a program is indirect, namely, volume gain foregone. Genetic selection for wood stiffness may be very profitable for some forest growers, and less so for others. Forest growers managing Douglas-fir on short rotations, such as 35 yr, and marketing the wood for high-stiffness applications (such as laminated veneer lumber) have the most incentive to select genetically for stiffness. Other forest growers predicting a future market niche for larger, higher stiffness Douglas-fir logs from older trees may also see value in selecting for stiffness. Large information gaps need to be filled as forest growers begin to include wood stiffness in tree improvement programs and operational forestry. These include

- obtaining stiffness breeding values;
- relating standing tree acoustic velocity data taken in young trees to lumber stiffness;
- mapping regional geographic trends in stiffness associated with geographic factors;
- understanding within-tree variation;
- incorporating stiffness into regional growth-and-yield models; and
- calculating economic weights for stiffness relative to height, DBH, and other economically important traits.

PART I. BACKGROUND, CONTEXT, AND JUSTIFICATION

I. RATIONALE, OBJECTIVES, AND INTENDED AUDIENCE

Improving the quality of wood produced from fast-growing, young plantations has become especially important for many advanced-generation tree-improvement programs. Currently, some growers are strongly interested in improving wood stiffness through selection. This is an appropriate time to consider the role of stiffness in cooperative Douglas-fir tree improvement in the PNW, as several important factors are now in place:

- recognition that stiffness is a very important trait for Douglas-fir lumber, engineered products, and reconstituted products
- a large number of selections in progeny tests where wood stiffness can be screened
- a large seed orchard capacity, where wood stiffness rankings can be translated to operational orchard seedlots with desired stiffness gains
- concern about the impact of intensive plantation management and reduced rotation lengths on wood properties, including stiffness
- awareness of the potential effects (positive or negative) of genetic improvement programs on commercially important traits
- interest by some cooperators in moving to a third cycle of breeding and testing and a desire to adequately factor wood stiffness into the program
- robust equipment capable of taking meaningful indirect measures of stiffness in the field, at costs higher than for routine measures of growth and form, but much lower than for direct bending tests in laboratories
- growing knowledge about the inheritance of stiffness in Douglas-fir and other commercially important plantation softwoods.

The primary audience for this paper is practitioners and industry members working with Douglas-fir tree improvement in the PNW. Tree improvement personnel interested in stiffness improvement in conifers outside the PNW comprise the secondary audience.

The objectives of this paper are

- to review
 - the major products of coastal Douglas-fir from the US PNW, their economic importance, and potential impacts of changes in stiffness due to various factors, including silviculture and management
 - methods of assessing stiffness in trees and lumber
 - information available on the inheritance of stiffness and related traits in Douglas-fir and other conifers and progress made in the improvement of stiffness in other plantation conifers
- to weigh pros and cons of implementing stiffness improvement in Douglas-fir, and to outline how such a program might be implemented if such implementation is desirable
- to describe information gaps and needs.

2. CONTEXT, KEY CONCEPTS, AND HISTORICAL BACKGROUND

2.1 DOUGLAS-FIR AS A MAJOR TIMBER SPECIES

Douglas-fir is the most important timber species in western North America. Production of coastal Douglas-fir lumber in western Oregon and western Washington ranged from 8.2 to 9.3 billion bd ft (13.9 to 15.8 million m³) between 2002 and 2006, or nearly 25% of total softwood lumber production in the United States (USDC 2007). In 1999, it comprised a third of all log exports from the country (Howard 2001).

2.2 WHAT IS STIFFNESS, AND HOW STIFF IS DOUGLAS-FIR WOOD?

Stiffness is a measure of resistance to deformation when subjected to a load: the higher the stiffness of a material, the more it can resist deformation. Bending stiffness (resistance to bending) is very important to load-bearing structural members. Important measures of stiffness include Modulus of Elasticity (MOE)—a board that deflects less has a higher MOE. Further details on the definition of stiffness and how it relates to strength are given in Appendix 1.

MOE can be determined nondestructively by several techniques. Campbell (1964) gave two estimates of MOE: 1.503 million psi (10.36 GPa) for slow-grown and 1.387 million psi (9.56 GPa) for rapid-grown Douglas-fir (age not specified). Green et al. (1999) provide a benchmark stiffness value for

coastal Douglas-fir of 10.77 GPa (1.56 million psi) when green and 13.4 GPa (1.94 million psi) at 12% moisture content. Corresponding values (million psi), for other major western conifers, green and at 12% moisture content, respectively, are 1.31 and 1.63 for western hemlock; 1.25 and 1.57 for grand fir; 1.38 and 1.72 for noble fir; 0.94 and 1.11 for western red cedar (Green et al. 1999). Other stiffness estimates for Douglas-fir in North America and elsewhere are shown in Table 1; two of these estimates, from New Zealand (Shelbourne et al. 1973; Knowles et al. 2004), are much lower than the Wood Handbook values, to the point that one would have to interpret them as comprising very different materials than those from the PNW (because of site, silvicultural, and growth rate differences), being obtained by different methods, or both.

2.3 WHY FOCUS ON STIFFNESS?

Productivity is a key selection trait for plantation forestry species, and coastal Douglas-fir is no exception. This trait is typically assessed in breeding programs as height, diameter at breast height (DBH), and conic volume $[(DBH)^2(\text{height})]$. Growers are also concerned about adaptability, especially tolerance to winter cold and late spring and early fall frosts, and stem quality (low incidence of forking, ramicorn branches, and sinuosity). Because gain in any one trait often decreases as the number of traits increases, the list of selection traits cannot expand indefinitely. So we need to choose carefully which—if any—wood properties should be added to the list of selection criteria. Wood stiffness seems the strongest candidate to be added, for several reasons.

Stiffness and strength are the most important wood properties for Douglas-fir. Knot size, frequency, and distribution are major drivers of lumber stiffness and strength (for example, Megraw 1986a; Shelbourne et al. 1973). Knot size seems to affect strength more than it does stiffness, however, and the general consensus is that knot size is better controlled by silvicultural management—spacing, thinning and pruning—than by genetic selection (for example, Shelbourne et al. 1973).

MOE, on the other hand, is under strong genetic control, and it is feasible to achieve high levels of genetic gain. Stiffness can be assessed nondestructively and at relatively low cost. (This topic is discussed at length in section 3.) Stiffness is positively correlated with Modulus of Rupture (MOR) (for example, McKimmy 1959) and specific gravity (SG) (for example, McKimmy 1959; Shelbourne et al. 1973; Knowles et al. 2004), so selection for stiffness will improve those traits as well.

Forest growers have no incentive to improve fiber traits, such as fiber length and coarseness. Although these traits affect pulp and paper production, those

Table 1. MOE values for coastal Douglas-fir from various reports (converted between psi and GPa, based on 10^6 psi = 6.894 GPa)

Description/Location	Age of trees (yr)	Overall estimate of stiffness (MOE)		Variation in MOE with vertical position in the tree	Reference
		Method of determination	GPa		
32 2 nd -growth trees, Oregon and Washington, USA	<160	Static bending, small clears, 6 ft from the ground	11.03	Measuring MOE on two bolts, one 6 ft from the ground and a second at heights of 35–121 ft, gives a rough estimate of a 5,316 psi/ft decrease (from ~1.6 million psi at 6 ft to 1.05 million psi at 100 ft)	McKimmy (1959)
In-grade testing studies, USA	Unspecified	Static bending, visually graded 2- x 4- in. lumber, 12% MC, sampled from mills	13.18 (Select Structural) to 10.91 (Stud grade)		Green and Evans (1987)
2 x 4 Standard & Better grade kiln-dried 96-in. lumber	Unspecified	Static bending, 297 boards, average MC 11.4%	12.3 (range 5.8–20.3)		Seaders (2004)
2 x 4 Stud grade kiln-dried 92- and 96-in. lumber	Unspecified	Static bending, 270 boards, average MC 11.0%	11.4 (range 6.2–18.4)		White (2005)
2 x 4 Stud grade kiln-dried 92- and 96-in. lumber	Unspecified	Static bending, 158 boards	10.8 (range 6.7–17.2)		Sinha (2007)
50 trees from each of six 2 nd -growth stands on Vancouver Island, BC	46–60	Bending tests, 2,016 2- x 4- in. boards, at 12% MC	11.79	Average MOE in 2- x 4- in. boards from the bottom, middle, and top logs was 1.82, 1.67, and 1.49 million psi, respectively; 49.0% of the boards came from the bottom logs (which are larger) and 18.8% from the top logs. The yield of visually graded Select Structural lumber was 54% from the bottom log and 41% from the top log.	Calculated from Barrett and Kellogg (1991)
First 16-ft log, average of four sites in Oregon and Washington	32–51	2- x 4- in. and 2- x-6 in. lumber, Metriguard E-computer	10.34	16-ft logs higher up in the tree (logs 4, 5, and 6) were more likely to be grouped within lower acoustic velocity and MOE classes than logs lower in the tree (especially logs 1 and 2).	Briggs et al. (2007)

3,000 logs from 1,400 trees (7 sites, 200 trees each) in Western Oregon	51–72	Stress-wave velocity, Fibre-Gen HM 200	Velocity decreased going up the tree. For example, from Table A3 we can estimate that V^2 decreased by 0.108 % / ft of height from log 1 to log 2 and by 0.189 % / ft of height from log 2 to log 3 (in trees with at least 3 logs). The decrease from log 1 to log 2 averaged $7.23 \times 10^6 \text{ ft}^2/\text{sec}^2$, but the decrease from log 2 to log 3 averaged $21.54 \times 10^6 \text{ ft}^2/\text{sec}^2$.	Calculated from Amishev (2008)
32 trees from a stand in compartment 1218, Kaingaro Forest, North Island, New Zealand	45	2 × 4-, 2 × 8- and 2 × 12-in. lumber by static bending	MOE in 2 × 8- and 2 × 12-in. boards in the first, second, and third 16-ft log was 0.96, 0.87, and 0.89, respectively. MOE in 2 × 4 boards in logs 1, 2, 3, 4, and 5 was 0.92, 0.85, 0.89, 0.95, and 0.95, respectively (all 16-ft logs).	Shelbourne et al. (1973)
18 trees in Rotoehu Forest, New Zealand	41	Static bending on small clears and on 50-mm × 100-mm boards, Silviscan measurements on cores	11.55 (small clears) 15.50 (boards), ring 20 at 1.4-m height	Knowles et al. (2003)
60 trees in a stand, South Island of New Zealand	18	Small clears taken from the 10th growth ring, 12% MC	6.47 (range 3.5–9.5) from small clears, 8.95 from SilviScan	Knowles et al. (2004)
New Zealand-grown Douglas-fir	Unspecified	Not specified, presumably static bending	10.0	Cown et al. (1991)
72 trees derived from 19 clones in France	17	Static bending, boards taken ~1.3 m from the ground	7–14 (board level), 8.9–12.9 (clone level); average ~10.9	Launay et al. (2000)
371 trees from a progeny test in western Washington	25	Static bending, boards taken from the basal log	10.8	Cherry et al. (2008)

MC, moisture content; V^2 , (velocity)²

products are made from low-value pulpwood (from early thinnings, cull logs, and tops) and mill residue.

2.4 PRIMARY PROPERTIES AFFECTING STIFFNESS

Density (DEN) or SG and microfibril angle (MFA) are the most important drivers of clearwood stiffness (see Glossary for definitions). It has long been purported that SG controls both strength and stiffness: for example, McKimmy (1959) reported a strong correlation (0.909) between SG and strength. The correlation between SG and MOR measured at a constant height of 6 ft from the ground was 0.67 (calculated from McKimmy 1959), however, less than the value of 0.909 reported in the paper; the corresponding correlation between SG and MOE (also calculated from McKimmy 1959) was 0.73. Kennedy (1995) recognized that strength adjusted for SG (specific strength = strength/SG) increases from pith to bark, indicating that SG is not the only driver influencing wood stiffness.

MFA also appears to affect clearwood stiffness (for example, Cave and Walker 1994; Cown et al. 1999). Ideally, this angle is close to zero, with the microfibrils oriented vertically. In general, MFA is inversely related to wood stiffness but positively correlated with longitudinal shrinkage. Reviews by Megraw (1986b) and Barnett and Bonham (2004) describe the relationships between MFA and other wood properties. On balance, MFA appears to be less important than DEN in explaining Douglas-fir wood stiffness. In addition to the factors affecting clearwood stiffness, the size, frequency, and distribution of knots are the major drivers of lumber stiffness and strength (for example, Shelbourne et al. 1973; Megraw 1986a).

2.5 MANAGEMENT OF DOUGLAS-FIR AND IMPLICATIONS FOR WOOD STIFFNESS

Large old-growth Douglas-fir was harvested from the mid-nineteenth to the mid-twentieth centuries. Naturally regenerated second-growth forests have been harvested from the mid-twentieth century to the present. Third-rotation planted stands, some established with orchard seed, are being harvested now. As harvests have shifted from large, old-growth trees in natural stands to smaller trees from planted forests, Douglas-fir has increasingly been used in engineered products, first in plywood and then in I-joists and laminated veneer lumber (McKeever 1997).

There were concerns even 50 yr ago about the effect of change from old-growth to second-growth Douglas-fir (for example, McKimmy 1959), even though “young-growth” was defined as less than 160 yr old! By and large, concerns about adequate stiffness from second-growth lumber have proved

unfounded. In fact, well-managed second-growth Douglas-fir 60 yr and older, harvested in the second half of the twentieth century, proved in many ways to be more efficient sources of structural lumber than old growth. These trees are more uniform in size, are easier to harvest and transport, and have few extra-large knots and less decay and rot. What has been reduced is production of clear appearance-grade wood, such as C select, D Select, and shop grades (Haynes and Fight 2004).

With advances in seedling technology, site preparation, weed control, and tree improvement, the rate of early tree growth in modern plantations (third and fourth rotation) greatly exceeds that of naturally regenerated unmanaged stands. At the same time, investments in these plantations are considerable—several hundred dollars per acre, in some cases. Many forest growers are leveraged by debt obtained on the commercial market, and there are pressures to recoup the investment as early as possible. Combined with the facts that (1) the premium on large logs has all but vanished, with many mills designed to use logs of maximum 14 in. DBH; and (2) having a large standing wood inventory can increase the risk of a hostile takeover of a publicly traded company, it is not surprising that rotation lengths of 35–40 yr are in use and may become more common. Even while under pressure to reduce rotation length, however, growers in the PNW have taken note of potential impacts of increased juvenile wood on the quality of the wood harvested (for example, Briggs 1997) and are aware of experiences with other fast-grown plantation conifers, such as radiata pine in the southern hemisphere.

2.6 PREVIOUS EFFORTS TO IMPROVE LOG AND WOOD PROPERTIES

Although volume growth has always been a priority, there has been a longstanding interest in selecting for tree form (straightness, lack of stem breakage) and wood quality, usually defined by SG (for example, Campbell 1964; Silen 1975; Woods 1993; FGCBC 2005; Howe et al. 2006). Early on, some organizations attempted to improve log quality by intensive phenotypic selection of plus-trees. Members of cooperative programs subsequently attempted to address wood and log quality concerns in the progeny-testing phase through screening families and forward selections for forking, ramicorns, sinuosity, and SG.

2.6.1 Genetic Selection against Forking and Ramicorn Branches

Forking and ramicorn branching are under weak to moderate genetic control (Howe and Jayawickrama 2002; Howe et al. 2006; Ye and Jayawickrama, unpublished data). These forms of stem defects are associated to some extent with lammas growth (Carter et al. 1986). Forks and ramicorn branches reduce stiffness in three ways: (1) they are larger than normal branches and produce larger knots; (2) due to the steep angle, they leave larger knots upon

sawing than flat-angled branches; (3) they cause large areas of deviant grain in the wood. They are a source of volume loss during log scaling, especially from commercial thinnings in young plantations. These traits have been scored routinely in first-generation progeny tests since the 1990s. A total of 12,586 parents from 59 first-generation programs have been ranked for forking and ramicorn branches. Predicted gains have been provided for 1,025 parents from four second-cycle programs (Jayawickrama, unpublished data). Cooperators usually avoided forward selections with noticeable defects (broken tops, forks or ramicorn branches) when establishing first-generation and 1.5-generation orchards.

2.6.2 Pruning and Reducing Knot Size

Knot size and frequency are typically the most significant cause of degrade in Douglas-fir lumber and veneer; Douglas-fir does not prune naturally, and branches can persist until trees are 100 yr old (Megraw 1986a). The diameter of the largest knot had a strong negative correlation (-0.63) with mean minimum MOE in an early New Zealand study (Shelbourne et al. 1973).

Pruning has been considered and researched for Douglas-fir in the PNW, as it became apparent that unpruned second-growth and plantation wood would produce far less clear wood than that obtained from old-growth stands (Cahill et al. 1986). Some Douglas-fir growers began to prune stands, but this practice has largely been discontinued, due to uncertainty about whether future premiums for clear wood will outweigh current costs.

2.7 STATUS OF TREE AND WOOD STIFFNESS IMPROVEMENT IN THE PNW

Cooperative Douglas-fir improvement dates back to the 1960s. The first cycle of testing has been completed, and the second cycle is now in progress. A very large number of selections exist in first- and second-cycle tests. First-cycle tests are almost all of an age where wood stiffness could be assessed; the second-cycle tests will reach that stage in a few years. Cooperative programs have moved to predicting genetic gains of important traits, using Best Linear Unbiased Prediction (BLUP) procedures. Many cooperators have expressed their desire to include genetic improvement of wood stiffness in third-cycle breeding and testing. Over 1000 ac of Douglas-fir seed orchards (Jayawickrama, unpublished data) produce most of the seed needed for operational plantations (Jayawickrama 2006), thereby providing the means to translate the gain available from breeding and testing to genetic gain in operational plantations.

To date, there has been no direct selection for wood stiffness in operational cooperative Douglas-fir programs in the PNW, but there has been indirect

selection via its correlated trait, wood SG. As far back as the 1960s, Campbell (1964) advocated wood SG as a selection criterion. SG has been assessed in cooperative Douglas-fir tests in the PNW since the 1980s, following many years of research showing strong genetic control of this trait in Douglas-fir and other conifers.

