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HARVESTING COASTAL SECOND-GROWTH FORESTS: SUMMARY OF HARVESTING SYSTEM PERFORMANCE

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Abstract

Since 1991, the Forest Engineering Research Institute of Canada has collected information on clearcut harvesting of coastal second-growth forests in British Columbia. This report summarizes the data gathered during the project, and presents basic productivity prediction models for a number of different harvesting systems. Information is also presented on machine operating costs, stem breakage during harvesting, site disturbance, and soil compaction.

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Disclaimer

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Summary

In 1991, the Forest Engineering Research Institute of Canada (FERIC) initiated a cooperative project with the Faculty of Forestry of the University of British Columbia to evaluate the economics of clearcut harvesting of coastal second-growth forests in British Columbia. Funding support for the project was obtained through the Canadian Forest Service under the Canada-British Columbia Forest Resource Development Agreement (FRDA II).

FERIC reviewed existing information on clearcut harvesting coastal second-growth stands and on predicting fibre yield and timber revenue; conducted field studies of several harvesting phases; and developed productivity and cost functions using stand characteristics as independent variables for a variety of harvesting options. The final product of the project was an interactive computer-assisted decision tool that predicts timber revenue and harvesting costs at the cutblock level, based on operational cruise data, sort description criteria, and harvesting productivity and cost data.

FERIC found that a wide variety of cable and ground-based harvesting equipment and systems is used to harvest coastal second-growth stands. While information on the performance of these systems (productivity, cost, and quality of work done) is still relatively limited, FERIC concluded that where conditions permit, ground-based systems with mechanical falling would be preferred over the traditional system of hand falling and cable yarding. Ground-based systems have lower wood costs and potentially less stem breakage, but many are limited to sites with gentler slopes and low risk of soil disturbance. As well, ground-based harvesting operations often require the use of large machines, particularly for falling and falling-processing, to successfully handle the size of trees typical of coastal second-growth forests. Data compiled by FERIC suggest that harvesting systems with feller-bunchers, loader-forwarders, grapple skidders, and processors working from roadside decks would provide attractive wood costs for clearcutting coastal second-growth forests.

Hand falling can be done in all second-growth stands with very little or no site disturbance or soil compaction. It is operationally flexible and can be combined with various degree of log manufacturing. The direct cost of hand falling compares favourably with that of mechanical falling, but because hand-felled stems typically are more scattered and less aligned, the extraction cost of hand-felled stems tends to be higher than for feller-bunched wood. FERIC's data also suggest a higher degrees of stem breakage in hand-falling operations compared to feller-buncher operations.

Most second-growth stands can be extracted with cable yarding systems providing there is adequate deflection and clearance for the line and the log load. In large wood, grapple yarders typically have lower yarding costs than yarders using chokers. However, grapple yarding cost is sensitive to average log volume as typically only one piece is extracted per turn. Yarders with chokers, on the other hand, can more easily hook several logs. As with ground-based operations, the cost of cable yarding operations is reduced when pre-bunched stems are extracted.

Information gathered on soil disturbance (as defined in this study) and soil compaction were inadequate to assess the impact of different harvesting systems on different sites.

Most of the available productivity data of second-growth harvesting operations were from operations in relatively favourable terrain. Therefore, the productivity and cost models developed by FERIC are limited to the impact of tree size (gross merchantable tree volume) and/or extraction distance. While these models will assist harvest planners in selection of harvesting systems for specific coastal second-growth stands, judgment based on personal experience and knowledge of local conditions must be exercised when applying that information. As more information on coastal second-growth harvesting operations becomes available, the findings and conclusions presented in this report will have to be re-assessed.

Sommaire

En 1991, l'Institut canadien de recherches en génie forestier (FERIC) entreprit un projet en coopération avec la faculté de Foresterie de l'Université de Colombie-Britannique, dans le but d'évaluer le rendement économique de la récolte par coupe rase des forêts côtières de seconde venue en Colombie-Britannique. Le Service canadien des forêts apporta un appui financier au projet dans le cadre de l'Entente Canada - Colombie-Britannique sur le développement des ressources forestières (FRDA II).

FERIC passa en revue l'information existante sur la récolte par coupe rase des peuplements côtiers de seconde venue et sur les prévisions du rendement en fibre et des revenus générés; effectua des études sur le terrain de plusieurs étapes de récolte; et développa des fonctions de productivité et de coût en utilisant les caractéristiques des peuplements comme variables indépendantes pour diverses options de récolte. Le résultat final du projet est un outil décisionnel interactif

assisté par ordinateur, qui prévoit les revenus générés et les coûts de récolte au niveau du bloc de coupe, en se basant sur les données réelles d'inventaire, les critères d'essence, de qualité et de dimensions qui définissent les classes de billes, ainsi que les données de productivité et de coût.

FERIC constate qu'on utilise une grande variété d'équipement et de systèmes par câble et par voie terrestre pour récolter les peuplements côtiers de seconde venue. Même si l'information sur la performance de ces systèmes (productivité, coût et qualité du travail effectué) est encore relativement limitée, FERIC conclut que là où les conditions le permettent, les systèmes par voie terrestre avec abattage mécanisé seraient préférables au système traditionnel d'abattage manuel et de téléphérage. Les systèmes par voie terrestre entraînent des coûts plus bas du bois et potentiellement moins de bris des tiges, mais plusieurs sont limités aux sites présentant une pente moins forte et un faible risque de perturbation du sol. De plus, les opérations par voie terrestre demandent souvent l'utilisation de machines puissantes, particulièrement pour l'abattage et l'abattage-façonnage, capables de manipuler les gros arbres caractéristiques des forêts côtières de seconde venue. Les données compilées par FERIC indiquent que les systèmes de récolte avec abatteuses-groupeuses, chargeuses à flèche articulée, débardeurs à grappin, et façonneuses travaillant à partir de dépôts en bordure de route assureraient des coûts du bois intéressants pour la coupe rase de ce type de forêts côtières.

