Thinning *Pinus radiata* plantations by operator selection: 2. Effect on harvesting productivity

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Summary

Productivity of single-grip harvesting machines, based on working elements only, was measured during two series of field trials to compare operator-selected thinning (OST) with conventional tree-marked thinning. In the initial trials, involving first and second thinning on low and high quality sites, there were no differences in the number of trees harvested or the volume of logs produced per productive machine hour. Work studies conducted during harvesting showed lower processing and falling times for OST in some thinnings. Low pruning on a high quality site was found to improve harvesting volume productivity during first thinning for both OST and tree-marked thinning. In the operational trial, involving second thinning on a medium quality site, OST resulted in more trees harvested per hour but did not affect harvested volume productivity.

Keywords: thinning, work study, selection criteria, pines, *Pinus radiata*

Introduction

It is conventional practice in plantation management to mark trees either to be removed or to be retained, before a commercial thinning operation. Alternatively, the harvesting machine operator may determine the trees to be thinned as an integral part of the harvesting operation, reducing thinning costs and preparation time. This operator-selected thinning (OST) is widely practiced in Scandinavia and Ireland (Bouvarel and Kofman 1995). It is recognised that thinning solely by rows or to a set pattern is an efficient harvesting method when trees are identical or residual tree form is not important (Raymond 1985), but some tree selection during thinning is necessary for the production of higher quality radiata pine sawlogs (Cremer and Meredith 1976; Lewis and Ferguson 1993).

The requirement for an operator to select trees during thinning, rather than observe previously marked trees, may influence the number of trees harvested per hour. While lengthy deliberation over trees will reduce the number of tree harvested per hour, it is possible for operators to select trees very quickly during log processing, or while moving the harvesting machine. Operators may become more fatigued from OST when the trees and ground surface make harvesting more difficult (Parker *et al.* 1996), but tree marking will also be slower and more costly in such conditions.

The size of trees selected and their location within the stand will influence the number of trees harvested per hour and the volume of logs produced per hour. Larger tree stems will result in a greater volume of logs harvested per hour during machine thinning, up to the size the machine can comfortably handle (Evanson and McConchie 1992; Tufts and Brinker 1993). The distance from the tree stump to the log pile can also influence the number of logs produced per hour during log processing (Duggan 1988), but this will be related to distance and the proportion of time spent on other work elements.

The aim of this study was to compare OST with conventional tree-marked thinning in respect to the number of trees harvested per productive hour and the volume of logs produced per productive hour. Productivity is based on working elements only and does not include delays such as minor repairs, servicing, and fire stand-downs. A work study was conducted during thinning operations to detect any changes in work patterns, or changes in distinct work element times, as a result of OST.

Two series of field trials were undertaken in *Pinus radiata* plantation thinning operations at Rennick Forest, Victoria, to study the effects of OST on the thinned stand and on harvesting productivity. The silvicultural implications of these thinning trials are discussed in Yeo and Stewart (2000). The initial trials were undertaken for first and second thinning on both low and high quality sites, including pruned and unpruned stands on the high quality site. The second series of trials was at operational scale in first and second thinning and tested specific guidelines for tree selection by the operator. Due to time constraints harvesting productivity was measured only in the second thinning.

Environmental factors can affect harvesting machine production and may be difficult to control (Eliasson and Lageson 1999), making comparison of thinning techniques difficult. The trials studied here, however, had the following environmental factors measured and they were similar between treatments in each trial (Yeo and Stewart 2000): average tree size, terrain, average ground slope, tree spacing, machine type and operator. Thinning was carried out by single-grip harvesters in all trials. It was not possible to use the same machine and operator for every trial as the study was conducted in ongoing commercial operations. Readers should bear this is mind when observing trends across these trials. Details of machines and operator experience are provided. While different operators may have conducted different trials, due to the layout of the trials and the manner in which they wereundertaken, each operator was exposed to both tree-marked thinning and OST during any given trial. Therefore there should be no bias towards either of the thinning approaches even though different operators had to be used between trials. The two distinct machine types used in these trials, wheeled harvester and excavators modified for harvesting trees, are expected to have different performance characteristics. Production levels among operators can also vary, and there are many factors influencing operator performance. Among 34 operators of tractor-mounted tree-felling shears Cottell *et al*. (1976) found operator manual dexterity, motivation and experience with the machine all had some influence on the number of trees felled per hour. It was beyond the scope of this study to accurately measure operators' personal attributes, and results from single operators will not hold true for all operators.

