GRADE RECOVERY, VALUE, AND RETURN-TO-LOG FOR THE PRODUCTION OF NZ VISUAL GRADES (CUTTINGS AND FRAMING) AND AUSTRALIAN MACHINE STRESS GRADES

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ABSTRACT

The objective of this study is to link radiata pine tree characteristics to the quality and value of boards in New Zealand (NZ) Cuttings, NZ Visual Framing, and Australian Machine Stress Grades (MSG) from both clonal and standing tree perspectives. Specifically, this paper presents an analysis of clonal variation in the quality and value of 2 × 4s, establishes the relationships between the tree and products characteristics, and documents the broad sense heritability of the tree variables associated with products value.

Ten clones were selected to cover a broad range of radiata pine representative of the forest being harvested in New Zealand in the coming years. Two trees were harvested for each clone. The trees were pruned up to 4 m. The stems were cut into logs, and four logs were cross-cut to be sawn: the pruned butt log and three unpruned. The yield analysis was performed separately for pruned and unpruned logs. Tree quality assessed included DBH, Branch Index, Internode Index, bulk density, outer wood density (from increment cores), ring width, microfibril angle, spiral grain, tracheid length, and compression wood. On the lumber pieces, knot area ratio was also assessed.

The value of boards in NZ Cuttings from pruned butt logs averaged 310 $\$/m^3$ as compared to 204 $\$/m^3$ for unpruned upper logs. These were significant differences between clones for pruned butt logs and for the boards from unpruned upper logs. Regression analysis confirmed that for NZ Cuttings, small trees with lots of small branches perform badly when compared to large trees with larger branches. Regression analysis also showed that for boards from unpruned upper logs, the longer the internode length, the better the yield in NZ Cuttings.

The value of boards in NZ Visual Framing from pruned butt logs averaged 333 $\$/m^3$ as compared with 227 $\$/m^3$ for unpruned upper logs. There was no significant difference between clones for boards from the pruned butt logs (P = 0.12), but there were highly significant differences between boards from unpruned upper logs. Regression analysis showed that best performing clones among the unpruned upper logs were the ones with small branches.

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The value of the boards in Australian MSG from pruned butt logs averaged 217 $/m^3 as compared with 197 $/m^3 for unpruned upper logs. There were significant differences between clones for the boards from the pruned butt logs but not for the boards from unpruned upper logs. Regression analysis failed to show any relationship between the tree characteristics and value in Australian MSG. As expected, a significant relationship was established between the modulus of elasticity of 2 × 4s and wood density, knot area ratio and ring width.

It would be worth examining more clones because it is likely that specific individuals would have all the favorable characteristics in a manner that would make them outstanding. These clones could then be used in a breeding program. This would, however, require a considerable effort. Tests on heritability showed that the tree characteristics that have a bearing on product value seem to be heritable and in particular can be bred for producing higher value structural products.

Keywords: *Pinus radiata,* clones, internode, branch, density, NZ Cuttings, NZ Visual Framing, Australian Machine Stress Grade, product value.

INTRODUCTION

This research is part of a larger study with the overall objective of optimizing manufacturing technologies to improve recovery from radiata pine (*Pinus radiata,* D. Don) logs and enhancing product values. Specific objectives of this paper were:

1. to analyze clonal variation in the quality and value of 2 × 4s in the following products: New Zealand (NZ) Cuttings, NZ Visual Framing, and Australian Machine Stress Graded (MSG);
2. to explore the relationships between products value and tree characteristics;
3. to report on the heritability of tree characteristics that have a bearing on intrinsic product value.

The three products were chosen because they represent a large proportion of the softwood lumber produced in New Zealand. Also, they are of three different types (one appearance grade, one structural grade determined visually, and one structural grade determined by machine testing), which allowed us to establish the relationships between these different grading methods and the tree characteristics. It is believed that the fundamental relationships would apply for other grading rules of the same generic type—U.S. MSR grades, for example.

To achieve these objectives, a comprehensive assessment of wood quality, tree and log characteristics was performed. After sawing, the evaluation of product characteristics, grade, and value was performed. Similar goals were pursued in the past using similar methods as reported in Shelbourne et al. 1973; Bier 1985, 1986; Haslett et al. 1991; Briggs 1992; Palmer et al. 1996; and Houllier et al. 1995, but never were so many variables considered simultaneously for radiata pine. Previous studies were done either at the board level or they related log characteristics to board performance. This trial tracked the relationships between whole trees of known qualities and genotype to product characteristics and value. A green lumber value FOB at the mill was allocated to each grade, and the clonal variation in the value of the output and also the monetary return-to-log were analyzed for each product.

METHODOLOGY

Sample material

A large proportion of the future forest establishment in New Zealand will be from progeny of the best seed orchard clones. This select group of parents is different in terms of growth and form from that currently being utilized by industry. It is known that intrinsic wood properties vary widely between clones; we actually know, for example, how wood density and branch cluster frequency vary in different seed orchard seedlots. Little is known, however, about how this variation can be used to any advantage during solid-wood processing.

The trees for these studies were selected to span a range of qualities typical of the crop being harvested now and in the near future. An additional requirement was the need to sample matching stems for the various processing pathways to be investigated, particularly Saw-Dry-Rip and cant sawing. A unique early clonal test in Compartment 1350 of Kaingaroa Forest, located in the Central North Island of New Zealand, planted in 1968, had the capability of providing several stems for each of several genotypes (clones). This stand had the required characteristics for the study, i.e., it was sufficiently large and mature.

The clonal trial was established with 216 clones that had been selected for high wood density; 500 trees were originally selected at a low intensity for vigor and stem straightness from two Kaingaroa Forest compartments (Cpt 12396, age 6 and Cpt 1301, age 5 from planting); their densities were assessed *via* increment cores. The lower density half of this group were discarded, and cuttings were collected from the remainder. These compartments had been planted with "felling select" seedlots with growth/form (GF) index rating of about 3. The GF index is indicative of the gain in growth and form obtained from the genetic improvement program when compared with the original radiata pine stock. A GF value of 3 corresponds to the level of genetic improvement obtained in the early sixties. The clonal test was established with 216 clones in June 1968 (Compartment 1350), consisting of open-rooted 1/1 cuttings. The mean density of the higher density ortets, the parent material from which clones are vegetatively propagated, with 331 kg/m^3 versus the mean of all 500 trees of 316 kg/m^3. One hundred seventy-five of the faster growing clones still remain and of these, 46 clones had adequate replication for study purposes (5 or more trees available for selection). Tree selection excluded smaller stems (DBH < 300 mm).

At the time of sampling, the stand was 27-years-old. Silvicultural regime was: establishment at 1,370 stems per hectare (spha); waste thinning initially to 700 spha (7 yr); and later (13 years) to a nominal stocking of 350 spha; pruning was performed in two lifts, first at age 4 and second at age 7, up to 4 m. The regime described is not representative of usual forest practice, but facilitated attainment of research priorities while maintaining tree growth and form. Nevertheless, according to the NZ Forest Research Permanent Sample Plot database (Dunlop 1995), the average final stocking in Kaingaroa Forest at the time was of 318 spha and ranged from 30 to 1,492 spha, which points to a wide variation in silvicultural regimes.

