An Investigation of Wood Fibre Recovery and Related Economics of Four Harvesting Systems Common to Northwestern Ontario

By
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A Graduate Thesis Submitted
In Fulfilment of the Requirements for the Degree of
Master of Science in Forestry

Faculty of Forestry and the Forest Environment
Lakehead University
Thunder Bay, Ontario
January, 1999

0-612-52074-9

ACKNOWLEDGEMENTS

I would like to thank Dr. Pulkki for providing guidance and support during the course of my research and writing. Through example, Dr. Pulkki has taught me the importance of approaching the field of forest harvesting with a level of professionalism and rigour often reserved for the pure sciences.

I would like to thank Dr. Murchison and Dr. Yang for serving as committee members and providing me with specific assistance in sampling design and wood science as it was required during the course of my work.

I would like to thank Bowater Pulp and Paper Canada Inc. for providing the generous funding required for this project. I hope that the information contained within this document and my previous reports is of assistance in their operational planning. Special thanks to Ray Markham and others at Bowater Pulp and Paper Canada Inc. who had a direct connection with this work as they made several valuable contributions.

I would like to thank all the equipment operators, supervisors and others directly involved with the logging operations that I studied. These people allowed me to conduct my research in and around their work area. Occasionally, they assisted me with special tasks such as weighing and chipping individual trees that cut into either break time or production.

I would especially like to thank my family who encouraged and assisted me in the completion of my MScF.

A CAUTION TO THE READER

This MScF thesis has been through a formal process of review and comment by at least three faculty members and an external reviewer.

It is made available for loan by the faculty for the purposes of advancing the practice of professional and scientific forestry.

The reader should realize that opinions expressed in this document are the opinions and conclusions of the student and do not necessarily reflect the opinions of either the supervisor, committee members, external reviewer, the faculty, or the University.

CLARIFICATION FOR THE READER

Since the research phase of this thesis ownership of Avenor Inc. has changed. The Avenor operations within northwestern Ontario have been sold and divided. Avenor's entire northwestern Ontario operations were first sold to Bowater Pulp and Paper Canada Inc. in 1998. Following this acquisition Bowater sold the Dryden/Ear Falls operations to Weyerhaeuser. Despite these ownership changes the text of this thesis refers to Avenor Inc. Woodlands Northwest as it existed during the summers of 1996 and 1997 when the research for this thesis was conducted.

ABSTRACT

Ride, K. R., 1998. An investigation of wood fibre recovery and related economics of four harvesting systems common to northwestern Ontario. M.Sc.F., Lakehead University, Thunder Bay, Ontario. 95 pp.

Key Words: fibre recovery, harvesting systems, logging, utilization, wood.

Wood fibre recovery levels of harvesting systems have increased steadily since the advent of mechanized logging in northwestern Ontario. Although wood utilization levels are commonly better than the legal specifications there remains room for improvement. Better knowledge of wood utilization levels can lead to a more efficient choice of harvesting systems and/or the improvement of elements within given harvesting systems. More efficient harvesting systems can be used to meet management goals of lower wood costs, greater fibre recovery, and/or less extensive cutting. The objectives of this study were to: 1) determine the relative amounts of wood fibre recovery of various harvesting systems currently being employed in northwestern Ontario, 2) quantify the amount of waste wood produced at each elements of those harvesting systems, and 3) determine the overall economic impact of achieving better recovery.

Sampling of wasted wood fibre from each element of three common harvesting systems; full-tree chipping (FT-CH), full-tree to roadside with shortwood to mill (FT-SW), and cut-to-length (CTL), occurred over two summers of typical operations. Detailed models of fibre recovery were developed for these three harvesting systems. As well, logical extrapolations were used to develop a fibre utilization model for a fourth system; full-tree to roadside with tree-length to mill (FT-TL). A wood flow analysis was conducted on a case study area using a raster based geographic information system. Results indicate that the most efficient systems in terms of fibre recovery are the FT-CH and the CTL system. The geographic wood flow analysis revealed that significantly less area would be required to be harvested if more efficient harvesting systems were used. Marginal cost analysis revealed that the CTL system should not be used to replace the FT-SW system. Slight reductions in the cost of the CTL system would, however, make the system more cost advantageous in the long term.

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INTRODUCTION

BACKGROUND

Fibre utilization research has proven successful in improving the operational efficiency of sawmills and pulp mills (Haygreen *et al.* 1986), however, relatively little research has been done concerning the fibre utilization of woodland operations. Pulkki (1990) makes the case that forest product firms should envision their whole business as one system, beginning at the stump and ending with a finished wood product, rather than in the commonly designated segments, woodlands and mill. This total system cost approach can have a significant impact on the overall efficiency of a firm (Pulkki 1990). Clearly, fibre utilization in woodlands operations should be investigated with the same rigour as mill operations.

Recent government initiatives, such as the Lands for Life process (OMNR 1997), have the potential, and are likely, to reduce the forest land base available to the forest industry. Possible changes in the land use policy of Ontario make research concerning fibre utilization timely. As the forest industry is forced to operate on a more limited land base, a desire to obtain higher yields of wood fibre from forest areas that remain accessible is only logical.

The need for better recovery from logging sites is not limited to Ontario. Guimier (1999) stresses the importance of better fibre recovery in his predictions for Canadian forestry operations in the next century. Modified harvesting techniques, improved technology and the utilization of previously unused species will be employed to meet the increasing demand for wood fibre (Guimier 1999).

The research that has been done to date in eastern Canada (Pulkki 1978, Gingras 1992, Young and Hynes 1996, Favreau 1997) indicates a historic improvement in woodlands fibre utilization since the 70's. However, the research to date has focused primarily on individual segments of a harvesting systems, and often in relatively coarse detail.

The importance of finer detail can be clearly illustrated if one considers the following example. Avenor Inc. harvests approximately 6 million m^3 of wood annually in northwestern Ontario to supply its two main mills. Given that the saw kerf of a typical feller-buncher is 5.5 cm thick the annual total volume lost to sawdust in the felling process has been estimated to be approximately 0.84%. This relates to a total loss of approximately 50,400 m^3. This amount of lost wood fibre can be visualized as a solid piece of cylindrical wood with a diameter of 20 cm extending between Thunder Bay and Toronto (approx. 1,600 km). At an approximate value of $50/$m^3$ (delivered to the mill) this wasted fibre could have had a value in excess of two million dollars. Clearly, the importance of seemingly minor fibre losses should not be overlooked.

The definition of merchantable fibre tends to vary from area to area and company to company. Merchantable fibre is considered to be the wood fibre found on a forest site prior to harvest that is considered to be economically feasible to harvest. However, most companies, governments and previous studies have defined merchantable fibre with specific dimensions relating to the bole of a standing tree. Merchantable fibre is usually described as being the wood fibre found between a certain maximum stump height up to a minimum top diameter of green, sound wood.

The current research has recognized the importance of stretching the commonly used definitions of merchantable fibre (Gingras 1992, Young and Hynes 1996, Favreau 1997). These studies have discussed or shown, that modern logging systems not only waste some merchantable fibre, but they also capture significant amounts of fibre otherwise considered unmerchantable.

More concise terminology for describing wood fibre that is or is not harvested from a given site is suggested by Ford-Robertson (1971). Waste wood is defined as "those portions of a tree or log that could be profitably utilized but are not", and refuse as "those portions of a tree or log whose removal from the forest or utilization at the mill cannot be justified economically". Residue is considered to be the combination of both waste wood and refuse and refers to "wood left over from any conversion process, whether true refuse, true waste wood or destined for further conversion" (Ford-Robertson 1971). Wood residue can be described as either logging residue or mill residue depending on where the wood fibre leaves the process. Residue may however be the raw material of another product as in the case of wood chips. Wood chips are a residue of the sawmilling process but they are the raw material of a pulp mill. Residual, refers to those stems left standing after the harvesting operations (Ford-Robertson 1971).

An increasingly wider array of species and sites are being harvested as mill and woodlands technology develop to allow for their efficient use. The emerging desire to gain the most utilization from existing wood supplies and maximum profit, has created a wide array of destinations for wood fibre. Any combination of sawmill, pulp mill, veneer mill, or other engineered wood product mills (*eg.*, oriented strand board or fibre board) may receive wood raw material directly or indirectly from an individual logging site or forest. This diversity of product demands from the logging site has had an impact on the diversity of harvesting systems being employed. A wide array of harvesting systems can currently be found within most of the forests of northern Ontario, and it is even becoming somewhat common to find several harvesting systems operating within the same site either concurrently or successively.

Harvesting systems are defined by "The tools, equipment and machines used to harvest an area", while harvesting methods are defined by "The form in which wood is delivered to the logging access road" (Pulkki 1997). In order to properly name a harvesting system each mechanical element of the system should be listed in the chronological order in which it is used. In the interests of brevity, the harvesting systems common to northwestern Ontario will be outlined in detail once, after which they will be referred to by an abbreviation.

There are four fully mechanized harvesting systems currently supplying Avenor Inc. with wood fibre in northwestern Ontario. The most widely used of these harvesting systems is the feller-buncher/grapple-skidder/delimber-debarker-chipper system. This system is employed mainly in the forest areas that directly supply Avenor's Thunder Bay kraft and thermo-mechanical pulping facilities. This system can be classified as a full-tree to roadside chip-to-mill (FT-CH) system as full-trees are brought to the roadside by the grapple skidder where they are then processed into pulp chips before being transported to the mill (Figure 1).

Wood fibre residue is produced by this system in several ways. Firstly, during the felling stage the feller buncher is responsible for leaving stumps, creating a saw kerf, leaving residual stems, and breaking stems. The grapple-skidder may miss individual or bunches of trees, it may drop trees accidentally and it may also break stems by running over them. Finally, the delimber-debarker-chipper may remove wood fibre during the debarking phase, and produce a certain amount of undersized chips.

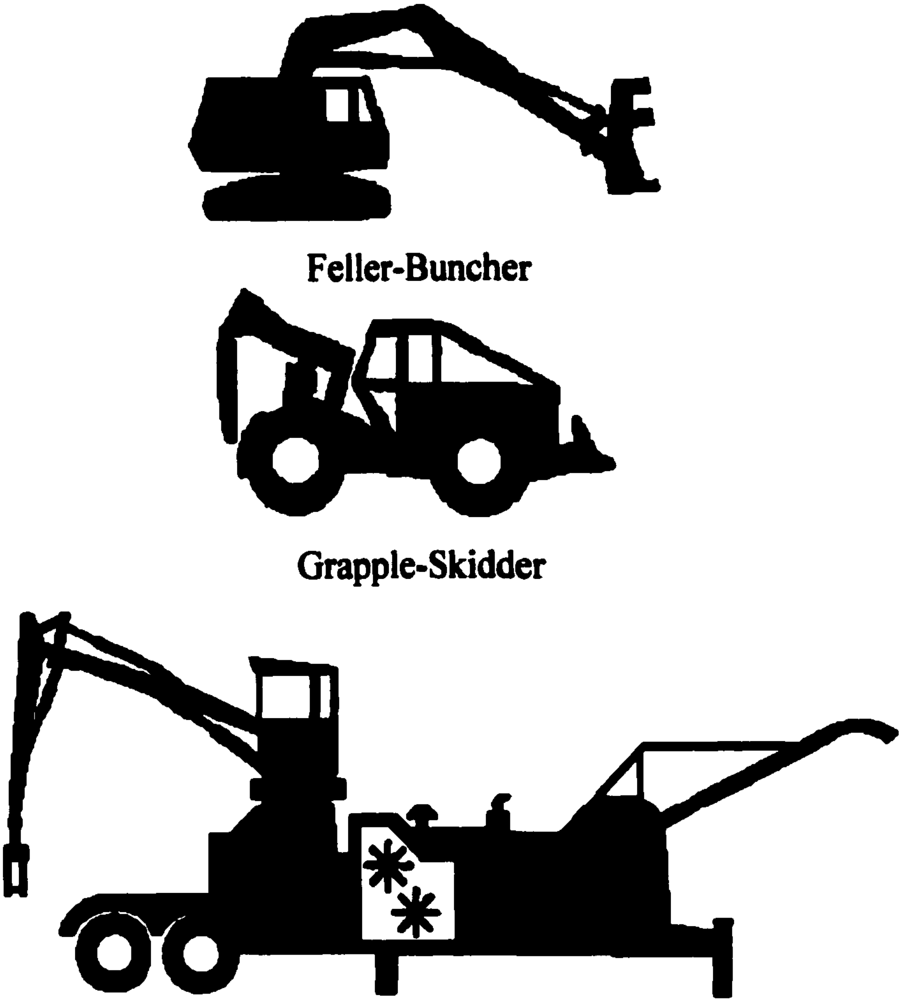
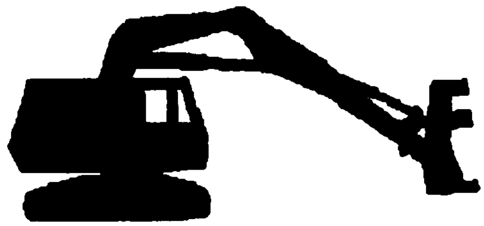


Figure 1. The mechanical components of the Full-Tree to Roadside Chip-to-Mill (FT-CH) harvesting system (Feller-Buncher/Skidder/Delimber-Debarker-Chipper Harvesting System).

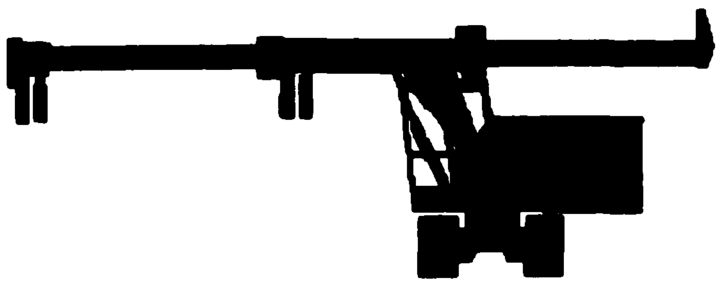
The next most common harvesting system employed by Avenor Inc. is the feller-buncher/grapple-skidder/stroke-delimber/slasher harvesting system. This system is often referred to as the conventional mechanized full-tree system and can be classified as a full-tree to roadside shortwood-to-mill (FT-SW) system. The FT-SW system is employed mainly in the forest areas that supply the Dryden mill with short wood for both its stud sawmill, and kraft pulp and paper mill (Figure 2).

The FT-SW system has similar felling and skidding fibre losses as the FT-CH system. Additional wood residue occurs at the roadside and is left in or near the remaining slash piles. During the course of operations the stroke-delimber may miss or break stems, or cut off excessively large tops. The slasher may also miss or break stems and it produces a certain volume in end pieces from each stem. These end pieces are commonly too short for transport and are therefore left on the site. The slasher also produces losses associated with the kerf of the saw.

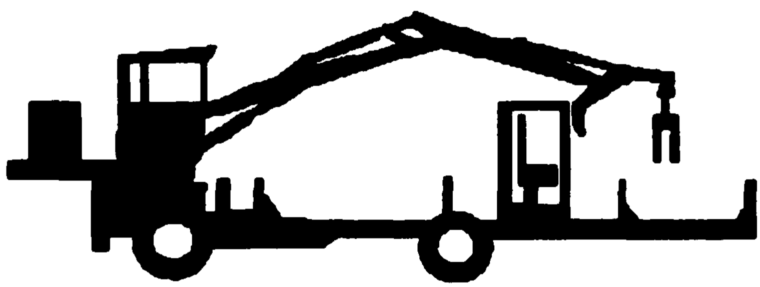


Feller-Buncher

Grapple-Skidder



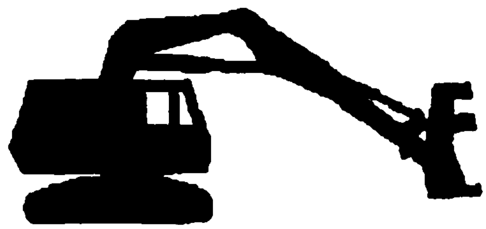
Stroke-Delimber



Slasher

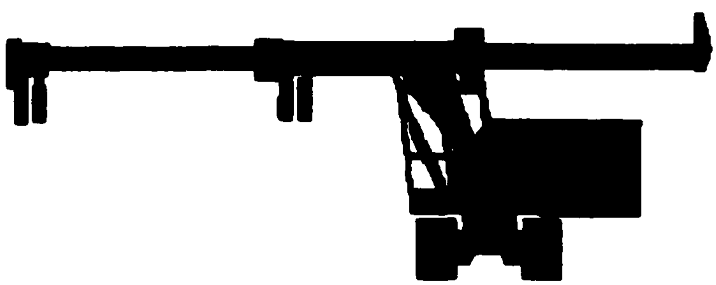
Figure 2. The mechanical components of the Full-Tree to Roadside Shortwood-to-Mill (FT-SW) harvesting system (Feller-Buncher/Grapple-Skidder/Stroke-Delimber/Slasher Harvesting System).