Methods

Layout of trials

At the time of the trials, Rennick Forest was State owned, and managed by Victorian Plantations Corporation (VPCorp) to produce high quality sawlogs at 33 years, after three commercial thinnings (D. Turner, 1996, *pers. comm*.). Selection of forest compartments for the trials, from compartments scheduled for thinning, was in consultation with local VPCorp foresters. Trees on high quality sites had thicker and longer branches than those on low quality sites, hence the trials were conducted on both high and low quality sites. The initial trials were as follows: first thinning on a low quality site (T1L); first thinning on a high quality site (T1H); second thinning on a low quality site (T2L); and second thinning on a high quality site (T2H). The operational trial was a second thinning on medium site quality and the area studied was larger than that for the initial trials (T2O). Further details of trial compartments are in Table 1.

Initial trials were undertaken during summer 1996/97. For each trial six sections of 'gullet' (extraction tree row and two rows either side) were located randomly within a compartment, as an unbiased sample of the compartment, and randomly assigned as either tree-marked or OST to give three sections of each. Each section was 150 m in length and five rows wide, except for the T1H trial, which comprised twelve sections of 75 m with six sections for each treatment randomly allocated, having every tree pruned to a height of 2 m. Trees were marked either by VPCorp employees or tree-marking contractors, based on the VPCorp prescriptions requiring removal of every fifth row, and defective, malformed, moribund, suppressed and sick trees in remaining rows to a specific number of trees per 20 m and trees per hectare. In all initial trials the operators were told to thin the OST sections to the same stocking and type of tree as in the tree-marked area, except for T2L, which was already being thinned by OST to VPCorp instructions to remove defective, malformed and smaller trees and to retain 25% of standing trees. Operators were given no prior training in OST, although some had carried out OST before (Table 2).

The operational-scale trial, a second thinning on a medium quality site, was undertaken during summer 1997/98 and covered an area of 15 ha. The purpose of this trial was to test OST over a longer time period, over a larger area, and to compare two different OST guidelines. The area was divided into three 5 ha portions, each containing 32 rows. One portion remained tree-marked, while the other two were unmarked for OST. The operator was instructed to follow guidelines for tree selection in this trial. These guidelines were derived with input from field supervisors and harvest machine operators, and using results from initial trials and pre-thinning assessment of operational-scale trials. Two sets of guidelines with different underlying philosophies were used – one selected trees based on diameter and the other selected trees based on spacing. The guidelines given to the operator for tree selection were as follows.

Trial T2O, operator-selected thinning guideline 1 (OST1):

Remove all defective trees as follows:

- *trees with forks below 6 m (approximately);*
- *trees with excessive bends (not making a future sawlog);*
- *trees leaning into other trees;*
- *trees damaged from first thinning;*
- *dying trees.*

Also remove all other trees smaller than 23 cm diameter over bark at breast height.

Trial T2O, operator-selected thinning guideline 2 (OST2):

Thin to retain the 3 best trees per 12 m of two-row bay, based on tree form and size.

Defective trees, which must be removed, are:

Table 1. Trial compartment details, prior to thinning trials

Trial	Year planted	Initial tree spacing (m)	Site index[a]	Stems per hectare[b]	Mean dbh (cm)[b]
First thinning on low site quality (T1L).	1984	2.4 x 2.4	26.2	1105	17.0
First thinning on high site quality (T1H).	1987	2.0 x 3.0	30.0	1312	18.9
Second thinning on low site quality (T2L).	1977	2.4 x 2.4	26.0	812	22.2
Second thinning on high site quality (T2H).	1969	2.4 x 2.4	29.6	634	30.7
Second thinning at operational scale (T2O).	1979	2.4 x 2.4	28.0	689	26.0

[a]Stand top height in metres at 20 years

[b]From Yeo and Stewart (2000)

Table 2. Operator experience and machinery type

Trial	Operator experience with the machine	Operator experience in OST	Type of machine used in the trial
T1L	18 months	3 hours	Rubber tyred single-grip harvester with retractable boom.
T1H	10 months	1 month	Tracked excavator with single-grip processing head.
T2L	5 years	2 years	As in T1H.
T2H	2 years	1 month	Tracked excavator with retractable boom and single grip processing head.
T1O	2 years	None	As in T1H.