Ten of the 46 available clones were selected to cover a range of diameter at breast height (DBH), internode length, branch size, and outerwood density at breast height. Since they do cover a range of tree characteristics, the selected clones are believed to be representative of the main body of the population as well as of more extreme values of stem parameters present in current plantations.

In November 1995, at age 27 years, two replications (trees) of each of the 10 selected clones were harvested, resulting in a total of 20 trees. The two replications were needed so that each clone could be processed by two different sawing strategies (Saw-Dry-Rip and Cant).

Log making and sawing.—Four logs were cut from each tree; these included the pruned butt log, the second log, one intermediate log, and the top log. The pruned butt logs were, on average, about 4 m long, and the rest of the remaining unpruned upper logs were about 4.9 m long. A top log from one tree was not suitable for sawing, since it was too small and crooked, and one extra intermediate log was taken from two trees. This resulted in 20 butt logs, 20 second logs, 22 intermediate logs, and 19 top logs—a total of 81 logs. The analyses were performed separately on pruned butt logs and on the unpruned upper logs. The two log types were considered to be materials different in nature. It is well known that after a pruning treatment, trees grow clear wood on the pruned log. For this reason, it would not make sense, for example, to compare visual grade yield from pruned versus unpruned logs.

The first 40 logs (one tree from 10 clones)

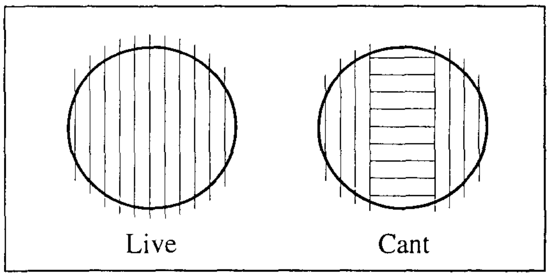

FIG. 1. Live and Cant sawpatterns.

were live-sawn into boards 40 mm thick, dried, surfaced on both sides, and then ripped to the 100- by 40-mm dimensions, equivalent to U.S. 2 × 4s (Fig. 1). This method, referred to as Saw-Dry-Rip, aims at reducing drying degrade. The second 41 logs (second replicate set of 10 clones) were cant-sawn by flat sawing 40-mm boards, leaving the central cant. Logs with small end diameter between 200–300 mm were sawn with a 100-mm cant and larger logs with a 200-mm cant. The cants were reduced to 100- × 40-mm Australian structural stock before drying. Comparisons of yield differences between the two sawing methods are not made in the present paper. Logs sawn by the two methods in this trial were considered to be "replicates," although they were different. They were pooled together in order to get clonal repetitions. Comparisons were then made between clones.

The logs were processed at Vanner Sawmill at Reporoa, New Zealand. All boards were dried in a commercial dry kiln on a high temperature schedule (120°C) and surfaced to allow for defect assessment and grading.

The information about the clone, tree, log position within a tree, board location within a low, sawing strategy, board grade, board dimensions, and defects were entered into a computer database.

Tree characteristics.—Some tree or clone traits are known to impact the quality of appearance and structural boards. Gazo et al. (2000) showed that Diameter at Breast Height (DBH), Branch Index (BIX), and Internode Index (IIX) can be used to predict characteristics of appearance boards. Outerwood density is often used for screening between high density and low density trees. The relationships between outerwood density and tree density patterns are also relatively well understood. Each tree was assessed for these variables. While DBH was measured on standing trees, the branch index (BIX) and internode index (IIX) were measured on each log and averaged on a per tree basis once the trees were felled and cut into logs.

The BIX is the average size of four branches per log, using the largest branch in each quadrant. The IIX is the sum of length of internodes of 0.6 m or longer, expressed as a fraction of the log length (Whiteside and Manley 1987). When the trees were cut into logs, the dimensions of each log were recorded (small end diameter, large end diameter, and length). The tree volume was then calculated using the sum of log volumes from each tree. The variation of tree characteristics and their bearing on the product's characteristics were analyzed across the clones.

Wood quality.—At the time of felling, disks were collected at the stump and then from the top of each log. These disks were used to determine corewood size (ten inner rings), basic density, and spiral grain. Basic density was measured on five ring groups, spiral grain was measured on two diametrically opposed radii (Young et al. 1991) where measurements were taken at every alternate ring from the pith. Compression wood was visually assessed as the percentage of each cross-section that was affected.

Pith-to-bark samples were also removed for X-ray densitometry, and for the measurement of tracheid length and microfibril angle. X-ray densitometry provided ring width and wood density measurements for each growth ring. Tracheid length was measured for rings 2, 5, 10, 15, 20, and 25 using the methods described by Harris (1966). Microfibril angle was measured on samples taken from ring groups 1–5, 6–10, and the outermost five rings; and 25 macerated tracheids were measured in each sample (George and Donaldson 1996).

In order to obtain per tree values for these wood quality variables, the disk measurements were used to compute log values, weighting the contribution of the disk size, and then the log values were given weights and averaged to yield a tree average. The wood quality assessment of the material in this trial is described in a comprehensive manner in McKinley et al. (1996).

These wood quality variables were allocated to each board for the purpose of performing analyses at the board level. To do so, the corewood percent of each board was used. On each log, the corewood zone (10 inner rings) had been identified on both ends using color paint. The corewood percent of each board was considered to be the average of the fraction of color paint on each end of the board. Boards, that had no paint at either end, were allocated the wood quality values of the mature portion of the log they originated from. Boards with a proportion of corewood and outerwood were allocated the average wood quality values of rings 5 to 15. Boards from 100% corewood but without pith were allocated the average wood quality values of rings 1 to 10. Boards with pith were allocated the average wood quality values of rings 1 to 5.

Board assessment and grading

After ripping, all the 100- × 40-mm lumber was graded to the New Zealand Cuttings grade, to the New Zealand Visual Framing grade (NZS 3631-1988, SAA 1998), and to the Australian Machine Stress Grade (AS 1748-1997, SAA 1997). Clear-cuttings greater than 0.3 m long were recorded for each individual timber length. Structural grades were allocated by experienced graders and the Cuttings grades were allocated by a computer based on the proportion of clear-cuttings. For NZ Cuttings grades, a nonstandard No. 3 Cuttings grade was assigned to boards that did not make a standard lowest grade of No. 2 Cuttings. The No. 3 Cuttings grade is basically a finger jointing stock grade and it is commonly used in New Zealand sawmills.[1]

The following board characteristics were also measured: modulus of elasticity as a plank ($E_{p\,min}$); knot area ratio; bow; crook; and twist. E_p values were assessed using a Computermatic stress grading machine, and machine grades were allocated using the Australian Yellow Program Card, (Grant 1987). These measurements allow for the exploration of more fundamental relationships between tree and products characteristics.

