POTENTIAL HARVESTING SYSTEMS FOR ROW THINNING OF PLANTATIONS FOR PULPWOOD

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ABSTRACT

Harvesting systems incorporating (conceptual) continuously moving machines could substantially reduce thinning costs, or facilitate thinning at an earlier age. Such systems could also cause less soil damage and compaction.

INTRODUCTION

Australia is increasingly dependent on its softwood plantations for pulpwood and sawlogs. Many of these forests are established on favourable terrain which, if combined with good site-preparation and improved planting stock, offers an opportunity to capitalise on the advantages of having trees presented in rows to harvesting equipment.

Of the cost of growing, harvesting, and transporting first thinnings to the mill, approximately 50% is spent on felling, delimbing, and extraction operations, about 25% on road transport, and about 25% on stumpage.

In harvesting thinnings trees must be selectively removed and there is a wide variation in tree form and size. These factors combine to necessitate the use of relatively inefficient tree-handling and processing systems. Current motor-manual systems are characterised by high labour inputs, and fully mechanised systems by substantial capital investments. The financial return to the forest owner from the first-thinning operation which yields mainly pulpwood is small in relation to the return from operations which yield sawlogs.

As Australia's plantations begin to yield large volumes of sawlogs, an alternative source of pulpwood in the form of mill waste will become available, reducing the demand for first thinnings. Forest managers are responding to the small uncertain nature of returns from pulpwood thinnings and the projected higher returns from sawlogs by planting trees at wider spacings with the objective of eliminating the pulpwood thinning operation. Early loss of volume production and financial returns are being accepted in return for maximum financial yields over the rotation.

Further improvements in planting stock, initial spacing, site preparation, weed control, and fertiliser application can reduce variation in stem form and size within a stand. Reduced variability will lessen the need for selective thinning of inferior trees and facilitate the automated processing of trees.

This analysis of harvesting systems was made to establish the magnitude of the potential monetary gains from harvesting whole rows of trees, as a basis for future research into appropriate harvesting technology and silvicultural regimes. For maximum effect the stand would be established with such harvesting systems in mind. Optimum conditions would involve an adequate spacing between rows for machine access (about 3 m), close spacing of trees along the rows, and favourable terrain. The following evaluation is based on an average tree size of 0.12 m^3, and the removal of every third row.

MATERIALS AND METHODS

The Harvesting Machines

Seven harvesting systems were evaluated, two based on conceptual machines and five based on conventional machines. In total nine machines were involved and these are detailed below.

Continuously Moving Feller (CMF): A self-propelled terrain-going machine (Fig. 1) which, by means of a circular saw, can fell trees without stopping. A machine of this type has not been manufactured on a production basis but prototype machines employing the required component are operating today.

Continuously Moving Processor (CMP): A machine which can delimb trees in a windrow (previously felled by the CMF) by elevating them into the machine, passing them between two chain flails, and collecting the stems in a bunk capable of holding 20 stems. The machine (Fig. 2) will process trees without stopping. A machine of this type has