- *trees with forks below 6 m (approximately);*
- *trees with excessive bends to make a future sawlog;*
- *trees leaning into other trees;*
- *trees damaged from first thinning;*
- *dying or suppressed trees.*

Operators and machinery

Harvesting machine operators and harvesting machines were not replicated for each trial because of the cost of moving the machinery and complications with operator wages and logging contractor log payment. Harvesting machine operators were not specifically selected for the trials; they were as allocated by the logging contractor. Any compartments having poorer operators, however, were avoided in order to reduce the risk of a degraded stand from OST. The level of operator experience and the type of harvesting machine used for these trials are listed in Table 2.

Table 3. Work elements

Element	Breakpoints	Description
Fall	Start	Processing head arrives at tree trunk
	includes	Clearing around lower trunk
		Cutting through trunk
		Guiding the falling tree, clearing it of hang-ups
	Finish	Tree rests horizontally (or thereabouts) and processing begins
Process	Start	Tree rests for processing to begin
	includes	Manoeuvring tree for processing
		Crosscutting, de-limbing, and stacking logs
	Finish	Final piece of tree is dropped from processing head
Approach	Start	Final piece of tree is dropped
	includes	Machine and/or processing head moving towards next tree
		Operator identifying the next tree
		Does not include moving debris
	Finish	Processing head arrives at tree trunk for 'fall'to begin
Other productive time	Can occur at any time	Other work associated with the operation that is infrequent but necessary and contributes to production
		Usually consists of moving loose logs and clearing obstructive slash
Non-productive time	Can occur at any time	Machine breakdown, stop to communicate with the logging contractor or forward operator, and tea break

Measurement of harvesting productivity

There were two parameters for harvesting productivity. One was the number of trees harvested per productive machine hour; the other was the volume of logs produced per productive machine hour - volume productivity. The term 'per productive machine hour' in this study refers to the time the machine is working and does not include time when the machine is idle or relocating between compartments. It is anticipated that OST will not influence time for machine repairs, relocation and fire stand-down. Operators were timed from when they began a trial strip to when they finished. Non-productive time during the trial strip, such as minor repair and tea break, was recorded and later subtracted from total time to give productive machine time (Table 3).

Harvested trees were tallied as they fell. During the first trial (T2L) logs were counted as they were processed, but afterwards it was realised that the stacked logs could be counted more accurately and segregated into products, so the former method was replaced by the latter. Total volume of logs produced per strip was that estimated by counting the logs per product then multiplying these figures by the quadratic mean volume per product. Where log diameters were unrestricted, a random sample of logs was measured and a quadratic mean log volume was calculated for each strip. Log specifications are in Appendix 1.

Work study

While the harvesting machine worked through each trial strip in the initial trials, times for individual work elements were recorded manually by an observer using a stopwatch and clipboard. Distinct work elements in the study consisted of:

- tree falling;
- processing the tree into logs; and
- moving to the next tree.

A work cycle is the sum of the three distinct elements for the one tree. Other work elements contributing to production, such as moving slash, are infrequent and grouped as 'other productive time'. Non-productive time, as mentioned previously, was also recorded. Breakpoints were allocated to define the beginning and end of each work element (Table 3).

Results

First thinning on the low quality site

Harvesting productivity and work element times for initial trials are given in Table 4.

The time taken to harvest each trial strip was about 75 minutes, and the strips were harvested over three mornings. The mean number of trees harvested per productive hour per strip was not significantly different between tree-marked and OST treatments (t = 0.25, P = 0.8). The mean volume of timber produced per productive hour per strip was not significantly different between treatments (t = 0.474, P = 0.6). There was a total of 25 minutes 'non-productive time', in the form of machine breakdown during the trial and repair, accounting for approximately 5% of the time spent in trial strips for both treatments. 'Non-productive time' per strip was not significantly different between treatments (t = 0.01, P > 0.9). 'Other productive' time was infrequent, totalling 1.5 minutes clearing old logs, and not significantly different between treatments (t = 0.62, P = 0.57).

Time taken to complete a work cycle, or any of the work elements, was not significantly different between the two treatments. The times in the first thinning on the low quality site were much lower per element than in the other trials.