At the time of this research Avenor Inc. was in the process of modifying its operations by removing the roadside slasher from its FT-SW harvesting systems. This new system can be described as a full-tree to roadside tree-length-to-mill (FT-TL) harvesting system (Figure 3). By removing the slasher from the FT-SW harvesting system the operation is reduced by one machine and one operator thus reducing the cost of wood delivered to the mill significantly. The cost of slashing is transferred to the mill yard where the process is more efficient, in part because there are no costs associated to frequently move equipment. This modification is also expected to recover more wood fibre by utilizing the ends of the trees that would otherwise be trimmed by the slasher and left on site because they would be too short for transportation.



Feller-Buncher

Grapple-Skidder



Stroke-Delimber

Figure 3. The mechanical components of the full-tree to roadside Tree-Length-to-Mill (FT-TL) harvesting system (Feller-Buncher/Grapple-Skidder/Stroke-Delimber Harvesting System).

The most recent harvesting system to emerge in northwestern Ontario is the single-grip harvester/forwarder system (Figure 4). This system is being used to a limited degree by Avenor Inc.'s contractors who supply sawlogs to local sawmills. To minimize costs several of Avenor Inc.'s contractors have begun retro-fitting excavators with single grip harvesting heads. Because these machines are not purpose built units they have significant performance limitations. Fortunately, Abitibi-Consolidated has a contractor in northwestern Ontario who was employing a purpose built single-grip harvester and forwarder and these machines were available for study. The use of these machines constitutes a return of the cut-to-length (CTL) harvesting method which was once used almost exclusively in eastern Canada before the advent of forest mechanization.

The return of the CTL system in northwestern Ontario can be attributed to a number of advantages over conventional mechanical harvesting. These advantages include:

-reduced soil impact,
-greater versatility in partial cutting scenarios,
-lower costs in small cut blocks,
-less roads and landings are required,
-cleaner and higher quality logs are produced,
-greater protection of advanced regeneration,
-no need for the disposal of roadside slash, and
-nutrient and seed sources are left on the logging site.

The CTL system produces residual wood fibre in several ways. During felling a stump and saw kerf are created, and a certain amount of residual and broken stems are produced. With the CTL system, bucking saw kerfs are also produced and the tops are left in the cutover. During the forwarding phase some logs may be missed or dropped and some logs may be damaged by being run-over.

Single-Grip Harvester

Forwarder

Figure 4. The mechanical components of the cut-to-length (CTL) harvesting system (Single-Grip Harvester/Forwarder Harvesting System).

Choosing the most appropriate harvesting systems is not an easy task. A given harvesting system may be a more efficient supplier for a specific wood using mill than another. However, there may inherently be excessive logging residues associated with an otherwise practical harvesting system. The economic effects of choosing between harvesting systems extends beyond the harvesting systems alone as there are always consequences on the costs of silviculture, transportation and handling at the mill. Minimum supply requirements of individual mills and site specific logging chance factors will also continue to play a role in choosing between harvesting systems. The amount of worker training and motivation required by each harvesting system will also factor into the choice of harvesting system.

This research project was undertaken with the support of Avenor Woodlands Northwest. Avenor Inc. has a continually changing demand for a variety of different species and forms of wood at a number of mill locations. Avenor Inc. has two main sources of wood fibre: wood harvested from Avenor Inc.'s own management areas by a large number of private contractors, and wood purchased or traded from the regional market. Considering the large volumes of wood, and the complexity of sources there is a clear need for tight control of the wood procurement system.

STUDY OBJECTIVES

The objective of this thesis is to determine the relative amounts of wood fibre utilization of each of the aforementioned harvesting systems. A secondary objective is to attribute the residual wood volume to specific elements of the harvesting systems in question. The third objective is to determine the economic impact of achieving a better utilization rate over a forest landscape and demonstrate how this could be measured in a real world situation.

This research has been limited both spatially and temporally. Sampling for this project occurred only during summer cut operations. The sampling was also limited to experienced contractors operating within Avenor Inc.'s Wabigoon, English River, Black Sturgeon, Dog River, and Matawin Crown Land Forest Management Areas and block 3 of Abitibi-Consolidated's freehold land. An underlying objective was to measure the efficiency of the harvesting systems and not the efficiency of individual contracting firms, supervisors or operators.

LITERATURE REVIEW

HISTORICAL DEVELOPMENT AND RESEARCH

The Canadian public's perception of wood fibre scarcity has changed since the early days of forest harvesting when poor logging practices were overlooked for what appeared to be a wholesome occupation. It is evident from works such as the Ontario Forest Policy Panel (1993) that the public now finds a broader spectrum of value in our natural resources endowment. The sustainable use of our resources is now an important objective for economic, aesthetic, intrinsic and ethical reasons. Although improvements in wood fibre utilization have been occurring over the past several decades, research concerning this subject is only now gaining wider popularity.

The earliest harvesting systems in Canada that extracted hewn timbers and large sawlogs had extremely poor wood utilization. Large felling notches, large tops, wasted slabs, and high-grading on the harvesting site would have all contributed to poor wood utilization.

Wood utilization improved somewhat as the pulp and paper industry emerged. Pulp mills could make use of smaller logs that were otherwise not used by the sawmills (Walker *et al.* 1946). Later the chips produced in the sawmills were also utilized by the pulp mills. The early pulpwood river drives were, however, inherently wasteful. Logs were often lost from breakage and sinking. Of the total amount of logs entering the drive upstream 5 % or more could be expected to sink (Walker *et al.* 1946). A considerable amount of waste due to the damaged pulpwood log ends was also realized (Walker *et al.* 1946).

Early efforts to increase harvesting productivity by complete mechanization did not immediately result in improved wood utilization. Pulkki (1978) performed one of the first comprehensive wood utilization studies in northwestern Ontario. Pulkki (1978) calculated merchantable fibre losses to be approximately: 15 - 20 % for cut and skid operations; 20 % for tree-length harvesters; and 32 - 36 % for short-wood harvesters. At this point in time fully mechanized systems were clearly not as efficient in terms of wood utilization as the conventional cut and skid operations.

Recent developments of harvesting machinery have been made with increasing attention paid towards improving fibre utilization. As an example, Kurelek (1984) lists six key objectives in felling head development, two of which relate directly to wood utilization:

-almost eliminate tree butt compression and splitting damage,
-cut full-size hardwoods and frozen trees,
-improve felling productivity rates,
-cut low stumps,
-be almost shear head tough,
-be adaptable to most existing swing boom feller bunchers.

Nantz (1990) compiled a list of the pulp and paper industry's primary requirements for harvesting systems; several of which relate directly to increased fibre utilization:

-the pulp and paper industry wanted to be able to secure clean, debarked, full-tree chips,
-increase fibre per acre,
-reclaim land with undesirable timber,
-reduce logging costs,
-decrease machines required,
-increase productivity,
-reduce roads and road building,
-reduce man hours,
-reduce wood room costs,
-increase quality of pulp and paper,
-reduce mill production costs,
-reduce land size requirements.

Recent studies have shown that fully mechanical harvesting systems have surpassed motor-manual operations in fibre utilization. Unlike Pulkki (1978), Young and Hynes (1996) observed larger fibre losses associated with motor-manual felling and processing than with most fully mechanized systems.

Young and Hynes (1996) have investigated the fibre utilization of several harvesting systems employed in Newfoundland during both summer and winter operations. Of the systems studied by Young and Hynes (1996), two are commonly used in northwestern Ontario; these are, the full-tree to roadside shortwood-to-mill (FT-SW), and cut-to-length (CTL) systems. During summer operations these two systems produced similar amounts of merchantable waste, 3.8 m^3/ha for the CTL system and 3.9 m^3/ha for the FT-SW system. Fibre lost within slash piles was not accounted for in this study and so there is likely an under-estimation of total fibre loss from systems employing delimbers and slashers.

During winter operations, the level of merchantable fibre waste measured by Young and Hynes (1996) was considerably higher than those of the summer. The cut-to-length system showed winter merchantable fibre losses of 7.8 m^3/ha while the shortwood-to-mill system showed losses of 7.1 m^3/ha.

Estimated amounts of fibre loss where motor-manual felling and delimbing occurred were approximately 5 - 6 m^3/ha of merchantable fibre for summer operations and 8 - 9.6 m^3/ha of merchantable fibre for winter operations (Young and Hynes 1996).

The highest amount of merchantable fibre loss found by Young and Hynes (1996) was a system requiring uncommonly high amounts of individual piece handling in the cutover (feller-buncher/processor/forwarder). The feller-buncher/processor/forwarder harvesting system was found to have a merchantable fibre loss level of 10.3 m^3/ha.

The Forest Engineering Research Institute of Canada (FERIC) has recently been investigating fibre utilization of modern harvesting systems (Gingras 1992, Favreau 1996, Favreau 1997). These studies have focused mainly on differences between logging systems and season of harvest and have occurred in the provinces of Nova Scotia and Quebec (Gingras 1992, Favreau 1997).

After studying several different harvesting systems, Gingras (1992) concluded that systems employing delimber-debarker-chippers and single-grip harvesters, are able to recover more fibre than initial cruise estimates of merchantable volume. The fibre yield indices were calculated by Gingras (1992) for each system. Fiber yield index was defined by Gingras (1992), as the amount of fibre recovered expressed as a percent of the initial standing volume before harvest. The CTL system and the FT-CH system showed fibre yield indices of 113 and 107 %, respectively.

The field chipping concept is meant to capture fibre from the tree tops and larger branches that would otherwise be lost (Nantz 1990, Buggie 1991). Field chippers are also expected to recover more fibre from a site because they are able to process small trees that would otherwise be wasted (Raymond and Franklin 1990).

The other two mechanical harvesting systems studied by Gingras (1992) showed less fibre recovery. The feller-buncher/skidder/delimber system and the feller-buncher/processor/forwarder system showed fibre yield indices of 91 and 87 %, respectively. However, in his study Gingras (1992) measured fibre loss at roadside for the system employing a roadside slasher, but no estimations of fibre loss at the roadside for the delimber-debarker-chipper were reported.

Favreau (1997) conducted a comparison of fibre loss between a conventional shortwood-to-mill (feller-buncher/skidder/delimber/slasher) system, with a cut-to-length (single-grip harvester/forwarder) system. This study was undertaken under both summer and winter conditions. The cut-to-length system revealed superior fibre recovery when compared with the shortwood-to-mill system for both seasons. Recovery of total fibre by the cut-to-length system was 96.2 % in summer and 93.6 % in the winter. The full-tree harvesting system recovered 87.9 % and 85.0 % of total fibre in summer and winter conditions, respectively.

Favreau (1997) also calculated the recovered amounts of unmerchantable fibre for each system by season. The cut-to-length system recovered 31 and 34 % of unmerchantable fibre during the summer and winter, respectively. The shortwood-to-mill system recovered 13 and 36 % of unmerchantable fibre during the summer and winter, respectively.

In western Canada some investigation has been made towards recovering cutover logging debris as chips suitable for pulp and paper production (Harrison *et al.* 1997). Screening of poor quality chips produced from logging slash and further sorting with optical sensors has the potential to produce quality chips in a cost effective manner and thus increase the overall efficiency of logging systems (Harrison *et al.* 1997).

The feasibility of upgrading the quality of chips from roadside slash may be limited to western Canada where roadside slash volumes are relatively high. In eastern Canada, efforts to treat roadside slash have been geared mainly towards either disposal or chipping for energy production (Desrochers 1996).

When considering utilizing greater amounts of wood fibre from each tree harvested, the quality of wood fibre should be considered (Yang 1986). Wood fibres are not of uniform quality (length and thickness) within a tree (Yang *et al.* 1994). In general, the stump contains a larger proportion of mature wood and longer fibres than the tip of the stem and so should be valued higher when considering measures to recapture unutilized fibre. The stump also has a larger diameter and therefore has the largest amount of better quality wood available compared to the rest of the tree.

POST HAUL FIBRE LOSSES

When considering the fibre loss of a harvesting system one should keep in mind the potential for fibre loss in further mill processing. Post haul fibre loss is often caused by negative quality factors attributed directly to harvesting.

Poor quality chips result in approximately 3.6 % fibre loss in the screening process at Avenor's Thunder Bay pulp mill (Markham 1997). Poor quality chips are those that are rotten, contain knots, have a high bark content, or may be of an undesirable size (i.e., fines or oversize). The majority of these chips are screened out to avoid uneven cooking in the digester and to improve the overall pulp quality.

High bark content is often caused by improper delimbing or by processing too many small diameter stems. Small diameter stems have a high bark to fibre ratio (Araki 1994). Undersized chips can be the result of colder ambient temperatures (Perrier 1990), low moisture content (Araki 1994), poorly maintained chipper knives, knife angle, improper anvil clearance and sharpness, poor operator in-feed techniques or improper feed speeds (Markham 1997). In addition to these losses, as much as 1 % of chips can be lost per month due to the degrading factors of storage such as rotting, drying and breaking (Pulkki 1991).

Wood in roundwood form also experiences significant amounts of fibre loss within the mill gate. Mill yard handling resulting in breakage occurs for wood in all forms, and can result in as much as 4 % fibre loss for wood in a tree-length form. Fibre losses of 0.5 - 2 % occur from slashing due to sawdust and short ends (Pulkki 1991). Depending on debarking method, wood quality, and intensity of debarking, losses of wood fibre within a mill commonly range between 1 - 10 % (Pulkki 1991). Fibre losses of approximately 0.5 % per month occur in roundwood from factors such as drying and rotting (Pulkki 1991).

SAMPLING FOR CUTOVER RESIDUE

The trend in utilization research is clearly towards recovery of as much fibre as is economically practical, and not simply what is defined by law to be merchantable (Gingras 1992, Young and Hynes 1996, Favreau 1997). Of particular interest regarding this trend is the work done by Fang (1993). Fang's (1993) thesis tested the statistical justifiability of a number of sampling methods used to estimate the volume of logging residues in cutovers of northeastern Ontario. Fang (1993) concluded that no survey method, aside from a complete survey, could be used to accurately determine the amount of merchantable fibre loss on a given site. Considering the historical trend of wood fibre utilization (Pulkki 1978, Gingras 1992, Young and Hynes 1996, Favreau 1997), Fang's (1993) work suggests that the recovery of merchantable fibre has improved to the extent that merchantable cutover wastes can no longer be feasibly sampled with any statistical confidence. Clearly the use of the term merchantability is outdated in regards to its application in the estimation of fibre utilization.

MARGINAL COST ANALYSIS

The relationship between marginal and average costs is crucial in economic theory. The marginal cost is the cost of production for an incremental unit. Average cost is the total cost of production divided by the total number of units produced. Optimality in any business is reached when the marginal costs are equal to the average costs (Klemperer 1996). This is a familiar concept to foresters who recognize that optimal production within a stand occurs when the mean annual increment equals the current annual increment of growth (Philips 1994).

The optimal situation where marginal cost equals average cost does not exist in wood procurement. The furthest wood will always cost more than the average in wood procurement. Because of this relationship, there is always a gain to be made if wood on the margin can be replaced with wood closer to the mill. A firm in the forest industry should be willing to pay more for wood that is closer to its mill if this new wood replaces wood currently being harvested on the margin. For this reason it is important for a forest company to make decisions of this nature based on marginal costing and not average costing.