L'abattage manuel peut être effectué dans tous les peuplements de seconde venue avec très peu ou pas de perturbation du site, ou de compactage du sol. C'est une opération flexible qui peut être combinée avec divers degrés de transformation des billes. Le coût direct de l'abattage manuel se compare favorablement à celui de l'abattage mécanisé mais, comme les tiges abattues manuellement sont en général plus dispersées et moins bien alignées, leur coût de débardage a tendance à être plus élevé que celui des arbres coupés par abatteuses-groupeuses. Les données de FERIC suggèrent également un degré plus élevé de bris des tiges dans les opérations d'abattage manuel, comparativement aux opérations par abatteuses-groupeuses.

Dans la plupart des peuplements de seconde venue, le débardage peut être effectué à l'aide de systèmes de téléphérage, pourvu qu'il y ait une courbure adéquate du câble et un dégagement suffisant pour la charge de billes. Dans de gros arbres, les câbles-grues à grappin donnent généralement des coûts de téléphérage moins élevés que les câbles-grues utilisant des colliers étrangleurs. Cependant, le coût du téléphérage avec grappins est influencé par le volume moyen des billes puisqu'une seule pièce est habituellement débardée à chaque voyage. Les câbles-grues avec colliers étrangleurs, d'autre part, peuvent plus facilement accrocher plusieurs billes. Comme dans le cas des opérations par voie terrestre, le coût des opérations de téléphérage est réduit quand les tiges ont été préalablement groupées.

L'information recueillie sur la perturbation du sol (tel que définie dans cette étude) et son compactage était insuffisante pour permettre d'évaluer l'impact des divers systèmes de récolte sur les différents sites.

La plus grande partie des données de productivité disponibles sur les opérations de récolte des peuplements de seconde venue provenaient d'opérations en terrain relativement favorable. Par conséquent, les modèles de productivité et de coût développés par FERIC sont limités à l'effet des dimensions des arbres (volume marchand brut par arbre) et de la distance de débardage. Même si ces modèles aideront les planificateurs à sélectionner des systèmes de récolte en fonction de peuplements de seconde venue particuliers sur la côte, il leur faudra exercer dans l'application de cette information un jugement basé sur l'expérience personnelle et la connaissance des conditions locales. À mesure que d'autres renseignements sur les opérations de récolte en forêt côtière de seconde venue deviendront disponibles, les résultats et les conclusions présentés dans ce rapport devront être mis à jour.

INTRODUCTION

The on-going shift from old-growth to second-growth harvesting, combined with recent changes in forest policy and increased global competition, provides new challenges and opportunities for the forest industry in coastal British Columbia. To meet these new challenges, the industry needs information on: harvesting productivities and costs for different harvesting methods in a variety of second-growth stand conditions; the volumes and revenues that can be obtained from these stands; and the impact of operations on site productivity. This information will aid in assessing the profitability of harvesting a particular stand, assigning harvesting systems to different stand types, and making capital investment decisions on future harvesting equipment. Making sound decisions is complicated and involves economic analyses of several different harvesting options, but decision making can be facilitated by interactive computer-assisted decision models.

To provide the forest industry in British Columbia with information on second-growth harvesting, and a model for system selection based on economic criteria, the Forest Engineering Research Institute of Canada (FERIC) initiated a cooperative project with the Faculty of Forestry of the University of British Columbia in 1991. Funding support for the project was obtained through the Canadian Forest Service under the Canada-British Columbia Forest Resource Development Agreement (FRDA II).

The project involved a number of components: reviewing existing information on harvesting coastal second-growth stands and predicting fibre yield and timber revenue; conducting field studies of several harvesting phases; and developing productivity functions using stand characteristics as independent variables for a variety of harvesting options in second-growth clearcut operations. The final product was an interactive computer-assisted decision tool that predicts timber revenue and harvesting costs at the cutblock level, based on operational cruise data, sort description criteria, and harvesting productivity and cost data.

Descriptions and results of the individual field trials were published in three FERIC Technical Notes (Andersson and Jukes 1995; Andersson and Warren 1996; Andersson 1997), and in a Master thesis at the University of British Columbia (Jukes 1995). As well, a second Master thesis described the computer model (Pavel 1997).

This report summarizes the information on clearcut harvesting of coastal second-growth forests. It also describes the sources and methods used to derive the productivity prediction functions and the operating costs incorporated in the computer model.

SCOPE OF THE PROJECT

For the purpose of this project, a second-growth forest is defined as being less than 150 years old, and having originated following harvesting or a natural disturbance. The most common species are Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western red cedar (*Thuja plicata* Donn), and amabilis fir (*Abies amabilis* (Dougl.) Forbes). The characteristics of second-growth stands now being harvested are diverse. Stand ages range from 50 to 150 years, volumes from 400 to 1100 m³/ha, and densities from 200 to 900 trees/ha. Tree diameter at breast height (dbh) can range from 15 to 150 cm, and tree heights from 20 to 60 m. Stands of natural origin may contain some large trees from the previous stand and/or large windfalls, while those having regenerated after clearcut logging will contain old-growth stumps.

STUDY OBJECTIVES

The objectives of this project were to:

- Develop productivity and cost models for harvesting systems operating in individual cutblocks of second-growth timber in coastal B.C. These models would combine stand and site data, such as diameter, terrain and slope, with production models for specific harvesting systems, to derive estimates of system performance on an individual cutblock basis.