First thinning on the high quality site

The time to harvest each trial strip varied from 31 to 73 minutes. Strips were harvested over three consecutive mornings. The only 'non-productive time'during harvesting of these trials was on the few occasions when the saw chain came off its guide bar, once in the pruned OST stand (4.2 minutes) and twice in the non-pruned tree-marked stand (4.8 minutes). The operator commented that the chain usually came off this often, and it was

Table 4. Mean harvesting productivity and work element times for initial field trials

Trial	Treatment[a]	Productivity[b]		Work elements (minutes)			
		Trees PMH^{-1}	Volume (m^3) PMH-1	Work cycle	Approach	Fall	Process
T1L	TM	113	9.7	0.53	0.12	0.10	0.34
	OST	110	9.4	0.55	0.13	0.10	0.36
T1H	TM	87	9.4†	0.69*	0.12*	0.14	0.45
pruned	OST	89	8.5†	0.66**	0.11*	0.12*	0.44*
T1H	TM	73	6.8	0.82	0.14	0.15	0.57
unpruned	OST	90	7.6	0.70*	0.13	0.13*	0.48*
T2L	TM	76	14.2	0.75	0.16	0.12	0.49
	OST	82	12.3	0.72	0.18	0.12	0.44*
T2H	TM	72	35.2	0.81	0.13	0.13	0.56
	OST	75	35.0	0.80	0.13	0.13	0.57

[a]TM = Tree-marked; OST= Operator-selected thinning

[b]PMH = Productive machine hour.

* Significant difference between treatments, at $P<0.05$

not related to tree selection. Total 'non-productive time' accounted for approximately 1.5% of the time spent harvesting all these trials. There was no 'other productive' time, probably because the forest floor was clear of large debris.

The mean number of trees harvested per productive hour per strip ranged from 73 to 90, with no significant effect of pruning, marking, or interaction of the two. The mean volume of timber produced per productive hour per strip ranged from 6.8 m^3 to 9.4 m^3. The variance in volume productivity was sufficiently different between treatments to cast doubt on results from a factorial analysis. No appropriate data transformation could correct the unequal variances for volume productivity data to make a confident analysis of variance. A plot of volume production within the four treatments revealed no interaction between pruning and marking, so the treatments were grouped into the main effects of pruning and marking, and compared using t tests. Thus, volume productivity was significantly greater where pruned (t = 2.28, P = 0.046), but there was no significant difference in volume productivity between the tree-marked and OST stands (t = 0.02, P >0.9).

There was no interaction between marking and pruning for the work elements. The time to convert a tree into logs (work cycle) was significantly less where the trees had been pruned (P<0.01), and significantly less for OST (P<0.01). Pruning also resulted in significantly reduced 'approach' (P = 0.04) and 'process' times (P<0.01). 'Fall' time was significantly less in OST (P<0.01) regardless of pruning.

Second thinning on the low quality site

Each trial strip was harvested in about 30 minutes. Harvesting was during the middle of the day. There was no 'non-productive time' while working in the trial strips. The mean number of trees harvested per productive hour per strip was not significantly different between tree-marked and OST (t = 0.88, P = 0.4). The mean volume of timber produced per productive hour per strip was not significantly different between tree-marked and OST (t = 2.03, P = 0.11). 'Other productive time' consisted of clearing the extraction track and was approximately 3% of productive time in either treatment and not significantly different between tree-marked thinning and OST (t = 0.46, P = 0.68).

The length of time to complete a work cycle, 'fall', or 'approach' was not significantly different between the two treatments. The work element 'process' was significantly different (less time) for OST; 'process' was also the longest work element. It was thought the number of logs produced from each tree could influence 'process' time. The time taken to process each tree and the number of logs produced from the tree were statistically correlated in each treatment, with correlation coefficients of 0.467 (P<0.01) for tree-marked thinning and 0.628 (P<0.01) for OST (Fig. 1). However, this is not a strong correlation and the data points do not show a definite pattern. There is no difference between the two fitted regression lines in slope (t = 1.09, not significant at P = 0.05) or intercept (t = 1.09, not significant at P = 0.05). Thus there is a general increase in 'process' time as the number of logs produced from a tree increases, but this is no different between tree-marked thinning and OST.