As the distance of forest operations from the mill increases so do the marginal and average costs. The most significant contributor to this increasing cost is the cost of transportation of the product to the mill.

If a given harvesting system were to have a greater level of wood utilization than another, a savings in transportation costs would occur. Marginal cost analysis is an appropriate tool for measuring the cost savings. Marginal cost advantage can be calculated with the following equation:

$$\text{Marginal Cost Advantage} = \frac{\text{\% Increase} \times \text{Initial Volume} \times (\text{High Cost} - \text{Low Cost})}{\text{Initial Volume} \times (1 + \text{\% Increase})}$$

Where the high cost is the cost furthest from the mill and the low cost is the cost closest to the mill. The value obtained from the marginal cost advantage calculation reflects the level of new costs that can occur without increasing the total average cost. This is necessary information for the decision making process as the new harvesting system may have a higher cost to roadside than the original system.

WOODFLOW ANALYSIS

There are numerous difficulties in calculating the long term total average and marginal costs on a landbase. Each year the locations of harvesting operations move and hauling trucks travel at different speeds on different road classes.

The problems with modeling the irregularity of a forest landbase and road network can be overcome with the use of a GIS (geographical information system). A GIS is simply a computerized map or layers of maps associated with a database. Pulkki (1996) demonstrated how a very simple GIS system could be used to solve complex real world problems associated with network analysis. By applying algorithms that account for variables, such as hauling speed, to the information contained within a GIS, calculations of total average cost and marginal costs can be approximated for real world situations.

CURRENT LEGISLATION AND REGULATIONS

Although the legal concept of merchantability will be ignored by this study a brief outline of the current legislation and regulations in Ontario is merited to provide the reader with a complete picture of current wood utilization issues.

The Scaling Manual (OMNR 1995a) and The Forest Operations and Silviculture Manual (OMNR 1995b) are two of four manuals empowered by section 68 of the Crown Forest Sustainability Act (1994). These two manuals in particular define wood fibre merchantability and dictate the amounts of allowable unutilized wood fibre left remaining on harvested forest land belonging to the Crown.

Five kinds of wasteful practices in harvesting operations in Crown forests are outlined by both the Scaling Manual (OMNR 1995a) and the Forest Operations and Silviculture Manual (OMNR 1995b): these are, leaving high stumps, leaving merchantable timber of any length, leaving merchantable trees, leaving lodged trees, and not utilizing wood chip fibre.

The stump height is defined by the Scaling Manual (OMNR 1995a) as: "the vertical distance between the horizontal plane through the highest point of the stump and the horizontal plane through the highest point of the ground at its base". Trees that are harvested must not have stump heights greater than 30 cm unless their diameter exceeds

30 cm (OMNR 1995a). If a stump exceeds a diameter of 30 cm its height is allowed to equal the diameter up to a maximum of 60 cm (OMNR 1995a).

No merchantable fibre of any length may be left behind after a harvesting operation has been carried out (OMNR 1995a). Within the context of typical boreal Crown forests, "merchantable fibre means: any conifer, poplar or white birch log in which more than one-half the total content, measured in cubic metres, is sound wood, and

i) in the case of felled white pine, red pine, hemlock, poplar or white birch has a diameter of 16 cm or more outside the bark at the smaller end; or

ii) in the case of a felled conifer other than white pine, red pine, or hemlock has a diameter of 10 cm or more outside the bark at the smaller end" (OMNR 1995a).

If in the opinion of the Minister, where sufficient markets exist and with the agreement of the licensee, the outside bark diameter of the smaller end of a merchantable log may be reduced as low as 10 cm in section i) (OMNR 1995a). The term merchantable does not apply to pieces of any length if they are separated from a merchantable part of the tree by a section that is considered non-merchantable (OMNR 1995a). In the cases of white pine and hemlock, the term non-merchantable includes cases where heavy branching cause a section of a tree bole to be not marketable (OMNR 1995a).

It is considered a wasteful practice to leave standing any merchantable conifer, poplar or white birch where more than one half of the total content of the wood is sound (OMNR 1995a).

It is considered a wasteful practice to not use wood chips produced from harvesting operations of Crown lands (OMNR 1995a). Wood chips are defined as "chip fibre of any species produced by a chip manufacturing facility, whether fixed or mobile" (OMNR 1995a).

METHODS

During the summers of 1996 and 1997 sampling of logging residue was done from three harvesting systems used in northwestern Ontario. Sampling from the FT-CH system was done near Thunder Bay in the Dog River-Matawin, and Black Sturgeon Forests. Sampling of the FT-SW system was done near Dryden in the Wabigoon and English River forests. Sampling of the CTL system was done from Block 3 of Abitibi Consolidated's freehold land.

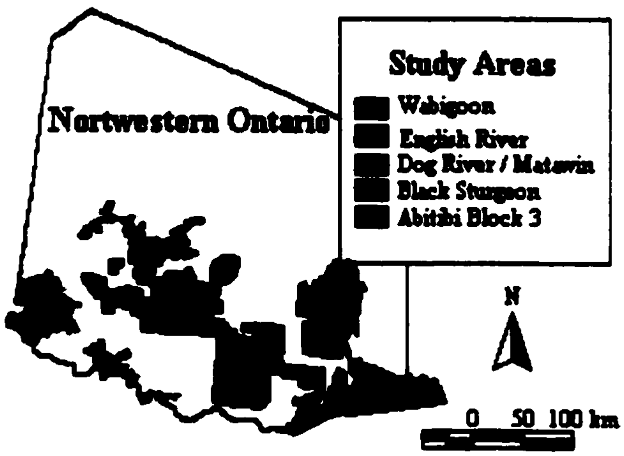


Figure 5. Map of northwestern Ontario showing individual forest management areas that comprised the study area.

The forests where sampling occurred represent the bulk of harvesting activity for Avenor Inc. and its contractors. An attempt was made to sample from a wide diversity of sites so that the results would be representative of Avenor's entire area of operations within those forests. Sampling from all of Avenor's forests would have been less practical logistically.

The areas sampled reflect a wide diversity of logging chance factors common to northwestern Ontario. In general the terrain ranged from very good ground strength, very even roughness and level slope (CPPA classification1.1.1.) (Melgren 1980) to wet, rough and steep. However, the combination of wet, rough and steep (CPPA classification 4.4.4.) never occurred simultaneously. In general the wet sites were relatively free of obstacles and level (CPPA classification 4.3.1), and the roughest and steepest sites were at worst freely drained (CPPA classification (2.4.4.). These worst case scenarios, however, represent only small isolated sections of any given logging site. In general the worst possible sites defined by the CPPA (*i.e.* level 5) never occurred on sites selected for harvest.

The forest cover types of the areas sampled were typical of northwestern Ontario, however, there were obvious differences between forests. In the Black Sturgeon Forest there is a preponderance of decadent balsam fir stands with mixed amounts of other species. The Dog River and Matawin Forests contain a wide mix of the common species to the region; black spruce, jack pine, balsam fir, trembling aspen and white birch. The Wabigoon and English River Forests are largely dominated by stands of black spruce and jack pine with less occurrence of trembling aspen and white birch.

An attempt has also been made to be fair in the comparison of fibre utilization between systems. To do this, the concept of merchantable fibre has been discarded. For the practical purposes of this project the gross total volume of a site is defined as the sum of all solid green wood inside the bark, that is above the ground or pronounced butt flare, up to an inside bark diameter of 4 cm.

SAMPLING OF CUTOVER RESIDUE - ALL SYSTEMS

The sampling technique used to estimate unutilized wood fibre remaining within cutovers was identical for each harvesting system. Circular 100 m^2 plots were randomly located within the cutovers of each system: 46 plots were used to sample the roundwood-to-mill system; 40 plots were used to sample the cut-to-length; and 69 plots were used to sample the chip-to-mill system. The number of plots for each system was dictated by the need to achieve reasonably meaningful confidence intervals. It was hoped that a confidence interval of +/- 10% of the estimate could be achieved. No plots were placed in dense residual standing birch, or within 50 m of roads and cut block edges.

Within the plot boundary, the diameter of all 4 cm or greater roundwood pieces (inside bark) was measured at both ends to the nearest centimetre. If a roundwood piece extended beyond the plot boundary the diameter was measured at the end within the boundary and at the boundary edge. Both the length of the roundwood piece within the plot and the entire length of the roundwood piece (if it extended beyond the boundary) were measured to the nearest decimetre.

By measuring all wood fibre (stems and stumps) down to a relatively small diameter and not only those pieces considered merchantable by the OMNR (1995a) this design avoids the problems encountered by Fang (1993). Fang (1993) had a large number of plots with no volume and thus had difficulties in calculating confidence intervals from a limited number of plots. It would be highly unlikely to have any plots from the chosen sampling design to have no measurable volume.

Smalian's formula was used to calculate the volume (m^3) contained within the plot of each roundwood piece:

$$\text{Volume} = \frac{\pi \cdot L\,(d_1^2 + d_2^2)}{8{,}000{,}000}$$

where:

d_1 and d_2 are the end diameters (cm) of each roundwood piece, and L is the length (cm) of the piece.

The top and bottom diameter of all stumps 4 cm or greater whose centre fell within the plot was measured to the nearest centimetre. Stump height was measured as the distance between the point where the butt starts to flare or the top of an adjacent obstacle, to the average top of the stump. The formula for the volume of the frustum of a neiloid was used to calculate stump volume (m^3):

$$\text{Volume} = \frac{H}{4} \cdot \frac{(a + (a^2 \cdot b)^{1/3} + (b^2 \cdot a)^{1/3} + b)}{1{,}000{,}000}$$

where:

$a = \pi\,(d_1/2)^2$
$b = \pi\,(d_1/2)^2$
d_1 and d_2 are the bottom and top diameters (cm) of the stump,
and H is the height (cm) of the stump.

In addition each piece was categorized according to species, quality and damage type. Quality was denoted simply as either good or poor. Good, refers to fresh pieces that were most likely alive at the time of harvest. Poor quality pieces were those that were sound, but showed some indication that they may have been dead or nearly dead at the time of harvest. No rotten roundwood pieces or stumps were tallied.

The damage classification describes roundwood pieces as: cut, broken, run-over, or left standing. A roundwood piece that had both a cut end and a broken end was classified as a cut stem. Roundwood pieces that were classified as run-over were those that were obviously run or pushed over (deliberately or accidentally) by a machine and not broken during some other element of the work cycle. Stems classified as run-over were often uprooted. It is possible that some logs classified as broken may have been run-over as there may have been no clear evidence to suggest otherwise.

Roundwood piece and stump volumes were regressed, against the plot basal areas. When significant correlations were found, Plonski's (1981) stand volume to basal area relationship (site class 1, jack pine [*Pinus banksiana* Lamb.]) was substituted for basal area into the regression equation:

$$\text{Basal Area} = (\ 0.1521912 \times \text{Gross Total Volume})$$

The resulting equation allows the prediction of fibre waste from initial stand volumes. Site class 1, jack pine was chosen because the factor (0.1521) is a reasonable approximation of the average of Plonski's (1981) other site classes that are common to the areas sampled.

SAW KERF FIBRE LOSS

Volume losses associated with the saw kerf were estimated by multiplying the average plot basal area by the thickness of the saw. A 5.5 cm thick kerf was used for this calculation in the roundwood-to-mill and chip-to-mill systems. This width of tooth is used widely on feller-bunchers used by Avenor and its logging contractors. A 0.8 cm saw kerf, as measured directly from a single-grip harvester, was used for the cut-to-length system calculations. The Plonski (1981) basal area to volume relationship (site class 1, jack pine) was again used to produce equations to predict saw kerf losses from initial stand volumes.

FT-CH SYSTEM SAMPLING

Loss Due to the Roadside Chipping Process

All chipper sampling was done from Shuniah Forest Products' two Peterson Pacific delimber-debarker-chippers during the summer of 1997. This contractor consistently produces high quality chips and its proximity to town made frequent sampling more efficient. Sampling from various contractors was considered unnecessary since preliminary work indicated that there was little variance of fibre loss between contractors and the type of machine.

A total of 20 trees of various species {10 aspen [*Populus tremuloides* Michx.], 5 spruce [*Picea mariana* (Mill.) B.S.P.] and 5 jack pine} were weighed using a load cell prior to chipping (Figures 6 and 7). Both ends of a chain were wrapped around the bole of the tree on either side of its approximate balance point. One end of the load cell was attached to the middle of the chain while the other end was attached to the clam on the end of the chipper boom. The operator was instructed to lift the tree to an appropriate height and hold it there so that a reading could be taken from the load cell's panel meter.

Figure 6. A Peterson Pacific DDC-5000 grapple arm, load cell and chain being used to weigh a black spruce tree prior to chipping.

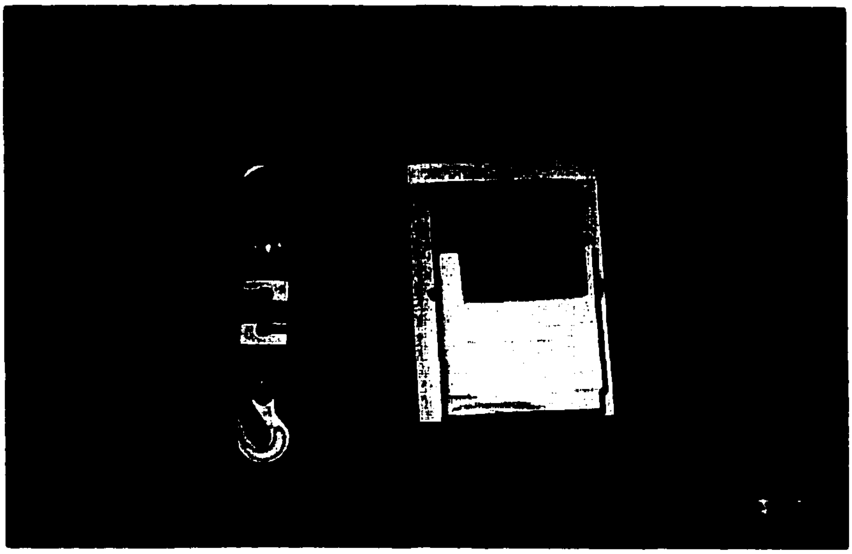


Figure 7. The "S" shaped load cell and panel metre (with power supply) used to determine the weights of trees prior to chipping.

Tarps were laid on the ground on either side of the chipper to collect debris from both the coarse fibre debris chute (Figure 8) and the bark chute (Figure 9) of a Peterson Pacific delimber-debarker-chipper. Most of the debris that exits the bark chute during the chipping of a single tree does not actually leave the chute. Because of this, debris in and in front of the bark chute was removed prior to chipping so that the majority of fresh debris could be collected directly from the chute (Figure 10).

Figure 8. The coarse fibre debris chute of a Peterson Pacific DDC-5000.

Figure 9. The bark chute of a Peterson Pacific DDC-5000.

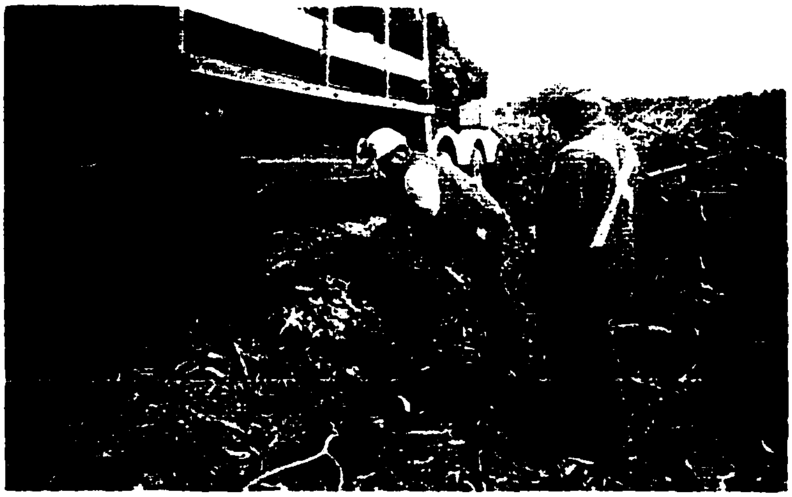


Figure 10. Collecting unutilized fibre and other coarse material from the bark chute of a Peterson Pacific DDC-5000.