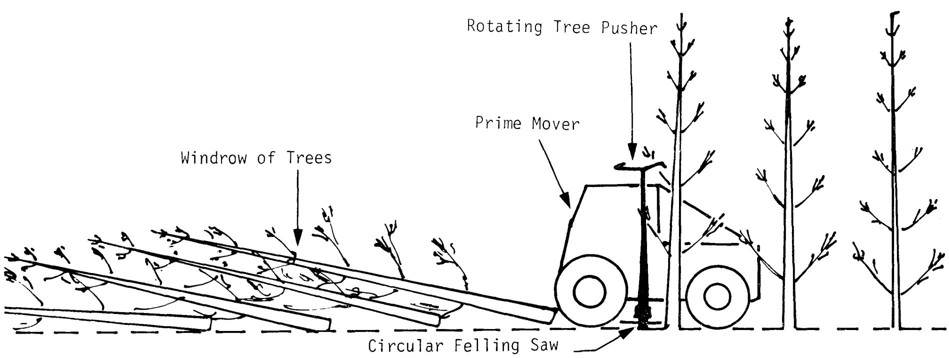

FIG. 1—A continuously moving felling machine

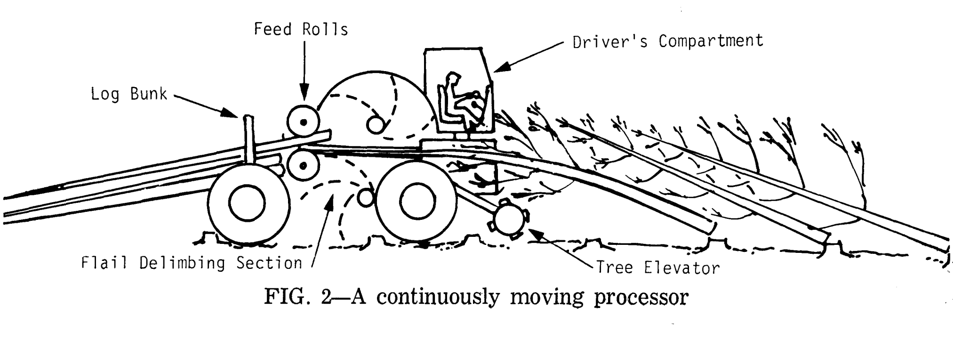

FIG. 2—A continuously moving processor

not been manufactured, nor is the concept technically proven although, with the exception of the in-feed, the componentry required is available.

Chain Flail Delimber (FLAIL): A machine which delimbs felled trees by passing a chain flail over the stems as they lie on the ground and thrashing the limbs from them. Such machines exist but are unproven in *Pinus radiata* D. Don or *P. elliottii* Engelm. in Australia on a production basis.

Accumulating Feller Buncher (FB): A rubber-tyred or tracked vehicle which carries a felling head (where a loader bucket might normally be) consisting of tree shears to sever the trunk, accumulating clamps to hold several stems in a vertical position after severing, and a lever system to lower the trees to the ground. This machine and those listed below are in production.

Long-Reach Feller Buncher (LRFB): A rubber-tyred vehicle which carries a felling head (as described for the FB) on the end of a two-piece boom. Trees within a 270° sector circle of 6 m radius can be felled from one machine position.

Step Feed Delimber (SFD): A machine which delimbs felled trees. It utilises a telescoping boom, incorporating a clamp on one section and a set of knives which wrap around the stem on the other. When the boom is lengthened the knives shear off limbs; when it is shortened the stem is fed through the clamp. A bunk to collect processed stems may be incorporated.

Harvester, Roll Feed (HRF): A machine incorporating a long-reach feller-buncher for felling and feeding the tree into a set of curved knives and feed rolls for delimbing; the feed rolls are used to drag the stem through the knives which remove the limbs.

Harvester, Step Feed (HSF): A machine which incorporates a felling head to sever the tree which is then lowered into a step feed delimbing mechanism as described above.

Grapple Skidder (GS): A machine used for extracting felled or felled-delimbed stems to roadside. A set of large opposing arms behind the machine gathers, clamps, and lifts one end of a bunch of stems which is then skidded to roadside.

Costing of Machines and Systems

Inputs and outputs: To allow comparisons of systems with different outputs, costs were assessed in terms of the ratio of inputs to output of the machine or system. Four different inputs were considered – volume of fuel, man-hours of labour, average capital invested, and total monetary cost. The common output was unit volume of merchantable wood.

Individual machines: The costs involved in owning and operating individual machines were assessed initially assuming an absence of operational delays resulting from interaction with other machines, although these inevitably occur in multi-machine systems. Operational delays between the machines were accommodated in the final analysis.

Output: Of the machines studied, only two have worked in the operational patterns envisaged in this analysis. It has therefore been necessary to estimate the productivity (volume of wood/unit time). The data used for the estimates came from a wide range of sources (e.g., analysis of films, element times from time studies, engineering specifications of machines, theoretical studies of wood cutting) in order to simulate the machine operations and estimate productivity.

Fuel input: Fuel inputs were determined by estimating duty cycles and assuming a fuel economy of 0.26 kg/kW/h. Accurate studies of fuel consumption on forest operations have not been done in Australia or overseas. Forestry machinery commonly operates on a rapidly varying duty cycle with corresponding fluctuations in power demand. As the method used for estimating fuel consumption was borrowed from agriculture it is probably not very accurate but is the best available.

Labour input: The labour input was taken as 2000 h/yr/machine. This figure was used regardless of the degree of utilisation of the machine.

Average capital invested: Average capital invested (ACI) was determined using Equation (1) from Warren (1977) –

$$\text{ACI} = [(\text{I-R})\ (\text{N}+1)/2\text{N}] + \text{R}$$

where I = initial cost
R = residual value
N = years of useful life.