- Develop models to predict harvested volumes by company log sort[1] on an individual cutblock basis, based on cruise compilation data and company sort specifications.

- Measure stem breakage and merchantable fibre losses, by harvesting phase.

- Measure the degree of site disturbance and soil compaction following harvesting, by source and type.

This report addresses primarily the project objectives related to estimating harvesting productivity, operating costs, and post-harvest site conditions. The second objective—the prediction of volume by sort based on operational cruise data and company sort description

[1] Logs manufactured to size and quality specifications to meet the internal or external log market of individual companies.

information—is being addressed in a separate report[2] that describes the computer model developed for predicting harvesting productivity and cost.

STUDY METHODS

FERIC reviewed published studies of harvesting coastal second-growth and old-growth forests in British Columbia, and, to a lesser degree, mature forests in interior British Columbia. The data were considered pertinent to the project if: harvested sites were coastal second-growth stands, or tree characteristics resembled those of coastal second-growth stands; and machine performance was related to the operating conditions. Studies in stands other than coastal second-growth were used primarily for comparison purposes.

Also, FERIC collected harvesting productivity data, using shift-level and detailed-timing techniques, during January to April 1993 and December 1993 to March 1994 at various harvesting operations on Vancouver Island and the Sunshine Coast. The studies monitored manual and mechanical falling; log alignment with a hydraulic log loader prior to yarding; and primary extraction with loader-forwarders,[3] grapple and running skyline yarders, and super snorkels.

Least-square regression analysis was used to test the influence of various operating factors on harvesting performance and to develop productivity prediction functions (Appendix I). The analysis assumed that differences in operator skill and sampling errors between studies were negligible. An operating factor was considered to influence machine performance if a statistically significant correlation (at the 95% confidence level) could be established between the operating factor and a harvesting activity.

Machine owning and operating costs were determined using FERIC's standard costing method (Appendix II). Costs exclude supervision, profit, or overhead, and may differ from the actual costs incurred by machine owners.

Operational cruise data were used to describe the stand conditions of the study sites, and to develop local stand tables by 1-cm diameter classes. These tables were used to determine the volumes of trees that were measured as part of the detailed-timing studies. Information on harvested volume from the study sites was obtained from the cooperating companies.

The line intercept method (Sutherland 1986) was used to sample wood residue and soil conditions following harvesting. As the purpose of the residue survey was to determine the total amount of merchantable fibre lost, all sound pieces >9.5 cm in diameter were measured, regardless of length, and were not differentiated as avoidable or unavoidable waste. In the soil survey, exposed mineral soil and alterations to the ground that resulted from harvesting and road or trail construction were defined as disturbance, and measured. Because those soil data were collected prior to the enactment of the British Columbia Forest Practices Code, the definition of soil disturbance differs from that defined in the Code.

Soil compaction data were collected with a Campbell Pacific Nuclear Moisture/Density Gauge (densiometer). Two or four samples, half on undisturbed ground and half on exposed soil with clear indications of machine travel, were taken near each plot. The soil compaction sample points are therefore more representative of the worst case scenario than of the average disturbance of the sites.

ABOUT THE DATA

The information presented in this report was obtained from several harvesting case studies, each of which used different study techniques, work study nomenclature, and volume data (scaled volume, cruise volume, or a measured sample of individual trees or logs) to determine productivity. Therefore, FERIC opted to harmonize the nomenclature (Appendix III), and to present the data from these reports in this report using lower precision (fewer decimals or rounded numbers) than presented in the referenced publications.

Predicting harvesting operation performance is based either on past experience (historic information) or on correlations developed between operating conditions and productivity. This study opted for the latter approach because it allows prediction functions to be developed in a more timely and efficient manner than by collecting historic data. However, prediction functions have drawbacks because the performance of harvesting operations may be influenced by many factors, such as stand and terrain characteristics, operational decisions (e.g., spacing and location of roads, bucking specifications, and desired level of fibre recovery), and human factors (e.g., quality of planning, and skill and aptitude of the work force). Consequently, identifying and quantifying all variables that affect performance is difficult. Assumptions and approximations of data must often be

[2] Andersson, B., Young, G., and Pavel, M. Design and validation of a decision support model for predicting net revenue of harvesting second-growth forests. FERIC, Vancouver. Report in progress.

[3] Hydraulic log loaders used to forward wood to roadside or landing. Also referred to as excavator-forwarders, hoe-chuckers, or shovel loggers.

made to simplify the relationship between input and output data, and to limit the prediction variables to those factors that are easy to measure and readily available, such as stand inventory data. They are usually expressed as averages, which facilitate calculation and stand description. Because averages may not portray the real conditions of the stand, the prediction accuracy could vary considerably for small individual settings, while the errors may balance for a group of cutblocks.

RESULTS

Development of Production Models for Harvesting Systems

The literature review provided general productivity information on manual and mechanical falling; primary extraction with grapple and choker yarders, and rubber-tired skidders; and manual and mechanical processing at roadside or landings. However, the reports seldom addressed the relationship between productivity and operating conditions, conditions created for subsequent harvesting phases, or the level of fibre recovery of the operation. As a result, most of the prediction functions in this report are developed from data collected in this project's field trials.

Hand Falling. Hand falling (Figure 1) can be done in all types of second-growth stands with very little or no site disturbance or soil compaction. This technique is operationally flexible and can be combined with various degrees of log manufacturing. However, compared to mechanical falling, hand falling has lower worker-day productivity; and, typically, hand-felled stems are more scattered and not well aligned. Adverse weather conditions such as high wind and heavy snow create hazardous working conditions for hand fallers, and consequently reduce available working days.