The green weights of coarse fibre, bark debris and branches were measured at Lakehead University. When samples contained a mix of bark and fibre, five 1,000 g sub-samples were taken from the larger sample. The fibre and bark of each sub-sample was sorted and an estimate of the total fibre content was made. Branch material was not included in the sum of wasted fibre. The weight of green chips produced by chipping was calculated by subtracting the weights of the two debris chutes from the initial tree weight. The total amount of fibre contained in the tree prior to chipping was calculated by summing the chip weight with the amount of fibre from each debris chute. The amount of fibre waste was expressed as a percentage of original fibre for each tree sampled. The average percentage fibre waste and the associated confidence intervals ($\alpha = 0.05$) were calculated from the data.

To ensure minimal change in weight associated with a change in moisture content the debris was transported in closed garbage bags and measurements were always made within 6 hours of chipping. The chips produced during sampling were blown onto the ground and not collected.

Loss During Loading

The amount of fibre lost in the loading process was also measured at the chipping site during the loading of 20 trailer vans. Tarps were laid out on the ground on the side of the trailer opposite of the chipper. Wood chips were shovelled off of these tarps and transported back to the lab. The total wet weight was measured and five 1,000 g sub samples were taken, dried, and weighed again to calculate the total dry weight of the sample. The estimated total dry weight of wood chips was compared with the total dry weight of the truck load, as recorded in the mill scale database, to produce an estimate of percent fibre loss.

Loss During Transportation

Two sites along highway 11-17 were chosen for sampling the transportation losses of fibre from chip trailers during highway hauling. These sites were selected because of their high concentration of traffic. One site was located just west of Shabaqua, the other just west of the Spruce River Road. Both sections of highway were smooth and relatively level. The maximum travel speed on each section was 90 km/hr.

At each site a section of road 25 m long was measured off and the passing trailers were watched for wood chips falling off within this distance. The wood chips were retrieved and taken to the lab to determine dry weights. Estimates of lost fibre (g/km) were calculated.

For each trailer passing by during the survey, information concerning the tarping system, rear door type, and trailer configuration was recorded. Whether or not the load was full or empty was also recorded.

Chips Remaining After Unloading

To determine the amount of wood chips remaining within the trailers after dumping, 15 trailers were sampled after leaving the weigh scales. The remaining wood chips were removed from the trailers and dry weights were obtained. Visual estimates of the wood chips in the front section of "B" trains had to be made because of the difficulty of entering this section. The dry weight of the collected chips was compared with the total load dry weight, as measured at the mill, to obtain a percent estimate of the amount of wood fibre remaining after dumping.

FT-SW SYSTEM SAMPLING

Sampling of slash pile wastes was done using two-stage sampling, with sub-samples from units of unequal size, as outlined by Cochran (1977). Three sub-samples were taken from each of 30 different slash pile units (Figure 11). The sub-samples consisted of 1 m by 2 m rectangular plots that were randomly located on top of each slash pile (Figure 12). All woody debris within the rectangular sub-sample plot was removed using a chainsaw. Each piece removed from the resulting hole was identified by species and measured for total length as well as top and bottom diameter (inside bark) to the nearest centimetre. Smalian's formula was used to calculate the volume of each piece removed. The total volume of each sub-sample plot and the average sub-sample plot volume of each slash pile were calculated.

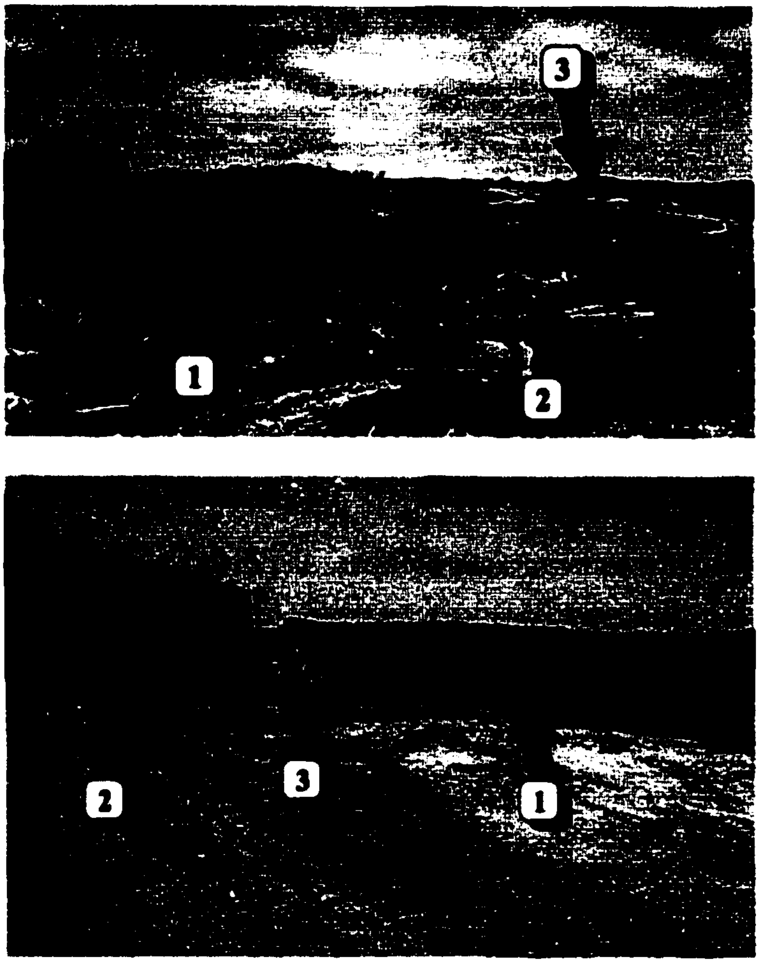


Figure 11. Typical sampling sites of roadside wastes from the shortwood system, showing; 1) slash pile, 2) end pieces from slasher and 3) roundwood piles.

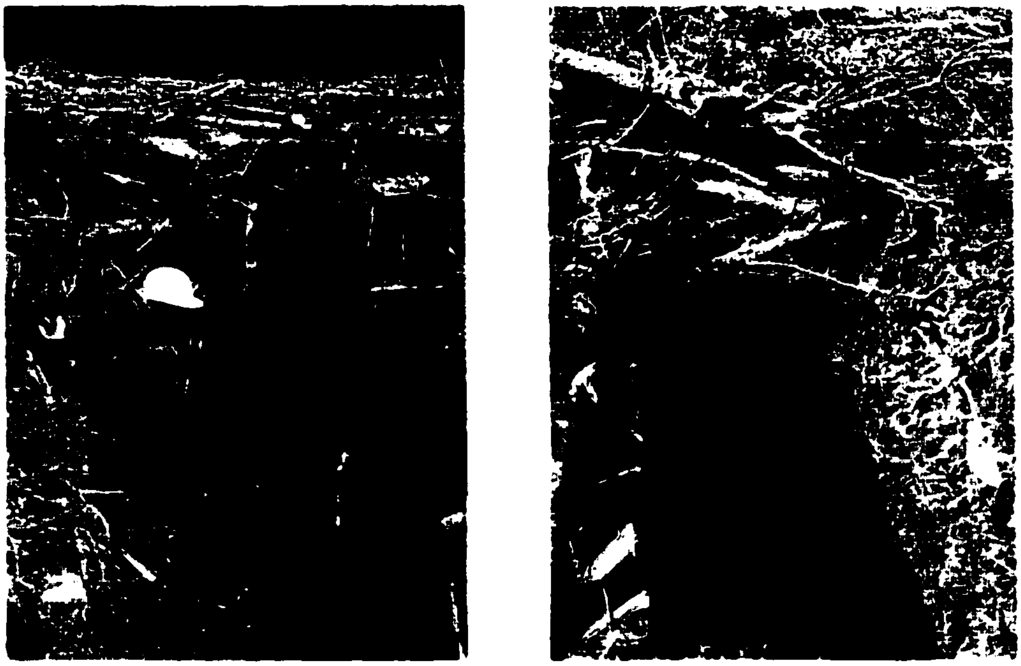


Figure 12. Typical 1 m x 2 m slash pile sampling pits excavated with a chainsaw.

The resulting sub-sample holes were measured for depth and distance from the edge of the slash pile nearest to the road. This was done to determine if possible correlation between either depth or distance from the edge could be found with sampled volume. If such a correlation could be found future sampling would be more easy to perform.

A closed traverse was established around the slash pile using a hip chain and compass to measure distances and azimuths. The total area of each slash pile based on a balanced closed traverse was calculated using a computer program written specifically for this project. Slash pile area was calculated in the field using a laptop computer. A minimal closure precision of 2 % was set as a standard for an acceptable traverse. This is the same level of accuracy accepted by the Forest Engineering Research Institute of Canada (FERIC) for closed traverses. If this precision was not attained the traverse was re-measured.

The log pile associated with each slash pile was scaled using the "Stacked Wood" method as outlined in the Ontario Scaling Manual (OMNR 1995a). The one deviation from this method was that the pile height occasionally exceeded the maximum limit of 4.00 m as dictated by the manual. This in no way violates the validity of the method.

According to the scaling procedure (OMNR 1995a), the length and width of the pile were measured and multiplied by the average height calculated from a series of evenly spaced measurements. This resulting volume was multiplied by a factor of 0.66 to determine the volume of solid wood within the scaled total volume of the pile.

Estimates of fibre loss due to the slasher saw kerf were made by multiplying the saw kerf (1.2 cm) by the surface area of the face of a typical solid cubic metre of roundwood with a length of 2.54 m. This provided an estimate of the percentage fibre loss per cubic metre of slashed wood produced. This technique was employed because all of the logs were slashed to a length of 2.54 m, longer logs were not produced.

Estimates of fibre loss due to the end pieces produced during slashing were made by measuring the length, top and bottom inside bark diameter of each piece on the roadside to the nearest centimetre. Smalian's formula was used to calculate volumes of each individual piece. The total wasted fibre volume of these pieces for each pile of roundwood was expressed as a percentage of the total amount of wood brought to roadside for that pile. The average percent loss and the confidence interval ($\alpha = 0.05$) were calculated across all of the piles.

By multiplying the average wasted fibre volume of each slash pile (m^3/m^2) by the area of each slash pile an average amount of wasted fibre per pile was estimated. Estimates of fibre waste within each slash pile were expressed as a percentage of the total amount of wood brought to the roadside associated with each pile. The mean average percentage loss was calculated across all slash piles and the associated confidence interval ($\alpha = 0.05$) was calculated.

CTL SYSTEM SAMPLING

An estimate of fibre loss to the single-grip saw kerf during bucking was made in a similar way as the estimate of fibre loss to the slasher saw kerf of the FT-SW system. The 0.8 cm saw kerf was multiplied by the solid surface area of a cubic metre of solid wood measuring 2.54 m in length. In order to make a direct comparison with the FT-SW system this calculation makes the false but not severe assumption that no 5.1 m logs are produced. As a typical CTL system in northwestern Ontario will also produce some 5.1 m sawlogs and thus perform less bucking, the estimate of bucking loss based only on 2.54 m lengths will be greater than the actual.

FT-TL SYSTEM EXTRAPOLATION

As the FT-TL system is intended to replace the FT-SW system in tbe Dryden area, the data collected in Dryden was used as the basis for predicting fibre utilization in the FT-TL system. The amount of unutilized fibre remaining in the cutover following harvest with the FT-TL system is assumed to be the same as with the FT-SW system.

Roadside losses are expected to be similar between the two systems. The end pieces lost during slashing and the slasher kerf will not be lost by the FT-TL system, however, some losses may occur at the mill. The end piece losses from the FT-SW system were not subtracted from gross volume in the extrapolated FT-TL model.

The switch from FT-SW to FT-TL will also dictate a change in the end diameter cut by the delimber. The end diameters of each tree will be cut at 3" (7.62 cm) instead of 4" (10.16 cm) resulting in an additional fibre gain over the FT-SW system.

Taper factors for the top ends of jack pine and spruce were calculated from the existing slash pile data. This was done by calculating the average change in diameter per metre of length for each species. The average length between 3" and 4" diameters was calculated for jack pine and spruce based on these factors. Smalian's formula was used to estimate the average volume between the 3" and 4" diameters for pine and spruce. The average volume gained by species was multiplied by the average number of stems per hectare found for that species. The result is an average fibre gain by species per hectare.

For simplicity, an average fibre gain by tree, due to decreasing the end diameters, was calculated from the weighted average fibre gains by species from the entire data set. The number of trees per plot was regressed by the basal area of each plot to provide an equation that predicts the number of trees per hectare from the basal area per hectare. Plonski's equation for predicting basal area from stand volumes was substituted into this equation. The resulting equation predicts the number of trees per hectare from initial stand volume. By multiplying the output of this equation by the average fibre gain per tree it is possible to predict the average fibre gain per hectare from initial stand volumes.

PART-TREE VERSUS FULL-TREE LOGGING CASE STUDY

During the course of field work the opportunity to collect experimental data as opposed to survey data was very limited. One occasion did allow for an experimental test between two harvesting systems. Within a very uniform stand of jack pine both a single grip-harvester and a feller-buncher were operating in distinct areas. The feller-buncher produced full-length material for the conventional FT-CH system. The single-grip harvester utilizing a fixed head felled and processed 5.1 m logs, as well as bunching the remaining branchy tops. Approximately 2 logs were being cut from each tree leaving a relatively small top. The bunches of tops were skidded to roadside to be chipped while the logs were forwarded to roadside.

15 post harvest volume estimation plots were randomly located within each of the respective areas harvested by the two logging systems. Estimates of stump and roundwood piece volumes were made for both of the harvesting systems. An analysis of variance was performed on the volume data.

MARGINAL COST IN WOOD FLOW ANALYSIS

In order to best analyze the economic implications of better wood utilization from the different harvesting systems in question, a wood flow analysis was performed on an arbitrarily chosen case study area.

The Wabigoon and English River forest areas were chosen for a wood flow analysis that incorporated the wood utilization results of the four harvesting systems. Provincial series maps (1:100,000), covering both management units were obtained. The 1000 m universal transverse Mercator (UTM) grid was used as a reference to manually generate a 136 by 209 raster-based map sheet covering both forests. Each km^2 of the UTM grid represented one pixel. Road classifications were obtained from Avenor's woodland office in Dryden. Pixels within the raster map were coded according to road class (1-4), management unit (5 = Wabigoon, 6 = English River, 8 = outside limits), and open water (9) (Figure 13).