Total monetary cost: The total monetary cost includes all costs of owning and operating each machine except management costs and profit. Owning costs were calculated on a yearly basis and include depreciation, interest on invested capital, and labour. Operating costs (i.e., repairs and maintenance, fuel, oil and lubricants, tyres and flails) were considered to be dependent on usage and were costed per productive machine hour. Machine life, and repairs and maintenance budgets were estimated taking into consideration the complexity of the machine, standards of engineering design, and type of use. All costs were as at September 1979. Assumptions concerning individual machines are shown in the Appendix.

The Systems

To produce delimbed wood at roadside each of the machines described must work in a system of several machines. Since machines are usually designed for component compatibility rather than production compatibility, the constituent machines of any one system are rarely perfectly matched.

Several factors were assumed when specifying the constituent machines of a system. Firstly, it was arbitrarily decided that no more than four machines of any one type were permitted. Secondly, short-term interruptions to the operation of one machine were considered not to affect other machines, that is, a buffer existed between each machine. Thirdly, where one high-output machine was servicing several less productive machines, it was assumed that travelling between work areas did not seriously affect production or costs. Finally, the configuration with the lowest total monetary cost per unit output was considered to be best.

The costing of the systems was done on a yearly basis. Depreciation, interest, and labour costs were considered to be independent of production, and were charged as such. All other inputs were treated on a productive machine hour basis. By comparing yearly outputs of each machine in a system, the required operating time of each machine per year was established. The various costs (viz fuel, labour, average capital, and total monetary) were assessed for each machine in the system and added to give the total cost of the system.

RESULTS AND DISCUSSIONS

Table 1 summarises the results. In order to compare the systems more readily, the four costs were indexed using System 1 as the base, with the result shown in Fig. 3. The continuously moving systems (1 and 2) are substantially more efficient in terms of fuel usage, labour, average capital, and interest cost than the conventional systems.

From our analysis it is clear that systems which incorporate continuously moving felling and processing machines have a distinct advantage with regard to resource use over the systems which have at least one machine which relies on one-tree-at-a-time processing or felling.

Labour and average capital invested (indirectly a measure of machine complexity) are most important in differentiating between the two basic classes of harvesting systems. Fuel was the least significant factor.

Work content: Operators of machines that handle small trees as discrete entities are called upon to make many decisions (Kerruish 1977), for as many as 10 different machine functions have to be co-ordinated in handling each tree. In contrast, the continuously moving machines integrate these functions by treating the trees as a continuum. The operator has only to steer the machine along the row.

Machine design: The present forest machines (excluding the HSF, which was developed in Australia) were designed and manufactured in either North America or the Nordic countries. They were designed primarily for clearfelling in natural forests, and consequently are complex in design and operation so as to be able to cater for adverse terrain, stand, and climatic conditions. First thinnings from plantations offer relatively

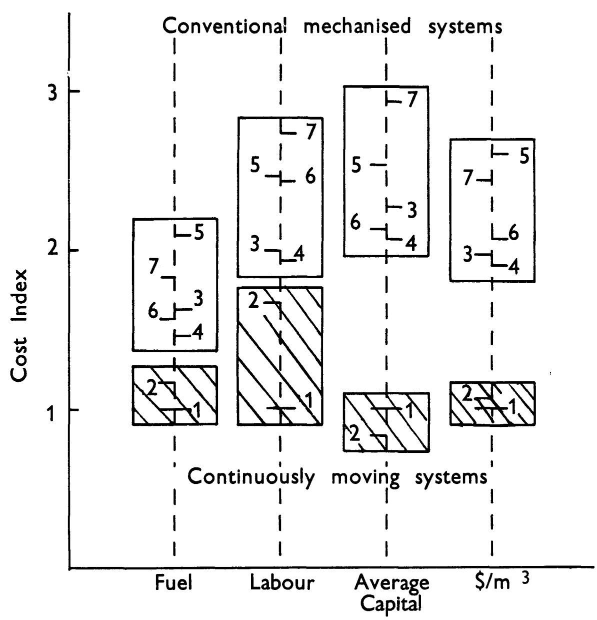

FIG. 3—Relationship between costs of systems

TABLE 1—Machine combinations, costs, and outputs of the systems

System No.	Machine combinations			Output (m^3/yr)	Total cost (A$/$m^3$)	Fuel use (l/m^3)	Labour use (man-h/m^3)	Capital use (A$/$m^3$)
1	CMF	3 × CMP	3 × GS	182 400	2.81	1.3	0.077	3.74
2	CMF	2 × FLAIL	3 × GS	96 000	2.94	1.54	0.125	3.19
3	3 × LRFB	4 × SFD	2 × GS	121 500	5.40	2.12	0.15	8.18
4	3 × FB	4 × SFD	2 × GS	121 500	5.26	1.87	0.148	7.52
5	2 × HRF		1 × GS	32 000	7.14	2.83	0.188	9.69
6	4 × HSF		1 × GS	53 760	5.89	2.04	0.186	7.60
7	2 × FB	3 × SFD	1 × GS	58 500	6.76	2.46	0.21	11.00