Two approaches have been taken: (1) check the SG only in forward selections from first-generation progeny tests considered suitable for use in seed orchards, usually after age-15 yr data collection, and (2) rank first-generation parents for SG (Jayawickrama, unpublished NWTIC data). In both cases, the candidate forward selections (or representatives of the half-sib family) were compared with 30 trees from the same test site as a measure of the site mean and of the unimproved population. For the second approach, six trees from the family of interest were cored on one site. Twelve-millimeter cores were used; SG was assessed on the last five to seven growth rings. About 7,100 progeny trees (families of interest or candidate forward selections) have been cored from 28 first-generation programs, and 3,150 trees cored as controls. The 7,100 progeny trees were from 2,105 families; 753 families from 18 programs have been ranked with at least 6 trees sampled per family. Work is underway to predict genetic gains for wood SG from these data.

Recent advances in technology have made screening for wood stiffness faster and far less expensive than in the past, prompting active research on Douglas-fir wood stiffness and exploring the role of this trait in tree improvement (for example, Knowles et al. 2003, 2004; Johnson and Gartner 2006; Shelbourne et al. 2007; Cherry et al. 2008). At the research level, Cherry et al. (2008) recently obtained heritabilities (see Glossary) of 0.31 in wood bending stiffness for a first-generation breeding program in Washington, with estimated gains from backward selection in this trait of 12.3%.

PART II. TECHNICAL ASPECTS OF WOOD STIFFNESS AND RELATED PRODUCT AND MARKET ISSUES

3. SURROGATE TRAITS, TOOLS, AND TECHNIQUES TO MEASURE STIFFNESS

3.1 SURROGATE TRAITS

3.1.1 Wood Specific Gravity

The water displacement method and other methods based on the weight of wood cores have long been used to assess wood SG directly. The Pilodyn wood tester (PROCEQ SA, CH-8034 Zurich, Switzerland), the IML Resistograph (IML GmbH, 69168 Wiesloch, Germany; for example, Eckard 2007), and SilviScan (CSIRO, Melbourne, Australia, described below), as well as X-ray diffraction and the Torsiometer, are some methods to obtain SG information indirectly. Until about 10 yr ago, SG was the only indirect selection trait available to screen for stiffness and strength on any useful scale in tree improvement programs. Reported correlations between SG and bending stiffness include the following [all are genetic correlations except Shelbourne et al. (1973), which is a simple correlation]:

Species/ Correlation (r)	Experimental material	Reference
Douglas-fir 0.37	SG: Discs taken at the tree base. MOE: Average of 2 × 4 boards for that tree	Cherry et al. (2008)
0.91	SG: Average of 2 × 4 boards for that tree MOE: Average of 2 × 4 boards for that tree	
Radiata pine 0.23–0.56	DEN: Discs MOE: On 2 × 4-, 2 × 8- and 2 × 12-in. boards in logs 1, 2, 3 or 4	Shelbourne et al. (1973)
0.73	SG: Disc taken at breast height MOE: Clearwood stick close to breast height	Kumar et al. (2002)
0.50	SG: 5-mm core taken at breast height MOE: Clearwood stick close to breast height	Kumar (2004)

0.51 (ring 3–4)	Clearwood stick taken at 1.4 m from the base	Kumar et al. (2006)
0.23 (ring 6–7)		
0.78 (ring 9–10)		
Hybrid larch		
0.87	Average of 6–9 clearwood sticks for a given tree	Fujimoto et al. (2006)

Using 5-mm outerwood cores as a means to select for stiffness in Douglas-fir gave corrected selection differentials (see Glossary) of 11–16% with respect to stiffness, at a cost of about NZ\$8 per tree in the field and NZ\$20–30 per tree selected (Knowles et al. 2004).

3.1.2 Microfibril Angle

Although MFA is an important driver of clearwood stiffness, cost has precluded its use to screen for stiffness on a large scale in any operational tree improvement program. SilviScan (described in section 3.2.2) is now often used to evaluate MFA for tree breeding research studies, as well as to determine SG. A combination of wood SG and MFA explains much of the variation in wood stiffness in some species (for example, various plantation-grown conifers, Cave and Walker 1994; *Eucalyptus delegatensis*, Evans and Ilic 2001), including Douglas-fir (Knowles et al. 2003). Density and MFA appear to be independent traits (Evans and Ilic 2001; Downes et al. 2002).

Some studies showed that MFA might not be important for outerwood MOE. For example, Cown et al. (1999) reported that both wood DEN and MFA significantly affected corewood MOE, but DEN alone explained most variation in the outerwood MOE. Knowles et al. (2003) reported an R^2 of 0.84 for DEN on stiffness in small clears, in contrast to an R^2 of 0.32 for MFA on stiffness; the authors attributed some of the relatively low correlations between stiffness and MFA to low variation among trees in MFA but large variation in density. (The trees in the study were chosen to cover a range of densities.) Breast height MFA (the kind of MFA information that might typically be taken in tree improvement programs) was not significantly correlated with MOE in this study.

3.2 TOOLS AND TECHNIQUES

3.2.1 Static Bending

Static bending is the original and most direct way to assess wood stiffness. A variety of tools and techniques, based on measuring the deflection of boards or sticks in response to an applied load, is available. Some, such as Metriguard 7100 CLT or 7200LS (Metriguard, Inc, Pullman, WA), Stress-O-Matic (Crow Machines, Garland, TX), and Strength Grader (John Ersson, S-812

90 Storvik, Sweden) are large systems suitable for use in a mill (Galligan and Kerns 2002; Pellerin and Ross 2002a); others are used for small-scale research projects using small clears.

Removal of small clears from standing trees is feasible (for example, Jayawickrama 2001; Kumar et al. 2002) but relatively expensive and rarely used in operational breeding programs. Testing boards involves felling trees, milling the boards, and conducting static bending tests. Tree-bending devices have also been developed for nondestructive evaluation of static bending on standing trees (Koizumi and Ueda 1986; Mamdy et al. 1999; Rozenberg et al. 1999; Launay et al. 2000), but do not seem to be widely used.

3.2.2 SilviScan

The development of SilviScan (<http://www.csiro.au/services/ps11i.html>) in the 1990s by CSIRO in Australia was an important breakthrough in wood quality research. Silviscan-2[®] provided an accurate assessment of stiffness at about NZ\$103 per tree assessed (adding both field and laboratory costs) and NZ\$500 per selected Douglas-fir tree (Knowles et al. 2004). It was more strongly correlated with MOE of small clears than IML Hammer (http://www.iml.de/eng/html/electronic_hammer.html), Pilodyn, and density methods, but was far more expensive (Knowles et al. 2004). Although SilviScan has been used in many important tree breeding research studies, it has been used very little in routine tree improvement because of the cost of obtaining and processing samples.

3.2.3 Acoustic Techniques

This is a field of very active research and development (Rippy et al. 2000; Beall 2002; Bradshaw 2002; Galligan and Kerns 2002; Pellerin and Ross 2002b,c; Wang and Ross 2002; Knowles et al. 2004). Acoustic tools are routinely used to segregate logs for different applications in Australia, New Zealand, the United States, Canada, the United Kingdom, and Scandinavia (Carter 2007).

A variety of tools and techniques is available. Some are large, expensive, high-production in-line systems suitable for use in a mill; some, such as the Fibre-Gen Director HM-200 (Carter 2007; www.fibre-gen.com), are suitable for logs in operational settings (acoustic resonance techniques); some are suitable for research work in laboratories; and others, using time-of-flight techniques, are being developed for standing trees—perhaps the most difficult application of all.

Although all such tools are naturally very important for the wood-processing industry, portable tools suitable for use on standing trees are the most relevant

to tree improvement and progeny testing (for example, Carter 2007). Measuring velocity in standing trees is much faster and less expensive than having to fell the trees. Standing-tree tools being tested or now in use include the Fibre-Gen Director ST-300 (Carter 2007), the FAKOPP TreeSonic (www.fakopp.com), TreeTap (Canterprise, University of Canterbury, New Zealand; described in Toulmin and Raymond 2007), and the IML Hammer.

Several recent studies have highlighted the promise of acoustic velocity as a surrogate trait for wood stiffness. The IML Hammer gave corrected selection differentials of 11–16% with respect to stiffness at a cost of about NZ\$4 per tree in the field and NZ\$20–30 per tree selected (Knowles et al. 2004). In a first-generation Douglas-fir breeding program, Cherry et al. (2008) estimated that bending MOE was genetically correlated with HM200 velocity ($r_A = 0.75$) and ST300 velocity ($r_A = 0.53$). The same study also found genetic correlations between bending MOE and HM200 MOE ($r_A = 0.92$) and ST300 MOE ($r_A = 0.57$). Stress wave analysis can be used to sort Douglas-fir logs for the production of high-MOE veneer (Rippy et al. 2000). A study of 114 Douglas-fir trees harvested from two sites in Oregon and two in Washington found an R^2 of 0.59 between MOE of lumber obtained from the first short log by Metriguard E-computer and acoustic velocity of the same log obtained with Director HM-200 (Briggs et al. 2007).

The FAKOPP TreeSonic provided good correlations with bending stiffness in a loblolly pine clonal study (NCSU-ICTIP 2007; Eckard 2007), with an estimated production rate of 800 trees/day for a two-person crew measuring every tree (personal communication, Tyler Eckard, Technical Forester-Geneticist, Smurfit-Stone Container Corporation, Florida, 2008). Huber et al. (2006) estimated 840 trees/day in a 8-yr-old slash pine trial, again with two people measuring every tree. These studies were done in favorable conditions. Acoustic velocity production rates may be considerably lower than this, especially if only a subset of families is measured—for example, 200–300 trees per day for a 2- or 3-person crew (authors' personal experience, and personal communication, Dr Kevin Harding, Department of Primary Industries and Fisheries, Queensland, Australia, 2008). Matheson et al. (2008) estimated about 40 sec to measure time of flight on a young tree with the IML Hammer; assuming another 40 seconds transitioning to the next tree and a 7-hr day in the field; this translates to 315 trees/day.

In the Queensland pine program, the Fibre-Gen ST300 has proved to be a relatively fast, reliable, and inexpensive screening tool for standing trees; readings from this tool (or similar standing tree acoustic systems) are relatively less expensive than extracting cores for density or SilviScan assessments or extracting and testing “Paddlepop” samples (Harding et al. 2007). Fakopp velocity in radiata pine had phenotypic correlations of about 0.82 with SilviScan MOE and between 0.85 to 0.96 with HM200 log MOE (Chauhan and Walker 2006).

3.2.4 Near-infrared Spectroscopy

Near-infrared (NIR) spectroscopy utilizes the near-infrared region of the electromagnetic spectrum (from about 800 nm to 2500 nm). It is used in agriculture to infer properties of a substance from its spectrum (e.g., protein or oil content in a grain crop). NIR has been used to estimate wood stiffness in several species (Schimleck et al. 2002, 2005) and wood density in Douglas-fir (Acuna and Murphy 2006; Belart Lengerich 2008). NIR has potential for use in forestry and tree improvement, but a rapid, robust, cost-effective tool usable in the field by tree breeders is still not available (Schimleck 2007).

3.3 EVALUATION OF STIFFNESS IN OPERATIONAL FORESTRY

Stiffness testing is already being used in operational Douglas-fir forestry in the PNW. Several companies are using acoustic tools for a variety of applications: to evaluate stiffness in mills (for example, to decide if a log should be peeled for veneer or sawn for lumber), to evaluate if the wood from a given stand is stiff enough to be worth purchasing, to inventory stands for future prediction of stiffness, to segregate logs in log yards, and so forth. Not surprisingly, given the price premium for high-stiffness boards or veneer sheets, the greatest interest is from companies producing engineered wood products. Typically, such companies ship their lower-quality wood to a second mill for processing into a lower-quality product. It is far more profitable to correctly assign a log to the most appropriate use as early as possible in the process, before incurring trucking, handling, peeling, and other costs.

There is already anecdotal evidence that stiffness tends to be higher in certain parts of the PNW than in others. The use of acoustic tools is an active area of development, and we expect more companies to implement such procedures. If their use becomes very widespread, the overall efficiency of the forest products industry in the PNW should improve. There is a possible drawback: if a large proportion of high-stiffness lumber is “high-graded” into engineered wood products and only low-stiffness logs remain for dimension lumber, the average stiffness of visually graded lumber may decrease. That is, the low-stiffness logs may yield boards that meet visual grades for knot size, wane, and so forth, but clearwood stiffness may actually be fairly low.

4. FACTORS AFFECTING OR LIKELY TO AFFECT WOOD STIFFNESS

4.1 POSITION IN TREE AND TREE FORM

4.1.1 Ring Number from Pith

According to Megraw (1986a), age is the primary determining factor for the basic wood quality parameters. Mature wood has characteristics (for example, high SG, small MFA, and high MOE) more suited for structural timber. A major concern about short-rotation softwoods is the higher proportion of juvenile wood in the logs. Juvenile wood has a low SG, large MFA, and low MOE. Jozsa and Kellogg (1986) studied the density (or SG) pattern from pith to bark at different sampling heights in Douglas fir. They found relatively low density juvenile wood from the first 15 to 20 yr of growth. Then a rapid increase was evident to about age 30, followed by a stable or slightly increasing density trend. Other researchers (e.g., Megraw 1986b; Gartner et al. 2002) reported similar trends. The gradient of SG from pith to bark is not very steep in Douglas-fir (Megraw 1986a); SG of rings age 30–40 is only 10% greater than that of rings age 10–20 (Jozsa and Middleton 1994, Figure 6). Abdel-Gadir and Kraemer (1993) reported that the transition from juvenile to mature wood in Douglas-fir, assessed on the basis of SG, can occur as late as ring 37, with a mean of 25 yr.

MFA has been reported to decrease gradually for the first 30 yr from about 32° to 7° (Megraw 1986a), and from 35° near the pith to 15° in ring 10 (Erickson and Arima 1974; Knowles et al. 2003). A decrease in MFA from the pith outward has been reported in Douglas-fir (Koshy 1993) and other conifer species (for example, Dungey et al. 2006; Baltunis et al. 2007). MFA is also high in compression wood.

Knowles et al. (2003) reported that ring number from the pith in small clears explains 31% of variation in MOE and 8% in density in Douglas-fir. In the properties assessed with SilviScan, the ring number from the pith explained 47% of the variation in MFA, 35% of the variation in MOE, and 3% of the variation in density. Knowles et al. (2003) also reported that clearwood properties (stiffness, density, and MFA) seemed to level off at about 15 rings from the pith, which could be considered a transition to mature wood. The one exception was MOE of boards, which may be a function of knots continuing to decrease as a proportion of boards as trees grew older and larger.

4.1.2 Vertical Position

For a given number of rings from the pith, SG in Douglas-fir has been reported to decrease by about 0.04 units going up the tree from 2 to 80 ft (Megraw 1986a). Knowles et al. (2003), however, reported increases in wood density from 400 to 450 kg/m³ going up a stem from 0 to 25 m, whereas Shelbourne et al. (1973) reported SG values varying little (0.37–0.39) in the first five 16-ft logs up the tree. Thus, the relation of SG to height in the tree appears to be inconsistent. There is also some information in the literature on the variation of stiffness with position in the tree (Table 1), where, again, both decreases and increases in stiffness with height have been reported.

4.1.3 Knot Size and Other Log Properties

An important sawmilling study of 32 New Zealand-grown Douglas-fir, harvested at age 45 from a single stand, was done by the New Zealand Forest Research Institute in the 1970s (Shelbourne et al. 1973). The highest correlations of MOE in 2- × 4-, 2- × 8- and 2- × 12-in. boards were with the diameter of the largest knot in the sawn timber (ranging from -0.33 to -0.74) and diameter of the largest branch (ranging from -0.15 to -0.58). Trees with timber of high MOE tended to have small branches, small stem diameters, straight stems, and high wood SG.

4.2 TREE SIZE AND GROWTH RATE

Many foresters and timber industry professionals strongly believe that fast growth invariably reduces wood SG and stiffness. This belief usually arose from comparing (A) slow-grown timber from old-growth with timber from fast-grown, intensively managed young trees or (B) wood from near the pith with wood from outer rings. In such situations, the association between ring width and SG or stiffness is indeed quite strong. The importance of age for making proper comparisons has been stressed by several authors (for example, Zobel and Talbert 1984; Briggs and Smith 1986; Megraw 1986a); when trees of the same age grown under the same conditions are compared at the same ring number from the pith and the same height from the ground, the association between tree size and SG (or between ring width and SG) generally declines or sometimes disappears.

Because growth rate is of primary importance to foresters, the relationship between growth rate and SG within stands is important and has been examined in numerous studies of Douglas-fir, with a variety of results. Some studies have found a negative association: for example, ring width and ring density (McKimmy 1959), lower density of trees in large-diameter classes (Kennedy 1995), a negative correlation of -0.12 between density and

volume on an individual-tree basis (Loo-Dinkins et al. 1991), and negative phenotypic and environmental correlations between DBH and SG in Johnson and Gartner (2006). In a New Zealand study with 32 trees in one stand, the correlations of density with DBH and height were 0 and -0.159 respectively (calculated from Table 2 in Shelbourne et al. 1973). Although such negative associations with growth rate may exist, differences caused by growth rate are small compared to differences caused by ring age (Kennedy 1995). A few reports show little or no association (for example, Megraw 1986a). The effect of ring age must be accounted for when examining between-tree associations; in many early studies (before x-ray densitometry), these adjustments were difficult to make.