Figure 1. Hand-falling operation in a coastal second-growth stand.

FERIC differentiated between three types of hand falling operations, depending on the degree of log manufacturing:

- Fall-only—no trees are delimbed or bucked.
- Fall-selective buck—some felled trees, usually the larger ones, are partially delimbed and/or bucked.
- Fall-process—all trees, with the possible exception of the smallest ones, are felled, delimbed, and bucked.

Productivity of second-growth hand-falling operations ranged from 22 to 37 m^3/productive machine (worker) hour (PMH) and is consistent with hand-falling operations in old-growth stands with similar tree size (Table 1). However, lower fibre losses from decay and falling breakage are expected in second-growth stands than in old-growth stands.

The variation in faller productivity is attributed to the amount of log manufacturing done during falling, the stand characteristics, and the skill of the fallers. However, only the impact of tree size has been quantified. Peterson (1987a) found a linear correlation between tree dbh and the actual cutting time per tree. Detailed-timing studies on hand falling have shown a correlation between tree volume and falling productivity (Andersson and Warren 1996; Andersson 1997).

No information was found relating post-falling conditions (e.g., stem breakage, average piece size, and stem orientation) to stand and terrain conditions. Such information is valuable because the conditions created by one harvesting phase affect the performance of the subsequent one. However, a comparison of average tree and log volumes provides an indication of the degree of stem fractionation resulting from hand-falling operations (Table 2).

Figure 2 shows the predicted productivity of hand-falling operations with three different degrees of log manufacturing (Appendix I), as functions of gross merchantable tree volume.

Mechanical Falling with Feller-Bunchers. Feller-bunchers have been used to harvest coastal second-growth timber since the late 1970s (McMorland 1982). Compared to hand falling, feller-bunchers provide a safer work environment for forest workers, have higher shift productivity, higher utilization (they can operate at night, and are less susceptible to adverse weather conditions), and less falling breakage (control of the falling tree is greater). Feller-bunchers also create better operating conditions for skidders and yarders because

Table 1. Productivity of Hand-Falling Operations: Summary

Falling operation	Average operating conditions [a] Stand vol. (m³/ha)	Tree vol. (m³)	Slope (%)	Faller productivity [a] (m³/PMH)	(m³/shift)	Study type [a]	Reference [b]
Coastal second-growth operation							
Fall-only	400	1.1	5	-	170	sl	2
Fall-selective buck	1300	2.6	15	37	210	sl	3
	460	1.0	5	-	103	sl	2
	710	1.1	25	33	196	dt	27
	460	0.9	0	29	161	dt	2
Fall-process	830	1.5	10	22	117	sl	4
	830	1.4	5	26	146	dt	4
Coastal old-growth operation							
Fall-selective buck	630	0.8	10	26	161	dt	30
Fall-process	810	2.2	20	40	231	dt	31
	1150	2.4	80	34	196	dt	31
	630	1.2	10	23	145	dt	30
	480	1.6	5	31	178	dt	31

[a] Definitions in Appendix III.
[b] Numbers correspond to items in the References section.

Table 2. Comparison of Average Tree Volume and Log Volume at Roadside Following Hand Falling and Timber Extraction

Falling operation	Extraction operation	Volume Tree (m³)	Log (m³)	Volume ratio log to tree	Reference [a]
Fall-selective buck	Grapple yarding	2.6	1.8	1:1.4	3
	Excavator-forwarding	1.0	0.8	1:1.3	2
Fall-process	Skyline yarding	1.5	0.7	1:2.1	4

[a] Numbers correspond to items in the References section.

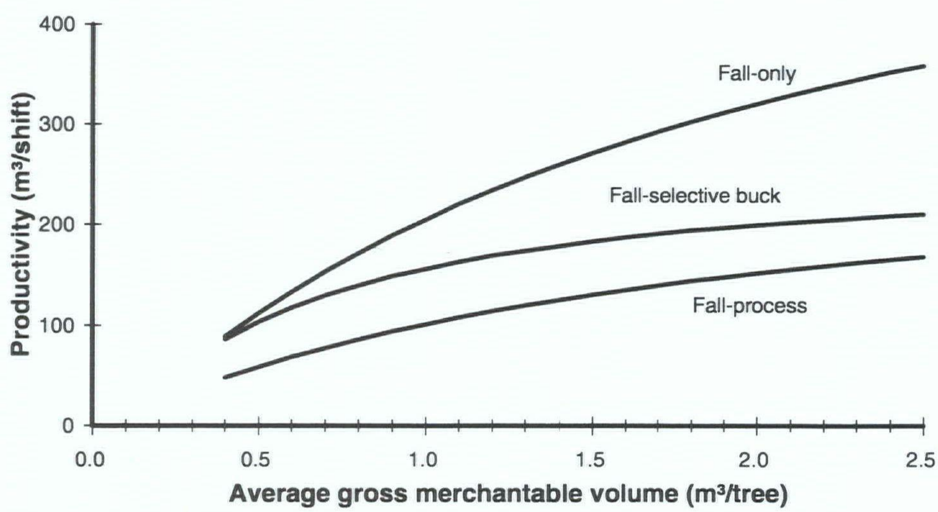

Figure 2. Predicted productivity of hand-falling operations, as a function of gross merchantable volume per tree.

the stems can be bunched with butts oriented in the desired yarding direction. However, the application of feller-bunchers is limited by tree size, ground bearing capacity, slope, and ground obstacles. The operable range depends on the machine weight, boom lifting capacity, and diameter-cutting capacity of the felling head.