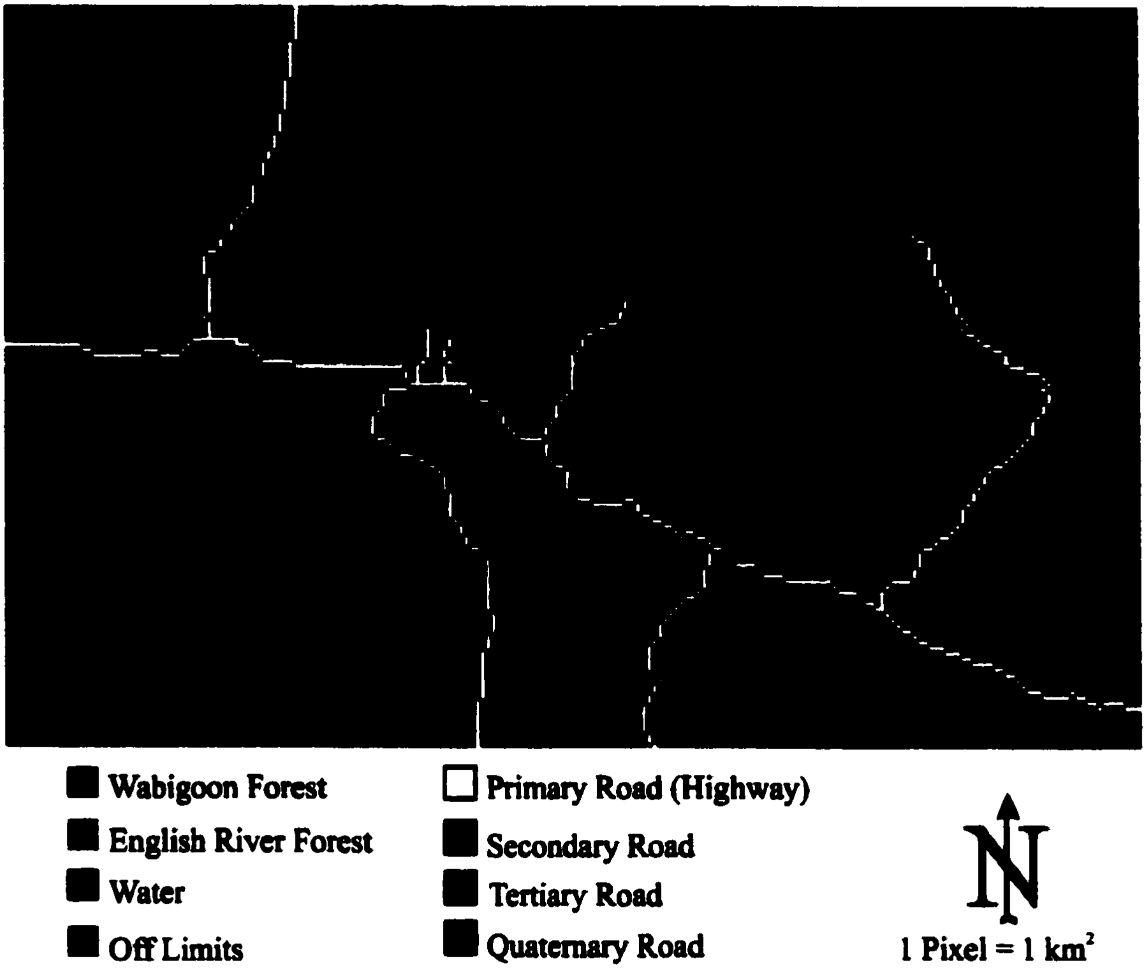


Figure 13. Raster road network map of the Wabigoon and English River forests.

A computer program was used to allocate the annual allowable cut of the Wabigoon (755,000 m^3) and English River (745,000 m^3) forests evenly across all non-water pixels found within each respective forest area. This step supposes that harvesting operations occur in all parts of the forest each year. This is a false assumption in the short term, but is suitable for long term planning. The actual long term average hauling distance will be closely approximated by the average hauling distance obtained with this method.

Again, using a computer algorithm, the allocated wood volumes were moved to the nearest road pixel. Thus a road network map was produced that included road classifications and average yearly hauling volumes from each road node.

The volume of wood in each pixel was assigned to the road pixel that gave the minimum combined round trip time of hauling to roadside and hauling to the mill. The network minimization algorithm outlined in detail by Pulkki (1996) was used for these calculations. The computer algorithm used for the network minimization compensated for distances travelled diagonally between the square road pixels. A winding factor of 1.38 was used for calculating the distance of off road transportation. Loaded hauling speeds for road classes 1-4 were set at 70, 50, 30, and 10 km/hr, respectively. Empty hauling speeds for road classes 1-4 were set at 80, 60, 40, and 20 km/hr, respectively. Individual haul truck volumes were assumed to be 50 m^3. The cost of operating a haul truck was set at $85 /hr.

The Dryden mill demand was fixed at 925 000 m^3; the approximate amount of wood currently received from the Wabigoon and English River forests by the FT-SW system. The allowable harvest of each forest was increased over current levels by the percentage expected to be gained over the FT-SW system by the other three systems. For the simplicity of these hypothetical examples the wood species within each forest was considered to be uniform.

The minimum cost to meet the Dryden mill demand from both forests for the FT-SW, FT-TL, and CTL harvesting systems was calculated. A map was generated that represented the extent of the landbase that each system required. Costs of transportation of wood nearest the mill and wood furthest from the mill were calculated for each system.

The average amount of volume harvested per hectare in the Wabigoon forest is 120 m^3. By working backwards through the fibre utilization model for the FT-SW system the initial gross total volume of a stand that would yield 120 m^3 after harvest from the FT-SW system was ascertained. This gross total volume (151 m^3) was substituted into the fibre utilization models for the FT-TL, FT-CH and CTL systems to obtain the estimated yields from these systems in m^3. The percentage increased fibre yield over the FT-SW system was calculated for the other three systems.

From the standard costing of each harvesting system (Appendix I) and the costs of wood transportation a marginal cost analysis was performed. A comparison between the CTL system and FT-SW system was most appropriate since each can be used to deliver wood in the same form to the mill. Costs within the mill attributed to each system could them be considered identical and could be removed from the analysis. The marginal cost advantage of the CTL system over the FT-SW system was calculated by subtracting the cost of the nearest wood from the cost of the furthest wood for the CTL system and multiplying the difference by the percentage of increased fibre yield of the CTL system over the FT-SW system.

Other information, obtained from Pulkki (1998), concerning the other advantages of the CTL system over the FT-SW system were added to the marginal cost analysis; this information includes, less dense road system, less transportation of equipment and workers, and new wood sources.

RESULTS

The amount of wood defined as poor quality remaining on a site following harvest was found to vary greatly from site to site and showed no clear relationships among the harvesting systems. For this reason only wood fibre defined as good quality is reported in these results.

In the sections to follow, flow charts are presented that demonstrate where wood fibre is lost within each harvesting system. The flow charts serve as merely a visual model of a wood loss equation for each system. The final result of these charts depends largely on the initial stand volume. For simplicity, 100 m^3/ha has been used as an arbitrary initial value in each of these systems. The purposes of these charts is to demonstrate how much fibre is lost at each stage of the system.

FT-CH SYSTEM

A flow cart of fibre loss within the FT-CH system (summer operations) is shown in Figure 14. The expected fibre loss at each stage of the system is given as a fixed value, equation or percent.

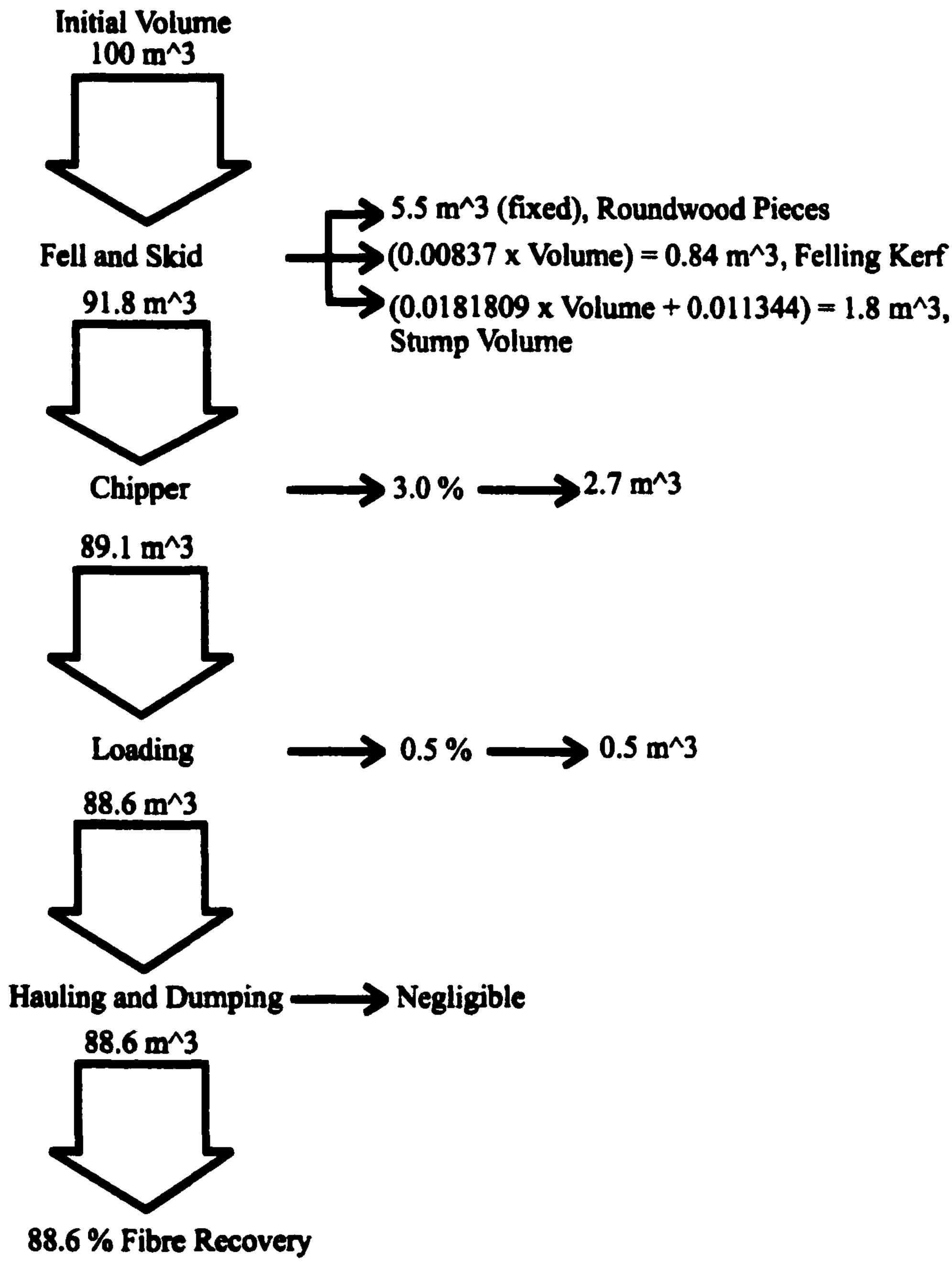


Figure 14. Wood fibre utilization model for the FT-CH system (feller-buncher/skidder/delimber-debarker-chipper). Descending arrows are to scale and indicate wood flow towards the mill. Horizontal arrows indicate fibre losses. The initial volume of 100 m^3/ha is used as an arbitrary seed value.

Table 1 displays the actual volume of cutover residue following harvest by the FT-CH system. The amounts of fibre loss are partitioned according to stumps, roundwood pieces and felling kerf; confidence intervals are provided ($\alpha < 0.05$).

Table 1. Average residual cutover fibre volumes measured following chip-to-mill system harvest derived directly from 100 m^2 sample plots ($\alpha = 0.05$).

	m^3/ha	+/-
Felling Kerf	1.7	0.1
Stumps	4.8	0.4
Roundwood Pieces	5.5	1.0
Total	12.0	1.1

Sampling of the chipper revealed that a total of 3.0 +/- 0.26 % ($P = 0.05$) of the green fibre entering the chipper is wasted. The low variation in fibre waste between species indicated that all of the species tested (spruce, jack pine, and aspen) have similar levels of fibre waste due to the chipping process. Based on the percentage of fibre loss, and the costing in Appendix I, approximately $ 41.94 worth of wood fibre is wasted for every 100 m^3 brought to the chipper.

The fibre loss due to chipping is distributed unevenly between the bark chute and the coarse fibre debris chute. The bark chute has losses of 0.2 +/- 0.09 % ($\alpha = 0.05$), while the coarse fibre debris chute has losses of 2.8 +/- 0.23 % ($\alpha = 0.05$).

Significant correlations were found between the measured stump fibre loss per plot and the basal area per plot (Figure 15). This relationship shown in Figure 15, was combined with Plonski's (1981) relationship for basal area and initial stand volume to yield the equation found in the fibre utilization model (Figure 14).

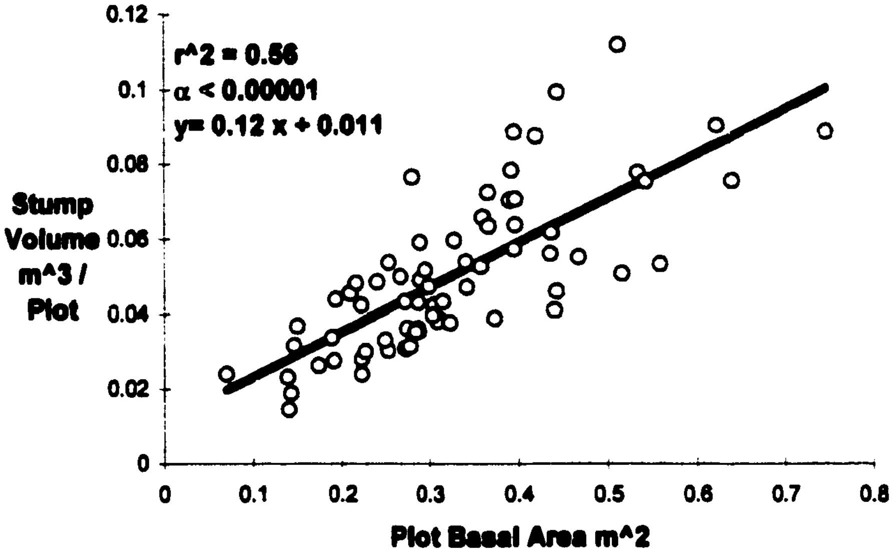


Figure 15. Regression of measured basal area per plot versus measured stump volume per plot for the FT-CH system.

In addition to the amount of fibre wasted within the chipper, 0.5 % +/- 0.4 % ($\alpha = 0.05$) of wood chips are lost during the loading of the chip trailers. When the trailer is nearly full, chips leave the chipper at such a high velocity that some bounce off of the chips already in the trailer and land on the ground.

Based on the costing models in Appendix I, the cost required to fell, skid and chip the wasted wood is approximately \$6.99 is for every 100 m^3 leaving the chipper. Although sampling for this element only occurred from chip vans, it has been observed that a similar amount of loss can occur from trailers with a "B" train configuration depending on the chipper operators diligence.

The average amount of wood chips lost during transportation (*i.e.,* blowing off on the highway) was found to be 4.5 g/km +/- 3.0 g/km ($\alpha = 0.05$). If one trailer were to travel a 200 km round trip it would only lose approximately 0.005 % of its load, or, one truck in about 20,000 is lost on the highway. This amount of fibre loss (0.005 %) is considered negligible in comparison to other losses within the FT-CH system.

All of the sampling done of chip loss during transportation occurred under ideal driving conditions. When following directly behind a trailer it can be observed that most of the chips fall off when the trailer passes over bumps. Also, empty trailers tend to lose a large amount of chips immediately after leaving the mill gate. Chips accumulate between trailer sections or on top of the second tarp while dumping and blow off as the trailer gains speed immediately after turning onto the highway. These factors would indicate that the estimated levels of chip loss are somewhat low. None the less, the actual values would have to be hundreds of times higher than the estimate before becoming important.

The amount of chips remaining after dumping (0.05 %) can be considered insignificant as the volume of chips is approximately equivalent to one truck in 2000. This wood is not actually lost, it simply makes a return trip to the chipping site. Although hauling chips twice does reduce the efficiency of the system, in this case the volumes are so small that they can be considered insignificant. Chips remaining after dumping are, however, expected to have significant negative effects during winter operations. Freezing often occurs between the chips and the walls of the trailers causing much larger amounts of chips to remain inside the trailer after dumping.

FT-SW SYSTEM

Figure 16 illustrates the fibre utilization model developed for the shortwood system. The expected fibre loss at each stage of the system is given as a fixed value, equation or percent.