uniform tree presentation and dimensions which are not capitalised on by the available mechanised harvesting systems. Simpler systems, represented by Systems 1 and 2, can be devised that handle the row of trees as a crop and not as a number of discrete objects.

Systems management: In agriculture, as the scale and output of machines were increased, utilisation of the machines was found to be lower than expected because of management practices. Although in general this is true for tree harvesting machinery, the fact that the proposed continuously moving systems are different in concept, rather than "bigger and better", leads us to believe that the potentially high productivity of these systems will not lead to lower utilisation. The costs of planning and control of systems involving continuously moving machines are expected to be less than with alternative equipment.

Silvicultural considerations: Australian plantations have been thinned for two reasons. Firstly, wide variation in tree form and vigour has made it necessary to plant extra trees to ensure final stocking of adequate quality. Secondly, early thinning produced a financial return that reduced the indebtedness of the plantation, this being facilitated by the strong demand for the limited volume of coniferous pulpwood available.

Today these reasons are not so compelling; tree variability has been reduced not only by improved planting stock but also by site preparation, weed control, and fertiliser application (particularly in the southern pines, e.g., *P. elliottii).* In addition, the low labour productivity and high costs of selective thinning reduce the financial return from first-thinning operations. These trends can be expected to continue and much current thinking favours wider initial spacing of genetically improved stock and the reduction or elimination of intermediate yields. The loss in total volume production because of the delayed occupancy of the site is offset by economic gains in harvesting and processing larger trees.

These same genetic improvements also facilitate a non-selective first thinning where a row of trees is removed. Stands could be established at non-uniform spacings within the row to give a yield of pulpwood by removal of highly stocked rows early in the rotation and the retention of widely spaced rows for the sawlog crop, these rows being thinned if required on a selective basis.

The silvicultural and management implications of row thinning have been explored for *P. radiata* by Cremer & Meredith (1976), Hall (1974, 1981), Shepherd & Forrest (1973), and for*P. elliottii* and *P. caribaea* Morelet by Bacon *et al.* (1982). Because many of Australia's forest soils have small reserves of nutrients the analysis has been confined to harvesting systems that leave most of the unwanted limbs and foliage, rich in nutrients, on the forest floor.

Soil compaction and disturbance: The main machine factors influencing the degree of soil compaction and disturbance are gross vehicle weight, number of passes, type and contact area of running gear, and mode of operation (e.g., draft, turning). By using a row-thinning regime and the proposed continuously moving harvesting machinery, gross vehicle weights may be less and the mode of operation can be favourable with regard to soil disturbance (no braking, turning, or accelerating). Moreover, with the high-production and low-cost machines envisaged, the opportunities to restrict machine operations to periods when soil damage is likely to be low are increased.

Log specification: The product of all these harvesting systems is tree-length roundwood for use in pulp manufacture. At present several log-quality requirements must be optimised. Firstly, since the log must be debarked, a limit on quality of delimbing is usually prescribed because poorly delimbed logs are more difficult, but not impossible, to debark. The standard of delimbing by chain-flail delimbers is of only modest quality. Secondly, the logs are usually cut into short lengths to allow drum debarking. This can certainly be done more cheaply at the mill than at roadside. Finally, because sand and dirt ingrained in the log cause wear in the wood-chipper, it is generally seen as best practice to keep the logs off the ground whilst delimbing and extracting, although the economic benefit of this has not been quantified. This is one argument against the use of the chain-flail delimber because the chains strike the ground as well as the log and embed some grit in the log.

CONCLUSION

Two harvesting systems incorporating conceptual continuously moving machines could possibly harvest wood at 46% of the average cost of systems based on existing machines. They may need only 62% as much fuel, 56% as much labour, and 39% as much capital per unit volume of wood delivered to roadside as systems based on existing machines, which cannot fully capitalise on the advantages of intensively managed plantations.

In addition to cost savings, it is likely that systems using the conceptual continuously moving machines would cause less soil disturbance and compaction if operated with this intent. Systems which cause least damage to the soil and return a high proportion of foliage, twigs, and bark uniformly to the forest floor have potential advantages.