In this study, FERIC differentiated between two types of feller-bunchers based on size. Large feller-bunchers are represented by the ACL 771B feller-buncher,[4] while medium feller-bunchers (Figure 3) are commercially marketed machines designed to fall trees with butt diameters up to 60 cm.

Studies on feller-bunchers in coastal second-growth forests show a productivity range of 90 to 159 m^3/PMH for large machines, and 35 to 71 m^3/PMH for medium machines. Average machine utilization was about 75% for both machine types (Table 3). The data for the medium feller-bunchers are from the mid-1980s, and include machines with shear heads, which are now rarely used to harvest coniferous stands. Recent information on medium feller-bunchers is from operations in interior B.C, and is not directly applicable to coastal harvesting conditions. McMorland (1982) found that the time to fell and bunch trees of the same dbh was similar in coastal and non-coastal operations, while feller-bunchers on the coast spent more time on preparing travel path and clearing debris by a factor of 5 to 6. Thus, feller-bunchers in coastal operations are likely to fell

Figure 3. Medium feller-buncher.

[4] This one-of-a-kind feller-buncher was custom designed and built for coastal conditions by Antler Creek Logging of Port Alberni, British Columbia. The machine is capable of felling and handling trees with butt diameters of nearly 80 cm.

Table 3. Productivity of Feller-Buncher Operations: Summary

Machine type	Average operating conditions [a] Stand vol. (m^3/ha)	Tree vol. (m^3)	Slope (%)	Machine performance [a] MU (%)	Productivity (m^3/PMH)	(m^3/shift)	Study type [a]	Reference [b]
Coastal second-growth operation								
Large feller-bunchers								
ACL 771B/Rotosaw	610	1.5	10	76	122	744	sl	3
	580	1.1	0	72	95	545	sl	3
	430	1.1	15	73	138	803	sl	2
	610	1.5	10	-	159	-	dt	3
	580	0.8	0	-	90	-	dt	3
	430	1.1	15	-	122	-	dt	2
Medium feller-bunchers								
Timbco 2518/Rotosaw	520	0.6	10	66	35	187	sl	20
Caterpillar 225/Drott shear	-	1.1	-	-	71	-	dt	18
Drott 50/Drott shear	610	0.7	10	79	49	313	dt	26
Drott 40/Drott shear	770	0.7	15	-	41	-	dt	18
Case 1187B/Drott shear	560	0.5	20	77	38	236	dt	26
Interior operations								
Medium feller-bunchers								
Timbco 2520/Rotosaw	-	0.9	15	67	60	325	sl	21
Timberjack 2520/Koehring	330	0.5	20	76	58	353	sl	23
Caterpillar 227/Koehring	340	0.5	10	76	48	294	sl	16
Timberjack 2520/Koehring	330	0.5	20	-	53	-	dt	23

[a] Definitions in Appendix III.
[b] Numbers correspond to items in the References section.

approximately 25% fewer trees/PMH than those working in interior operations.

By combining mechanical harvesting with hand falling, feller-bunchers can be employed in stands with oversized trees. Peterson (1986) studied feller-bunchers equipped with 50-cm shear heads working in two 100-year old Douglas-fir stands with volumes averaging 0.6 and 1.1 m^3/tree. He found that the feller-bunchers harvested 97% (87% of volume) and 87% of the trees (55% of volume) in these stands, respectively. The trees actually cut by the feller-bunchers on the two sites averaged 0.54 and 0.70 m^3/tree, respectively. The hand fallers cutting the oversized trees averaged 151 and 162 m^3/worker-day, respectively.

The productivity of feller-bunchers, within their operating ranges, is strongly influenced by tree volume (McMorland 1982; Andersson and Jukes 1995). Detailed-timing data on the ACL 771B feller-buncher showed no significant difference in the time to fell and bunch trees of different sizes when felling only one tree per cycle. Because most trees in second-growth stands are likely to be felled and bunched individually (especially with medium feller-bunchers), machine productivity, expressed as trees/PMH, is expected to be relatively constant and thus, when expressed as m^3/PMH, would vary with average tree volume.

The impacts on feller-buncher productivity of other stand factors, such as stand density, amount of brush and non-crop trees, and terrain conditions, are not well documented. As operating conditions approach the terrain limitations for the machines, the time spent on activities other than felling and bunching will likely increase. Thus, machine productivity will become more dependent on stand factors other than tree size.

Figure 4 shows the projected productivity of large and medium feller-bunchers as a function of gross merchantable tree volume (Appendix I). FERIC assumes that in operations with medium feller-bunchers, some hand falling of oversized trees is required, with the number of oversized trees increasing with the average tree size of the stand (Peterson 1986).

Mechanical Falling and Processing. Cut-to-length harvesters are currently more common in thinning operations than in clearcut harvesting. The advantages of these harvesters are: logging debris is left at the felling site; fibre recovery is potentially higher (they are well suited to processing logs from small trees, windfalls, and broken trees); and log breakage is reduced. Many cut-to-length harvesters are equipped with computerized log-measuring systems to assist the operators with bucking decisions. However, like feller-bunchers, the application of cut-to-length harvesters is limited by tree size (diameter and weight) and terrain conditions. While harvesters can manufacture long logs (>10 m), they are designed to manufacture shorter logs (<7 m). Therefore, cut-to-length harvesters will likely produce a large number of pieces at the felling site, which would adverely affect the productivity of extraction machines that are sensitive to piece size.