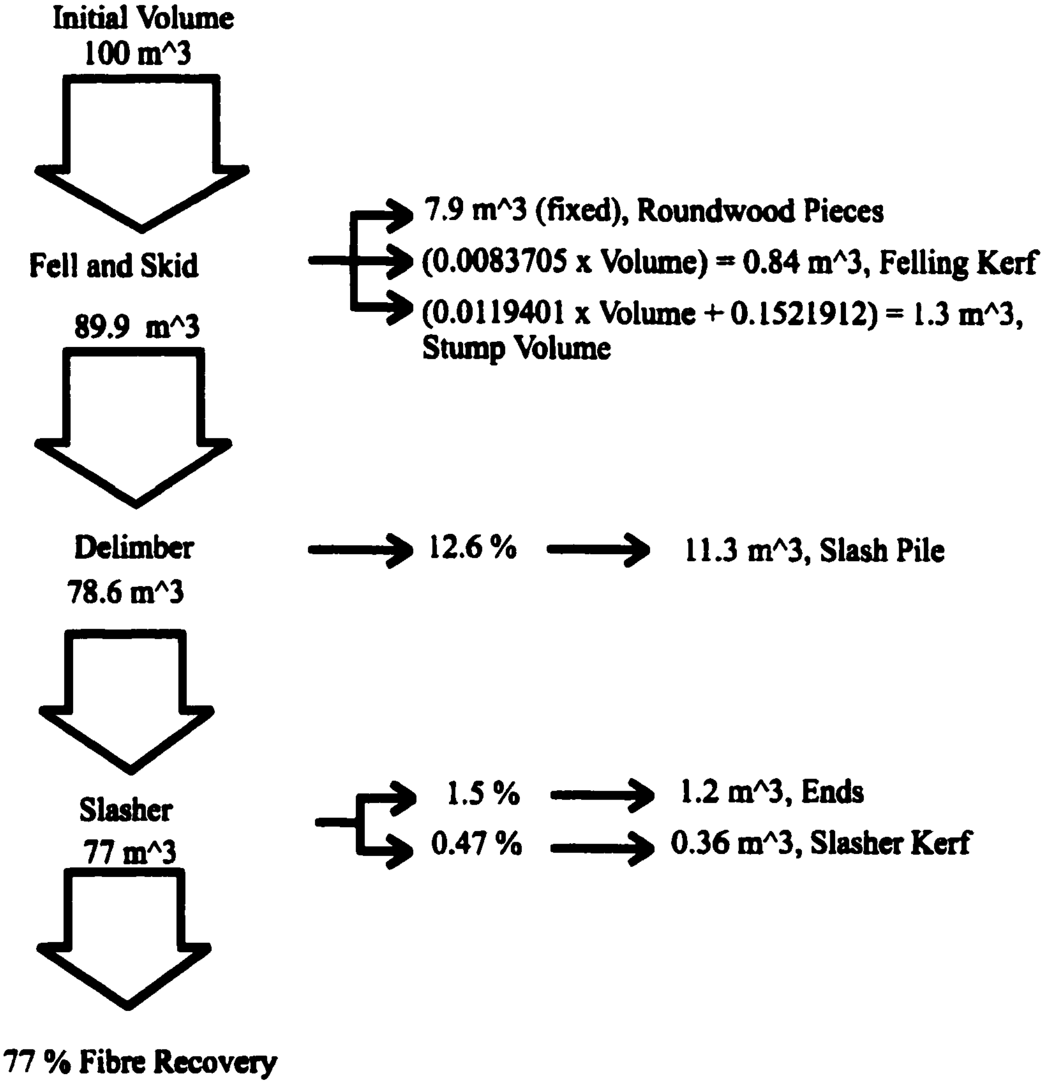


Figure 16. Wood fibre utilization model for the FT-SW (feller-buncher/skidder/delimber/slasher) system. Descending arrows are to scale and indicate wood flow towards the mill. Horizontal arrows indicate fibre losses. The initial volume of 100 m^3/ha is used as an arbitrary seed value.

Table 2 summarizes the actual volume of wood fibre remaining within cutovers following the implementation of the FT-SW harvesting system.

Table 2. Average cutover logging residue measured following FT-SW harvest (α = 0.05).

	m^3/ha	+/-
Saw Kerf	2.0	0.2
Stumps	3.1	0.5
Roundwood Pieces	7.9	3.8
Total	13.0	3.8

Stump volume per plot was found to be correlated with the basal area per plot (Figure 17). Although a relatively weak fit ($r^2 = 0.48$) was found, the relationship is highly significant ($\alpha = 0.00016$). By substituting this equation in Plonski's (1981) stand volume to basal area equation (site class 1, jack pine), one can predict residue stump volume from initial stand volume. The combined equation is used in the fibre utilization model (Figure 16).

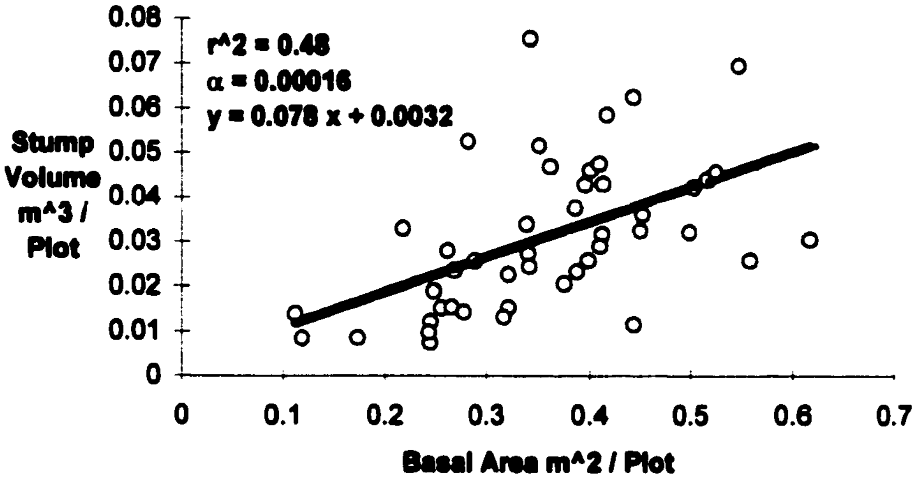


Figure 17. Regression of measured basal area per plot versus measured stump volume per plot for the FT-SW harvesting system.

The roundwood piece volume per plot was not significantly correlated with the basal area per plot, therefore, it is assumed that fibre wastes due to roundwood pieces are independent of initial stand volume. Because roundwood piece volume was found to be independent of initial plot volume a fixed amount of loss, *i.e.*, independent of initial stand volume, appears in the Figure 16 fibre utilization model.

Delimber fibre losses found within the slash piles, amounted to 12.6 +/- 2.2 % ($\alpha = 0.05$) of the solid wood fibre volume brought to roadside. Based on the costing of Appendix I approximately $120.83 worth of wood fibre is wasted in the slash pile for every 100 m^3 brought to roadside. Fibre losses due to the end pieces produced by the slasher amounted to 1.5 +/- 0.2 % ($\alpha = 0.05$) of the solid wood fibre brought to roadside. Again, based on the costing in Appendix I approximately $17.52 worth of wood fibre is wasted for every 100 m^3 brought to the slasher. The combined total of roadside wastes from both the delimber and slasher is 14.1 +/- 2.3 % ($\alpha = 0.05$). In addition to these roadside wastes, 0.47 % of the slashed wood is lost due to the saw kerf of the slasher.

The regressions of sub-sample pit depth and distance from roadside were not significantly correlated with sub-sample pit volume. The lack of a significant correlation removes the possibility of conducting further sampling of slash pile volume in a more efficient manner.

CTL SYSTEM

Figure 18 illustrates the fibre utilization model developed for the CTL system. The expected fibre loss at each stage of the system is given as a fixed value, equation or percent.

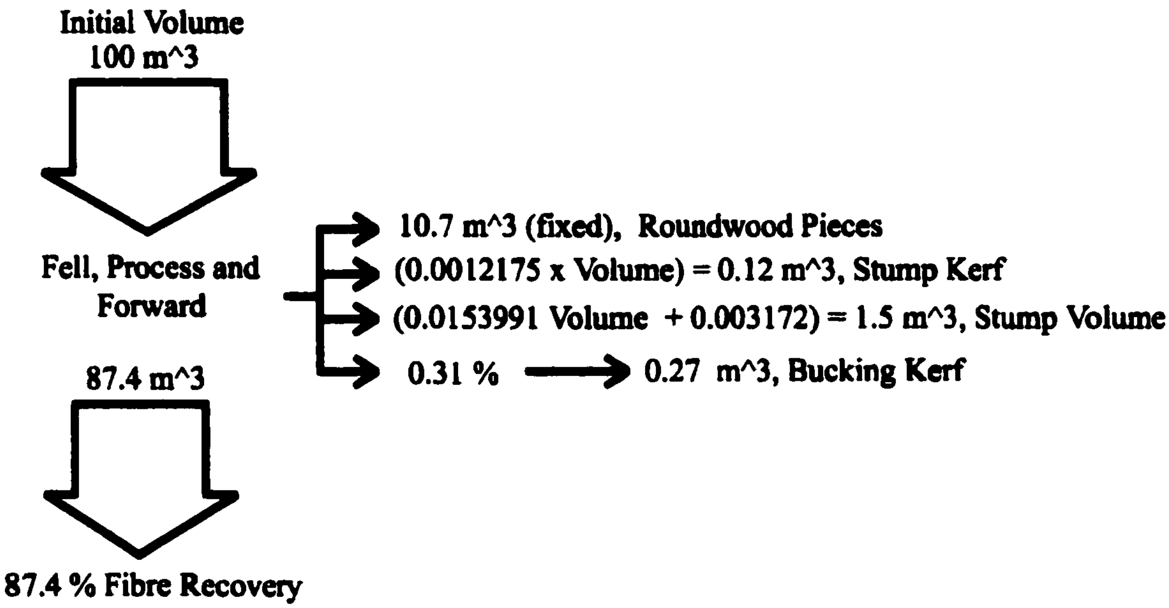


Figure 18. Wood fibre utilization model for the CTL (single-grip harvester/forwarder) system. Descending arrows are to scale and indicate wood flow towards the mill. Horizontal arrows indicate fibre losses. The initial volume of 100 m^3/ha is used as an arbitrary seed value.

Table 3 summarizes the volume of residue wood fibre remaining within cutovers following the implementation of the CTL system. In addition to these losses 0.31 % of the wood bucked by the harvester head is lost to sawdust.

Table 3. Average cutover wood fibre residue volumes measured following CTL harvest ($\alpha = 0.05$).

	m^3/ha	+/-
Saw Kerf	0.26	0.02
Stumps	3.6	0.4
Roundwood Pieces	10.7	1.6
Total	14.5	1.7

Stump volume per plot regressions against the basal area per plot were found to be correlated (Figure 19). Although a relatively weak fit ($r^2 = 0.43$), the relationship is highly significant ($\alpha < 0.00001$). This relationship, combined with Plonski's (1981) stand volume to basal area relationship, allows for the prediction of wasted stump fibre from the initial stand volume. This combined equation is used in the fibre utilization model (Figure 18).

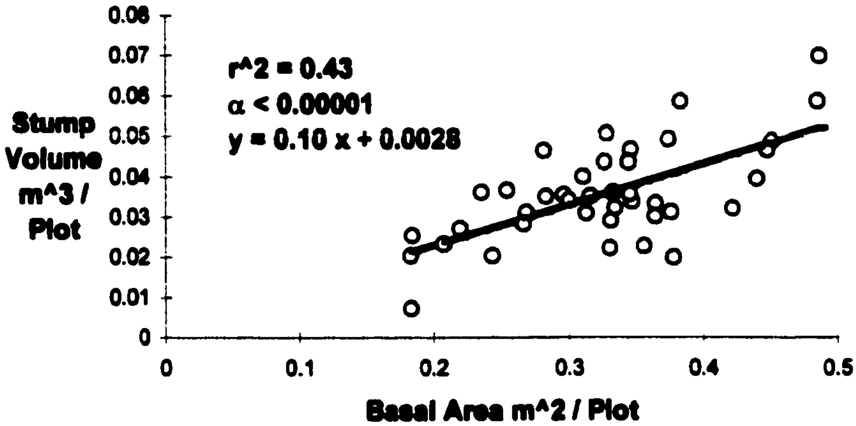


Figure 19. Regression of measured basal area per plot versus measured stump volume per plot for the CTL system.

FT-TL SYSTEM

Figure 20 illustrates the derived fibre utilization model developed for the FT-TL system. The expected fibre loss at each stage of the system is given as a fixed value, equation or percent.

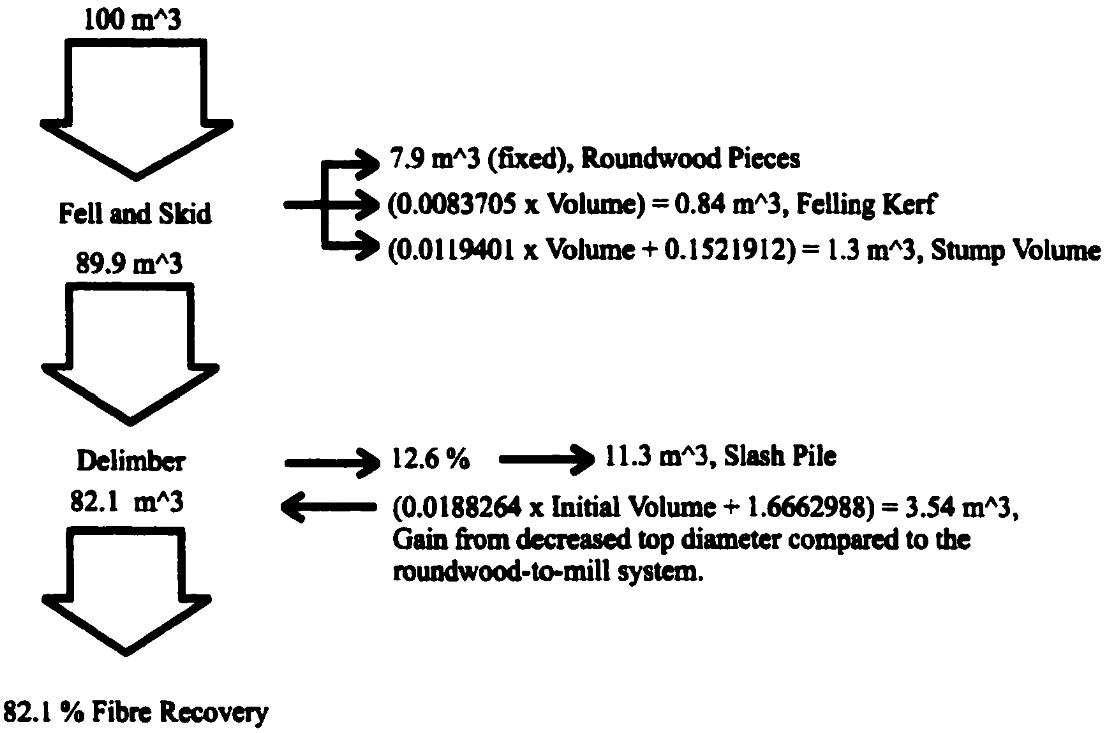


Figure 20. Wood fibre utilization model for the FT-TL (feller-buncher/skidder/delimber) system. Descending arrows are to scale and indicate wood flow towards the mill. Horizontal arrows indicate fibre losses. The initial volume of 100 m^3/ha is used as an arbitrary seed value.

Figure 21 shows the regression used to relate the basal area with number of trees per hectare for the roundwood system. This relationship was used to calculate gains from changing the end diameter cut of 4" to 3" on each log brought to roadside (Figure 20).

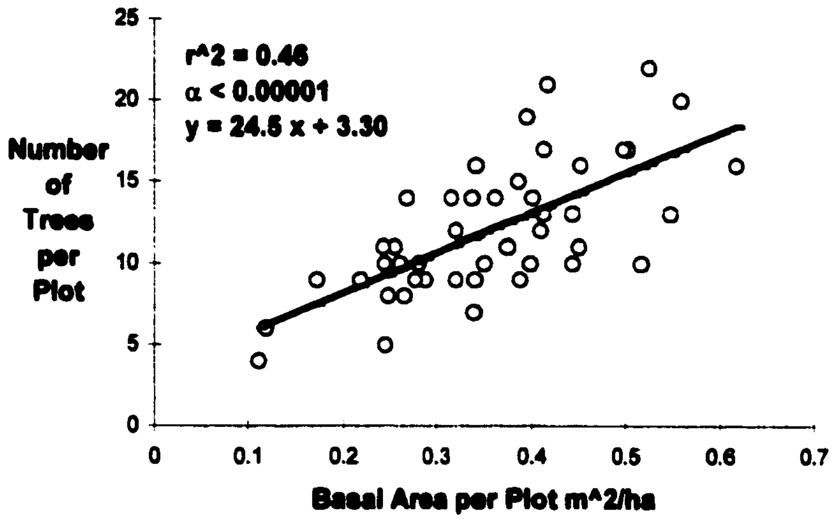


Figure 21. Regression of basal area per plot and number of trees per plot for the tree-length-to-mill system.