The relationship between wood quality and tree size is again being studied, with the focus now on stiffness. A recent study on four sites in the PNW (Briggs et al. 2007) gave mixed results; in some plots, there was hardly any noticeable trend in acoustic velocity, even though DBH varied from 8 to 21 inches, whereas other plots showed a downward trend with increasing DBH. The authors noted that the older installations (45 and 51 yr old) were established when they were 29–32 yr old and producing mature wood; increased growth following subsequent thinning may have reduced stiffness. The younger installations (ages 31 and 36) were established when they were between 15–18 yr old, at the time of transition to mature wood; subsequent thinning may have accelerated tree growth and accumulation of higher stiffness mature wood (although there would be an associated, and adverse, effect of thinning in larger knots). In a study by Johnson and Gartner (2006), phenotypic correlations (r_p) of velocity with height and DBH were -0.08 and -0.25, respectively, and environmental correlations (r_e) of velocity with height and DBH were -0.09 and -0.25, respectively. In a third study, conducted on seven sites in western Oregon, the R^2 between DBH and acoustic velocity averaged 0.21, ranging from 0.07 on the site with the weakest R^2 to 0.32 on the site with the strongest (Amishev 2008); the correlations between DBH and acoustic velocity within a site averaged -0.565 (range = -0.296 to -0.672, calculated from data in tables A1 to G1 in Amishev 2008). In a New Zealand study on one site, individual-tree volume was negatively correlated with stiffness, but there was no indication that the number of rings per inch had any direct importance to timber stiffness (Shelbourne et al. 1973). Fast-grown trees typically have higher MFA (Barnett and Bonham 2004).

Zobel and van Buijtenen (1989) summarize growth rate/SG relationships in other conifers as follows: “Species such as Douglas-fir and the larches have wood similar to the hard pines and respond to growth rate changes in somewhat the same manner, although negative correlations appear to be more common”. We concur that the correlation between SG or stiffness with tree diameter, at the same age and on the same site, will often be negative.

4.3 RELATIVE EFFECT OF WITHIN-TREE EFFECTS

Knowles et al. (2003) attempted to estimate the effect of various factors on stiffness. They found that 35% of the total variation was due to a “tree effect” (75% of which was due to variation in clearwood stiffness and about 10% to variation in branch diameter). Another 27% of the total variation was due to “position in tree”; of that, 90% was due to ring age. About 28% of the total variation was attributed to random board-to-board variation in clearwood stiffness and knot distribution.

4.4 VARIATION AMONG TREES

Wood properties have been shown to vary among trees within a site, between sites, and at different elevations, longitude, and latitude.

A large range in SG (about 0.15 to 0.20 units) is frequently seen among trees in a stand of the same age. Megraw (1986a), for example, reported a range of 0.37 to 0.55, similar to that reported by Shelbourne et al. (1973).

An early report on 36 trees from nine stands suggested little effect of location on SG (McKimmy 1959). The Western Wood Density survey, however, a much larger study, included 4,323 coastal Douglas-fir trees (USDA Forest Service 1965); after adjustment for tree age, it was predicted that 100-yr-old trees would decrease in SG from an average of 0.52 at 500 ft elevation to 0.46 at 5,000 ft elevation. After taking age, elevation, and diameter into account, SG decreased northward, from ~0.49 and higher in northern California to 0.43–0.45 in northern Washington. Cown and Parker (1979) reported that site-to-site variation accounted for 56.7% of the total variance in SG in their study, and tree-to-tree variation within plots accounted for 27.3%.

Recent studies indicate site-to-site variation in stiffness. Dynamic MOE ranged from 8.31 to 8.96 GPa [individual tree standard deviation (SD), 1.09–1.30] and density ranged from 404 to 446 kg/m³ (individual tree SD, 26–34) on four coastal Oregon sites (Johnson and Gartner 2006). Mean acoustic velocity recorded by Briggs et al. (2007) ranged from 3.6 to 4.0 km/s in four installations from 32 to 51 yr old. Amishev (2008) found that mean acoustic velocity ranged from 3.46 to 3.92 (harvest sites ranging from 51 to 72 yr) by site, and the average recovery of the highest two grades of veneer (G1 and AB) ranged from 6.87% to 23.93%.

As in the case for SG, stiffness and acoustic velocity variation between trees in an even-aged stand typically dwarf variation between stands of the same age. Acoustic velocity varied from 2.5 to 4.2 km/sec within one of the installations measured by Briggs et al. (2007). Amishev (2008) found that the highest

acoustic velocity in a 200-tree sample on a site was typically 50–60% higher than the lowest. Mean tree MOE varied from 0.63 to 1.13 psi in a 45-yr-old stand of Douglas-fir in New Zealand (Shelbourne et al. 1973). About 35% of the variance in timber stiffness was attributed to tree-to-tree variation (Knowles et al. 2003).

4.5 VARIATION DUE TO PROVENANCE AND FAMILY WITHIN PROVENANCE

There is strong evidence, described in more detail in Section 7, of differences between families and clones in wood stiffness. There may be some differences between provenances, but it appears that most of the differences lie between genotypes within provenances. For example, Cown and Parker (1979) found no consistent trends for provenance variation in SG from site to site. Loo-Dinkins et al. (1991), in contrast, found significant provenance differences in SG at three sites; the provenance means ranged from 0.375 to 0.457; volume and wood density were negatively correlated on a provenance-mean basis. The fastest-growing provenance was 37% superior to the other seven provenances on the basis of dry weight and 41% on the basis of volume, despite its density being 3.8% lower (calculated from Loo-Dinkins et al. 1991).

4.6 SILVICULTURE AND MANAGEMENT

Silvicultural practices tend to act indirectly on wood quality through their effect on the growing environment of the crown and roots (Zobel and van Buijtenen 1989). These effects could be applied either directly on individual trees (e.g., thinning, spacing) or through modifying the site (e.g., fertilization, weed control). According to Megraw (1986a), crowding stifles crown vigor in Douglas-fir. Resulting smaller growth rings may increase latewood percentage and higher SG. On the other hand, if summer moisture is limiting, lack of moisture can reduce latewood production. Thinning could increase SG in such conditions (for example, Posey 1964).

5. STIFFNESS REQUIREMENTS AND RATING OF DOUGLAS-FIR PRODUCTS

5.1 LUMBER

5.1.1 Visually Graded Lumber

Most Douglas-fir lumber is graded and sold on the basis of visual grading rules. The main function of grading is to sort lumber into classes with associated design values that are used by the engineers in designing structures, in accordance to National Design Specification (NDS) for Wood

Table 2. Examples of design values for visually graded Douglas-fir/Larch dimension lumber and decking. Courtesy, American Forest & Paper Association, Washington, DC. Excerpted from AF&PA (2005): Reference Design Values for Visually Graded Dimension Lumber (Table 4A, 2–4 in. thick; Table 4D, 5 in. x 5 in. and larger; Table 4E, decking).

Grading rules agency	Size classification	Commercial grade	Design values (psi)						Modulus of elasticity (MOE)	
			Fiber stress in bending (F_b)	Tension parallel to grain (F_t)	Shear parallel to grain (F_v)	Compression Perpendicular to grain (F_c)	Parallel to grain (F_c)	E ($\times 10^6$)	E_{min} ($\times 10^5$)	
WCLIB, WWPA	2 in. & wider	Select Structural	1,500	1,000	180	625	1,700	1.9	6.9	
		No. 1 & Better	1,200	800	180	625	1,550	1.8	6.6	
	2 in. & wider	No. 1	1,000	675	180	625	1,500	1.7	6.2	
		No. 2	900	575	180	625	1,350	1.6	5.8	
		No. 3	525	325	180	625	775	1.4	5.1	
	2–4 in. wide	Stud	700	450	180	625	850	1.4	5.1	
		Construction	1,000	650	180	625	1,650	1.5	5.5	
	WCLIB, WWPA	Beams and Stringers	Standard	575	375	180	625	1,400	1.4	5.1
			Utility	275	175	180	625	900	1.3	4.7
		Dense Select Structural	Dense Select Structural	1,900	1,100	170	730	1,300	1.7	6.2
Select Structural			1,600	950	170	625	1,100	1.6	5.8	
Dense No. 1		Dense No. 1	1,550	775	170	730	1,100	1.7	6.2	
		No. 1	1,350	675	170	625	925	1.6	5.8	
Dense No. 2 Dense (WWPA only)		Dense No. 2	1,000	500	170	730	700	1.4	5.1	
		No. 2	875	425	170	625	600	1.3	4.7	
Posts and Timbers		Dense Select Structural	1,750	1,150	170	730	1,350	1.7	6.2	
		Select Structural	1,500	1,000	170	625	1,150	1.6	5.8	
Dense No. 1	Dense No. 1	1,400	950	170	730	1,200	1.7	6.2		
	No. 1	1,200	825	170	625	1,000	1.6	5.8		
Dense No. 2 Dense (WWPA only)	Dense No. 2	750	475	170	625	700	1.3	4.7		
	No. 2 Dense	850	550	170	730	825	1.4	5.1		
Dex decking										
WCLIB, WWPA	2–4 in. thick	Select				625		1.8	6.6	
		Commercial				625		1.7	6.2	
WWPA	4 in. & wider	Commercial				625		1.7	6.2	

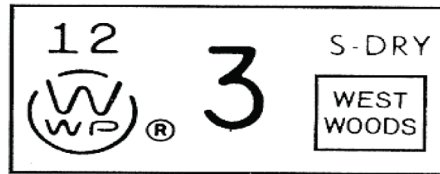


Figure 1. Typical grade stamps for visually graded lumber.

Construction (AF&PA 2005). A typical grade stamp for visually graded lumber is shown in Figure 1.

The rules used today have evolved since the early twentieth century (Johnson 1986). The American Softwood Lumber Standard, PS-20 (USDC 2005), a voluntary product standard under the US Department of Commerce, is the basis for lumber grading in the United States. The local rules-writing (regulatory) agencies that publish Lumber Grade Rules, issue grade stamps to mills, and inspect lumber products affecting coastal Douglas-fir in the United States are the Western Wood Products Association and the West Coast Lumber Inspection Bureau (Cheung 2002).

Visual grading is based on factors such as knot size, checks, warp, wane, grain orientation, and decay. Relative size of lumber and its anticipated use are also used in grading lumber. There are three main size categories of structural lumber: boards, dimensional lumber, and timbers (Appendix 2). Typical commercial grades vary within different size and use categories. Typical grades for Douglas-fir/Larch for various size categories are shown in Table 2. There are dimension lumber, structural decking, and timber categories, and there can be grades within each product category. Examples of design values (allowable stress values) for various Douglas-firs, grades, and uses are also given in Table 2. The design values in Table 2 must be used with adjustment factors as outlined in the National Design Specification[®](NDS) for Wood Construction (AF&PA 2005). For example, there are formulae to adjust stiffness and strength based on whether use is as a wall stud, joist, or rafter (edgewise application) or a plank (flatwise application), wet or dry, as a single member or one of many members (WWPA 1996, 2005a).

During routine visual grading, design values (stiffness or strength) are not evaluated. When builders and engineers use lumber, however, design values are assumed for each category. Guidelines on how to determine strength and stiffness and how to assign design values to various grades are given in ASTM standards (ASTM 2007). Table 2 shows the MOE of various size and use categories and grades of Douglas-fir. For example, the higher-grade select structural category in Douglas-fir/larch is assumed to have an MOE of 1.9 million psi, whereas the MOE of the construction category is assumed to be only 1.5 million psi (WWPA 1996, 2005a,b). Large variation in MOE is frequently found within a given size and use category, however; for example,

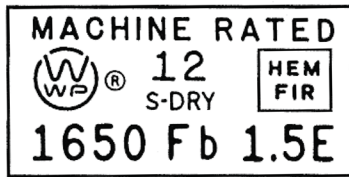


Figure 2. Typical grade stamp for mechanically graded lumber.

see the variation reported by Seaders (2004), White (2005), and Sinha (2007) and summarized in Table 2.

The MOE assumed for Douglas-fir/larch is 10–50% higher than those for other western conifer lumbers (Hem-fir, Spruce/Pine/Fir, and western cedars) of the same visual grade and about 20% higher than for that for Douglas-fir South (from Arizona, Colorado, Nevada, New Mexico, and Utah) (WWPA 2005a).

5.1.2 Mechanically Graded Lumber

Mechanically graded lumber is nondestructively evaluated for MOE, density, or both, using machines and sensors. Most grading machines in the United States evaluate lowest flatwise bending MOE on a given span (generally 4 ft) and average flatwise MOE for the entire board. A continuous lumber tester (CLT) applies a small known deflection to the flat board and force is measured. Force, deflection, span, and cross-sectional dimensions are used to determine MOE.

Mechanically tested lumber is known as machine-stress-rated lumber, or MSR (Galligan and Kerns 2002). This category has evolved since the 1960s, partly as a way to improve the grades and values of lumber categories severely downgraded by visual grading rules (especially ring width restrictions). For example, boards with 90–100% juvenile wood had a volume-weighted fifth percentile for short-term strength of 2,890 psi, 2.19× as high as the strength corresponding to their visual grade (Barrett and Kellogg 1991). MSR lumber is also covered by WWPA lumber grading rules; in addition to the stress rating, MSR lumber also needs to meet certain visual requirements for checks, skips, wane, splits, and other defects (WWPA 2005b). Table 3 shows design values for MSR lumber. WWPA (2005b) shows 14 categories with MOE increasing from 0.9 million to 2.3 million psi; other categories can also be formed. The grade stamp in Figure 2 shows MOE and extreme fiber stress in bending (F_b) for MSR-rated wood.

The major use of MSR lumber is in trusses. MSR systems include density-based systems, static bending systems, and systems based on stress waves. Unlike New Zealand and Australia, where most lumber is mechanically tested, and despite the existence of technology for high-throughput implementation of MSR rating (2,000 ft/min), the MSR category remains a small proportion (about 1 billion bd ft/yr of lumber, or about 2%) of the lumber market in the United States. The main cost of this production type is actually the cost of kiln-drying the boards: MSR is conducted on kiln-dried wood to remove the

Table 3. Design values for Machine Stress Rated (MSR) lumber (≤ 2 in. thick, ≥ 2 " wide) (AF&PA 2005). Courtesy, American Forest & Paper Association, Washington, D.C. Taken from: Table 4C (AF&PA 2005) Reference Design Values for Mechanically Graded Dimension Lumber. Tabulated design values are for normal load duration and dry service conditions, unless specified otherwise. See NDS 4.3 for a comprehensive description of design value adjustment factors. Use with Table 4C adjustment factors.

MSR grade	Design values (psi)					Grading rules agency
	Fiber stress in bending (F_b)	Tension parallel to grain (F_t)	Compression parallel to grain (F_c)	Modulus of elasticity		
				E ($\times 10^6$)	E_{min} ($\times 10^6$)	
900f-1.0E	900	350	1,050	1.0	0.51	NELMA, NSLB, WCLIB, WWPA
1200f-1.2E	1,200	600	1,400	1.2	0.61	NELMA, NLGA, NSLB, WCLIB, WWPA
1250f-1.4E	1,250	800	1,475	1.4	0.71	WCLIB, WWPA
1350f-1.3E	1,350	750	1,600	1.3	0.66	NLGA, NELMA, NSLB, WCLIB, WWPA
1400f-1.2E	1,400	800	1,600	1.2	0.61	NLGA, WWPA
1450f-1.3E	1,450	800	1,625	1.3	0.66	NELMA, NLGA, NSLB, WCLIB, WWPA
1450f-1.5E	1,450	875	1,625	1.5	0.76	WCLIB, WWPA
1500f-1.4E	1,500	900	1,650	1.4	0.71	NELMA, NLGA, NSLB, WCLIB, WWPA
1600f-1.4E	1,600	950	1,675	1.4	0.71	NLGA, WWPA
1650f-1.3E	1,650	1,020	1,700	1.3	0.66	NLGA, WWPA
1650f-1.5E	1,650	1,020	1,700	1.5	0.76	NELMA, NLGA, NSLB, SPIB, WCLIB, WWPA
1650f-1.6E-1075f _t	1,650	1,075	1,700	1.6	0.81	WCLIB, WWPA
1650f-1.6E	1,650	1,175	1,700	1.6	0.81	WCLIB, WWPA
1650f-1.8E	1,650	1,020	1,750	1.8	0.91	WCLIB, WWPA
1700f-1.6E	1,700	1,175	1,725	1.6	0.81	WCLIB, WWPA
1750f-2.0E	1,750	1,125	1,725	2.0	1.02	WCLIB, WWPA
1800f-1.5E	1,800	1,300	1,750	1.5	0.76	NLGA, WWPA
1800f-1.6E	1,800	1,175	1,750	1.6	0.81	NELMA, NSLB, NLGA, SPIB, WCLIB, WWPA
1800f-1.8E	1,800	1,200	1,750	1.8	0.91	WCLIB, WWPA
1950f-1.5E	1,950	1,375	1,800	1.5	0.76	SPIB, WWPA
1950f-1.7E	1,950	1,375	1,800	1.7	0.86	NELMA, NLGA, NSLB, SPIB, WCLIB, WWPA
2000f-1.6E	2,000	1,300	1,825	1.6	0.81	NLGA, WWPA
2100f-1.8E	2,100	1,575	1,875	1.8	0.91	NELMA, NLGA, NSLB, SPIB, WCLIB, WWPA
2250f-1.7E	2,250	1,750	1,925	1.7	0.86	NLGA, WWPA
2250f-1.8E	2,250	1,750	1,925	1.8	0.91	NLGA, WCLIB, WWPA
2250f-1.9E	2,250	1,750	1,925	1.9	0.97	NELMA, NLGA, NSLB, SPIB, WCLIB, WWPA
2250f-2.0E-1600f _t	2,250	1,600	1,925	2.0	1.02	WCLIB, WWPA
2250f-2.0E	2,250	1,750	1,925	2.0	1.02	WCLIB, WWPA
2400f-1.8E	2,400	1,925	1,975	1.8	0.91	NLGA, WWPA
2400f-2.0E	2,400	1,925	1,975	2.0	1.02	NELMA, NLGA, NSLB, SPIB, WCLIB, WWPA
2500f-2.2E	2,500	1,750	2,000	2.2	1.12	WCLIB, WWPA

MSR grade	Design values (psi)					Grading rules agency
	Fiber stress in bending (F_b)	Tension parallel to grain (F_t)	Compression parallel to grain (F_c)	Modulus of elasticity		
				E ($\times 10^6$)	E_{min} ($\times 10^6$)	
2500f-2.2E-1925f _t	2,500	1,925	2,000	2.2	1.12	WCLIB, WWPA
2550f-2.1E	2,550	2,050	2,025	2.1	1.07	NELMA, NLGA, NSLB, SPIB, WCLIB, WWPA
2700f-2.0E	2,700	1,800	2,100	2.0	1.02	WCLIB, WWPA
2700f-2.2E	2,700	2,150	2,100	2.2	1.12	NELMA, NLGA, NSLB, SPIB, WCLIB, WWPA
2850f-2.3E	2,850	2,300	2,150	2.3	1.17	NELMA, NLGA, NSLB, SPIB, WCLIB, WWPA
3000f-2.4E	3,000	2,400	2,200	2.4	1.22	NLGA, SPIB

NELMA, Northeastern Lumber Manufacturers Association; NLGA, National Lumber Grades Authority; NSLB, Northern Softwood Lumber Bureau; SPIB, Southern Pine Inspection Bureau; WCLIB, West Coast Lumber Inspection Bureau; WWPA, Western Wood Products Association

variable effect of moisture content (MC) on the stiffness measure and to get the stiffness measure at the MC that the wood will have in service.