Value of the products

In order to estimate value of products generated by each clone, a dollar value was allocated to each grade of timber. The NZ structural timber and clear visual grade values came from TIF (Timberfed News 1996). The NZ Cuttings were obtained from a telephone survey of three suppliers and five customers. Australian MSG prices were based on a John Cook and Sons F5 price; prices of F4, F8, and F11 grades were based on differentials provided by the QFRI.[2] In order to transform these Australian FOB prices to New Zealand FOB mill prices, the following operations were performed: 1) AUS$60/m^3 was deducted for trans-Tansman freight; 2) AUS$45/m^3 was deducted for drying; 3) AUS$25/m^3 was deducted for boron treatment and AUS$60/m^3 for CCA treatment; 4) AUS$25/m^3 was deducted for gauging; 5) AUS$15/m^3 was deducted for wrapping and shipping to the wharf; 6) the result was multiplied by 0.87 to convert from AUS$ to NZ$. For the rejected pieces (Box grade), a minimum value of AUS$150/m^3 was allocated if the value of any corresponding product was lower. These assumptions and calculations resulted in the prices shown in Table 1. Unless stated otherwise, all prices are in NZ$.

Two variables were used to assess the qual-

[1] Jost Siegfrield, personal communication, MOF, Rotorua.

[2] Graeme Palmer, personal communication, Queensland Forest Research Institute, Aus.

TABLE 1. *Lumber prices by category and grade.*

NZ grades for appearance lumber	Price green FOB mill ($/m3)	NZ Visual grades for structural lumber	Price green FOB mill (%/m3)	Australian MSG structural lumber	Price green FOB mill ($/m3)
Clear	550	Engineering	400	F11	300
No 1 Cuttings	380	No 1 Framing	350	F8	240
No 2 Cuttings	260	No 2 Framing	220	F5	210
No 3 Cuttings	200	Box	150	F4	150
Box	150			Box	150

ity of the output by each clone in terms of dollar value. The first variable, called value, is the sum of the individual values of all boards from a clone over the volume of those boards ($\$/m^3$—boards); it could also be called the intrinsic value of the products. The second, the return-to-log, is the sum of the values of all boards from a clone over the volume of logs constituting the tree ($\$/m^3$—logs). This latter variable corresponds to the intrinsic value multiplied by the conversion factor.

Statistical methods

Tree and clonal averages of value and return-to-log were calculated by weighting values from individual logs by their relative volumetric contribution in each tree. Analysis of Variance was used to establish differences between clones for the various traits. Once differences had been established between clones, regression analysis was used to explore the relationships between the value of the clones and trees characteristics. Broad sense heritability (h^2) of the relevant characteristics was estimated using the following relationship:

$$h^2 = \alpha^2_c/(\alpha^2_c + \alpha^2_e) \quad (1)$$

where α^2_c is the variance among clones and α^2_e is the variance of the residuals. The significance of this broad sense heritability was tested against the null hypothesis.

TABLE 2. *Tree characteristics by clone.*

Clone no.	Diameter at breast height (DBH) (cm)	Branch index (BIX) (cm)	Internode index (IIX) (%)	Volume (m^3)
1	51.1	4.9	14	3.046
2	48.0	4.8	59	2.516
3	61.6	5.2	7	5.264
4	42.0	3.6	19	2.174
5	46.7	5.4	47	2.936
6	42.2	3.5	16	2.330
7	32.7	3.3	0	1.080
8	44.4	4.0	12	2.237
9	37.7	3.3	0	1.588
10	60.5	6.5	59	4.142

RESULTS

The clone characteristics are presented in Table 2. Clone size varies between 32.7 cm in DBH and 1.080 m^3 in volume for clone 7 to 61.6 cm and 5.624 m^3 for clone 3. A wide range of variation can also be observed for BIX, from 32.6 mm for clone 7 to 65.0 mm for clone 10, and for IIX, from 0% for clones 7 and 9 to 59% for clones 2 and 10. The Maximum Defect Core values vary roughly in the same manner as DBH—the clones with the smallest and largest defect core are also the ones with the smallest and largest DBH. This variable is expected to be of importance in the yield of appearance grades from pruned butt logs. The table also shows the good correlation between visual and measured BIX's and IIX's. These variables will be used to explain differences between clones in intrinsic product value yield and return-to-log value yield among the various product types.

The wood properties are presented in Table 3. Wood properties varied widely between clones with heartwood content varying between 19 and 40%, corewood between 37 and 56%, density between 354 and 438 kg/m^3, spiral grain between 2.37 and 5.35°, tracheid

TABLE 3. *Summary of wood properties by clone.**

Clone no.	Heartwood (%)	Corewood (%)	Basic density (kg/m^3)	Spiral grain (°)	Tracheid length (mm)	Microfibril angle (°)
1	24	47	429	2.91	3.2	23.2
2	20	42	383	2.37	3.0	24.6
3	30	44	406	2.50	3.4	25.2
4	34	48	434	5.35	3.5	23.3
5	29	45	397	5.77	3.5	23.4
6	32	41	358	4.88	3.4	26.8
7	40	56	411	3.05	3.4	22.5
8	36	45	354	3.62	3.0	24.8
9	38	52	438	4.44	3.2	24.7
10	19	37	397	3.59	3.6	22.9

* Weighted average properties evaluated from disks taken at both ends of each log from each tree—2 trees per clone.

length between 3.0 and 3.6 mm, and microfibril angle between 22.5 and 26.8°. This amount of variation was important in order to get some discriminating relationships with the clone grade and product value yields.

Processing of the 81 logs from the 2 replicates of the 10 clones resulted in a total of 1,633 boards. From these, 1,321 were of the main product (100 × 40s) and the rest were by-products (75 × 40s and 25-mm boards) recorded for conversion purposes only. All boards constituted a total output volume of 26.2 m^3 from a log input of 42.7 m^3, for an overall conversion of 61%. The statistical analyses were performed on the main product only. The analyses were performed separately on pruned butt logs and unpruned remaining logs, which were considered to be a material of different nature. For the purpose of the assessment of differences between clones, the 2 trees sawn by two different sawing methods were considered to be two replicates of the same clone.

Conversion

Table 4 presents the conversion rates achieved at Vanner sawmill in this sawing trial. Conversion rates averaged 61% with individual logs ranging from 44.2 to 78.7%. As expected, larger trees achieved higher conversion rates, while smaller trees had lower rates. The extremes of conversion by clone are: clone 7 with 58.5% and clone 10 with 65.2%.

It must be noted, however, that the purpose of this trial was not to optimize volume recovery but rather to establish linkages between tree characteristics and quality and val-

TABLE 4. *Conversion from clone log volume to lumber volume.*

Clone	No. of trees	No. of logs	Log volume[a] (m^3)	Lumber volume[b] (m^3)	Conversion yield (%)
1	2	8	4.411	2.627	59.5
2	2	8	4.438	2.633	59.3
3	2	8	6.675	4.137	62.0
4	2	8	3.340	1.898	56.8
5	2	8	3.957	2.528	63.9
6	2	8	3.647	2.326	63.8
7	2	7	1.772	1.036	58.5
8	2	8	4.018	2.564	63.8
9	2	9	2.999	1.753	58.4
10	2	9	7.449	4.855	65.2

[a] Log volume estimated using the 3D formula (Ellis 1982).
[b] Lumber volume based on nominal length of boards to nearest 30 cm.