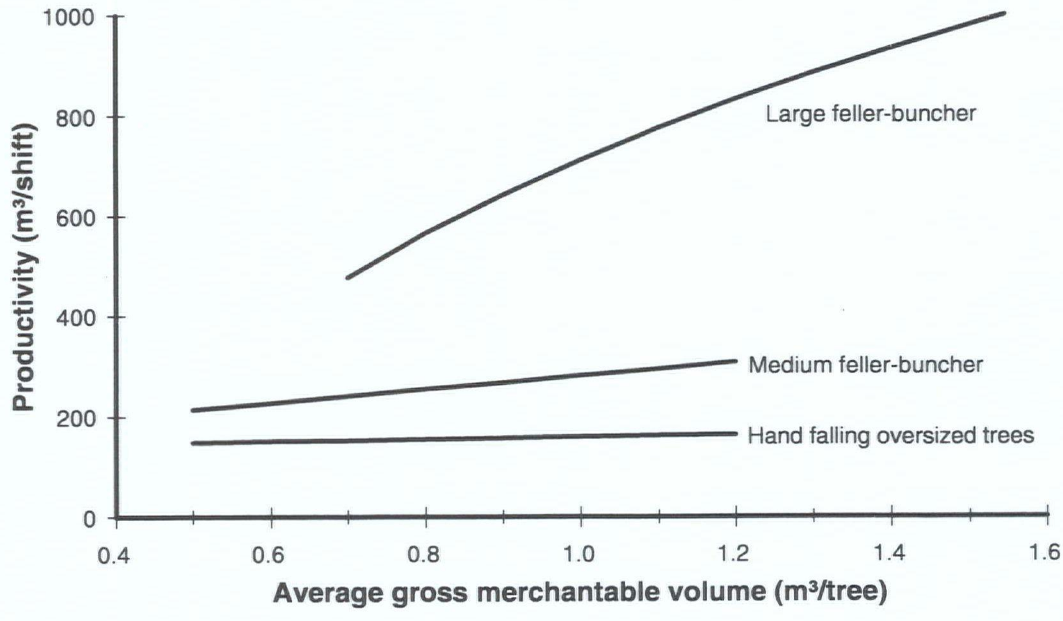

Figure 4. Projected productivity of large and medium feller-bunchers, as a function of average gross merchantable volume per tree.

The only information available to FERIC on cut-to-length harvesters working in coastal second-growth clearcutting operations is from a two-day detailed-timing study of a Valmet 500T single-grip harvester (Appendix IV). The machine (Figure 5) operated in a Douglas-fir stand with an average tree size of 0.5 m^3, and averaged 30 m^3/PMH. The harvester's tree size limitation was apparent during the study, as the feed rollers did not have enough power, or traction, to pull stems larger than about 40-cm dbh through the processing head.[5] Instead, the stems were processed by moving the head and/or the machine along the stem.

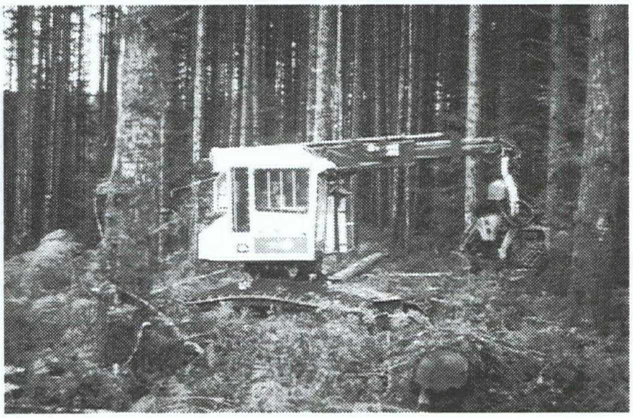

Figure 5. Valmet 500T harvester operating in a coastal second-growth stand.

The productivity of cut-to-length harvesters is expected to be lower than that of feller-bunchers because stems are also processed into logs. In the above-mentioned study, 31% of the machine's productive time was spent processing stems, but this component was proportionally less for small stems than for large stems. Studies in non-coastal conditions have also shown that the productivity of harvesters increases with an increase in tree size, and decreases with an increase in the number of logs processed per stem and the amount of brush in the stand (Andersson 1994; Gingras 1994).

Loader-Forwarding. Hydraulic log loaders are commonly used to extract timber to roadside in coastal second-growth stands in British Columbia (Figure 6). The method works well on terrain with firm ground and slopes up to 35%. Occasionally, tree size might be a limiting factor in second-growth stands, and some large stems may require bucking. Soft ground conditions also restrict the use of loader-forwarders, but their operable range can be extended if the machine corduroys its own travel path during timber extraction.

In this study, FERIC differentiated between two types of loader-forwarders, based on size. Large machines are loaders in the 40–50 tonne class (e.g., John Deere 992

Figure 6. Large loader-forwarder operating in a coastal second-growth stand.

and Hitachi EX400), while medium loader-forwarders are those weighing 25–30 tonnes (e.g., John Deere 690).

Loader-forwarders use one of two working patterns (Figure 7). In the up-and-down pattern, machines forward the wood in a series of progressive strips perpendicular to the haul roads. In the serpentine pattern, wood is forwarded in continuous passes, usually parallel to the haul road. FERIC found no evidence that one working pattern is more productive than the other (Andersson and Jukes 1995), but on soft ground where corduroying the travel path is required, the serpentine pattern may be more suitable.

Most information available on loader-forwarders is for large machines. Productivity ranges from 53 to 96 m^3/PMH for mechanically felled stems, and from 42 to 73 m^3/PMH for hand-felled stems (fall-only and fall-selective buck) at an external forwarding distance[6] of between 90 and 210 m (Table 4). Average machine utilization is about 85%. Only one study was available on medium loader-forwarders, where a John Deere 690 averaged 30 m^3/PMH at an average external forwarding distance of 40 m (Appendix IV).