An example of the selling price difference is shown by the following comparison for 2000–2007 (US\$/1000 bd ft; calculated from Random Lengths 2007):

2-in. \times 4-in. \times 8-ft Douglas-fir	
green stud grade	\$302.60
kiln-dried stud grade	\$340
green 1 & Btr	\$353.60
(recognized as a stress grade)	
2-in. \times 4-in. Fir-larch, kiln-dried	
1800f MSR	\$396
2400f MSR	\$462.50

Thus, the high-stiffness MSR commanded a \$160/MBF price differential over a medium-level visual grade and \$108 over a high-level visual grade over 8 yr.

Four MSR manufacturing facilities, using mostly Douglas-fir, are listed in Random Lengths (2006); however, the total 8-hr Douglas-fir production capacity¹ listed for these four mills is 578 MBF, 4.3% of the 12,922 MBF for all sawmills listed for the West Coast. Another indirect estimate of the

¹ Refer to pages 9–23 in Random Lengths (2006). Most mills have production listed as 8-h capacity; for mills with no listing, 8-hr capacity (MBF) was approximated as [(1000) annual production (MMBF)]/[(365)(2)], assuming the mill to run year-round with two 8-hr shifts per day. The records also provide a percentage of Douglas-fir used, so Douglas-fir 8-hr production was obtained by multiplying the total 8-hr production by the Douglas-fir percentage. NOTE: We can assume these four mills produced other products than MSR lumber, but the details are not available.

proportion of Douglas-fir lumber that is MSR can be obtained from Haynes and Fight (2004): “structural items” including all MSR lumber and several other categories amounted to only 8.6% of Douglas-fir lumber production. We can guess from these figures that MSR lumber does not exceed 5% of Douglas-fir lumber production from the PNW and may be as low as 2–3%, leaving perhaps 95–98% as visually graded. Using a crude estimate that 70.4% of the production from Douglas-fir is sawlogs (described later), we can make an equally crude estimate that about 68% of Douglas-fir ends up as visually graded lumber.

5.2 ENGINEERED WOOD PRODUCTS

5.2.1 Plywood

Plywood, the first engineered product manufactured from Douglas-fir, dates back to 1905. It is composed of thin sheets of veneer, or plies, arranged in layers to form a panel. Plywood always has an odd number of layers, with each layer consisting of one or more plies (APA 2004); 3-, 4-, 5-, 6-ply and other combinations are produced. The knot-free outer wood from old-growth trees was ideally suited for peeling high-quality veneer.

Bending strength is a routinely tested and important property of structural plywood. Douglas-fir from Oregon, Washington, California, Idaho, Montana, Wyoming, and British Columbia is grouped by APA in Group 1. This group also contains four southern pines, two tropical pines, four North American hardwood species, and three trade groups of tropical hardwoods. Group 1 is the highest stiffness species group and is designated as having a clearwood MOE of 1.857 million psi (APA 2007).

Strength tests, thickness, and species groupings are translated to Span Ratings in the Sheathing and Single Floor plywood grades. These denote the maximum recommended center-to-center spacing of supports, in inches, over which the panels should be placed in construction applications (APA 2004); the stronger the plywood, the greater the span rating. Generally, the stress rating along the long axis of the plywood is much higher than the rating across the sheet (APA 2004). Stiffness increases dramatically as the thickness of the sheet increases; in A-A or A-C grades, for example, the stiffness increases from 15,000 to 760,000 psi as thickness increases from 0.25 to 1 in. It is accepted that design is conservative (APA 2004); in other words, structures are built to hold considerably greater stresses than expected.

High stiffness veneers command a higher price in the internal markets within integrated companies, or in sales between veneer manufacturers and secondary manufacturers. Prices of Metriguard-graded veneers are not published in the

PNW, so rigorous price comparison of different stiffness grades of veneer is not possible. Checking with informed sources, we gathered that for a “regular market”, for 0.1-in. veneer, one can add \$17, \$15, and \$13/1000 ft² to the commodity CD veneer price to get an approximate price for G1, G2, and G3 respectively. The average CD 0.1-in. fir veneer price from 1997 through 2007 was \$51.3 (Random Lengths 2007), so by the calculation above the G1 grade appears to sell for about a 30% premium over CD.

5.2.2 Oriented Strandboard

Oriented strandboard (OSB) is a more recent engineered product that has gained importance in the last 20 yr. OSB is manufactured in a cross-oriented pattern similar to that of plywood to make a strong, stiff structural panel; thin rectangular wood strands are arranged in layers at right angles, which are laid into mats to form a panel. OSB is used for roof and wall sheathing, subfloors, and single-layer flooring. OSB is rated for stiffness, and this is expressed in span ratings (APA 2000, 2004). For reasons discussed later, however, OSB is not currently a significant application for Douglas-fir in the PNW.

5.2.3 Glulam

Glulam is another product with over 100 yr of history for which coastal Douglas-fir is ideally suited. This product is made up of wood laminations bonded with adhesives; the grain of all laminations runs parallel to the length of the member. Individual laminations are typically 1.5 in. thick for western species, including Douglas-fir; glulam is typically manufactured to be 2.5–10.75 in. wide, though other widths are possible. Glulam is stress rated and can be built to carry heavy loads, such as roofs of large buildings and pedestrians and vehicle bridges (APA 2006). Two PNW laminated beam manufacturing facilities, both using mostly Douglas-fir, are listed in Random Lengths (2006); facilities in other parts of the country are also listed as using Douglas-fir. The total production of glulam in the United States in 2005 was 470 million bd ft (APA Media Center News Release #C1-2006, January 30, 2006).

5.2.4 Structural Composite Lumber

Laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL), and oriented strand lumber (OSL) are categorized as “Structural Composite Lumber” and consist of small pieces of wood glued together into sizes common for solid-sawn lumber. Although design stresses are important, no standard grades have been established (Moody et al. 1999).

LVL dates back to the 1940s and is a high-value product. Veneers are carefully selected, often by ultrasonic testing, to ensure that the finished product will

have the desired engineering properties. Sheets are commonly produced in 2- to 4-ft widths, 1.5 in. thick. About 50% of LVL production is used in production of flanges for I-joists and I-beams (Bowyer et al. 2002).

Douglas-fir is one of the species commonly used to manufacture PSL, a composite of wood strand elements with wood fibers primarily oriented along the length of the member. LSL and OSB are extensions of the technology used to produce OSB panels.

5.3 RECONSTITUTED WOOD AND FIBER PRODUCTS

Particleboard is produced from sawdust, planer shavings, and other residue. MOE and MOR requirements for particleboard are low (0.55–2.75 GPa and 3–23.5 MPa, respectively); those for medium density fiberboard are slightly higher (1.4–3.45 GPa and 14–34.5 MPa, respectively) (Younquist 1999).

Wood stiffness does not directly impact pulp production from Douglas-fir wood, but traits that affect stiffness (density, fibril angle) can also affect pulping properties.

5.4 STIFFNESS AND STRENGTH IN THE CONTEXT OF BUILDING DESIGN & CONSTRUCTION

5.4.1 How Building Codes and Design Specifications Affect Lumber Grading and Markets

About 80 to 90% of all structures in the United States are built of wood (CUREe 1998). Most of these buildings are single-family residences, but apartment complexes and commercial and industrial buildings may also have wooden frames. Wood-frame construction has evolved over time, moving from the use of rules of thumb or intuition to modern design codes (AF&PA 2005). Most states in the United States follow codes developed by the International Code Council (ICC) [International Building Code (IBC) and International Residential Code (IRC)] for designing all types of buildings, including wood frame buildings. These codes rely on reference consensus standards, such as ASTM and PS-20 for wood specification (grading and design values) and the National Design Specification (NDS) (AF&PA 2005) for design of wood frame structures. IBC (for example, ICC 2006a) is an engineered code (an engineer must perform calculations to design specific components of a building), whereas IRC (for example, ICC 2006b) is a prescriptive code, where no calculations are performed.

An engineer using IBC or NDS for designing wood structures utilizes MOE in calculating deflection of bending members, checking lateral stability of beams, determining group action factor and column buckling in multiple bolted connection design, and calculating deflection of shear walls (SW) and horizontal diaphragms (HD). Even though MOE is needed and is important in these calculations, other geometric factors have a bigger impact on design of these elements. For example, beam deflection is inversely proportional to MOE, but also inversely proportional to the cube of the depth of the beam. Therefore, a small increase in MOE will cause a small reduction in deflection, but a small increase in the depth of the bending member will cause a large reduction in deflection. Similarly, increase in nailing density has a much bigger impact on SW and HD deflection than does an increase in MOE of framing.

A small increase in MOE also may not have a big impact on design of most wood-frame buildings because most wood-frame buildings are highly redundant or indeterminate structures (Breyer et al. 2007)—that is, these structures have additional safety features. They can redistribute forces if portions of the structure are overstressed or even fail. Redundancy may result from having extra members in the structure or from the geometry of the structure. As a result, redundant structures have much smaller forces (stresses) and displacements than do nonredundant (determinate) structures. In addition to their extra capacity, redundant structures are stiffer and have small deflections. Redundancy provides substantial increases in structural stiffness and also increases stability against both horizontal and unexpected loadings (White et al. 1976).

5.4.2 Reductions Due to Shorter Rotations and Other Factors: Impacts on Building Construction

Small changes in MOE are unlikely to have much impact on building construction because (1) most wood frame construction is prescriptive, where design calculations are not performed, and the quality of construction depends mainly on the size and grade of lumber; (2) most wood frame construction is highly redundant²; and (3) size and other factors impact the performance of the structure more than does MOE. A reduction in the variability of MOE may have a greater impact on building construction than a small change in MOE itself. The only place MOE may affect design values is in engineered wood products, such as glulam and LVL.

² For example, WWPA (2005b) states: “For all normal construction, use of the average (E) values provides a conservative prediction of deflections which will occur in wall, floor and roof assemblies. Tests by government, university and private research organizations show that deflections occurring when loads are applied are less than predicted with use of average (E) values”.

6. VOLUMES OF VARIOUS DOUGLAS-FIR PRODUCT CATEGORIES, WITH IMPLICATIONS FOR WOOD STIFFNESS

Haynes and Fight (2004) provide helpful background on trends of prices and volumes of major Douglas-fir lumber categories. Since the year 2000, 90–95% of the volume of coastal Douglas-fir lumber has been produced as light framing, heavy framing, or structural items³ (Haynes and Fight 2004; Warren 2005). On the one hand, the high-value C Select and Shop grades had virtually disappeared by 2002; on the other, utility and economy grades had also decreased. Both these changes were attributed to greatly reduced harvest of mature stands. Price premiums for large-dimension lumber [structural items (boards 2–4 in. thick, ≥5 in. wide) and heavy framing (boards ≥5 in. thick, width 2 in. or more greater than thickness)] over light framing are predicted to continue steady or even increase up to 2050 (Haynes and Fight 2004). It is noteworthy, however, that structural items (which included MSR lumber, select structural lumber, and laminating stock) did not command a consistent price premium over heavy framing from 1971 to 2002; for 16 of those 32 yr, heavy framing prices per 1000 bd ft were actually higher (Haynes and Fight 2004).

The proportion of Douglas-fir harvest used for lumber declined from 74% in 1950 to 45% in 1979, whereas the proportion used for plywood rose from 9% to 24% (Haynes 1986). At that time, it was estimated that about 68% of Douglas-fir wood was used for housing (Ernst and Fahey 1986). A more recent breakdown of all softwood harvest in the PNW (Smith et al. 2004) showed 1.162 billion ft³ (9.44 billion bd ft) going to sawlogs; 0.0375 billion ft³ (2.34 billion bd ft), to veneer logs; 0.288 billion ft³, to pulpwood; and 0.693 billion ft³, to posts, poles, and pilings. Thus, of the total volume harvested, about 70.4% appeared to be used as sawlogs and 17.4% as veneer.

From 2000 to 2003, the volume of Douglas-fir logs exported from the Seattle and Columbia-Snake customs districts ranged from 487.4 to 668.7 million bd ft (Warren 2005). This is only about 5% of sawlogs harvested. About 2.6 billion ft² of plywood was reported to have been produced in Oregon in 2004, and the state was reported to be the largest producer of plywood for the last 50 yr. Another 2.2 billion were produced in Washington, Montana, and Idaho (APA—The Engineered Wood Association Media Center News release, March 9, 2005; http://www.apawood.org/level_d.cfm?story=1701.) Although Douglas-fir is suitable for use in OSB, there are no OSB plants in western Oregon or western Washington (Random Lengths 2006).

³ Warren (2005) categories, in terms of WWPA (2005A) categories: Light framing = Structural light framing + Light framing + Stud (WWPA); Structural Items = Structural joists and planks + Structural decking (WWPA); Heavy framing = Beams and stringers + Posts and timbers (WWPA). Personal communication (Debra Warren, USDA PNW Research Station, Portland, 2008).

Coastal Douglas-fir has never been intentionally grown for pulpwood, particleboard, or medium-density fiberboard (MDF) by any significant forest grower in the PNW; these products are made from wood residue in sawmills and other processing facilities, low-grade logs, and tops from final harvest and commercial thinning. Given the type of raw material used and its low value, there is no reason for forest growers in the PNW to gear their management strategies to stiffness needs of these products.

We conclude from this review that, for the majority of wood products originating from coastal Douglas-fir in the PNW, stiffness is either explicitly important and assessed (MSR lumber, plywood, glulam, OSB) or implicitly important, as reflected in design values and building codes (visually graded lumber). Reductions in wood stiffness thus might have short- or long-term repercussions, if not for the fact that current building codes and design codes contain a large margin to absorb stiffness reduction without affecting building integrity and safety.

PART III. GENETICS OF AND SELECTION FOR WOOD STIFFNESS AND RELATED TRAITS: STATE OF KNOWLEDGE

7. INHERITANCE OF STIFFNESS AND RELATED TRAITS IN DOUGLAS-FIR AND OTHER MAJOR CONIFERS

7.1 SPECIFIC GRAVITY

Most of the genetic research to date in Douglas-fir wood quality has been on SG, as it is more easily measured than many other wood properties. This trait is moderately to highly heritable (King et al. 1988; Vargas-Hernandez and Adams 1991, 1992; Koshy 1993; Johnson and Gartner 2006; Cherry et al. 2008). Family \times site interaction is generally low. For example, Johnson and Gartner (2006) reported a type-B genetic correlation of 0.86.

The individual components of SG (for example, proportion of latewood) have been studied (Li and Adams 1994; Vargas-Hernandez and Adams 1994). Selection for increasing SG would cause an earlier transition to latewood formation, negatively affecting the growth rate. Overall wood core density was negatively correlated genetically with the dates of cambial growth initiation ($r_A = -0.41$) and latewood transition ($r_A = -0.62$), and positively correlated with the date of cambial growth cessation ($r_A = 0.40$) (Vargas-Hernandez and Adams 1994).

Many researchers have reported other negative correlations between SG and growth in Douglas-fir (King et al. 1988; Vargas-Hernandez and Adams 1991; Koshy 1993; Johnson and Gartner 2006; Cherry et al. 2008), which has implications for selection in breeding programs. Results vary between studies, however, and it is possible to find selections with both growth and SG enhanced (King et al. 1988). Many studies focus on diameter growth, which tends to be more negatively correlated with SG than height. For example, Vargas-Hernandez and Adams (1991) found a genetic correlation of -0.19 between age 15 height and density, and -0.63 between age 15 DBH and density. Therefore, it is possible to design breeding strategies to maximize either growth or SG, to maximize both traits, or to maximize growth while not reducing SG (King et al. 1988; Vargas-Hernandez and Adams 1991)—by using tandem selection or selection indices, for example.

Age-age correlations for SG are generally strong. For example, Vargas-Hernandez and Adams (1992) found that indirect selection at age 7 yr for density was 79% as efficient as direct selection at age 15.

Relationships between tree height, DBH, branch diameter, wood density, and tree value for lumber production were investigated by Aubry et al. (1998). Value of lumber recovered from each tree was determined in a mill study according to both visual and MSR grading rules. Tree value was related to the growth and wood quality traits by multiple linear regression. Stem volume and branch diameter significantly influenced tree value under visual grading, with relative economic weights of 0.06 dm³ and -5.22 cm, respectively. Wood density significantly influenced tree value under MSR grading, with relative economic weights of 0.06 dm³, -6.69 cm, and 0.06 kg/m³, for volume, branch diameter, and DEN, respectively. These regression coefficients can be used directly as economic weights in selection indices in the development of breeding programs for Douglas fir.

7.2 MICROFIBRIL ANGLE

MFA is under moderately strong genetic control (Wu et al. 2007; Baltunis et al. 2007). In radiata pine, MFA heritabilities were highest in the juvenile corewood (Donaldson and Burdon 1995; Dungey et al. 2006). Dungey et al. (2006) found that genetic correlations between MFA and stiffness were strongly negative; note that stiffness was predicted from MFA and density in their study, so correlations can therefore be inflated. The genetic correlation between wood SG and MFA varied from positive near the pith to negative by ring 7.

Variability and heritability of MFA also decrease from pith to bark (for example, Dungey et al. 2006); this could be reflected in patterns and genetic control of stiffness as well. Due to the consistency and strength of pith-to-bark patterns, it is very important to report genetic parameters for specific individual growth rings or contiguous series of growth rings.