TABLE 5. *New Zealand Cuttings production: Grade distribution, intrinsic value (average value per m^3 of output) and return-to-log (value of output per m^3 of input).*

Clone	Grade (% of board by grade on a per tree basis) Clear	No. 1 Cutting	No. 2 Cutting	No. 3 Cutting	Box	Intrinsic value green lumber FOB mill ($/m³)	Return-to-log ($/m³)
Pruned butt logs (20 logs)							
1	17.88	16.24	19.97	29.96	15.95	297.60	179.20
2	16.64	34.41	6.79	31.34	10.82	320.90	199.20
3	39.24	25.15	6.36	17.81	11.45	375.10	243.10
4	17.01	13.20	14.21	41.12	14.47	288.00	175.30
5	39.80	18.04	0.00	36.08	6.08	369.00	255.00
6	10.92	28.78	10.92	32.77	16.60	288.70	227.00
7	9.81	0.00	0.00	54.21	35.98	208.50	117.20
8	28.35	18.64	13.59	22.91	16.50	331.90	225.30
9	0.00	24.19	13.17	27.96	34.68	234.40	173.70
10	39.96	26.60	13.25	12.82	7.37	391.00	270.20
Average	21.96	20.53	9.83	30.70	16.99	310.50	206.60
ANOVA[a]						$P = 0.003$**	$P = 0.001$**
Unpruned upper logs (61 logs)							
1	0.00	3.55	4.84	58.15	33.47	192.70	115.20
2	0.00	36.97	5.96	35.14	21.93	259.00	152.40
3	0.00	4.63	14.73	65.39	15.25	209.60	128.10
4	0.00	0.00	16.48	63.92	19.60	198.50	116.90
5	0.00	3.30	12.33	58.99	25.37	200.90	127.50
6	0.00	0.00	5.48	75.13	19.39	193.80	117.70
7	0.00	0.00	0.00	26.88	73.12	163.20	106.10
8	0.00	0.71	1.99	67.73	29.57	87.70	120.50
9	0.00	1.65	1.88	39.65	56.82	174.10	101.70
10	0.00	30.04	23.44	35.57	10.95	262.50	168.90
Average	0.00	8.09	8.71	52.65	30.55	204.20	125.50
ANOVA[a]						$P = 0.000$**	$P = 0.000$**

[a] The ANOVA tests against difference between the clones.
[b] ** = difference highly significant (1% level).
* = difference significant (5% level).

ue of resulting products. That is why presentation of results is focused on the intrinsic value of the products instead of conversion rates. However, the conversion and return-to-log results are also given to provide broad indications of the size effect on value recovery while processing clones of different characteristics.

Grade and value

NZ Cuttings.—Table 5 displays the grade distribution, the value and return-to-log by clone in the production of NZ Cuttings lumber. The wide range of clone characteristics included in the study is reflected in the corresponding range of grade recovery. Clones 3 and 10, by far the largest trees, as well as clone 5, yielded much more clear wood from the pruned butt logs. For unpruned upper logs, the two long internode clones, 2 and 10, yielded much higher proportions of No. 1 Cuttings with respectively 37% and 30%. In contrast, clones 7 and 9, small trees with internode values of zero, yielded a very high proportion of box grade (73% and 56%).

These differences in grade distribution are confirmed by the analysis of the product value (Table 5). The average value of boards from pruned butt logs is more than 50% (310 $/m³)

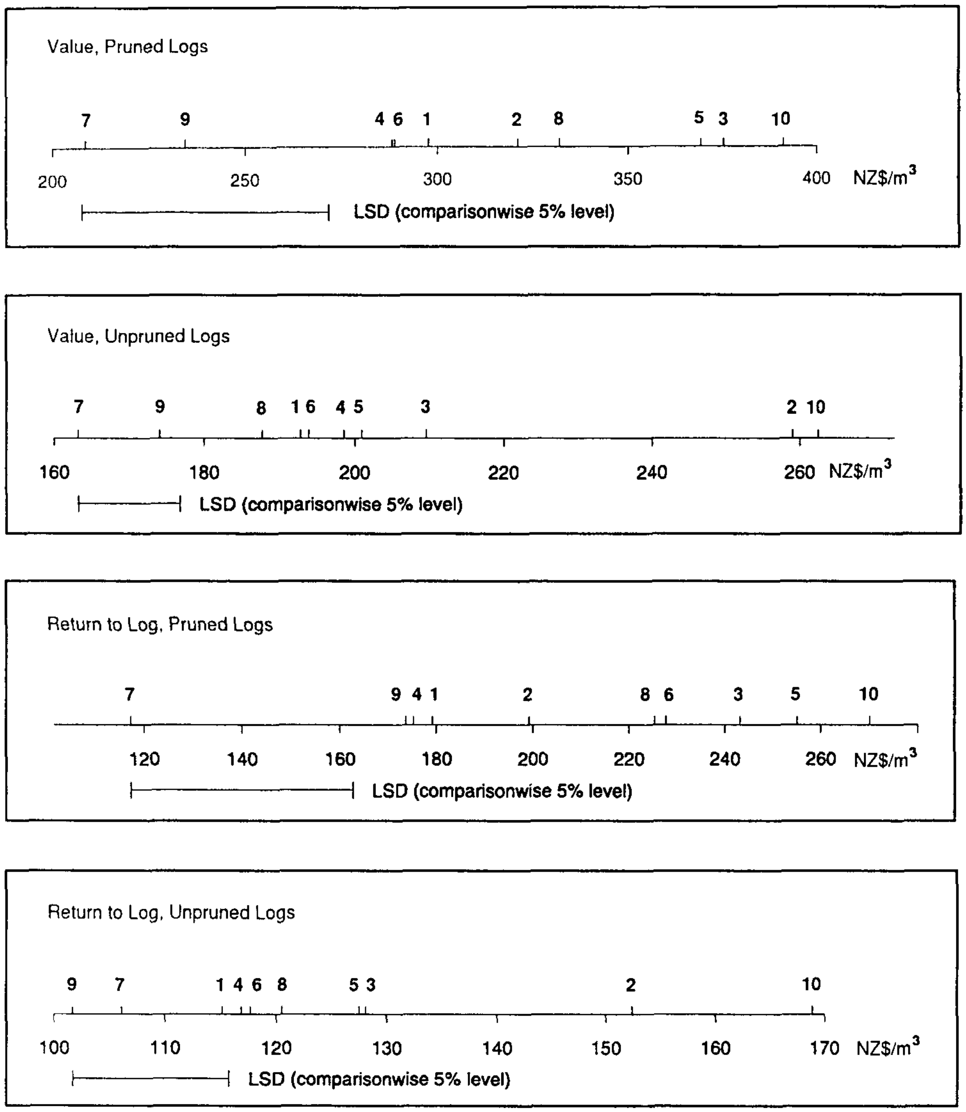

FIG. 2. Clonal differences in intrinsic value (average value per m^3 of output) and return-to-log (value of output per m^3 of input) for NZ Cuttings grades.

higher than the value of boards from unpruned upper logs (191 $\$/m^3$). There are significant differences between clones for the value of boards from the pruned butt logs (Fig. 2), the values ranging from 208 $\$/m^3$ for clone 7 to 391 $\$/m^3$ for clone 10. For the boards from unpruned upper logs, a very significant difference also was observed, the value of the output ranging from 88 $\$/m^3$ for clone 8 to 262 $\$/m^3$ for clone 10. Although the value of 88 $\$/m^3$ for clone 8 appears dubious, the clone with the second lowest value is 7 with 163 $\$/m^3$, and it is still almost 100 $\$/m^3$ lower than the highest ranking (clone 10 at 262 $\$/m^3$). This means that for NZ Cuttings, small trees with lots of small branches perform badly when compared to large long internode trees.