The variation in productivity is attributed to differences in forwarding distance, piece size, concentration of wood, falling method, and slope. Machine productivity in hand-felled wood is lower than in correctly bunched feller-bunched wood because initially more time is required to pick up, turn, and accumulate the stems. Once hand-felled stems have been aligned, subsequent handling differs little between felling methods. Incorrectly bunched feller-bunched stems must also be turned and re-aligned by the loader-forwarder, thus reducing machine productivity and increasing stem breakage.

[5] A representative for Valmet America Inc. recommended that the machine operator not cut trees >40-cm dbh.

[6] The average of the maximum distances of all turns timed.

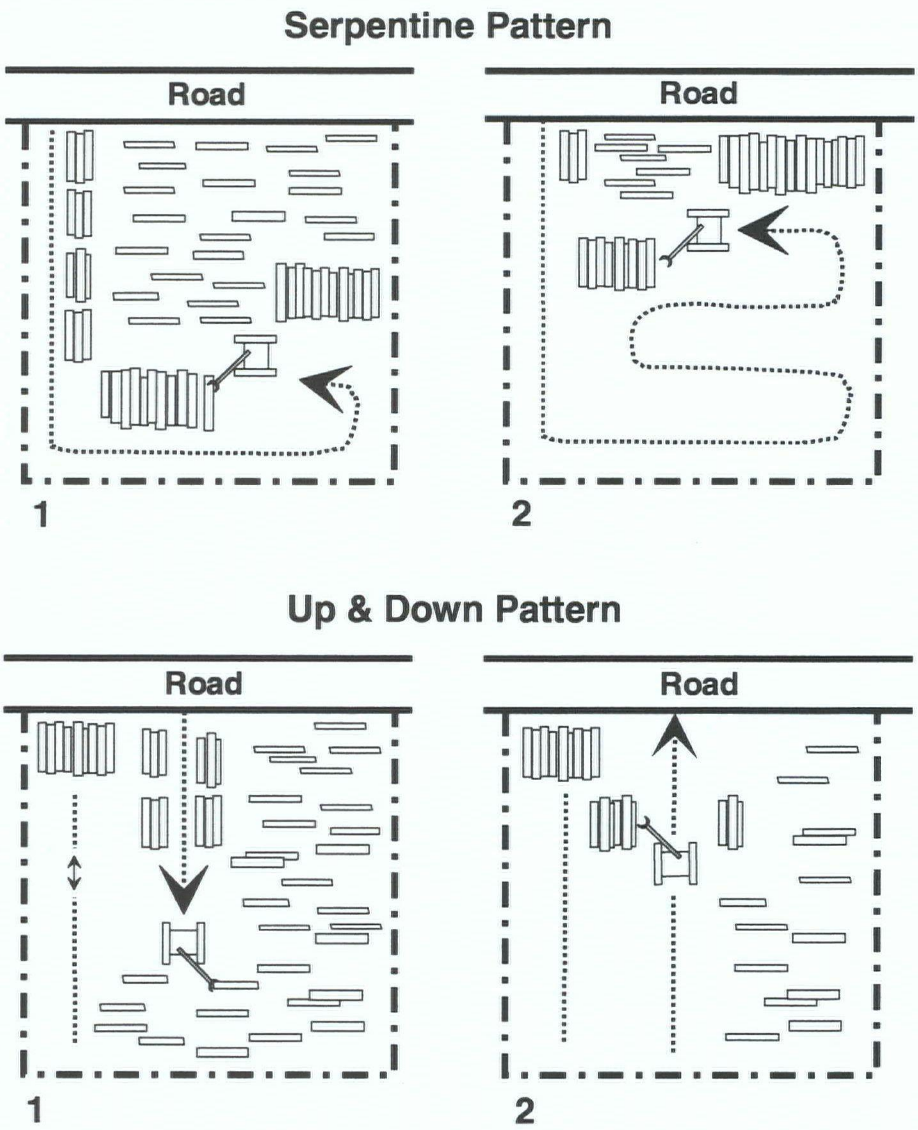

Figure 7. Serpentine and up-and-down working patterns for loader-forwarders.

The impacts of forwarding distance on loader-forwarder productivity were assessed by Andersson and Jukes (1995), who reported little effect on the machine's productivity (expressed in stems/PMH) in feller-bunched wood on flat ground. However, as more data became available (Andersson 1997), forwarding distance was found to have a greater impact on loader-forwarder productivity than shown initially, even though more wood was forwarded per turn with increased forwarding distance, and thus partly offset the greater turn time. The bias in the early study may have resulted because the effect of stem size (Figure 8) and the concentration of stems on the ground could not be adequately assessed. However, it is clear that the productivity of large loader-forwarders is less affected by forwarding distance than that of medium machines because large loader-forwarders can handle more wood per turn.

FERIC observed that little or no delimbing was required at the roadside following the loader-forwarding operations because most branches broke off during forwarding.

Based on available data, Figure 9 projects productivity of large loader-forwarders in feller-bunched wood, and medium loader-forwarders in hand-felled and bucked wood, with both machine types operating on level or favourable (downhill) slopes <10% (Appendix I). Lower productivity is expected where the machine forwards the wood uphill.