7.3 STIFFNESS

7.3.1 Stiffness Heritability in Douglas-fir

Researchers have been interested in wood stiffness for many years. Wood technologists have examined the static bending stiffness of Douglas-fir, often testing small, clear, knot-free wood samples (for example, McKimmy 1959). A report written 44 yr ago, before any studies on the inheritance of stiffness, hypothesized 10% heritability and a 4–6% stiffness genetic gain in Douglas-fir from selecting the top 1% of individuals (Campbell 1964). Until recently, however, few genetic studies have examined stiffness in this species. Because wood stiffness cannot be fully explained simply by assessing SG, new ways of estimating stiffness have recently been developed, including nondestructive

tools. These tools are now enabling geneticists to assess stiffness in breeding programs.

Using a log acoustic velocity tool (HM200), Johnson and Gartner (2006) assessed dynamic wood stiffness across four sites of a first-generation Douglas-fir progeny test in coastal Oregon. Based on their measures, dynamic MOE was moderately heritable ($h_i^2 = 0.55$), with little family \times site interaction ($r_B = 0.85$), but was slightly less heritable than basic density ($h_i^2 = 0.59$). The dynamic MOE measured in their study, however, had more genetic variation than did wood density. The genetic correlation between the dynamic MOE and wood density was 0.76. Dynamic MOE was negatively correlated with tree height and diameter ($r_A = -0.3$ and -0.5 , respectively); the negative correlation with height was attributed to the indirect effect of height being correlated with DBH. There also appeared to be a negative genetic correlation between taper and stiffness: families that were more cylindrical than conical appeared to be denser and stiffer (Johnson and Gartner 2006). Sonic velocity has shown moderately high heritability for Douglas-fir in New Zealand (Shelbourne et al. 2007).

Cherry et al. (2008) assessed acoustic velocity at two sites of a first-generation Douglas-fir progeny test in coastal Washington, using both a log acoustic tool and a standing-tree tool. Dynamic MOEs (combining SG and acoustic velocity, as described before) for these tools were also assessed at one site. All acoustic traits were moderately heritable⁴ ($h^2 = 0.30\text{--}0.43$) and similar to the heritability for basic wood density of basal disks ($h^2 = 0.34$). Acoustic velocities did not exhibit significant genotype \times environment interaction.

7.3.2 Stiffness Heritability in Other Conifers

Stiffness has been extensively studied in other species. Static and dynamic MOE and velocity of acoustic waves are moderately to highly heritable in radiata pine (Kumar et al. 2002; Kumar, 2004; Lindström et al. 2004; Kumar et al. 2006; Dungey et al. 2006; Baltunis et al. 2007; Gapare et al. 2007; Matheson et al. 2008), hybrid larch (Fujimoto et al. 2006), and slash pine (Huber et al. 2007; Li et al. 2007a,b). Moderate to high type B genetic correlations (see Glossary) are reported, such as 0.70 for velocity² (V^2) in slash pine (Li et al. 2007b); 0.45 between a New Zealand site and an Australian site, 0.94 between two New Zealand sites (Kumar 2004, acoustic velocity in radiata pine), 0.91 (Baltunis et al. 2007, dynamic MOE in radiata pine); and 0.95 (Matheson et al. 2008, time of flight in radiata pine). Static and dynamic MOE are strongly correlated in both radiata pine (Kumar et al. 2002; Lindström et al. 2004) and Douglas-fir (Knowles et al. 2003; Carter

⁴ Narrow-sense heritability was estimated with additive variance assumed to be 3 \times family variance instead of 4 \times , which had been used in many other studies.

Table 4. Predicted genetic gains for bending stiffness and acoustic velocity in some reports on conifer species.

Species	Target trait	Selection trait	Selection scenario	Predicted genetic gain (%)	Reference
Radiata pine	Bending stiffness	Acoustic velocity	Selection intensity of 1	4.1	Kumar et al. (2002)
		Bending stiffness	Top 1% of individuals	16	Kumar (2004)
		Acoustic velocity	Top 1% of individuals	9	Kumar (2004)
		Time of flight	Top 10% of trees on the basis of breeding values	21	Matheson et al. (2008)
Slash x Caribbean pine	Bending stiffness	Bending stiffness	Top 12 of 34 clones, the 34 preselected from 175 clones on the basis of volume superiority, stem straightness, tree form, branching, wood density, and predicted stiffness	17	Harding et al. (2007)
Loblolly pine	Bending stiffness	Bending stiffness	Top 1% of clones	21	Eckard (2007)
		Acoustic velocity	Top 1% of clones	16.2	
Slash pine	(Acoustic velocity ²)	(Acoustic velocity) ²	Top 15 of 139 polymix families	24	Li et al. (2007) b
Hybrid larch	Dynamic MOE	Dynamic MOE	Top 5% of families	12.1	Fujimoto et al. (2006)
		Bending stiffness	Top 5% of families	11.4	
Douglas-fir	Dynamic MOE	Dynamic MOE	Top 4 of 39 open-pollinated families	11.0 (selection differential)	Johnson and Gartner (2006)
	Bending stiffness	Bending stiffness	Top 2.5% of parents	12.3	Cherry et al. (2008)
		Acoustic velocity (HM200)	Top 2.5% of parents	9.6	
		Acoustic velocity (ST300)	Top 2.5% of parents	7.1	

et al. 2005). The main implication is that acoustic tools will be very useful for ranking parents based on stiffness and making selections in breeding programs. Indirect measures of wood stiffness have been found to be almost as effective as direct bending MOE (Kumar et al. 2002) and sometimes have even higher predicted gain, due to higher h^2 (Kumar 2004). Because indirect measures are relatively easy to use operationally, they should be easy to incorporate into progeny test assessments and can be obtained in conjunction with progeny test thinning.

An adverse correlation was weaker between DBH and acoustic velocity than between DBH and density in one radiata pine study (Kumar et al. 2002) and at the Warrengong site in Kumar (2004). In contrast, other estimates (Kumar 2004; Kumar et al. 2008) gave similar adverse genetic correlations

for DBH:density and DBH:acoustic velocity; in data from the Kaingaroa site in Kumar (2004) and the high-density population in Kumar et al. (2008), the DBH:acoustic velocity correlation was more adverse than that for DBH:density. About one-fifth of the slash pine families tested had positive breeding values for V^2 and height, and V^2 and volume (Li et al. 2007b). There is evidence that stiffness or velocity is more likely to be adversely correlated with diameter growth than with height growth; in some instances, there are even favorable correlations between height and stiffness (for example, Li et al. 2007b). Appendix 3 shows a deterministic simulation of the potential gain loss in age-25 stiffness when 30% age-15 volume gain is assumed, with various combinations of genetic parameters. For example, a 30% gain increase in age-15 VOL, assuming MOE25 and VOL15 are similar in both heritability estimate and coefficient of phenotypic variation, could cause 6% loss in age-25 stiffness when the genetic correlation (r_A) between MOE25 and VOL15 is -0.2, and 3% loss if r_A is -0.1. Note that the correlated response in whole tree stiffness at rotation age will be less than the correlated response at age 25.

Potential stiffness gains reported in the literature are summarized in Table 4. To maximize genetic gain in corewood (juvenile wood) in radiata pine, selection for MOE would be most effective around rings 4–8 (Dungey et al. 2006). It is possible to assign appropriate weight to acoustic velocity (or stiffness) and growth traits such as height (or DBH), in order to obtain gains in both the wood trait and the growth trait of interest (for example, Johnson and Gartner 2006; Eckard 2007; Li et al. 2007b), but maximum gains will not be obtained in either trait. Work on developing economic breeding objectives for radiata pine showed that different entities (a forest grower, a sawmill, and an integrated company) could put quite different emphases on Mean Annual Increment (MAI), stem straightness, branch index, and MOE and get quite different gains for those traits (Wu et al. 2007). Note that, given an imperfect genetic correlation between bending stiffness of clearwood samples and the average whole-tree stiffness (which is the actual target trait), the predicted genetic gain in the actual target trait is likely to be less than the values shown in Table 4.

7.3.3 Sample Size per Family in Stiffness Studies

Sampling five to seven trees per family resulted in reasonable heritabilities with standard errors ranging from 0.13 to 0.17 (Kumar et al. 2002). Subsequent work increased this sample size to 15, 18, and 22 per half-sib family at four sites (Kumar 2004). For V^2 in slash pine, sampling nine trees per site resulted in the same heritability as sampling six per site, and six per site gave adequate precision; the mean and median number of trees sampled per family was 18 (Li et al. 2007b). A total of 19 trees (on average) was assessed per family across all four sites in the Johnson and Gartner (2006) Douglas-fir study,

resulting in strong heritabilities and genetic correlations, and differences in wood traits significant to $p = 0.0001$. Six ramets per clone were sufficient to obtain a clone mean repeatability of 0.85 in a loblolly pine study for stress wave velocity (Eckard 2007); six ramets per clone were also sampled in a pine hybrid screening trial in Queensland (Harding et al. 2007). Cherry et al. (2008) assessed 7–22 trees per family per trait in Douglas-fir. Thus, 5–22 trees per entry appear to have been adequate to estimate heritabilities, clonal repeatabilities, and breeding values. In a different application (estimating the stiffness of a stand), the sampling strategy developed was to sample 4 plots per stand and 12 trees per plot (Toulmin and Raymond 2007). Where estimation of genetic correlations between traits is desired, particular attention needs to be paid to sample size (number of families and progeny per family). For example, sampling five to seven trees per family resulted in reasonable genetic correlations, but the standard errors ranged from 0.03 to 1.44 (Kumar et al. 2002). Large standard errors were also obtained for wood traits with only seven trees per family (Cherry et al. 2008)⁵.

The New Zealand radiata pine program has concluded that a sample of about 16 trees from each open-pollinated family is needed in order to obtain breeding values of stiffness. The number has varied from 15 to 25, with an average of about 18 trees in most cases (personal communication, Dr Satish Kumar, Scion, Rotorua, New Zealand, 2008). The Southern Tree Breeding Association in Australia has adopted a two-stage sampling process for radiata pine. In Stage 1, a 10% random sample is taken, resulting in about two trees assessed per family per trial. This is generally achieved by measuring one tree per family per replicate in two replicates, taking the first (or most consistent) tree in the plot. In Stage 2, a 10% targeted sample is taken aimed at the highest value trees in terms of the National Net Present Value Index, to ensure that about four or five trees in the top families are actually assessed. Lower value families would not be represented in this sample. Generally, with most families occurring in 3–10 trials, a total of 6–20 trees are assessed per family on a random basis; with the targeted sample, a lot more trees are assessed in some families (personal communication, Dr Mike Powell, Southern Tree Breeding Association, Australia, 2008).

8. INCLUDING STIFFNESS IN OPERATIONAL TREE IMPROVEMENT: INSIGHTS FROM SELECTED PROGRAMS

8.1 RADIATA PINE

Due to the need to address problems caused by shortened rotations, the

⁵ Standard error of heritability estimate is related more to number of families than to number of trees per family. We generally need to test a large number of families in order to get reliable estimates of heritability. If the purpose is to get precise prediction of parental breeding values, however, an adequate number of trees per family is required.

radiata pine breeding programs in New Zealand and Australia have made serious efforts to improve stiffness. Jayawickrama (2001) summarizes the past activities and future prospects for breeding radiata pine for stiffness. This process began with a large screening project for SG in which 6,000 cores were taken in 1975, followed by establishment of a High Wood Density breed in 1986 and then a Structural Timber breed (Jayawickrama 2001). A combination of density, branch cluster frequency, and a nondestructive test seemed likely to provide the information needed to rank genotypes for stiffness (Jayawickrama 2001). New Zealand's GF Plus rating scheme includes information on wood SG (RPBC 2002).

Radiata pine breeders appear to be switching from selecting for density to selecting for dynamic MOE, acoustic velocity, or time of flight at age 4–8 (Dungey et al. 2006, 2007; Matheson et al. 2007). The Radiata Pine Breeding Company has already screened about 500 families in the existing trials (aged 12–17 years), and parental BLUP breeding values for acoustic stiffness are available for making desirable crosses in the existing seed orchards, as well as for elite crossing. All the new progeny trials would be measured for acoustic stiffness at around 7–8 years of age (personal communication, Dr Satish Kumar, Scientist, Scion, Rotorua, New Zealand, 2008). A large research investment has been made in trying to improve juvenile wood properties, such as a \$6 million project in Australia (Wu 2004). The focus of the third-generation breeding in the Southern Tree Breeding Association has shifted to wood quality (Wu et al. 2007).

8.2 SOUTHERN PINES

Until recently, relatively little has been done by either indirect or direct measures to actually improve stiffness in the breeding populations in the southeastern United States, despite the extensive research on wood properties in these species. Some cooperators screened first-generation plus-trees for SG, and this selection would have obtained some gain in the orchards; there was also some emphasis on SG during the second cycle (Jett and Talbert 1982). The availability of rapid screening tools, along with the increased emphasis on growing sawlogs and the decline in the pulp and paper industry due to competition from overseas, may result in wood properties being used more frequently as selection traits. The North Carolina State program is likely to start using wood stiffness as a selection trait (personal communication, Dr Steve McKeand, Director, NCSU-ICTIP, North Carolina State University, Raleigh, NC, 2008).

One recent development is a Wood Quality Elite population in the Western Gulf Tree Improvement Program (Byram et al. 2005). Individuals were selected based on a pulp yield index score that weights improvements in

SG about 7× more heavily than improvements in growth rate. The goal is to create an elite population of 120 individuals. Crosses are being made and established in block plots. Clonal testing is also being used to select individuals within full-sib families (Byram et al. 2006). Another development is a decision to incorporate breeding values for stiffness, volume, straightness, and wood SG into a sawlog index so breeders can rank candidates for inclusion in seed orchards (Raley et al. 2007).

The state of Queensland in Australia has a very intensive research program for slash pine and its hybrid with Caribbean pine, intensively screening genotypes (especially clones) for wood stiffness. This screening has taken place in clone banks, seed orchards, progeny tests, and clonal tests; sawmillers and other wood processors in the state are keen that steps be taken to maintain and improve wood stiffness in conifer plantations (personal communication, Dr Kevin Harding, Department of Primary Industries and Fisheries, Queensland, Australia, 2008). A comparison of the cost-effectiveness of assessing SG and acoustic velocity with the FibreGen ST300, Ensis “Paddle-pop” sticks, and SilviScan (Harding et al. 2007) has been undertaken (see section 3.2.4 for cost comparisons). The correlations between average MOE of all boards in a tree with ST300 mean velocity, SilviScan-predicted MOE, and Paddle-pop MOE were 0.88, 0.89, and 0.89 respectively. The top 12 clones had 17% higher average stiffness and 4.8% higher strength than the other 22 clones tested; all 34 clones had high volume gain, stem straightness, tree form, and good branch habit. Current economic models in Queensland still suggest that gains in stem productivity are the main driver of improved value. In 4 of the top 12 clones, average stiffness exceeded 8.5 GPa at age 6.8 yr, which strongly indicated they could be used to grow stress-grade rated structural timber (MGP10 under the current Australian pine grading system).

8.3 SITKA SPRUCE IN THE UNITED KINGDOM

The role of wood stiffness and strength has been documented clearly and succinctly in this program (Lee 1999, 2001). As far back as 1972, the breeding goals had included “wood qualities satisfactory for the sawn timber market”. The negative correlation between stem diameter and wood SG ($r_A = -0.66$) has been recognized (Lee 1999).

First-generation progeny were screened for stem straightness, branch quality, and wood SG, determined with the Pilodyn. A selection index was generated to weight diameter, wood SG, and stem form (presumably straightness) appropriately. After this exercise, four populations were selected: a “General Breeding Population” (GBP), a “General Production Population” (GPP, aiming to increase stem volume and straightness while keeping wood SG at the current level), a “High Density Production Population” (HDPP, with a greater weight on density at the expense of diameter), and a “High

Straightness Production Population” (HSPP, favoring stem straightness while trying to achieve acceptable levels of wood SG and diameter). The GPP and HDPP were predicted to obtain about 80% and 50% of the maximum gain possible for diameter if selecting only for diameter. The GPP kept density more or less constant (no loss), and the HDPP would obtain about 50% of the gain possible if selection were based on density alone.

The program is currently researching methods to screen for microfibril angle and stiffness, and recently conducted an economic analysis of the impact of various factors on profitability. Diameter was the individual selection trait that most influenced production system profitability, followed by stem score, branch score, stress wave velocity, and Pilodyn. Adding stress wave velocity as a fifth trait to four-trait selection on DBH, stem score, branch score, and Pilodyn gave no additional benefit (personal communication, Dr Steve Lee, UK Forestry Commission, Midlothian, Scotland).

8.4 DOUGLAS-FIR IN NEW ZEALAND

The breeding strategy has recently been revised, and breeding goals include improving wood stiffness via selection for outerwood density, sound velocity, or both (Shelbourne et al. 2007). The selection criteria will include light, well-distributed branching; outerwood SG; and/or sound velocity. Knowles et al. (2003) reported that a 1 GPa increase of wood stiffness might be achieved by increasing mean tree wood density by 30 kg/m³, reducing mean MFA by 2.60, or reducing branch index by 1 cm.

PART IV. BREEDING FOR STIFFNESS IN DOUGLAS-FIR IN THE PNW: PROS AND CONS, OPTIONS, AND METHODS FOR FUTURE WORK

9. To SELECT FOR WOOD STIFFNESS OR NOT?

The preceding review supports the view that stiffness should be monitored, and sometimes improved, in Douglas-fir forestry and wood production. This leads to the question of when wood stiffness should be improved and what tools (including tree improvement) are available for this task.

9.1 REASONS TO SELECT FOR STIFFNESS

9.1.1 Selection to Maintain Douglas-fir's Niche

Douglas-fir is only one of many usable softwoods; we can envisage a future where it competes with radiata, loblolly, slash, slash × Caribbean hybrid, and central American pines from the southeastern United States, South America, and Australasia. Given that the PNW is a relatively high-cost wood producer, due to steep terrain and high labor and regulatory costs, it seems prudent to do all that is reasonably possible to maintain the quality of the resource.

9.1.2 Expectation of Premiums for Higher Stiffness Wood

Until recently, stiffness of logs has not been measurable in production settings, so no price premiums could be assigned. Now that the technology for measuring and sorting by stiffness is available, and assuming processors requiring high-stiffness wood will compete to obtain such wood, we could see a quality premium in the future.