These results are very similar to those obtained by analyzing clones for production of U.S. random width boards (Beauregard et al.

TABLE 6. *Tree characteristics versus intrinsic product value in NZ Cuttings.*

Model	Pruned butt logs		Unpruned upper logs	
	R^2	F	R^2	F
Value = $b_o + b_1$ DBH	0.63	0.01	0.47	0.01
Value = $b_o + b_1$ BIX	0.62	0.01	0.53	0.01
Value = $b_o + b_1$ IIX	0.30	0.02	0.75	0.01
Value = $b_o + b_1$ CBH + b_2 IIX	0.69	0.01		
Value = $b_o + b_1$ DBH + b_2 BIX + b_3 IIX			0.90	0.01

1999). This was expected, as the two products are of the same type; they are both for appearance use, in long clear products, components or finger jointing stock. These comparable results hold true in spite of vast differences in the way the two grading rules apply.

The return-to-log values (RTL) (Table 5 and Fig. 2), although they cover a narrower range than the intrinsic value, follow a similar pattern. Clone 10, a large internodal clone, yielded the highest RTL values, both for pruned and unpruned upper logs, while clones 7 and 9, two small multinodal clones, yielded the lowest RTL. These differences were very significant.

Relationships between tree characteristics and value in NZ Cuttings.—Regression analysis was used to explore the relationships between the tree characteristics and the value of products once differences between clones had been established. The value variable here again is the intrinsic value of products expressed in $/m³ of output.

A first group of 4 models presented in Table 6 shows the value of products as it relates to the 4 variables individually. This shows that, for pruned butt logs, the value of products is significantly related to DBH, BIX, and IIX. For pruned butt logs, maximum R^2 values of 63% and 62% are recorded for DBH and Branch Index. This points to the fact that DBH and BIX are fairly good predictors of the value in NZ Cuttings from pruned butt logs. IIX alone explains only 30% of the variation in value.

Next, multiple regression was used. Results show that, when DBH is used simultaneously with IIX, DBH has a significant contribution in the pruned butt log model of intrinsic value, while IIX has only a marginal contribution. Overall, this model explains 69% of the variation in value. This is not much better than using DBH or BIX alone. Other combinations of these variables were examined, but no significantly better models than the ones using one variable at a time could be derived (Table 6).

Regression models achieved better results predicting the value of products from unpruned upper logs. The three single variable models all show a significant relation with the value of NZ Cuttings. The IIX alone explains 75% of the variation in intrinsic value of NZ Cuttings. When we looked at multiple regressions, DBH, IIX, and BIX all contributed significantly in the model and produced an R^2 of 90%.

This allows us to conclude that DBH, BIX, and IIX are the best variables to predict the variation in the value of NZ Cuttings. Regressions including other variables did not generate any model with better predicting power (R^2).

NZ Visual Framing.—Table 7 displays the grade distribution, the intrinsic value, and return-to-log produced by the logs from each clone in the production of NZ Visual Framing lumber. There is again a range in grade distribution between the clones. Among pruned butt logs, clones 3 and 10 yielded more than 54% of Engineering grade due to the large size of pruned butt log. The Engineering grade is actually more of a clear grade. It represents a piece of lumber of standard dimensions, without defects. Presently, no mechanical test data are available to give this grade a higher rank-

TABLE 7. *New Zealand Visual framing production: Grade distribution, intrinsic value (average value per m^3 of output) and return-to-log (value of output per m^3 of input).*

Clone	Grade (% of board by grade on a per tree basis)				Intrinsic value green lumber FOB mill ($/m3)	Return-to-log ($/m3)
	Engineering	No. 1 Framing	No. 2 Framing	Box		
Pruned butt logs						
1	36.96	28.32	15.65	19.08	311.00	187.20
2	46.04	17.12	22.62	14.22	317.90	197.80
3	54.21	26.71	15.26	3.82	349.40	227.70
4	44.42	26.40	23.60	5.58	328.30	197.70
5	52.35	34.12	10.98	2.55	357.20	248.40
6	34.24	46.43	16.39	2.94	340.00	259.30
7	12.62	35.98	46.26	5.14	282.50	153.40
8	56.31	27.96	9.32	6.41	350.60	235.90
9	33.87	48.66	10.48	6.99	338.90	231.90
10	61.75	18.59	12.82	6.84	350.90	247.20
Average	43.28	31.03	18.34	7.36	332.70	218.70
ANOVA[a]					$P = 0.12$	$P = 0.005$**
Unpruned upper logs						
1	0.00	9.35	32.58	58.06	190.30	114.10
2	0.00	24.22	30.79	45.00	220.10	132.30
3	0.75	23.43	43.92	31.90	229.10	139.40
4	1.67	22.52	49.11	26.69	231.40	132.40
5	1.26	8.96	39.51	50.27	198.40	126.30
6	2.35	33.83	40.17	23.65	251.50	147.00
7	0.00	20.30	67.67	12.03	238.10	143.60
8	0.71	25.04	39.65	34.61	229.60	144.70
9	0.00	45.06	36.24	18.71	264.60	142.40
10	2.78	16.98	34.07	46.17	214.70	141.90
Average	0.95	22.97	41.37	34.71	226.80	136.40
ANOVA					$P = 0.000$**	$P = 0.03$*

[a] The ANOVA tests for differences between the clones.
** = difference highly significant (1% level).
* = difference significant (5% level).

ing. In theory, a piece of Engineering grade could be weaker than a No. 1 Framing if it has a high proportion of juvenile wood or if it comes from a weaker (less dense or with more spiral grain) tree. Still among pruned butt logs, clones 5 and 8 yielded more than 84% of No. 1 Framing and better (including Engineering and No. 1 Framing); they, along with clones 3 and 10, are the large size clones. Clone 7 performed worst, it was the only clone to produce more than 50% of No. 2 Framing and worse grade among pruned butt logs. For unpruned upper logs, clones 9 and 6, small BIX clones, performed well, producing more than 35% of No. 1 Framing and better. The four clones (1, 2, 5, and 10) yielding more than 45% Box grade (the reject category in this grading system) are the ones with larger branches. Among them, clone 1 is the worst, producing more than 58% Box grade.