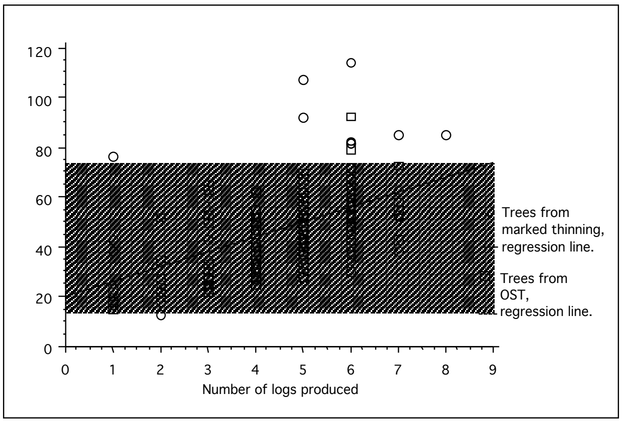

Figure 1. Plot of process time and number of logs produced for both tree-marked thinning and OST, with fitted regression lines, second thinning on low quality site

Second thinning on the high quality site

The time to harvest a trial strip varied from 50 to 70 minutes, and strips were harvested over two consecutive mornings. The mean number of trees harvested per productive hour was not significantly different between tree-marked thinning and OST (t = 0.71, P = 0.5). The mean volume of timber produced per productive hour was not significantly different between tree-marked thinning and OST (t = 0.10, P>0.9).

'Non-productive time' accounted for 5% of the time spent working in tree-marked strips and 9% of time in OST strips. This time consisted of saw chain adjustment and communication with the forwarder operator and the logging contractor. The saw chain required attention periodically in either treatment, and although the communication breaks occurred while in the OST area, they had no relation to tree selection. Therefore operator tree selection is not considered to have had any bearing on the occurrence or duration of 'non-productive time'. 'Other productive time' consisted of clearing the extraction track for the machine, accounting for 1%-2% of productive time and was not significantly different between treatments (t = 2.25, P = 0.09).

Time taken to complete a work cycle, or any of the work elements, was not significantly different between the two treatments.

Operational scale trial

During thinning, the harvesting machine productive time was approximately 55 minutes per hour for each treatment. 'Non-productive time' was around 5 minutes per hour and consisted of chain adjustment and checking log dimensions; it was not significantly different between the three treatments ($F = 0.98$, $P = 0.4$).

The number of trees harvested per productive hour was significantly different between the three treatments. A Games-Howell procedure revealed a significant difference between each treatment, increasing from tree-marked to OST1 to OST2 treatments (Table 5). The volume of logs produced per productive hour increased in the same manner but was not significantly different between the three treatments.

Table 5. Harvesting productivity in operational trial T2O

Treatment	Productivity[a]	
	Trees PMH^{-1}	Volume (m^3) PMH^{-1}
Tree-marked	39 a	11.6
OST1	46 b	12.7
OST2	55 c	13.5

[a]PMH = Productive machine hour

Letters denote significant differences at $P < 0.05$.

Discussion

For first thinning on the low quality site, harvesting productivity (the number of trees harvested and volume of logs produced per hour) was high compared with other studies of first thinning (Granskog 1975; Griffin 1986; Evanson and McConchie 1992). OST was no different to tree-marked thinning for harvesting productivity or work elements, and may have been more productive if there were fewer trees of poor form (Yeo and Stewart 2000) as harvesting machine productivity has been found to decline with the number of malformed and large-branched trees (Evanson and McConchie 1992).

For first thinning on the high quality site, harvesting productivity was low compared to other studies of first thinning (Granskog 1975; Griffin 1986; Evanson and McConchie 1992), but was similar to that recorded by another operator with limited experience (ten months) of harvesting machines (Parker *et al.* 1996). Pruning did not affect the number of trees harvested per hour, but the volume of logs produced per hour increased through pruning in both methods of tree selection. Average tree diameter at breast height, stand basal area, or number of poorly formed trees were no different between treatments before or after thinning (Yeo and Stewart 2000), so the operator was not taking larger or better-formed trees than the tree markers. As the number of trees harvested per hour was no different, this increase in volume productivity (volume of logs produced per hour) is likely to be a result of the operator getting more volume of logs through better utilisation when the stem can be clearly seen. The operator had to determine the log products to be cut from the tree stem, as the harvesting machine did not have a diameter sensor. It did, however, have a measuring device for log lengths. Harvesting work cycle time was significantly reduced by OST and by pruning. The faster work cycle for OST is attributed to faster falling and processing. This may be a consequence of the operator choosing trees that allowed a better falling pattern than that created by tree-markers in this fairly dense stand. When trees are pruned, one would expect faster processing due to less de-limbing, and possibly easier falling. The only significant difference in work elements as a result of pruning, however, was the 'approach' time.