9.1.3 Selection as a Long-term Input

Unlike many silvicultural inputs that can be repeated, modified, and, more rarely, reversed (for example, multiple thinnings), a forester can only affect the genetics of a plantation once (that is, at the time of planting). Thus, the choice of the genotype to plant is important, and the seriousness of that decision increases with the length of the rotation. Gains obtained in one cycle of genetic selection can be maintained or added to in subsequent cycles of selection, if selection continues in the same direction.

9.1.4 Costs and Likely Gains for Selection Compared with Silvicultural Methods

Advances in treatments such as intensive weed control, planting of large, high-quality seedlings, browse control with bud caps or hunting, use of micronutrients, or mid-rotation fertilization with nitrogen (for example, Cafferata 1986; Talbert and Marshall 2005) can dramatically increase plantation growth rate and average tree size in coastal Douglas-fir. There is little evidence, however, that any of these or similar tools could be used to improve wood stiffness. Genetic selection stands out as one of the few tools, along with branch size control, available to the forester to improve or maintain stiffness.

The direct costs of genetic selection for stiffness are likely to be much lower than those for controlling branch size by pruning (discussed below). Branch size control could very easily add up to hundreds of dollars per acre, and heavy initial stocking could lead to expensive precommercial thinning, but it is possible to produce orchard seed at a cost equivalent to \$5–20 per reforested acre. Although the costs of establishing genetic tests and orchards are high—tens of millions of dollars in the PNW—they are largely sunk costs, and incremental costs for incorporating wood stiffness as a selection criterion are far smaller. Due to the potential adverse correlations with volume gain, however, intense selection for wood stiffness will result in foregoing some volume gain.

9.1.5 Costs and Likely Gains for Selection Compared with Technological Innovations

The direct cost of genetic selection for stiffness is likely to be less than the cost of technological changes, especially with rapidly rising energy, water, and other raw material costs and increasing regulatory pressure and environmental concerns. In one sense, “building in” higher stiffness at the time of planting by use of appropriate genotype and then letting trees grow using renewable resources is far more efficient than using heat, pressure, chemicals, and other means to make those changes during processing.

9.1.6 Likely Consequences of Ignoring Stiffness

Ignoring stiffness would have consequences to growers only if there is a price differential for different stiffness levels. Any consequences would arise from the indirect changes brought about by selection for traits currently of interest. There are indications of moderate adverse correlations, discussed earlier, between stiffness and growth traits. The level of selection for volume in Douglas-fir breeding programs has been low until recently, so we would not

expect much change to have occurred. Increased emphasis on genetic gain, however, could change the situation. Even for a forest grower willing to grow trees on longer rotations (60 yr or more), considerable volumes would be extracted in one or two commercial thinnings. If genetic selection for growth rate reduces stiffness noticeably, this could affect the value and usefulness of wood from thinnings.

9.2 REASONS NOT TO SELECT FOR STIFFNESS

9.2.1 Benefits from Growing Larger Trees Rather than Selecting for Stiffness

Tree breeding is only one of several processes that can be employed to manipulate wood properties. Attempting to improve stiffness by genetic selection involves substantial costs. The most substantial, by far, is the volume gain foregone by concentrating on stiffness. The log market in the PNW has consistently rewarded growers for increasing log size (although many modern mills are not set up to handle the large logs once harvested from old-growth forests); larger trees are more likely to produce large-dimension higher-value boards, and larger knots are permitted in such boards for a given lumber grade. Rewards for logs of higher stiffness, however, have been largely nonexistent. As mentioned before, there was no consistent price premium for “structural items” (MSR lumber, select structural, and laminating stock) over large-dimension “heavy framing” during 1971–2002, nor has a price premium been projected for 2010–2050 (Haynes and Fight 2004). A substantial premium for “heavy framing” over “light framing” has existed, however, and was projected to increase (Haynes and Fight 2004), underscoring the benefits of larger trees from faster growth or longer rotations.

9.2.2 Nongenetic Methods to Improve or Deal with Changed Stiffness

9.2.2.1 *Rotation Age*

The simplest means to improve overall wood stiffness would be to allow trees to grow longer, because the proportion of juvenile wood decreases as trees mature. This is a very effective tool for growers who have this option (nonindustrial private forest owners, state and federal agencies, family-owned businesses). Douglas-fir is very well suited for growing on 50-, 60-, or even 80-yr rotations, more so than many conifers, because the MAI does not start declining until 60 or 70 yr (McArdle et al. 1961) or even later (Tappeiner et al. 2007). For example, instead of clearcutting at 40 yr and replanting, a Douglas-fir grower can commercially thin a 40-year-old forest, grow the remaining trees another 20 yr, and produce a large amount of high-quality wood with very little effort or direct cost (no site preparation, replanting, or

weed control are required). There is a cost, however: the opportunity cost of carrying the investment for 20 more years, which is substantial for those who base their decisions on net present value calculations. Business realities make this kind of management difficult for some forest growers, especially real estate investment trusts (REITs), timber investment management organizations (TIMOs), and publicly owned corporations. Those entities often need to provide a steady flow of cash and dividends to owners, cannot support compounding costs over a long period, or are wary of the increased likelihood of hostile takeovers if there is a large inventory of lumber to be “raided”. Some companies also need to continue supplying wood to their own mills.

9.2.2.2 Location

Certain geographic areas are likely to produce inherently stiffer wood, based on trends for SG for Douglas-fir and other species (for example, USDA Forest Service 1965; Cown et al. 1991). There is anecdotal evidence that log buyers for certain mills are targeting stands from specific areas on the basis of expected stiffness values. Most forest growers are already well established in certain geographic areas, however, so selling that land base and buying land in a high-wood-stiffness area is hardly a realistic option.

9.2.2.3 Branch Size Control

Branch size can be controlled by pruning and by stocking level. In addition to the main benefit of improving the production of clear wood (for example, Cahill et al. 1986), the complete removal of branches by pruning should improve stiffness by reducing the discontinuities caused by knots (Megraw 1986a) and by minimizing the demonstrated adverse correlation between knot size and MOE (for example, Shelbourne et al. 1973). Shelbourne et al. (1973), in fact, stated, “Branch diameter must be controlled, either by pruning or by appropriate initial spacing and thinning regime, if high quality structural and framing timber is to be produced”. Few publications, however, actually document the effect of pruning on MOE in Douglas-fir.

In spite of its potential benefits, pruning is not practiced on any significant scale for Douglas-fir in the United States (for example, Briggs 2007). Because of the high cost (multiple lifts are needed in order to minimize the knotty core), very few growers believe that the premium for clear wood will pay back the cost of pruning plus interest. A pruned-stand certification scheme also is lacking. Those who do prune do so for nontimber reasons, such as habitat creation. High-quality wood produced from pruning would probably be used for appearance-grade lumber and veneer, rather than for structural uses. Haynes and Fight (2004) projected price premiums of \$300~400 per MBF of D select and shop grade lumber over “structural items” and “heavy

framing”. A grower wishing to improve wood quality by pruning could prune to 27 ft height (equivalent of three peeler lengths) in two lifts (personal communication, M Newton, Department of Forest Science, Oregon State University, 2008). The projected break-even cost for pruning is about \$25 per tree (Haynes and Fight 2004).

Stocking control is much more widely practiced in PNW forestry. In theory, it would be possible to start with a very dense stand, carry out a precommercial thinning followed by several commercial thinnings, and so keep knots small. This, too, is an expensive proposition: precommercial thinning yields no revenue, and a series of light thinnings would generate little revenue. Pruning and very high stocking are also likely to result in some loss of total volume growth, while large-scale pruning could perhaps increase the risk of attack by pathogens and other pests.

A somewhat more realistic regime would be to plant fairly tightly [(for example 11-ft spacing, 360 trees per acre (TPA)] and not thin until the lower branches (on the bottom log) die. Natural in-growth would increase stocking at some level. The stand could be commercially thinned around age 25–30 yr, culling forked and crooked trees, with a second thinning around age 40 yr, and the remaining trees grown until they are about 60 yr. The grower would probably have to accept some loss of volume growth to get the quality (small knots) and reduced taper (Cahill et al. 1986), and it will need to be determined if quality premiums will provide profits that outweigh the revenue lost from volume reduction. In one study with Douglas-fir, soil expectation values were quite similar at age 60 yr for 100, 150, and 250 TPA, but substantially lower for 500 TPA (Fight et al. 1995). Nevertheless, such a regime does have some advantages: fewer acres to plant each year, reduced weed control and site preparation costs in the next rotation, and lower costs than pruning.

9.2.2.4 Log Segregation Based on Stiffness

Log segregation can benefit both sellers and buyers because logs can be bought and sold on the basis of better information. Logs can be assessed in a landing or a log yard and sold to the buyers who can best use logs of that particular type (dimension, stiffness, and so forth). Log segregation is already well established in Australia and New Zealand. It is currently practiced in the PNW, and the practice is likely to increase. There is ample evidence that preselecting logs based on tests such as stress-wave analysis can increase the yield of high stiffness veneer; for example, when 35-ft butt logs were each cut into four 8-ft bolts, 83% of the high-MOE veneer came from the bottom two bolts (Rippy et al. 2000). On-site average log acoustic velocity estimated with the Fibre-Gen HM200 had an R^2 of 0.62 with estimated break-even prices for veneer (Amishev 2008); for example, logs from a site with an acoustic velocity

of 3.61 had a log value of \$975/MBF, and logs from a site with an acoustic velocity of 4.10 had a log value of \$1140/MBF. Segregation within sites will generally be more useful than between sites, because there is ample evidence that the largest sources of stiffness variation are (1) between trees in a given even-aged stand and (2) at different numbers of rings from the pith.

9.2.2.5 Board Segregation Based on Stiffness

Stiff wood can be found in relatively young fast-grown trees, and weak wood is present in old trees. Because factors such as ring width are not very effective in predicting stiffness, the current system of visual grading is only partially successful in assessing the stiffness of boards. A system where each board with structural application is stress-rated would be much more accurate and would lead to more efficient utilization of lumber (and, from there, to more discriminating management of forests) in the PNW. Machine grading can improve the assigned design properties, especially in the presence of substantial amounts of juvenile wood (Barrett and Kellogg 1991). At one point, visual grading was the dominant grading system in Australasia, but this changed rapidly with the widespread adoption of MSR lumber grading; it is now almost impossible to sell visually graded lumber except in low-value markets or as low-value products.

Nevertheless, given that MSR has failed to become the dominant grading system 45 yr after its initiation in the PNW, we should not expect a major transformation of the grading system in the near future, barring bold, concerted efforts by the lumber-producing industry.

9.2.2.6 Compensatory Design of Wood Structures

As discussed before, current building codes, designs, and standards tend to be very conservative. Thus, a small decrease (say, 5%) in average wood stiffness may not affect building integrity or performance substantially. Alternately, it would be very simple to compensate for such a reduction, if necessary, by modest changes in design—for example, by reducing spans by a few inches, using deeper boards, or both.

A 5% decrease in stiffness could be compensated by a mere 1.5% increase in depth of the board, given that deflection is proportional to $1/h^3$ where h is the depth of the board. Thus, a 2×8 used as a joist, currently dimensioned to 7.25 in. deep, would need to be 7.36 in. deep if 5% less stiff in order to provide the same resistance to deflection. Because retooling sawing dimensions would be slow and expensive, it would be simpler for builders and engineers to decrease the span of the joists. For example, decreasing the span from 24 in. to 19.2 in. would more or less compensate for a change from select structural

2 × 8 (1.9 million psi) to No. 2 2 × 8 (1.6 million psi), a 20% decrease in E design value (WWPA 2005a). Changing codes is generally a long, slow, and expensive process, but an informed engineer or architect could exceed design codes to compensate for perceived or real reductions in stiffness.

9.2.2.7 Technological Innovations to Compensate for Reduced Stiffness

Time and time again, changes in technology have compensated for changed, generally lower-quality, raw materials. A century ago, species such as western hemlock were not even harvested from PNW forests—now, they are widely used. Plywood was developed to compensate for reduced availability of clear wood; OSB later substituted for plywood. I-joists and I-beams have partially substituted for large-dimension boards and beams such as 2 × 12s; the rapid growth of the I-joist/beam market has been an important driver for adoption of acoustic methods for rating logs and trees. We can expect that technology can be developed that compensates for reductions in average wood stiffness, especially if the reductions are small (for example, 5%).

9.3 WOULD GENETIC IMPROVEMENT FOR WOOD STIFFNESS BENEFIT ALL GROWERS EQUALLY?

It is unlikely that genetic improvement for wood stiffness would benefit all growers equally. Some regions may naturally produce trees with higher than average stiffness due to a high latewood ratio or other factors, and some growers (for example, federal and state agencies) still use relatively long rotations. If much of the harvest is already of high quality, increasing stiffness could be less beneficial. Regions with no market for high-stiffness wood may also see less benefit from increased stiffness. We already see logs and veneer hauled hundreds of miles, however; if high-stiffness wood gets scarcer, we may see buyers searching farther and farther for desired logs.

The greatest incentive for intense genetic selection for stiffness would be in the case of a grower growing Douglas-fir on a short rotation on a landbase that does not produce stands with high stiffness, facing a current or likely future market rewarding high wood stiffness, and having access to a tree improvement program with stiffness data and the seed production capability to translate data to gain in the field. In fact, we propose that such a forest grower would be foolish not to use genetic selection, in combination with all other available and affordable tools, to improve stiffness. Other forest growers predicting, and positioning themselves for, a future market niche for larger, higher-stiffness Douglas-fir logs from older (for example, age 60 yr) trees may also see value in selecting for stiffness.

10. APPROACHES TO CONSIDER IN IMPROVING WOOD STIFFNESS IN DOUGLAS-FIR

10.1 SELECTION METHODS

Selection refers to differential reproduction of genotypes to maximize the genetic worth of those selected. In other words, genetic progress is made by selecting trees with high breeding values as parents to produce the next generation. Breeding values of trees cannot be observed directly, however, so we have to predict them based on phenotypes. This chapter describes several selection methods that are potentially applicable to the genetic improvement of wood quality. The choice of selection method depends on the trait(s) of interest, the number of traits, their relative importance, and the available genetic information.

10.1.1 Single-trait Methods

Single-trait selection, where just one trait is of interest, would be useful when the genetic improvement of wood quality is the primary goal in a breeding program; in practice, this has rarely been the case. The target trait can be the same as the measured trait (direct selection), or it could be different (indirect selection).

10.1.1.1 Direct Selection

Mass selection involves selecting individual trees based on their phenotypic values compared with those of neighboring trees. This is normally the only feasible selection method at the start of tree breeding programs, as no pedigree information is available. Appendix 4 details the methodology for estimating gains from mass selection. Mass selection is effective for populations and traits with high individual-tree heritability and large phenotypic variation. The practice of scoring plus-trees for highly heritable traits such as stem straightness and wood SG by comparing them with a few other trees in the same stand is a good example, and there is evidence that some gain in wood traits has been obtained from that practice. For example, King et al. (1998) reported that mass selection appears to be very profitable for wood and fiber traits from western hemlock in British Columbia. Given the advanced state of Douglas-fir improvement in the PNW, this approach is unlikely to be used now to improve stiffness.

Family selection is selection of entire families based on the parental breeding values predicted from progeny tests. The equation for estimating gains from mass selection (Appendix 4) can be used with two changes to predict the genetic gain from family selection: (1) h^2 is the estimate of family-mean

heritability, and (2) S is the family selection differential (that is, how much better the selected families are above the average). With many progeny per family, the heritability estimate is usually much larger at the family-mean level than the individual-tree level. Hence, family selection is useful when the estimate of individual-tree heritability is low, but the estimate of family-mean heritability is high. Family selection for low heritability traits like height growth is more cost effective than intensive individual-tree selection in black spruce and jack pine (Morgenstern et al. 1975).

Combined selection is the combination of family and within-family selection. It weights family and individual performance appropriately to predict a breeding value for each parent and tree in progeny tests. Combined selection is commonly used in advanced-generation breeding programs, where we increase emphasis on within-family selection instead of eliminating large numbers of inferior families. It helps slow the buildup of relatedness in the breeding population (White et al. 2007). The general equation for combined selection is given in Appendix 4.

Best linear unbiased prediction (BLUP) is widely accepted as the best predictor of genetic merit of individuals, so selecting individuals with high BLUP values is common (Henderson 1984; White and Hodge 1989; Borralho 1995). BLUP accommodates unbalanced data and heterogeneous genetic parameters and optimally weights the data from various sources such as different sites, ages, and generations. BLUP is currently the dominant methodology for predicting breeding values (Lynch and Walsh 1998). Some details on BLUP methodology are given in Appendix 4. BLUP has been used in tree improvement for individual selection, family selection, and combined selection. It is the standard analysis method in cooperative improvement of Douglas-fir in the PNW.

10.1.1.2 Indirect Selection

Indirect selection is defined as genetic improvement of a trait of economic importance (called the target trait) through selection on a correlated trait (called the measured trait) (Appendix 4). Indirect selection has been widely used in tree improvement programs (White et al. 2007). It can be advocated over direct selection if the measured trait (1) is less expensive to assess than the target trait, which reduces cost; (2) can be assessed earlier in the lifetime of a tree than the target trait, which will reduce generation intervals; and/or (3) has a higher heritability than the target trait, which could increase accuracy of breeding value prediction. Some examples include selection of wood stiffness of mature trees on the basis of SG of juvenile wood and selection for wood stiffness by using acoustic tools. For example, indirect selection on acoustic velocity in radiata pine provides 80% of the gain from direct selection on MOE (Kumar et al. 2002). In Douglas-fir, indirect

selection on acoustic velocity would provide between 58% and 78% of the gain from direct selection on bending stiffness, depending on which tool is used (Cherry et al. 2008).