These differences in grade distribution were confirmed by the analysis of the value of the products (Table 7). The mean value of boards from pruned butt logs is of 219 $/m³, while the mean value of boards from unpruned upper logs is of 136 $/m³. There is no clear difference in intrinsic value between clones for the pruned butt logs (Fig. 3), although there seems to be a trend ($P = 0.12$), with values ranging from 282 $/m³ for clone 7 to 357 $/

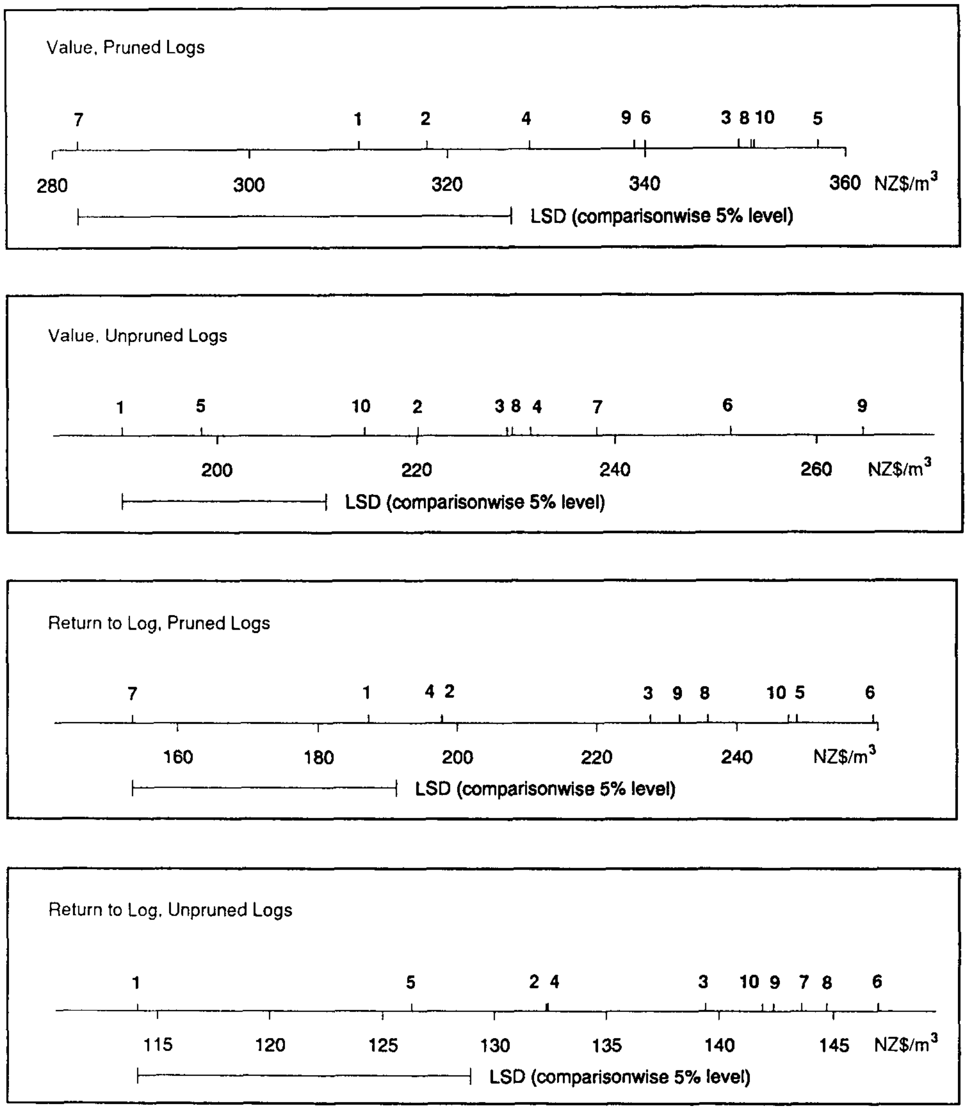

FIG. 3. Clonal differences in intrinsic value (average value per m^3 of output) and return-to-log (value of output per m^3 of input) for NZ Visual grades.

m^3 for clone 5. The most important values here are from unpruned upper logs since production of NZ Framing lumber from pruned butt logs is unlikely. For the boards from unpruned upper logs, very significant differences in intrinsic value can be observed. Value range from 190 $/m^3$ for clone 1 to 264 $/m^3$ for clone 9. It appears that the best performing clones among unpruned upper logs are the ones with small BIX (clones 6 and 9).

The return-to-log values cover a wider range ($106/$m^3$) for pruned butt logs than do the intrinsic values (75/m^3). For unpruned upper logs, RTL values are less variable ($33/$m^3$) than the intrinsic values (74/m^3). Among pruned butt logs (Table 7 and Fig. 3), RTL ranges from 153 $/m^3$ for clone 7 to 259 $/m^3$ for clone 6. There are highly significant differences among pruned butt log RTL values. The RTL from unpruned upper logs ranges

TABLE 8. *Tree characteristics versus the intrinsic product value in NZ Visual Framing.*

Model	Pruned butt logs		Unpruned upper logs	
	R^2	F	R^2	F
Value = $b_0 + b_1$ CBH	0.13	0.12	0.22	0.04
Value = $b_0 + b_1$ BIX	0.07	0.12	0.47	0.01
Value = $b_0 + b_1$ IIX	0.02	0.54	0.25	0.02
Value = $b_0 + b_1$ Density	0.05	0.35	0.0006	0.92

from 114 \$/m^3 for clone 1 to 147 \$/m^3 for clone 6. The same clones appear at the extremes of RTL as in intrinsic value for producing NZ Framing from unpruned upper logs. Clonal differences in RTL values are significant for unpruned upper logs.

Relationships between tree characteristics and value in NZ Visual Framing.—The models presented in Table 8 show the value of products as it relates to five clone variables considered individually. For pruned butt logs, no significant relationship exists. Even DBH and Max Defect Core, which have the highest probability of having a significant relationship, explain no more than 14% (R^2) of the variation in value of NZ Visual Framing. No multiple regression model provided a better prediction of the value in Visual Framing from pruned butt logs.

The simple regression models achieved better results for predicting the value of Visual Framing products from unpruned upper logs. Simple variable models with DBH, IIX, and BIX all show a significant relationship with the intrinsic value in NZ Visual Framing. BIX alone explains 47% of the value variation. Density had no predictive power, which was expected. This variable was brought in only to provide a contrast with Australian MSG framing grades, which are mechanically tested products. No multiple regression model achieved better results than BIX alone.

Australian Machine Stress Grade.—Table 9 displays the grade distribution, the value, and return-to-log results by clone in the production of Australian MSG boards. The Australian Machine Stress Grading system is based on rules that are different from the NZ Visual Framing system. The Australian MSG mechanically tests each piece of lumber. Hence, we would expect trees with good wood quality to perform better than, for example, low density, high spiral grain trees. This was confirmed by the grade distribution from pruned butt logs. The three clones with the highest density (Table 3), clones 1, 4, and 9 were the ones yielding the highest percentage of F11 grade with 12%, 22%, and 16%, respectively. Also, clone 6, which produced the highest proportion of F4 and worse (30%), is among the lowest density (358 kg/m^3) clones. For unpruned upper logs, the same trend is evident as two of the best performing clones (4 and 7), with a yield of 30% of F8 and better, are both above-average density, small BIX clones. At the other extreme, the four worst performing (2, 3, 5, 8, and 10) clones, with more than 34% of F4 and worse, all show below-average density and medium to large BIX.

These differences in grade distribution are only partially confirmed by the analysis of the value of products (Table 9). The average intrinsic value of boards from pruned butt logs is 217 \$/m^3, while the mean value of boards from unpruned upper logs is of 197 \$/m^3. The differences between clones in the intrinsic value of boards from the pruned butt logs is significant (Fig. 4). Values range from 202 \$/m^3 for clone 8 to 238 \$/m^3 for clone 4. This can be explained by the fact that clone 8 shows the lowest density, while clone 4 is among the highest in wood density. For the boards from unpruned upper logs, there is no significant difference between the clones. In terms of Return-to-Log (Table 9 and Fig. 4), the clones are marginally different for boards from pruned butt logs ($P = 0.09$) and range between 121 \$/m^3 for clone 7 to 176 \$/m^3 for clone 6.