For second thinning on the low quality site, harvesting productivity was consistent with other studies of single-grip harvesters in second thinnings (Roberts and McCormack 1991; Tufts and Brinker 1993). The only difference between the two tree selection methods in this trial was a shorter 'process' time when thinning by OST. As tree size, spatial distribution and proportion of defect trees were similar between treatments (Yeo and Stewart 2000), and number of logs produced had little influence on processing time per tree, processing was favoured by some other factor. Duggan (1988) found processing time for a single-grip harvester to become longer when distance and swing to log stacks increased. Operators selecting trees to be thinned have the opportunity to create openings for log stacks in convenient locations, whereas the tree marker is not concerned with this aspect and logs are stacked wherever a gap happens to occur. The operator was very experienced and could have been applying this strategy. Although there was no increase in harvesting productivity, processing and possibly forwarding were made easier through OST.

In second thinning on the high quality site, harvesting productivity and work element times were no different as a result of OST. Harvesting productivity was high as a result of large trees and relatively fast work cycles. Although this trial was conducted during daylight, the operator said that at night a paint mark is much easier to see than a whole tree, and OST at night is likely to reduce tree harvesting rate as operators have to spend more time selecting trees.

Both OST guidelines at operational scale resulted in harvesting more trees per hour than the tree-marked thinning, but there was no difference for volume of logs produced per hour. The faster harvesting for the diameter limit guidelines (OST1) can be attributed to the smaller trees harvested in this treatment (Yeo and Stewart 2000). The spacing guidelines (OST2), however, resulted in harvesting larger trees than OST1. As volume of logs produced per hour was no different, there may be poorer utilisation of the trees harvested using the spacing guidelines. Site variations can obscure differences that might otherwise be statistically significant, but there was little site variation in this fairly uniform *Pinus radiata* plantation. In practical terms, there was no significant difference in volume productivity of the three thinning methods.

Conclusion

In the initial trials there was no change in harvesting productivity as a result of the operators having to select trees or the trees they selected. These trials, however, were over relatively short periods and operators remained fresh and alert. Low pruning on a high quality site was found to increase the volume of logs produced per hour during first thinning for both OST and tree-marked thinning. Two operators demonstrated faster processing in OST, most likely as a result of better falling patterns. The retractable boom on machines would allow more flexibility in tree selection but it was the fixed-boom excavator-based machines that were used in the faster processing times. It was not possible to compare individual operators and/or machines; different performance characteristics among operators would be expected.

OST diameter limit guidelines and spacing guidelines both increased the number of trees harvested per hour, but volume productivity was unchanged. The faster harvesting under diameter limit guidelines is largely attributable to the harvesting of smaller trees. Spacing guidelines, harvesting the same sized trees as tree-marked thinning, allowed for fast harvesting but the harvested trees had insufficient log volumes to increase volume productivity.

There is no evidence to suggest that the time taken in selecting trees reduced the number of trees or volume of logs harvested per hour. As operators become experienced in tree selection while harvesting, and approach full potential (Tufts and Brinker 1993; Parker *et al*. 1996), increased harvesting productivity is likely. OST can be carried out without endangering the stand's future; it all depends on clearly spelt out thinning prescriptions.

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Appendix 1. Log specifications

Trial	Product	Length (m)	Diameter minimum (cm)	Diameter maximum (cm)
T1L	Post	1.8	8.5	12.5
	Rail	2.4	11.0	14.0
	Chip-log	3.6	8.0	16.0
T1H	Small strainer	2.4	8.0	16.0
	Big strainer	2.4	16.0	No limit
T2L	Post	2.4	8.0	12.5
	Rail	3.0	12.5	16.5
	Sawlog	3.6	16.0	28.0
T2H	Post	2.7	7.5	10.5
	Chip-log	4.8	8.0	24.0
	Sawlog	4.8	13.0	17.0
	Sawlog	5.4	17.0	No limit
T2O	Post	1.8	13.0	18.0
	Post	2.4	5.5	11.0
	Post	3.0	11.0	13.0
	Sawlog	3.7	15.0	No limit