10.1.2 Multitrait Methods

Inevitably, there is a need to select and breed for more than one trait in tree improvement programs. For example, tree breeders often wish to improve or maintain wood quality while assigning priority to increasing growth of planted trees (Dean et al. 1983; Ernst et al. 1983; King et al. 1988; Park et al. 1989; Magnussen and Keith 1990; Corriveau et al. 1991; Yanchuk and Kiss 1993; Byram et al. 2005). An adverse genetic correlation may exist between growth rate and wood quality traits (Olesen 1976; King et al. 1988; Byram et al. 2005; Dean 1990; Wu et al. 2004). Simultaneous improvement of adversely correlated traits is a major challenge faced by tree breeders. Several mechanisms for multitrait selection have been proposed and used in tree breeding in order to maximize economic genetic value. Note that different selection approaches can be combined into a multistage selection.

10.1.2.1 Tandem Selection

Tandem selection is selection for two or more traits, one trait at a time—one trait is selected for a cycle of breeding or until acceptable improvement is achieved, and then a second trait is selected for. This method is only practical for very few traits and short breeding cycles, so application to Douglas-fir is limited. It has been used in some tree improvement programs in that considerable emphasis was given to stem form in the first cycle and less in subsequent cycles. It would be interesting to investigate the consequences of shifting the emphasis from growth to wood quality in the third cycle of improvement for Douglas-fir (or a comparable conifer).

10.1.2.2 Independent Culling

Independent culling, presented initially by Young and Weiler (1960), is the simplest multitrait selection method. Culling levels for selection are chosen arbitrarily and separately for each trait, and trees are selected only if they surpass the culling levels for every trait of interest. Because of its simplicity, this method is still commonly used in spite of its inferiority to index selection. It relies strongly on the experience and judgment of breeders and is unlikely to maximize gain because no genetic parameters are used to set up culling levels. If we are too lenient in culling, the purpose may be defeated, but if we hold rigidly to a tougher culling level, trees outstanding for other traits may be eliminated for weakness in one trait. White et al. (2007) suggested a combination of independent culling and selection index, with the high-

priority traits included in the selection index and independent culling levels set for the low-priority traits.

10.1.2.3 Index Selection

Index selection is defined in Appendix 4. This approach allows the weaknesses a tree has in one trait to be compensated for by its strengths in other traits. Selection using a selection index will maximize the overall economic merit of the selected group, provided that the correct economic values have been chosen. Because of its superiority, index selection has been extensively applied to forest tree improvement programs (for example, Wilcox and Smith 1973; Bridgwater and Stonecypher 1979; Burdon 1979, 1982; Shelbourne and Low 1980; Cristophe and Birot 1983; Talbert 1984; Land et al. 1987). In selecting the Sitka spruce breeding population in the UK, diameter gains were maximized without a decline in wood SG when the respective economic weightings were +1.0 and +0.5 (Lee 1999). There are, however, some restrictions on index selection: (1) the economic weights may be poorly known or may change over time and across market conditions; (2) for index selection to be possible, all trees must be retained as long as needed to measure all traits. It will be expensive if one trait has to be assessed when trees are mature, while others could be evaluated at a juvenile stage. Note that selection indices may be used without assigning economic weights (White and Hodge 1989).

10.1.2.4 Selection on Multivariate BLUP

BLUP and index selection are similar in theory for multiple-trait selection; both are Best Linear Prediction methods and allow for prediction of breeding values based on combinations of information from different traits. The BLUP approach differs from index selection in two aspects and is generally superior to index selection:

- Index selection uses the same vectors and matrices for all candidates and therefore develops a single set of coefficients for all candidate trees (Eq. [4-8], Appendix 4). This is not desirable when data are highly unbalanced. Trees are more likely to be selected from families with few trees than from families with many trees, owing to a larger error of prediction associated with the smaller families (White and Hodge 1989). In contrast, BLUP accommodates imbalance of data by developing a different set of coefficients for each candidate tree. Hence, index selection is a special case of BLUP.
- Index selection procedure assumes that all records are well adjusted without error for identified systematic effects, such as site, age, or generation. This is rarely the case in forest genetic trials; check lots

may be absent, the families in a given test may not be a random sample from the base population, generations may not be distinct, and so forth. BLUP is essentially an extension of index selection but allows for estimation and adjustment for systematic effects simultaneously with prediction of breeding values.

Multivariate BLUP is the most flexible and powerful approach to analyzing forest genetic trials, yet it is usually difficult to model, implement, and interpret. It has only become feasible with the recent advances in computing technology and software development (Jarvis et al. 1995; Mrode 2005; Gilmour et al. 2006).

10.1.3 General Comments on Selection Methods

Wood quality traits, such as SG, stiffness, and MFA, usually have higher heritability, yet are more difficult and expensive to assess than growth traits (Zobel and van Buijtenen 1989; Johnson and Gartner 2006). The choice of selection methods will influence the gain obtained both in the short and long term. Tree breeders may need to consider the following tactics:

- (1) including only a few of the most important economic traits;
- (2) using indirect selection to shorten the breeding cycle—this includes early or juvenile selection; selection by new evaluation techniques, such as SilviScan, IML hammer, TreeTap, Director ST300, HM200; and marker-aided selection; and
- (3) effectively combining family and individual information on all traits by using selection index/BLUP techniques.

10.2 DECIDING WHETHER TO MAINTAIN OR AIM TO INCREASE WOOD STIFFNESS

Forest growers will need to decide whether maintaining wood stiffness in the breeding/orchard populations is adequate or whether wood stiffness needs to be increased. The former can usually be achieved by culling selections of particularly low stiffness or using a restricted selection index (Cunningham et al. 1970); the latter will require more priority on stiffness and will have a greater negative impact on volume gain. Apiolaza (2007) raised two interesting points relevant to selecting Douglas-fir for stiffness. First, even when there are price premiums for increased wood quality, they are not linear—i.e., there is a high financial value for going above a certain quality threshold, but little reward beyond that. Second, screening out low wood-quality genotypes is often easier than bringing in new genotypes.

10.3 OPERATIONAL SCREENING OF FIRST-GENERATION AND SECOND-CYCLE TESTS

First-generation tests in the region range from 40 to 15 yr. They are at an age where meaningful stiffness data can be obtained; trees can be felled if needed to measure acoustic velocity in logs. There would be some challenges, however. First, most of these tests have been thinned at least once, so relatively few trees per family will be present on a site. Second, locating trees could be difficult in some cases, due to thinning, loss of tags, and map errors. Third, most of the trees have probably grown under moderate to severe competition for many years, affecting radial growth and, thereby, wood properties.

Cooperative second-cycle tests in the region range from age 10 yr to recently planted. These contain most of the entries of interest to applied tree improvement (as parents or progeny), are routinely monitored, and are free of excessive inter-tree competition. The intent, however, was to include only parents (or forward selections) from the top 10% of families based on growth rate in first cycle tests. In practice, because data analysis and selection strategies have changed over time, some of the selections crossed to establish second-cycle tests came from families considerably below a top 10% threshold for age-15 volume gain predicted by BLUP. If cooperators want better selection intensity for wood stiffness and are willing to accept lower gain for growth, they may decide to assess selections with lower growth rankings in the first cycle tests.

10.4 HANDLING WOOD STIFFNESS THROUGH THE PRODUCTION POPULATION (SEEDLOTS)

One way to address stiffness issues is by carefully screening the existing breeding population, selecting parents with desired stiffness properties, and collecting seed from such parents or establishing new seed orchards. In this model, there would be no attempt to modify the overall stiffness in the breeding population; instead, the high genetic variation that occurs in such populations is utilized. The advantage of this approach is that no separate breeding population focusing on stiffness would be established; it would be an effective strategy at this stage of tree improvement, since there are still many first-generation and second-cycle selections to choose from.

It is fair to point out, however, that, in the long run, potential gains obtained this way would not be as high as is possible where wood stiffness becomes a trait actively selected for in the breeding population. If selecting for wood stiffness from the current programs were practiced for many cycles, effective population size of high-stiffness seedlots could decrease because, if there is no improvement (or a decline) in the average stiffness value of the breeding

population, eventually fewer parents in the population will be able to deliver high stiffness gains. Given the long breeding cycles and even longer rotations, it would be many decades before the effects of such declines would be apparent.

10.4.1 Open-pollinated or Control Mass-pollinated Lots in Existing Orchards

Collecting open-pollinated seed by parental clone has become routine in the PNW. It would be quite feasible to combine seed from high-stiffness parents in existing orchards and generate high-stiffness seedlots, and very little additional expense would be incurred. This would be an effective short-term strategy for delivering stiffness gains immediately. Because the resulting high-stiffness seedlots would be collected from a subset of orchard parents, however, it comes at the cost of a lower diversity than the orchard was designed to maintain. This strategy may not be useful in the long term unless landowners are prepared to change their standards for maintaining diversity or plan to deploy such seed only on select sites.

There have been some efforts to produce control mass-pollinated (CMP) seed in the PNW in the last 5 yr. It would be quite feasible to produce specific crosses between high-stiffness parents, and the expected stiffness gains of such crosses and seed lots would be greater than from open-pollinated seed from such parents. The added costs for such CMP seed is likely to be at least \$500/lb (over and above open-pollinated seed); however, given that a pound of seed can result in 16,000 plantable seedlings, this could reforest 40 ac for an added cost of \$12/ac.

10.4.2 Establishing New Orchards

New seed orchards are established in the PNW every year, and it would be relatively straightforward to establish orchards with parents specifically selected from the first-generation or second-cycle populations for high wood stiffness. These orchards could be established within the next few years and can be expected to start producing small amounts of seed about 5–6 yr after grafting and large amounts after about 10 yr. Establishing new orchards with an adequate number of parents would address the question of reduced population size mentioned above.

10.5 CREATING A HIGH-WOOD-STIFFNESS POPULATION IN THE THIRD BREEDING CYCLE

Organizations that find that the natural variation in stiffness in the breeding population is inadequate and wish to shift the population mean could establish a separate high-stiffness elite population, along with the normal growth and form populations. This kind of elite population has been established for some pine species.

The highest level of commitment to wood stiffness would be changing the emphasis of the entire breeding program in the third cycle, from growth rate, form, and adaptability (as in the first and second cycles) to wood stiffness, without attempting to obtain additional large gains in growth rate in the third cycle.

II. INCORPORATING STIFFNESS INTO DOUGLAS-FIR IMPROVEMENT IN THE PNW

II.1 WHAT ARE REASONABLE GOALS FOR STIFFNESS?

It is important to have clear, well-reasoned, achievable, and measurable goals. For example, “keep stiffness similar to woodsrun (= unimproved seed)” is perhaps clear, achievable, and measurable. Yet it may not be meaningful and sufficient if stiffness is being decreased by other factors (shorter rotations, wider spacing, and so forth).

The current lumber grades have been in place for many years; although the grades may not be perfectly correlated with MOE, no major problems have been reported by end-users. We do not hear, for example, that current builders and homeowners are dissatisfied with the stiffness of construction Douglas-fir framing lumber. As described previously, design values for lumber are obtained by testing agencies, the design values are used to establish building codes, and lumber grades are linked to expected design values.

As mentioned earlier, the likely rotation age for industrial wood is on the order of 40 yr; state and federal agencies and some private growers may hold the trees for as long as 60 yr. The No. 2 grade in four “Douglas-fir/Larch” categories (Structural Light Framing; Structural Joists & Planks; Timbers, Beams, and Stringers; and Studs; both dry and green) totaled 1,875,343 MBF in 2006. These categories comprised 44.2% of the total Douglas-fir production reported in WWPA (2006) and had added value. The average weighted price for this volume was \$378/MBF, compared to \$361/MBF for the total Douglas-fir volume. This grade is expected to have a base MOE

value of 1.6 million psi (Cheung 2002; WWPA 2005a,b), close to the reference number for Douglas-fir (1.56 million psi; Table 5-3b, Green et al. 1999). We therefore propose as a preliminary estimate, to be evaluated and modified later, that the breeding goal for Douglas-fir in the PNW should be to approach an average whole-tree bending stiffness MOE of 1.6 million psi (10.34 GPa).

Note the following:

- This average level of stiffness is quite feasible, as evidenced in the fact that 51% of Douglas-fir being produced already meets or exceeds this standard⁶.
- If the entire breeding or orchard population meets this goal, some genotypes will be stiffer than others.
- The older trees are allowed to grow before harvest, the less we would need to emphasize genetic selection for stiffness to meet this goal. If landowners wish to produce an average stiffness of 1.6 million psi at age 35 or 40 yr, stiffness will need to be a high priority in the breeding program; if rotation age is 70 yr, it probably won't need to be.
- Individual landowners could set their targets even higher than this goal of 1.6 million psi and aim for other products (for example, 1.8 million psi to meet the 1800f-1.8E MSR grade), but the higher the goal is set, the less likely it will be met and the greater the loss in gain for volume growth. For example, only 6.8% of the 2006 lumber production fell in the No. 1 or Select Structural categories (WWPA 2006), meeting or exceeding 1.7 million psi; setting the overall breeding goal at that value seems quite unrealistic and unachievable.
- Selection for stiffness in the tree improvement program will still need to be coupled with segregation of logs, boards, and veneer sheets on the basis of stiffness in order to use the resource efficiently and profitably: there will still be variation in stiffness among trees in a stand, from pith to bark at a given height in a tree, and from the base to the top of a tree.
- The higher value products will probably still generate a disproportionately high share of the profit: for example, the 6.8% of wood in the No. 1 and Select Structural category averaged \$456/MBF (WWPA 2006), and average MSR lumber prices for 2006 were \$493/MBF for 2400f 2 × 6 and \$537/MBF for 2400f 2 × 4 (data provided by Steve Gennett, Random Length Publications, Inc); these

⁶ Adding the categories (No. 1, Select Structural), which exceed the design values of No. 2, we find that 51.0% of the 2006 Douglas-fir production fell in the No. 2 & Btr, No. 1&Btr, or Select Structural categories (WWPA 2006). The total value of these categories was \$840,653,493.

were considerably higher than the \$361/MBF for the total Douglas-fir production (WWPA 2006)

11.2 FUTURE AND ANTICIPATED IMPLEMENTATION OF SELECTION FOR WOOD STIFFNESS

In every likelihood, stiffness will be incorporated into the Douglas-fir genetic improvement program in the PNW within the next few years. Several ways this could occur are described in this section.

11.2.1 Selection Criteria

The selection criteria used in operational tree improvement are likely to be one or several of the following measurements taken on standing trees: (1) acoustic velocity, (2) SG, and (3) an index of branch size and frequency.

11.2.2 Genetic Materials and Sampling Procedures

The materials would be progeny growing in either first-generation or second-cycle progeny tests, with the focus both on ranking the parents and evaluating forward selections. Optimal strategies to sample both first- and second-generation tests (paying particular attention to genotypes common to both generations) and to combine their data will need to be developed. It is likely that only a subset of the families in a given series, meeting some threshold of growth rate, form, and tree health, will be assessed. The number of sites to sample per test series will need to be determined; assessment will probably occur on no more than four sites, given that genotype \times environment interaction is low to moderate for wood properties. Some measure of “unimproved base population” will be required (a sample of families, or a true woodsrun checklot).

The number of trees per family that will need to be assessed for stiffness is not fully determined. Since individual-tree heritabilities for wood traits are higher for height or DBH, the number of trees to be sampled will be less than the number assessed for those traits (around 100 trees/family in first-generation Douglas-fir tests). On the basis of previous work on several species, we could envisage 25 trees as an upper limit of the number of trees that would need to be sampled per family. Although many past studies were based on assessing multiple locations per tree, we will need to establish if that procedure is appropriate for breeding value estimation—for example, whether there is more benefit in sampling more trees per family than sampling multiple locations per tree. Work is underway to establish efficient sampling strategies for Douglas-fir (M Cherry, unpublished data).

11.2.3 Age of Assessment

We can be confident of ranking older trees (>20 yr or older) effectively. At this point, the minimum age for ranking is not clear. We have very little information on whether trees as young as 9 or 10 yr can provide meaningful stiffness data or be sampled efficiently—a 9- to 10-yr-old Douglas-fir tree is much smaller than an 8-yr-old radiata or loblolly pine. The most obvious short-term solution is to assess stiffness early, at about age 10 yr, and reassess about 5 yr later; this is the same approach used for growth and form (first measurement around age 7 yr and a second measurement at around age 12 yr). One advantage of assessing small trees is that the variation in standing-tree acoustic velocity between different sides of the tree appears to decrease (for example, Toulmin and Raymond 2007), so assessing one location per tree may be adequate.

We also still lack evidence of genetic correlation between MOE in juvenile wood and mature wood. If the correlation is low, early selection for MOE could yield substantial gain in MOE in juvenile wood, but only small gains in MOE in mature wood. Because of apparent low genetic correlation between corewood MOE and outerwood MOE in radiata pine, high age-age genetic correlation for DEN, and strong correlation between DEN and MOE in the outerwood, Kumar et al. (2006) suggested using combined selection for corewood DEN and MOE, with the objective of increased gain in both corewood and outerwood MOE.

11.2.4 Adjusting for Knots

Another question is how to adjust for the presence of knots, especially in young trees in which knots could be a very large proportion of the stem cross-sectional area near branch whorls. It is encouraging that velocity measured on 5.8-yr-old hybrid pine was very strongly correlated with static bending MOE of boards when the same trees were 6.8 yr old (Harding et al. 2007). The trees were 150–233 mm diameter under bark at breast height. Chauhan and Walker (2006) found that the Fakopp standing-tree time-of-flight tool generally provided reliable data despite the presence of knots, because the leading edge of the propagating wavefront bypasses knots in branch whorls reasonably rapidly. More research is needed in this area.

If it is established that knots will hinder the ranking of second-cycle Douglas-fir progenies, a subset of second-cycle tests (after the second growth measurement around age 12 yr) could be pruned to 2 m from the ground (at least on one side of the tree) and remeasured after some period (for example, 5 yr) adequate to allow the formation of some wood at least partially clear of knots. Thinking one step further, we could consider establishing one or

two sites in the third cycle with perhaps 10–12 trees per cross, at wider (for example, 10-ft) spacing, and pruning them early (for example, age 7 yr) to about 6 ft height, specifically for acoustic velocity assessment.

11.2.5 Data Analysis and Interpretation

It is now customary in cooperative Douglas-fir improvement programs to present genetic worth as predicted genetic gains. The same can and should be done for the component traits of wood stiffness. Ideally, we will reach a state of sophistication where gains for individual traits (for example, SG and acoustic velocity) can be combined and extrapolated to provide a value that is meaningful to users (for example, whole tree stiffness at age 40 or age 50 yr).