TABLE 9. *Australian Machine Stress Graded (MSG) production: Grade distribution, intrinsic value (average value per m³ of output) and return-to-log (value of output per m³ of input).*

Clone	Grade (% of board by grade on a per tree basis)					Value green lumber FOB mill ($/m³)	Return-to-log ($/m³)
	F11	F8	F5	F4	Box		
Pruned butt logs							
1	12.52	41.28	38.15	8.05	0.00	229.20	144.20
2	0.00	36.35	36.03	15.51	12.12	205.70	138.10
3	2.54	49.41	27.79	11.35	8.90	215.00	144.90
4	22.08	40.10	31.98	5.84	0.00	237.70	150.30
5	10.20	36.27	35.49	8.43	9.61	219.50	170.60
6	2.73	42.65	24.58	27.10	2.94	207.30	175.60
7	5.14	48.60	30.84	10.28	5.14	220.70	121.50
8	0.00	30.10	42.72	18.64	8.54	202.10	150.80
9	16.40	38.17	24.46	20.97	0.00	223.50	166.80
10	1.60	26.82	47.12	12.61	11.86	205.10	164.30
Average	7.32	38.98	33.92	13.88	5.91	216.60	152.70
ANOVA[a]						$P = 0.02$*	$P = 0.09$
Unpruned upper logs							
1	2.18	20.08	51.53	13.47	12.74	200.90	119.50
2	0.00	12.38	48.59	24.37	14.67	190.40	116.80
3	1.92	21.42	39.94	24.46	12.25	195.90	120.60
4	1.67	28.05	49.01	14.60	6.67	206.20	120.40
5	0.00	17.36	45.88	30.16	6.60	193.00	123.40
6	0.00	20.00	46.61	27.83	5.57	195.80	118.90
7	0.00	31.77	56.20	6.02	6.02	212.30	130.70
8	0.00	13.40	49.01	25.11	12.48	191.50	122.50
9	0.00	19.06	47.18	26.24	7.53	194.30	110.70
10	0.00	16.74	49.27	21.43	12.57	194.70	130.90
Average	0.58	20.03	48.30	21.37	9.71	197.5	121.40
ANOVA						$P = 0.39$	$P = 0.22$

[a] The ANOVA tests for differences between the clones.
** = difference highly significant (1% level).
* = difference significant (5% level).

A size effect can explain this difference, with clone 7 being the smallest, achieving a much lower conversion rate. There is no significant difference between the clones for the RTL in Australian MSG lumber from unpruned upper logs. It is possible that various factors interact and cancel each other. More explanation for this is included in the next section.

Relationships between tree characteristics and value in Australian MSG Framing.—The first group of 4 models presented in Table 10 shows the value of products as it relates to each of four tree (clone) variables. This shows that, for pruned butt logs, the value of products is significantly related only to density, which explains 63% (R^2) of the variation in value in Australian MSG Framing. No multiple regression model could provide better prediction of the value in Visual Framing from pruned butt logs.

Regression models failed to show positive results when predicting the value in Australian MSG from unpruned upper logs. None of the single variable models show a significant relationship with intrinsic value in Australian MSG. Only density is marginally ($P = 0.07$) related to the value and explains 17% of the variation in value. Multiple regression with density and BIX achieved only slightly better results than density alone, but it failed to pass

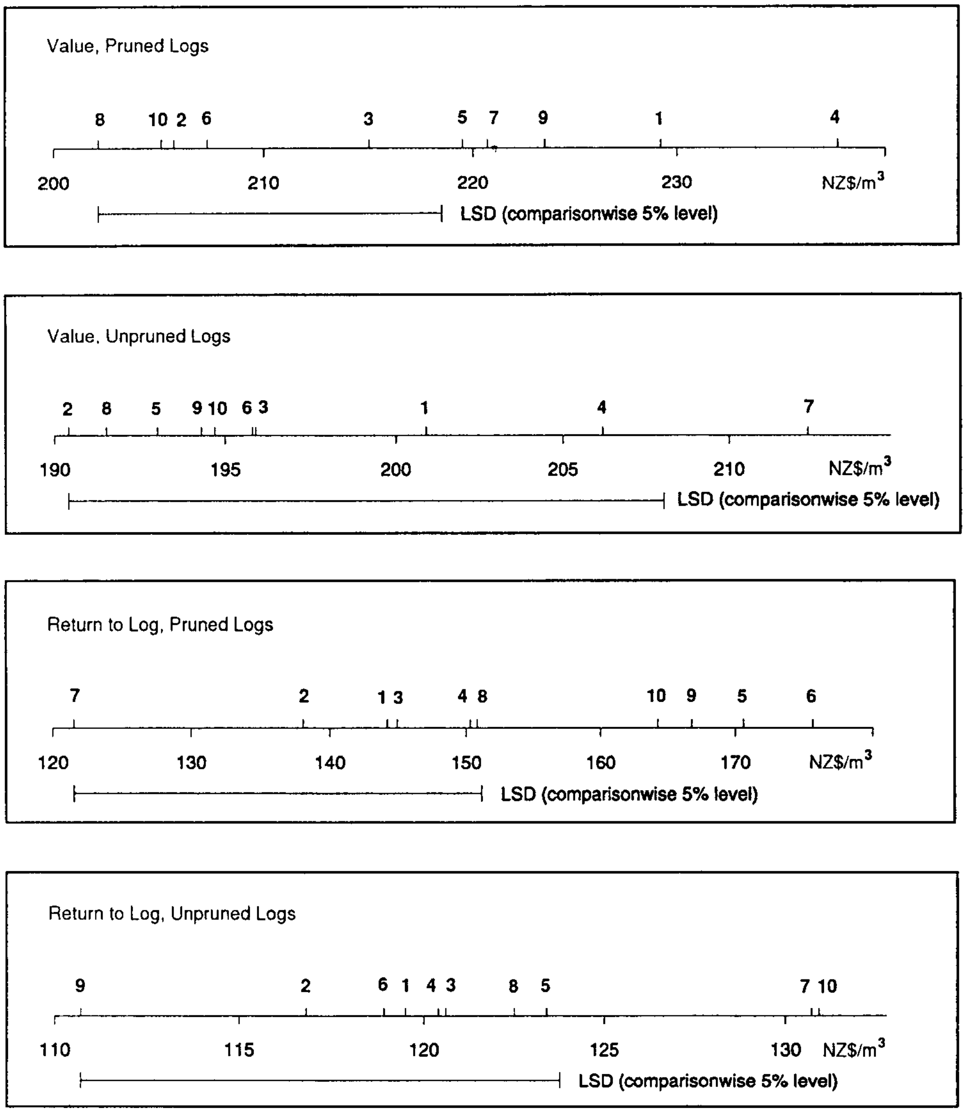

FIG. 4. Clonal differences in intrinsic value (average value per m^3 of output) and return-to-log (value of output per m^3 of input) for Australian MSG.