There is a clear savings in wood fibre by substituting the FT-SW with the FT-TL system, however, there is still considerable fibre loss. Based on the costing in Appendix I approximately $87.06 worth of wood fibre is wasted in the slash pile for every 100 m^3 brought to the roadside. There will also be further losses at the mill in handling (breaking) and slashing.

SYSTEM COMPARISONS

The volume distribution by length class of residual roundwood pieces is shown in Figure 22 for each harvesting system. Although the CTL system has the most cutover waste in terms of roundwood piece residue, most of the waste is due to relatively short pieces, with most being under 5 m. In comparison the FT-SW system, which has less overall cutover waste, has more evenly distributed residue pieces up to 10 m lengths. The FT-CH system, like the CTL system, has most of its roundwood piece cutover waste attributed to shorter pieces.

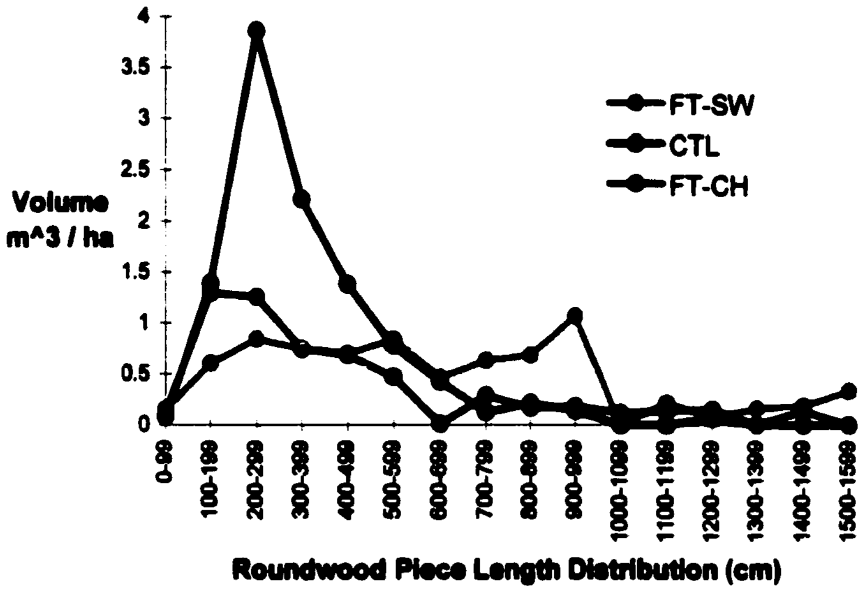


Figure 22. Volume of cutover roundwood pieces distributed by 100 cm length class for the FT-SW, CTL and FT-CH systems.

The volume of cutover residue roundwood pieces distributed by diameter classes is presented in Figure 23. The wasted roundwood pieces of the CTL system have a smaller average diameter than the other two systems. The FT-SW and FT-CH systems have similar distributions of wasted roundwood volume by diameter class.

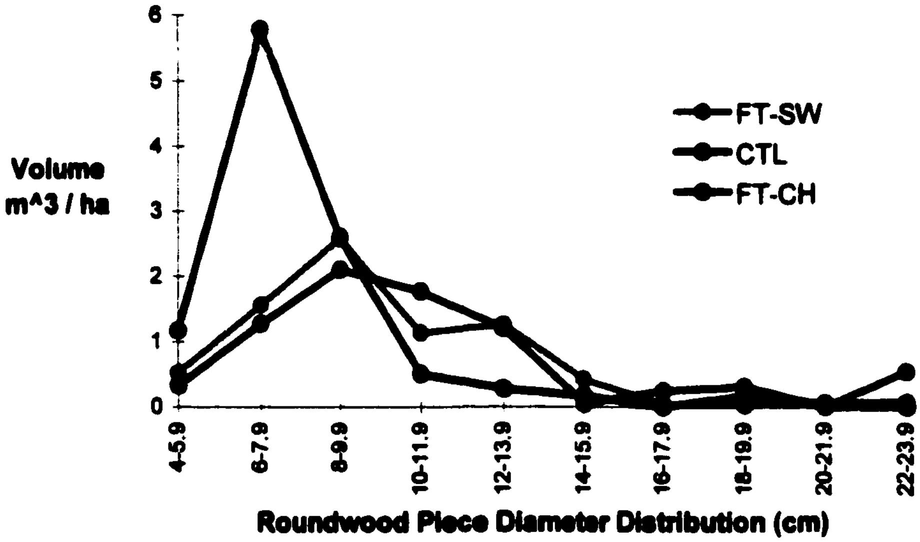


Figure 23. Volume of roundwood pieces distributed by 2 cm diameter class for the FT-SW, CTL and FT-CH systems.

The percentage of wasted roundwood piece volume by damage classification for each system is shown by pie chart in Figure 24. The FT-SW system has a relatively even distribution of volume from between the broken, cut and run-over damage classifications. The FT-CH system shows a less even distribution, with most losses derived from broken pieces followed by cut and run-over. The CTL system shows that the majority of lost roundwood volume is attributed to cut pieces. A minimal percentage of roundwood volume is lost to run-over and broken pieces in the CTL system. The

CTL system is the only system that has measurable amounts of residual volume still standing after harvest.

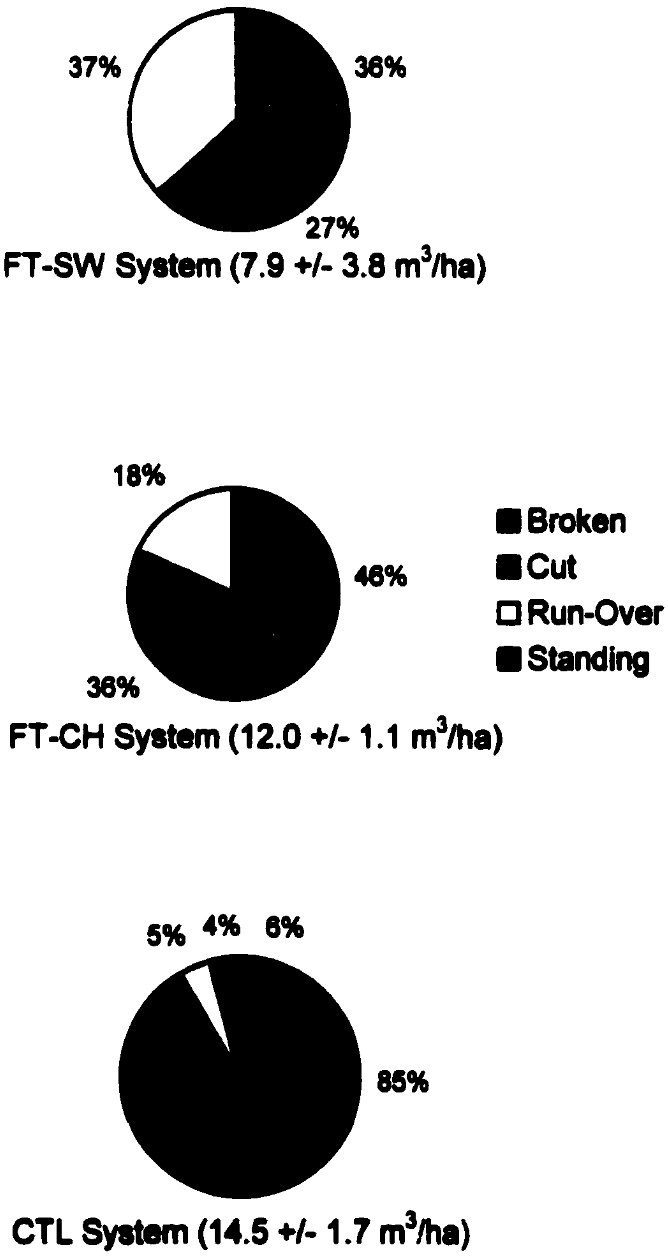


Figure 24. Damage classification for each harvesting system shown by the percentage volume of residual cutover roundwood pieces.

Figure 25 shows the relative utilization efficiency of each system over a range of initial volumes. The CTL and FT-CH systems are best at capturing most of the available wood fibre, 88 to 94 % and 89 to 92 %, respectively. The CTL system appears to be just marginally more efficient at higher initial volumes. The FT-SW system shows the lowest overall fibre utilization ranging between 77 to 81 %. The FT-TL system is expected to yield fibre recovery levels between 82 to 85 %.

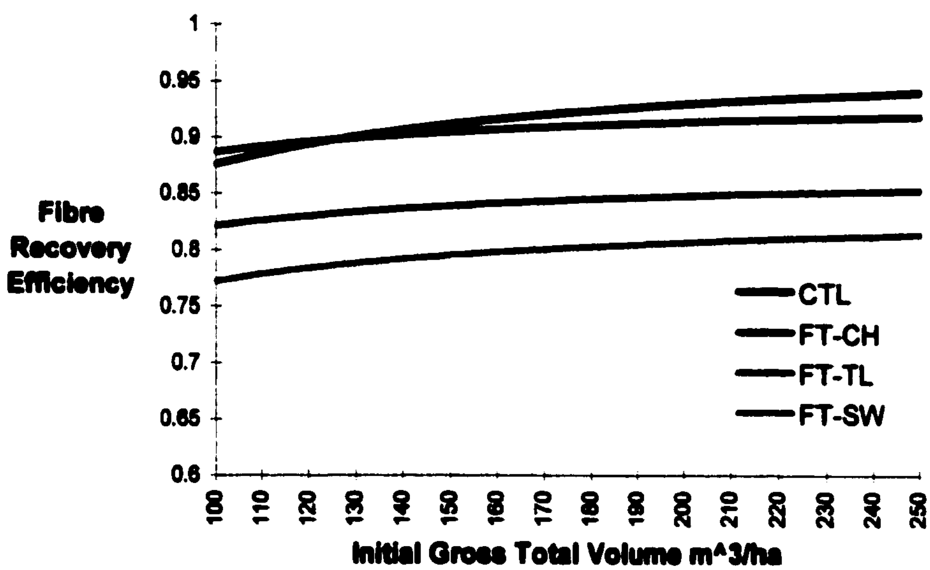


Figure 25. Expected fibre recovery efficiency across a range of initial gross total volumes of four common harvesting systems; FT-SW, (feller-buncher/skidder/delimber/slasher), FT-CH (feller-buncher/skidder/delimber-debarker-chipper, CTL (single-grip harvester/forwarder), and FT-TL (feller-buncher/skidder/delimber).

Based on the average yield of 120 m^3/ha from the Wabigoon forest and the fibre utilization model of the FT-SW system (Figure 16), the initial gross total volume (from the base of the stump up to a 4 cm top) for the FT-SW harvesting system should be 151 m^3/ha. The recovery and percentage increased yield over the FT-SW system, based on this initial gross total volume, is presented in Table 4 for the FT-TL, FT-CH and CTL systems.

Table 4. Estimated average yield and percentage increase over the FT-SW system for the FT-TL, FT-CH and CTL harvesting systems.

	FT-SW	FT-TL	FT-CH	CTL
Yield m^3/ha	120	126.8	136.5	137.8
Percent Increase	0%	5.5%	13.6%	14.7%

PART-TREE VERSUS FULL-TREE LOGGING CASE STUDY

Table 5 shows the different volumes of residue found after harvesting by a feller-buncher in a full-tree-to-roadside system versus a single-grip harvester in a part-tree-to-roadside system. The analysis of variance revealed significant differences between the part-tree and full-tree logging systems for the residual roundwood volume ($\alpha < 0.005$) but not for stump volume.

Table 5. Residue wood volume (m^3/ha) following full-tree and part-tree harvesting, including confidence intervals ($\alpha = 0.05$).

	Part-Tree (m^3/ha)	Full-Tree (m^3/ha)
Roundwood Residual	13.9 +/- 4.8	6.8 +/- 2.4
Stump Residual	4.3 +/- 0.3	4.3 +/- 0.3
Total Residual	18.2 +/- 4.9	11.1 +/- 2.5

During the course of operation the single-grip harvester with the fixed harvesting head often lifted trees completely off the ground resulting in frequent breakage. Lifting trees is an act uncommon to single-grip harvester operation. Additional damage also occurred as the felled stems were often turned into the adjacent standing trees before being bucked. The operator made piles of both 16' logs and random length tops. The logs were forwarded to roadside while the tops were skidded out for chipping. The piling of both logs and branchy tops likely resulted in logs being lost under the top pile. These piles were also not as neat as might be expected, likely due to the machines lack of dexterity. Many broken log sections were found within the track of the forwarder under branchy tops. In many cases the forwarder driving over the logs was the obvious cause of the break.

MARGINAL COSTS AND WOOD FLOW ANALYSIS

The minimum and maximum return trip hauling times required to bring 950 000 m^3 annually to the mill for the FT-SW, FT-TL and CTL harvesting systems are presented in Table 6. The shorter maximum hauling times represent the benefit gained from increased wood utilization. Clearly, a smaller landbase is required as more efficient harvesting systems are employed.

Table 6. Maximum and minimum return trip driving times required to meet the annual wood demand for the Dryden mill from the Wabigoon and English River forests with the FT-SW, FT-TL and CTL harvesting systems.

	Minimum Time (hours)	Maximum Time (hours)
FT-SW	0.25	3.90
FT-TL	0.25	3.75
CTL	0.25	3.51

The marginal cost advantage calculated for the CTL harvesting system over the FT-SW is \$0.66 /m^3. This represents the financial benefit gained in reduced travel costs per cubic metre by replacing the higher cost wood at the extreme of the FT-SW systems limits with the higher utilization of the CTL system. This is based on the haul rate of \$85 per hour and an estimated average 50 m^3 per truck load.

Pulkki (1998) suggests other marginal cost advantages; these include, 4% less land base taken up by roads because of an increased optimal road spacing for the CTL system, and 10% increased recovery because of the possibility of using the CTL technology for partial cutting operations in reserve areas. The complete marginal cost advantages of the CTL system over the FT-SW system is presented in Table 7.

Table 7. Complete marginal cost advantage of the CTL harvesting system over the FT-SW harvesting system for the Wabigoon and English River forests.

	Percentage Increased Wood Yield	Marginal Cost Advantage
Increased Utilization	14.7 %	\$0.76 /m^3
Road Land Reclaimed	4.0 %	\$0.23 /m^3
New Wood Sources	10.0 %	\$0.54 /m^3
Total	28.7 %	\$1.53 /m^3

Although the CTL system is expected to have higher costs to the roadside than the FT-SW system, \$15.79 /m^3 and \$13.93 /m^3 respectively, the difference (\$1.86 /m^3) is only \$0.33 /m^3 higher than the total marginal cost advantage (\$1.53 /m^3) of the CTL system. Assuming all of the previous cost estimations are correct, a lower long term operating cost would be realized by continuing with the FT-SW harvesting system.

In economic analysis cost assumptions are rarely precise and a sensitivity analysis is frequently merited. Considering that the CTL system is relatively new we can expect the cost of the system to decrease with time as contractors become more familiar with it. A cost decrease of 10% for the CTL system would cause the cost to roadside of the CTL system to be only \$0.28 /m^3 higher than the FT-SW system. This would cause the CTL system to have a marginal cost advantage of $1.25 /m^3 over the FT-SW system. Clearly the marginal cost difference between these two systems is very sensitive to estimations of system costs.

Figure 26 demonstrates the relationship between increasing the wood fibre yield above that of the FT-SW system and the associated marginal cost advantage for the Wabigoon and English River forests. Based on the working definition of merchantable fibre, the maximum increased yield possible directly from a logging site of the FT-SW system is approximately 25 %.