12. KNOWLEDGE GAPS ABOUT DOUGLAS-FIR WOOD STIFFNESS AND FUTURE RESEARCH NEEDS

If growers in the PNW are serious about managing wood stiffness in planted forests in a scientific and data-driven way, we feel that many information gaps need to be filled, in addition to getting good estimates of stiffness breeding values. Several of these are discussed below.

12.1 ENVIRONMENTAL TRENDS IN STIFFNESS

There is every reason to believe that trends in stiffness will be associated with environmental clines. Douglas-fir is grown from sea level to 5,000 ft elevation, and there is likely to be an elevation trend, whether strong or modest, for wood stiffness. Douglas-fir is also grown in a wide rainfall gradient, from as little as 20 in./yr with a pronounced summer drought to over 100 in./yr. There are also possible local “hot-spots” for high or low stiffness.

We see a strong rationale for a regional synthesis of information on stiffness, perhaps based on a comprehensive regional study. The one precursor to such a study, the Western Wood Density Survey, is long outdated, referring to a resource comprising second-growth stands that regenerated naturally in the late nineteenth and early twentieth centuries and are no longer being harvested. The Stand Management Cooperative based at the University of Washington would be one entity that might conduct this type of regional study. Such information should be fed into regional growth models within a short period, as discussed below.

12.2 BREEDING VALUES FOR STIFFNESS

As discussed in detail in this document, knowing the stiffness breeding values of the key genotypes used in seed production would be useful for forest growers. Part of that breeding value prediction will include relating nondestructive measures of stiffness, especially young trees in second-cycle tests, to meaningful measures of lumber stiffness.

12.3 ECONOMIC WEIGHTS

As with any multi-trait selection effort, breeders will require economic weights for stiffness (and other traits) in order to allocate appropriate emphasis on each trait. The information required for economic analysis includes: (1) future needs over the next one or two rotations; (2) the degree of improvement feasible through tree breeding and the associated cost; (3) the increased value of the final product; and (4) the costs and benefits of tree breeding compared with alternative methods.

12.4 GROWTH-AND-YIELD MODELS TO PREDICT STIFFNESS IN PLANTED FORESTS

Forest managers in the PNW depend increasingly on growth models and decision support systems to make decisions. This is partly because they are operating with an increasingly leaner workforce, and partly because without such models and support tools, it is otherwise very difficult to account for complex information from multiple sources. For example, consider that stiffness could be affected by (1) age of tree, (2) location of stand, (3) site productivity, (4) planting density and subsequent thinning (mainly due to effects on knot size and ring width), or (5) stiffness breeding value. It would be very difficult, if not impossible, to combine all such information without good models.

12.5 WITHIN-TREE TRENDS FOR STIFFNESS

As discussed, there are substantial within-tree trends in stiffness (pith-to-bark and base to top). If good information on those trends is combined with sawmilling simulators and models of branch frequency and size, we can envisage models predicting the output of sawn lumber of various stiffness grades, and so forth. Combined with the projections from growth-and-yield models, we could then make reasonable projections of wood production by various lumber grades from a stand, forest, or plantation base.

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UNIT CONVERSIONS

1 acre (ac) = 0.4047 hectare (ha)
1 inch (in.) = 2.54 centimeters (cm)
1 foot (ft) = 0.305 meter (m)
1 ft² = 0.093 m ²
1 ft³ = 0.028 m ³
1 board foot (bd ft) = 2.36 cubic decimeters (dm ³)
1 pound (lb) = 453.6 grams (g)
10⁶ lb/in.² (psi) = 6.894 gigapascals (GPa)

GLOSSARY OF TERMS

TERM	DEFINITION
Density (DEN)	The mass or weight per unit volume at a given moisture content, usually expressed in kg/m ³ , g/cm ³ , or lb/ft ³ (Bowyer et al. 2002)
Dynamic modulus of elasticity (MOE)	Estimated as MOE = (density)(stress wave velocity) ² (Pellerin and Ross 2002b)
GPa	Gigapascals
Heritability (<i>h</i> ²)	The ratio of genetic variance to phenotypic variance, used to measure the degree to which progeny resemble their parents. Narrow-sense heritability refers to the additive part of genetic variance; broad-sense heritability considers all genetic variance
Index selection	Selection that combines phenotypic information optimally on the basis of the economic values of the traits and their heritabilities and genetic correlations
MBF	Thousand board feet
Lift	One pruning event, generally removing a whorl or a year's production of branches. Due to the need to (1) retain adequate live crown while (2) pruning early enough to allow clearwood to form, it is not possible to complete pruning a tree in one event
Microfibril angle (MFA)	The orientation of cellulose microfibrils in the S2 layer; the second and thickest layer in the secondary cell wall of a wood fiber (Fibers are made up of a primary and secondary cell wall; the latter is composed of three layers)
Type A correlation (<i>r</i> _A)	Genetic correlation of different traits measured on the same trees
Type B correlation (<i>r</i> _B)	Genetic correlation of the same trait measured at different sites. High <i>r</i> _B implies low genotype-by-environment interaction.
Selection differential	The difference between selected trees, families, or clones and the average of the population from which it was taken
Small clear	Small knot-free wood sample with wood grain parallel to the longitudinal direction, used in testing mechanical properties of wood
Wood specific gravity	The ratio of the density of wood to the density of water. It is always calculated from oven-dry weight and volume at a given moisture content (Bowyer et al. 2002)
Woodsrun seed	Seed obtained from trees with no history of genetic selection or genetic improvement. In the PNW this would typically be from naturally regenerated forests

APPENDICES

APPENDIX I: BASIC EQUATIONS DEFINING STIFFNESS

The properties of stiffness and strength together describe a solid material. Stiffness is a measure of how stiff or flexible a material is, whereas strength is the force or stress needed to break an object.

Stiffness is the slope of the stress-strain curve before the proportional limit. Axial stiffness is measured with either a compression or a tension test and Eq. [A1] below. Bending stiffness is measured with a three-point or four-point bending test and Eq. [A1-2a] or [A1-2b]:

Axial stiffness:

$$E = (P/\Delta)(L/A) \quad [A1-1]$$

where P/Δ = slope of load deflection curve before proportional limit
 L = specimen length over which deflection measurement was taken
 A = cross-sectional area of the specimen

Bending stiffness:

(a) three-point bending test

$$E = (P/\Delta)(L^3/4bh^3) \quad [A1-2a]$$

(b) four-point bending test

$$E = (P/\Delta)(23L^3/108bh^3) \quad [A1-2b]$$

where (P/Δ) = slope of load deflection curve before proportional limit
 L = test span
 b = specimen width
 h = specimen depth

With everything equal (size, loading configuration, applied loads, temperature, moisture content, and so forth), materials with high stiffness will deform less than materials with lower stiffness.

APPENDIX 2: SIZE AND USE CATEGORIES OF LUMBER IN THE PNW

Western solid-sawn lumber is grouped into three broad categories: framing (or structural lumber), which is graded for strength; appearance lumber, which is not graded for strength; and industrial lumber, which is generally graded for specific end uses or remanufacturing (WWPA 2005a). Commonly used size categories of visually graded lumber include

Boards	0.75–1.5 in. thick ≥2 in. wide
Dimension lumber	2–4 in. thick ≥2 in. wide

Several use categories are available within each main size category. We will focus on dimension lumber:

Structural Light Framing (SLF)	2–4 in. thick & 2–4 in. wide
Light Framing (LF)	2–4 in. thick & 2–4 in. wide
Studs	2–4 in. thick & ≥2 in. wide (length limited to 10 ft)
Structural Joists and Planks (SJ&P)	2–4 in. thick & 5 in. and wider
Decking (Structural or Commercial)	2–4 in. thick & 4 in. and wider
Timbers	
Beams and Stringers (B&S)	≥5 in. thick, >2 in. thick
Posts and Timbers (P&T)	≥5 in. thick, ≤2 in. thick

SLF is comprised of Select Structural, No. 1, No. 2 and No. 3; LF, of construction, standard and utility; SJ&P, of Select Structural, No. 1, No. 2 and No. 3.

APPENDIX 3. DETERMINISTIC SIMULATION OF CHANGES IN CORRELATED GAIN OF MOE AT AGE 25 WHEN SELECTING FOR TREE VOLUME AT AGE 15

The correlated response CR of the target trait, MOE25, through indirect selection on the measured trait, VOL15, can be expressed as

$$CR_{MOE25, VOL25} = i_{VOL15} r_A \sigma_{P(MOE25)} \sqrt{h_{MOE25}^2 h_{VOL15}^2} \quad [A3-1]$$

where

i_{VOL15} = selection intensity on VOL15

$\sigma_{P(MOE25)}$ = the phenotypic standard deviation of MOE25

r_A = genetic correlation between MOE25 and VOL15

h_{MOE25}^2 and h_{VOL15}^2 = heritability estimates (Falconer and Mackay 1996)

The selection response on VOL15, R_{VOL15} is expressed as

$$R_{VOL15} = i_{VOL15} \sigma_{P(VOL15)} h_{VOL15}^2,$$

where $\sigma_{P(VOL15)}$ is the phenotypic standard deviation of VOL15 and other terms are as defined previously.

Thus,

$$\frac{\Delta CG_{MOE25, VOL15}}{\Delta G_{VOL15}} = \frac{CR_{MOE25, VOL15} / \bar{X}_{MOE25}}{R_{VOL15} / \bar{X}_{VOL15}} = r_A \frac{CV_{P(MOE25)}}{CV_{P(VOL15)}} \sqrt{\frac{h_{MOE25}^2}{h_{VOL15}^2}} \quad [A3-2]$$

where \bar{X}_{MOE25} and \bar{X}_{VOL15} are population means and $CV_{P(MOE25)}$ and $CV_{P(VOL15)}$ are coefficients of phenotypic variation.

Although we lack comprehensive scientific data to choose the most suitable sets of parameters for Douglas fir, studies on different tree species have provided some useful information.

(1) Ratio of heritability: Cherry et al (2008) reported that MOE25 had higher h^2 than DBH25 in Douglas fir

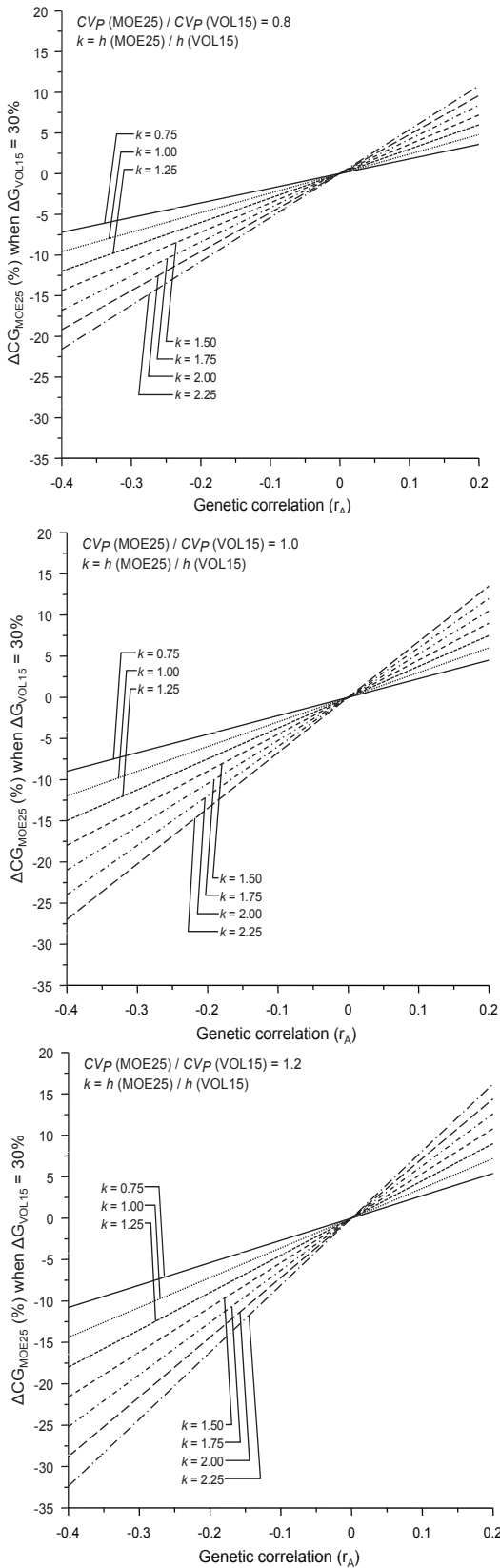


Figure A3-1. Correlated response in age-25 stiffness from selection on age-15 volume, for various combinations of assumed genetic parameters and assuming a 30% genetic gain in volume at age 15.

($h_i^2 = 0.31$ and 0.18 , respectively; $h_f^2 = 0.53$ and 0.40 , respectively). Johnson and Gartner (2006) also showed higher h_i^2 of MOE20 (0.55) than of DBH20 (0.25). Given the age difference (25 for MOE vs. 15 for VOL), the difference in h^2 between MOE and VOL is expected to diminish. NWTIC data showed that h^2 for growth traits usually increases with age (e.g., a 28% increase from age 15 to age 24 in the Sunday Creek 1st-generation testing program). On the other hand, the h^2 for MOE is likely to decrease with age. According to Kumar et al. (2006), h^2 for MOE decreased from 0.29 at age 11-15 to 0.18 at age 21-25 in radiata pine.

(2) Ratio of coefficient of phenotypic variation (CV_p): This parameter has seldom been reported in the literature. Cherry et al. (2008) reported similar CV_p for MOE25 and DBH25 (0.54 vs. 0.60).

(3) Genetic correlation (r_A): Diverse results have been reported, ranging from -0.5 to 0.1 between MOE and DBH at age 24-29. The r_A estimates in the literature are likely to overestimate the r_A relevant to our question for three reasons:

- they are usually made for the same age (e.g., age 8 in radiata pine), whereas the r_A of real interest is between selection-age volume and rotation-age stiffness;
- they are usually for the stiffness at breast height, while the r_A of real interest is with whole-tree stiffness;
- height is rarely measured, and the r_A of stiffness with DBH is likely to overestimate the r_A of stiffness with volume.

We used three combinations of parameters: ratio of heritability from 0.75 to 2.25, ratio of coefficient of phenotypic variation from 0.8 to 1.2, and genetic correlation from 0.2 to -0.4. The results are shown in Figure A3-1.

APPENDIX 4: DETAILS ON GENETIC GAIN ESTIMATION

MASS SELECTION:

The genetic gain ΔG from mass selection can be predicted with the following equation (Falconer and Mackay 1996):

$$\Delta G = h^2 S = i h^2 \sigma_p \quad [A4-1]$$

where h^2 = the estimate of individual-tree heritability

S = the selection differential (the difference between the selected trees over the average)

i = the selection intensity

σ_p = the phenotypic standard deviation.

COMBINED SELECTION

The genetic gain from combined selection is expressed as

$$\Delta G = h_F^2 S_F + h_W^2 S_W \quad [A4-2]$$

where h_F^2 and h_W^2 are family-mean and within-family heritabilities, respectively, and S_F and S_W are family and within-family selection differentials, respectively.

BEST LINEAR UNBIASED PREDICTION (BLUP)

The fundamental framework for BLUP analysis is based on the general mixed model:

$$\mathbf{y} = \mathbf{X}\mathbf{b} + \mathbf{Z}\mathbf{u} + \mathbf{e} \quad [A4-3]$$

where \mathbf{y} is a vector of phenotypic values for a trait; \mathbf{b} is a vector of fixed effects; \mathbf{u} is a vector of random effects including breeding values; \mathbf{e} is a vector of residual deviations; and \mathbf{X} and \mathbf{Z} are incidence matrices relating a given phenotypic observation to its corresponding fixed or random effects. Solutions for fixed effects and random effects (including breeding values) are obtained by solving the mixed model equations (Henderson 1984):

$$\begin{bmatrix} \mathbf{X}'\mathbf{R}^{-1}\mathbf{X} & \mathbf{X}'\mathbf{R}^{-1}\mathbf{Z} \\ \mathbf{Z}'\mathbf{R}^{-1}\mathbf{X} & \mathbf{Z}'\mathbf{R}^{-1}\mathbf{Z} + \mathbf{G}^{-1} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{b}} \\ \hat{\mathbf{u}} \end{bmatrix} = \begin{bmatrix} \mathbf{X}'\mathbf{R}^{-1}\mathbf{y} \\ \mathbf{Z}'\mathbf{R}^{-1}\mathbf{y} \end{bmatrix} \quad [A4-4]$$

where \mathbf{R} is the variance/covariance matrix of the residuals and \mathbf{G} is the direct sum of the variance/covariance matrices of each of the random effects. Pedigree information of trees is embedded in the matrix \mathbf{G} .

INDIRECT SELECTION:

The genetic gain in the target trait from indirect selection on the measured trait, $\Delta G_{T.M}$, can be predicted as a correlated response:

$$\Delta G_{T.M} = i_M h_M h_T r_A \sigma_{p_T} \quad [A4-5]$$

where

- i_M = selection intensity on the measured trait
- h_M and h_T = the square roots of the heritabilities for the measured and target traits
- r_A = the genetic correlation between the target and the measured traits
- σ_{p_T} = the phenotypic standard deviation for the target trait.

SELECTION INDEX:

The theory of classical selection index has been well described in the literature (e.g., Henderson 1963; Lin 1978; Falconer and Mackay 1996). In short, the selection index (I)

$$I = \mathbf{b}'\mathbf{p} \quad [A4-6]$$

maximizes the aggregate breeding value (H)

$$H = \mathbf{a}'\mathbf{g} \quad [A4-7]$$

when the index weights are calculated by

$$\mathbf{b} = \mathbf{P}^{-1}\mathbf{G}\mathbf{a} \quad [A4-8]$$

where \mathbf{p} is a vector of phenotypic observations; \mathbf{b} is a vector of index weights; \mathbf{g} is a vector of unobservable genetic values; \mathbf{a} is a vector of economic weights; \mathbf{P} is a matrix of variances and covariances among observations; and \mathbf{G} is a matrix of covariances between observations and breeding value to be predicted.

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