Even though the machines envisaged in the continuously moving systems are technically unproven, and both costs and outputs are best estimates, the magnitude of the gains which are suggested by this analysis are such as to justify exploratory work on development. A continuously moving machine to delimb and bunch stems is likely to be of greatest benefit.

If the harvesting cost structure suggested here is feasible, there will be an opportunity for drastically different management regimes. By divorcing the stem-volume/harvesting-cost relationship, as has been done with the continuously moving harvesting system, rows of trees can be removed for commercial purposes from plantations at earlier ages than has ever been feasible using conventional systems, and still be economically viable. Similar technology is applicable to eucalypt plantations and short-rotation tree crops.

REFERENCES

BACON, C. J.; HAWKINS, P. J.; WARD, J. P. 1982: Productivity of commercial thinning operations in Queensland plantations: Influence of alternative silvicultural options. **New Zealand Journal of Forestry Science 12(2):** 308–23.

CREMER, K. E.; MEREDITH, E. W. 1976: Growth of radiata pine after row thinning compared with selective thinning. **Australian Forestry 39:** 193–200.

HALL, M. J. 1974: A plantation simulation model for radiata pine. **Appita 27:** 251–61.

——— 1981: A note on the flexibility of options in thinning **Pinus radiata**. Paper presented at IUFRO meeting "Economics and Techniques of Thinning Plantations in Australia and New Zealand", Canberra, 28 Sept - 2 Oct.

KERRUISH, C. M. 1977: Developments in harvesting technology relevant to short rotation crops. **Appita 31(1):** 41–8.

SHEPHERD, K. R.; FORREST, W. G. 1973: Growth of radiata pine following thinning. **Commonwealth Forestry Review 52:** 133–42.

WARREN, B. J. 1977: Logging cost and production analysis. **Louisiana, Mississippi State Universities, Logging and Forestry Operations Centre, Timber Harvesting Report No. 4.**

APPENDIX

Table A1 shows relevant data used in machine costings and in choosing the configurations of the various systems. Where a range of value is given in the output column, the actual output used in a particular system is dependent on the interaction between the component machines. Figure A1 shows the relationship between machine time elements. In this analysis non-productive work, wet weather delays, personal delays, and other delays are ignored. Operational delays are assumed as 5% of work time. Mechanical delays were chosen on the basis of the complexity of the machine and the standard of its engineering design. Utilisation is calculated as productive work plus operational delays divided by work time.

For the analysis of costs (Table 1 and Fig. 3) the following were assumed:

Operator's salary	A$14 400/yr
Fuel price	20c/l
Fuel density	0.83 kg/l
Lubricants	1/3 of fuel cost
Interest	12%
Depreciation	Straight line method
Fuel consumption	0.26 kg/kW/h
Tyres	Ignored except for skidder
Repair and maintenance	Taken as a fraction of depreciation
Work time	2000 h/yr

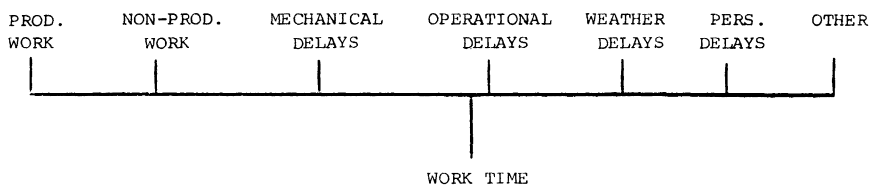

FIG. A1—Relationship of the machine time elements

TABLE A1—Machine costing data

Machine	Price (A$)	Life (yr)	Residual value (A$)	Rep. & maint. budget* (%)	Power (kW)	Load factor	Utilis.† (%)	Output (m^3/h)
CMF	25 000	5	6 000	80	45	0.72	70	144
CMP	250 000	6	50 000	80	150	0.72	75	43
FLAIL	90 000	7	25 000	80	90	0.8	75	36
FB	80 000	4	20 000	80	70	0.6	80	27
LRFB	125 000	7	30 000	100	100	0.6	75	27
SFD	235 000	7	55 000	120	125	0.55	75	13–22
HRF	190 000	6	40 000	120	110	0.75	70	13
HSF	130 000	6	30 000	120	70	0.7	70	10
GS	80 000	6	20 000	80	90	0.6	80	20–38

* Repairs and maintenance, as a fraction of depreciation cost

† See Fig. A1