Figure 26. Relationship between increasing the yield of the FT-SW harvesting system and the marginal cost advantage of reduced hauling costs for the Wabigoon and English River forests.

DISCUSSION

ASSUMPTIONS

Several assumptions were necessary in order to build the four fibre utilization models. These assumptions were employed to make the models more useful and comparable with one another. A brief discussion of each assumption is merited so that the reader is made aware of some important underlying issues and is not misled by the results.

Basal Area to Volume Relationship

The use of Plonski's (1981) basal area to volume relationship from site class 1 jack pine is admittedly somewhat arbitrary. Since residue stump volume was found to be correlated with basal area, it was necessary to build the fibre utilization models to compensate for different initial stand volumes. To ensure that the different models were compatible with each other a set standard for all of the models was necessary. The use of a published source was considered to be the best way of setting this standard. However, there are no yield tables that accurately predict basal area from volume for the average forest conditions of the areas sampled in this survey. Site class 1 jack pine from

Plonski's (1981) yield tables seemed most appropriate. This was chosen over other possibilities because the coefficients used in the equation are close to the average of coefficients found in the rest of Plonski's (1981) tables.

Roundwood residue was not found to be correlated with the plot basal area. As basal area is widely assumed to be correlated with stand volume it has been assumed that roundwood residue is not related to initial stand volume. This lack of correlation may in fact be due to the sampling design employed. As an example, most of the roundwood pieces left after logging from the cut-to-length system are from tops of trees. Higher stand volumes are logically correlated with higher stocking, and so higher stand volumes should yield a higher frequency of tops. However, unexpectedly the residual volume due to roundwood pieces was not found to be significantly correlated with plot basal area. The tops of trees may have consistently fallen outside of the plot where their associated stump was located. Larger sample plots or a linear transect style sampling method may have shown this relationship.

Consideration of Site Factors

Site factors may contribute to the fibre utilization levels of each harvesting system. Site factors did differ widely between the areas of operation for each system studied. The FT-SW system, operating exclusively in the Wabigoon and English River forests, was operating in stands comprised mostly of conifers with few aspen. However, the FT-CH system, operating in the Dog River - Matawin and Black Sturgeon forests, was operating in more mixed-wood conditions.

When considering the high fibre utilization of the CTL system it should be remembered that this system was operating under relatively good terrain conditions in comparison to the other systems. During sampling the CTL system was employed on very flat ground with few obstacles in stands comprised almost entirely by conifers. This system may not yield such high fibre utilization rates if it were operating on the same range of terrain conditions as the other systems.

Winter conditions were not included in this study and so no estimates of winter residue wood can be made. Winter conditions should however contribute to increased levels of residue. In particular stump height would logically increase with snow depth. Difficulty in penetrating hard packed show or ice and the fear of hitting a solid obstacle hidden within fluffy snow are impediments to low stumps. Snowfall may also hide piles of recently cut cut-to-length logs and bunches of full-trees. In cold weather a higher frequency of broken tops is likely to be experienced in full-tree systems as the stems become more brittle. Also, at the roadside breakage of full-trees will likely increase as stems become frozen to the ground and snow loading will increase the stress on the stems as they are lifted.

ISSUSES CONTRIBUTING TO WOOD FIBRE LOSS

In general the results of this study indicate that increased handling is a major factor in causing fibre loss. Those systems with little handling are more efficient than systems with more handling. Extra handling at the roadside for the FT-SW and the FT-TL systems cause significantly higher levels of fibre loss. Although the CTL system produces the same product as the FT-SW system all processing is done more carefully by a single machine. Shorter pieces that are less likely to break are produced immediately at the stump.

Supervision is also considered to be a major factor in determining the level of fibre utilization. In some operations workers are instructed to keep an eye out or even search for lost logs within a cut block. In other operations, workers are instructed to run or knock over smaller less economical trees. As most of the sampling for each system took place from a wide spectrum of harvesting camps, the effects of management practices on fibre utilization can be considered controlled.

Broken and lost roundwood pieces are relatively high contributors to fibre losses within cutovers. Although many of these pieces are undersized some losses of larger lengths and diameters do exist. The nature of the equipment is likely the cause of much of this loss. A feller-buncher felling head is a very productive and highly aggressive device that is likely to break some stems in its normal use. Grapple skidding will likely result in the odd tree shaking free out of the bundle or catching on an obstacle. Stumps are likely to continue to exist because operators guard against damaging the felling head on the ground or rocks. These types of losses may be reduced by greater operator care and planning but it is doubtful that they will ever be completely eliminated.

ISSUES FOR WOOD UTILIZATION IMPROVEMENT

Two basic potential approaches exist in recapturing fibre loss of harvesting systems; these are, improving particularly wasteful and costly elements within systems, or switching to a more efficient harvesting system altogether.

Within Systems Improvements

Felling Kerf

Losses associated with the saw kerf are relatively high, however, the width of kerf permits the use of "hot saw" technology that maintains high productivity. A hot saw circular blade runs continuously, where the saw blade severs the stem just before the stem is grabbed. The saw blade needs to be thick enough to withstand the high impact forces that occur momentarily as the tree is cut. Reductions in the thickness of a feller-buncher saw kerf would reduce the overall productivity of the operation and increase costs. Any change in technology designed at capturing fibre lost to the current felling kerf should also match the cost of a hot saw feller-buncher.

FT-CH System

The delimber-debarker-chipper shows relatively little wood fibre loss and little overall variation in that loss when sampled over an extended period of time from a consistently high quality chip producer. There appears no reason to believe that chip quality, and thus mill fibre recovery, is improved or reduced by better wood utilization within the delimber-debarker-chipper.

Fibre lost out of the coarse fibre debris chute of the delimber debarker chipper in many cases appears relatively bark free. Although this fibre is undesirable in terms of length and thickness many similar pieces can be found in the mill's chip piles and is obviously used. In the future this fibre may be economically valuable if screening and processing procedures within the mill were able to accommodate this fibre source.

Losses of chips while loading is small in relation to other losses, however, the cost factors make it seem quite feasible to be captured. The chips need to be slowed down as they exit the chip spout of the delimber-debarker-chipper and they need to be deflected straight down so that the operator does not need to pay as close attention to the loading process. A cyclone style device that rotates the chips around a metal cylinder before they drop straight down onto the load might be considered. Any such device would only have to cost less than \$0.07 /m^3 of output to be cost effective as this is an approximate value of chips lost in loading per cubic metre of production.

Chips lost during hauling are considered to be negligible, although losses do exist. These losses have likely been reduced even further as Avenor Inc. has since

mandated the use of high quality tarping systems on all haul trucks delivering wood fibre to the mill since this study was conducted. This issue is more of an aesthetic and safety issue than a wood loss issue.

Single-grip Harvesters

The case study of part-tree and full-tree logging methods revealed significantly higher levels of cutover residual fibre waste from the part-tree system over the chip-to-mill system. Although no valid statistical comparison can be made for the part-tree survey data, the part-tree system seems at least as efficient in terms of fibre utilization as the chip-to-mill system. The discrepancy between part-tree results is likely a function of the type of equipment used and operator skill.

The single-grip harvester used in the part-tree versus full-tree logging experiment was a crawler style prime mover that was retro-fitted with a solid mounted single-grip harvester-head to its knuckle boom (Figure 27). The survey data collected for the cut-to-length fibre utilization model was from a machine that was purpose built for single-grip harvesting (Figure 28). This machine incorporates a parallelogram boom with telescoping action and a dangle style harvester-head. The two operators of this machine were well trained in its use.

Figure 27. The single-grip harvester used in the part-tree versus full-tree logging case study experiment; a Hyundai excavator fitted with a solid mounted harvester head.

Figure 28. The Timberjack 1270 single-grip harvester with dangle head from which the cut-to-length fibre utilization model survey data was collected.

Unlike the retro-fitted single-grip harvester the purpose built single-grip harvester's operators never lifted felled trees. This method likely results in less breakage. The greater machine dexterity and operator skill are other likely factors contributing to higher fibre utilization.

Changing Mill Technology

This thesis has presented the amounts of fibre loss only from the stump up to the mill gate. The form and quality of wood delivered to the mill will have additional ramifications on the utilization within the mill.

Fibre losses of each system up to the mill gate could be increased depending on the technology within the mill. The implementation of a Fuji King debarker, for example, could have such an effect. The design of this debarker allows for the handling of diameters as small as 5 cm. Although estimates of fibre loss within the Fuji King debarker have not been made a brief inspection by this author indicates that it is clearly more fibre efficient than conventional drum debarking. The CTL system and FT-SW system could be adapted to work in conjunction with the Fuji King debarker through greater utilization of longer random length tree tops. Delimbing in both systems could be carried out for the entire stem and bucking or slashing could be made down to a 5 cm diameter. The productivity trade-offs should be examined for both systems.

Between Systems Improvements

In this study it was found that the FT-CH and CTL systems had superior fibre utilization, than the FT-SW and FT-TL systems. This is similar to the findings of

Gingras (1992). The more modern single-grip harvesters and the delimber-debarker-chippers would seem to be more conducive to better wood utilization.

Wood utilization is not the only criteria for choosing a harvesting system. Costs are most likely the main consideration for choosing a harvesting system. The FT-CH system originated from an effort to reduce the cost of wood supply and thus it is not only more efficient in terms of wood utilization it is also cost effective (Markham 1995).

Although the CTL system has a higher cost to roadside than the FT-SW and FT-TL systems, the greater wood recovery causes offsetting transportation cost savings thus improving its cost effectiveness. The wood flow analysis reveals that a less extensive road network would be required and less overall area would require regeneration investment. There would also be less area lost to landings and slash piles. Longer optimal forwarding distances of the CTL system would require a less dense road network. CTL technology also lends itself to partial cutting in reserve areas that will also increase the overall yield from sources near the mill. In general CTL technology may be the best choice in certain situations.

MARGINAL COSTS IN WOOD FLOW ANALYSIS

The marginal cost and wood flow analysis procedure has demonstrated the economic benefit of better wood utilization. Better utilization from more careful logging will generally increase cost. However, if the additional wood replaces higher cost marginal wood then it is cost effective.

The marginal cost analysis provides crucial information required for business decisions. In our example the CTL system should not be employed in place of the conventional FT-SW system. The sensitivity analysis revealed that substantial cost reductions may be realized if the actual operating costs of the CTL system are lower than the cost estimations.

In our example of bringing wood to a sawmill the difference in haul time between the closest wood and the furthest was under 4 hours for a return trip. If this analysis were used for a pulp mill, the difference in haul time between the closest wood and the furthest wood could be in excess of 7 or 8 hours. This greater haul time difference lends itself to a potentially larger marginal cost advantage. In other words, a pulp mill that brings wood in from a further distance can realize a greater cost savings per unit of effort spent on increasing wood yield than a sawmill with a less extensive woodlands operation.

APPLICATION OF LEGISLATION AND REGULATIONS

In general, the harvesting operations studied are well within the limits of the current regulations, however, some discrepancies do exist. The rare high stump and merchantable piece of timber can nearly always be found with a prolonged search of a cut-block. There is, however, relatively good compliance with the spirit of the regulations as wasteful practices are commonly offset by the frequent use of non-merchantable fibre. Perfect compliance with the regulations is likely an impossibility as we can always expect some errors to occur where humans and human designed machines are involved.

As technology develops the importance of improving wood utilization is increasingly becoming influenced by economics rather than regulation. As an example, the Scaling Manual (OMNR 1995) clearly specifies that not utilizing wood chip fibre is considered a wasteful practice. The relatively small amount of wood chips that are commonly wasted during the loading of each haul truck has never been considered as a wasteful practice, despite being in clear violation of the law. The economic value of these chips is a more likely incentive of capturing this lost volume than legislation.

ISSUES AND RECOMMENDATIONS FOR FURTHER STUDY

All measurements for this project were made from operations under spring and summer conditions. It is very likely that fibre utilization levels will differ in the winter season. Higher stumps and more lost roundwood pieces are probable for each system, although, Favreau (1997) actually found higher rates of fibre recovery in the winter for both tree-length and cut-to-length harvesting systems. At this point it is unclear whether the relative fibre utilization of the four systems would change with the season. Similar studies should be conducted in winter conditions to be sure of seasonal wood utilization levels.

Estimations of roadside losses from the FT-TL system are based on logical extrapolations from the FT-SW system. Although reasonable assumptions have been made the FT-TL model does not have the same credibility that it would if direct measurements were made. To be certain about wood wastes within the FT-TL system direct sampling should be performed.

CONCLUSIONS

Of the four harvesting systems considered in this study the CTL and FT-CH systems yield the highest overall fibre utilization. Gains in wood utilization of these two systems can be in the order of 14 to 15 % greater than the conventional FT-SW system. The FT-TL system is expected to yield only approximately 5 % more fibre than the conventional FT-SW system.

All of the harvesting systems studied show improved fibre efficiency with increasing initial stand volume. This is due mainly to the fact that as a tree gets larger its stump, although also increasing in size, gets proportionally smaller with respect to the rest of the tree.

The increased handling, supervision, operator skill and level of technology are all considered to contribute to wasted wood fibre. The harvesting systems with more machine components typically have more waste. Although not accounted for in the sampling design, the level and style of supervision was observed to have significant influence on fibre recovery. Greater operator skill and more modern technology have been shown to improve wood utilization.

Improvements in wood utilization can be made either by changes between systems or by modifications within harvesting systems. The ability to make modifications within harvesting systems is limited by cost and productivity trade-offs, however, some opportunities do exist. The most cost effective and simplest within system modification is likely to be realized by reducing the amount of chips blown onto the ground at roadside chipping sites of the FT-CH system.

The form and quality of wood acceptable by the mill can have an overall impact on fibre utilization. Improving the quality of woodlands products and/or improving the technology within the mill to accommodate smaller diameters and lower quality wood products will likely improve the overall fibre utilization.

Wood utilization should be considered as an important factor when making operational decisions in forest harvesting. Geographic wood flow analysis techniques can be combined with wood utilization information to greatly assist in the decision making process. This thesis has shown that, for a specific landbase, the long term costs of harvesting with a CTL system are expected to be slightly higher than the conventional FT-SW system. Relatively small reductions in the cost of the CTL system would however cause the CTL system to be much more cost advantageous than the FT-SW system. Similar results may or may not be found for other management units, however, the method used is applicable and could be useful in other areas.

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APPENDIX

APPENDIX I

Costing of Various Harvesting Machinery Based on Straight Line Depreciation

	Feller-buncher	Grapple-skidder	Delimber	Slasher	Single-Grip Harvester	Forwarder	Delimber-debarker-chipper
Scheduled days/yr	250	250	250	250	250	250	250
SMH/day	18	18	18	18	18	18	18
Utilization	0.75	0.85	0.90	0.90	0.75	0.80	0.70
Productivity, m3/yr	90000	90000	135000	135000	50000	50000	120000
Purchase price, $	400000	225000	350000	250000	550000	450000	850000
Salvage value, $	40000	22500	35000	25000	55000	45000	85000
Machine Life, yrs	5	5	5	5	5	5	5
Interest Rate	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Fuel Consumption, L/PMH	20	20	20	20	17.5	17.5	100
Fuel price, $/L	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Engine oil, L/PMH	0.1	0.1	0.1	0.1	0.1	0.1	1.5
oil price, $/L	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Hydraulic oil, L/PMH	0.2	0.1	0.2	0.1	0.2	0.2	2
Hydraulic oil price $/L,	1.325	1.325	1.325	1.325	1.325	1.325	1.325
Annual repair costs, % of purchase	25	30	25	25	25	20	40
Operator wage, $/SMH	20	20	20	20	20	20	20
Fringe Benefits, % of wage	36	36	36	36	36	36	36
Insurance, % of purchase	3.2	3.44	3.1	2.75	3.1	2.6	3.5
Total annual cost, $/yr	359000	180163	335771	282005	432505	356877	825177
Cost per hour, $/SMH	79.78	62.26	74.62	62.67	96.11	79.31	183.37
$/m3	3.99	3.11	2.49	2.09	8.65	7.14	6.88

Loading costs = $ 2.25/ m^3
(does not apply to FT-CH system)

from : Pulkki (1999)