TABLE 10. *Tree characteristics versus intrinsic product value in Australian MSG Framing.*

Model	Pruned butt logs		Unpruned upper logs	
	R^2	F	R^2	F
Value = $b_0 + b_1$ DBH	0.06	0.30	0.09	0.20
Value = $b_0 + b_1$ BIX	0.09	0.20	0.14	0.11
Value = $b_0 + b_1$ IIX	0.13	0.11	0.13	0.11
Value = $b_0 + b_1$ Density	0.63	0.01	0.17	0.07
Value = $b_0 + b_1$ OuterWoodDensity	0.72	0.01	0.11	0.15
Value = $b_0 + b_1$ Density + b_2 BIX			0.28	0.06

TABLE 11. *Correlations between $E_{p\,min}$ and wood quality variables at the board level.*

Wood characteristic	Correlation with $E_{p\,min}$
Density	0.49
Knot area ratio	0.48
Ring width	0.46
Microfibril angle	0.30
Spiral grain	0.25
Tracheid length	0.35
Compression wood	0.20

the significance threshold (P = 0.05); this multiple regression can explain 28% of the variation in value in Australian MSG. Wood density of five outer rings was also significant in predicting the variation in value in material from pruned butt logs. Outer wood density is important because it is a nondestructive method, using an increment core to assess tree and stand wood density. It seems to be at least as good, if not better, as the whole tree density in predicting power (R^2 of 72% compared to 63%).

Tree characteristics and performance of products

All statistical analyses so far were performed at the tree level, using average-tree wood characteristics. One reason for poor prediction of the value in Australian MSG may be that variation in wood properties is often greater within tree than between trees. Even if no differences were detected between clones, it does not mean that all boards from these clones are the same. A significant amount of variation may be predicted at the board level.

Correlation was established at the board level to explore the relationship between wood characteristics and the mechanical performance of each board. The variable studied was the minimum modulus of elasticity on each plank ($E_{p\,min}$). $E_{p\,min}$ is the value that determines machine stress grades in Australian and New Zealand MSG rules. It is also a controlling factor in Japanese and North American MSR rules. Table 11 shows that three variables did correlate at a relatively high level (correlation coefficient > 0.40) with $E_{p\,min}$, these were wood density, knot area ratio, and ring width. Ring width is not necessarily an intrinsic quality of wood, but it is sometimes used as a surrogate for density.

Regression analysis was performed to assess the relationship between $E_{p\,min}$ and all the variables listed in Table 11. The best model of this stepwise statistical procedure included density, knot area ratio, and ring width:

$$E_{p\,min} = B_0 + b_1\text{Density} + b_2\text{KAR} + b_3\text{RW})$$

This model is highly significant (F = 0.01) and explains 35% (R^2) of the variation of $E_{p\,min}$. The variables selected for this model were the same as the ones observed in similar trials (Bier 1985; Houllier et al. 1995). This however does not prove that microfibril angle, spiral grain, or compression wood have no bearing on the mechanical properties of radiata pine. Microfibril angle for example varies more within logs from pith to bark than between logs. Since the position of each piece of lumber within the log was not recorded, it was impossible to establish clear relationships between microfibril angle for example and either $E_{p\,min}$ or Australian MSG grades. This is one limitation of this study.

Heritability

Among the variables that turned out to have some bearing on the value of NZ Cuttings, NZ Visual Framing, and Australian MSG Framing, three have already been proven to be highly heritable (Beauregard et al. 1999). That study showed that DBH, BIX, IIX have a broad sense heritability (h^2) of 61%, 84%, and 94%, respectively. The broad sense heritability values of three other wood properties were calculated, and the results for density, spiral grain, and microfibril angle are shown in Table 12. These intrinsic wood properties appear to be even more heritable than variables mentioned above. Considering the relationship established previously between density, mechanical properties, and grade yield for Australian MSG, this shows that radiata pine trees can be bred for producing higher value structural

TABLE 12. *Broad sense heritability of clonal traits related to the performance of structural lumber.*

Clonal trait	Mean	h^2	*P*-value	Significance
Density	467	0.99	0.0001	**
Spiral grain	43.9	0.84	0.0003	**
Microfibril angle	0.240	0.94	0.0001	**

products. Spiral grain and microfibril angle, although they did not come out in the best model to predict $E_{p\ min}$, appear also to be very heritable (0.84 and 0.94).

CONCLUSIONS

The objectives of this paper were to link radiata pine resource characteristics to the quality and value of NZ Cuttings, NZ Visual Framing, and Australian MSG grades, from a clonal and tree characteristics perspective. In this report we analyze clonal variation and heritability of the traits related to the quality and value of 2 × 4s. Finally, the relationships between these tree characteristics and the value of the products were explored.

The value of the boards in NZ Cuttings from pruned butt logs averaged 310 $/m³ as compared with 204 $/m³ for unpruned upper logs. There were significant differences between clones for the boards from the pruned butt logs, the values ranging from 208 $/m³ for clone 7 to 391 $/m³ for clone 10. For the boards from unpruned upper logs, there was also a significant difference, the value ranging from 88 $/m³ for clone 8 to 262 $/m³ for clone 10. Clone 7 appeared to be the worst for the production of NZ Cuttings, while clone 10 was obviously the best. Regression analysis confirmed that for NZ Cuttings, small trees with lots of small branches perfom badly when compared to large trees with larger branches. It also showed that for boards from unpruned upper logs, the longer the internode length, the better the yield in NZ Cuttings.

The value of the boards in NZ Visual Framing from pruned butt logs averaged 333 $/m³ as compared with 227 $/m³ for unpruned upper logs. There was no significant difference between clones for the boards from the pruned butt logs (P = 0.12), although there seemed to be a trend, with values ranging from 282 $/m³ for clone 7 to 357 $/m³ for clone 5. For the boards from unpruned upper logs, there was a highly significant difference with values ranging from 190 $/m³ for clone 1 to 265 $/m³ for clone 9. Regression analysis showed that the best performing clones among unpruned upper logs were the ones with small branches.

The value of the boards in Australian MSG from pruned butt logs averaged 217 $/m³ as compared with 197 $/m³ for unpruned upper logs. There were significant differences between clones for the boards from the pruned butt logs, the values ranging from 202 $/m³ for clone 8 to 238 $/m³ for clone 4. For the boards from unpruned upper logs, there was no significant difference. Regression analysis also failed to show any relationship between the tree characteristics and the value in Australian MSG; but at the board level, a significant relationship was established between the modulus of elasticity of planks and wood density, knot area ratio, and ring width.

If among the 10 studied clones one were to be selected for the production of NZ Cuttings, it should be clone 10, which yielded the best results both for pruned and unpruned logs. If one were selected for framing, it should be clone 9, which yielded the highest value in NZ Visual Framing; this clone is the highest density one and it has the smallest branches. Tests on heritability showed that the tree characteristics that have bearing on the products value are heritable. Considering the relationship established previously between density, mechanical properties, and grade yield for Australian MSG, it can be concluded that radiata pine trees can be bred for producing higher value structural products.

It would be worth examining more clones because it is likely that a specific individual would have all the favorable characteristics in a manner that would make it outstanding. These clones could then be used in a breeding program. This would, however, require considerable effort.

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