Ground Skidding. Three types of skidders can be used in coastal second-growth harvesting operations: line skidders, grapple skidders, and clambunk skidders. The machines can either be rubber-tired or tracked. Ground skidding is generally limited to sites with good

Table 4. Productivity of Loader-Forwarding Operations: Summary

Felling method, machine size	Average operating conditions [a]				Machine performance [a]			Study type [a]	Reference [b]
	Stand vol. (m^3/ha)	Stem vol. (m^3)	Slope (%)	Distance (m)	MU (%)	Productivity (m^3/PMH)	Productivity (m^3/shift)		
Coastal second-growth operation									
Feller-buncher, large machine	610	1.5	10	200	83	75	500	sl	3
	580	1.1	0	150	83	55	360	sl	3
	430	1.1	15	120	86	75	513	sl	2
	610	2.2	10	180	-	96	-	dt	3
	610	1.6	10	200	-	78	-	dt	3
	450	1.3	0	120	-	66	-	dt	2
	610	1.1	5	210	-	71	-	dt	3
	430	0.9	15	100	-	53	-	dt	2
Hand fall-only, large machine	400	1.1	5	120	92	68	498	sl	2
	400	1.2	5	90	-	73	-	dt	2
Hand fall-select buck, large machine	1 300	2.6	10	175	89	42	303	sl	3
	460	0.8	5	120	93	45	336	sl	2
	1 300	2.1	0	200	-	69	-	dt	3
	460	0.8	5	120	-	57	-	dt	2
Hand fall-process, medium machine	690	0.7	10	40	-	30	-	dt	Appendix IV
Coastal old-growth operation									
Hand fall-process, large machine	1 090	2.2	-	130	85	94	642	sl	33

[a] Definitions in Appendix III.
[b] Numbers correspond to items in the References section.

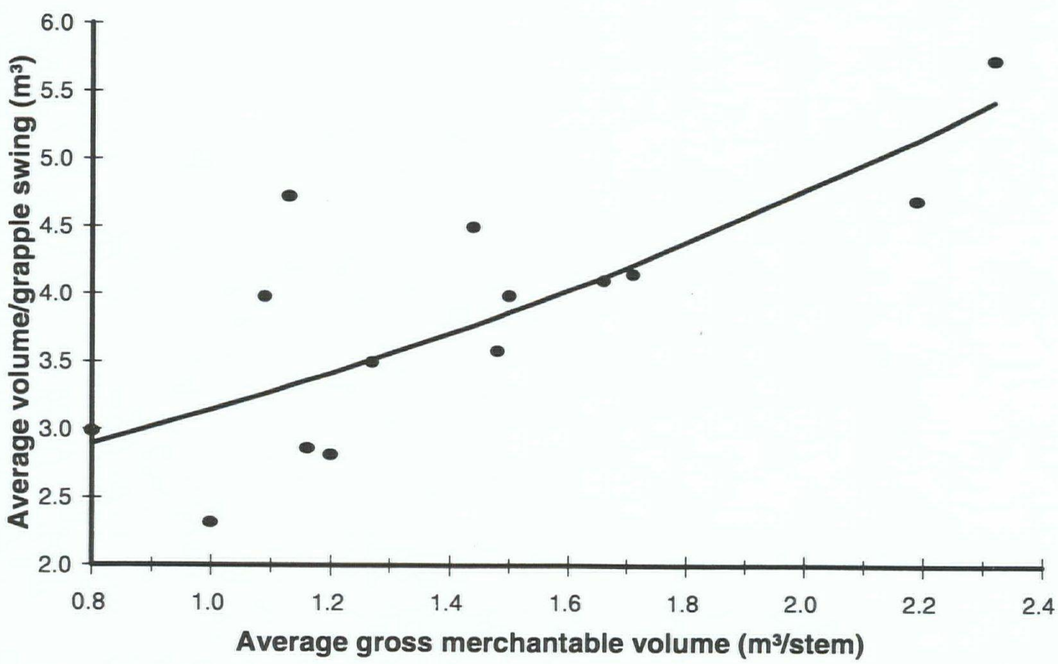

Figure 8. Impact of stem size on volume per grapple swing of large loader-forwarders in feller-bunched wood.

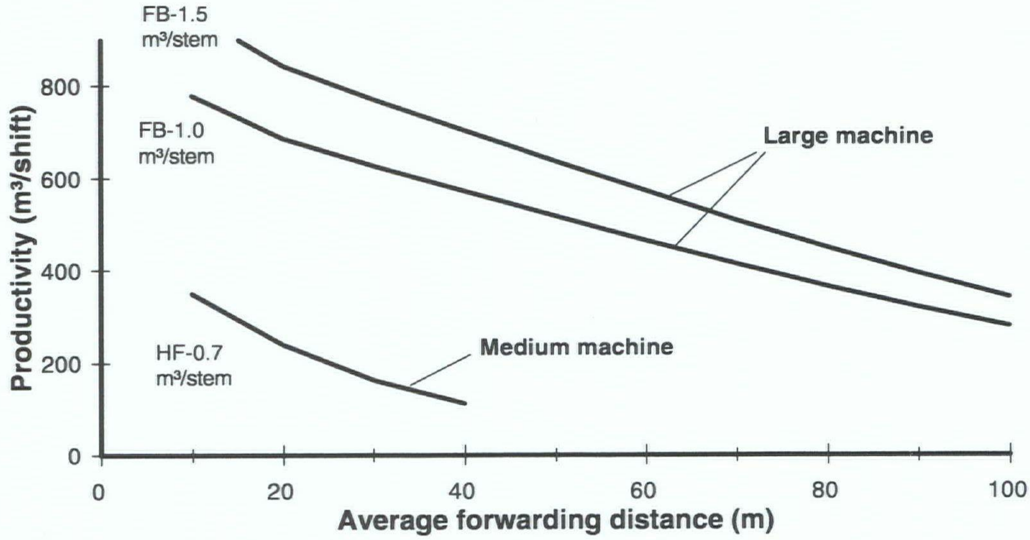

Figure 9. Projected productivity of large loader-forwarders in feller-bunched wood, and medium loader-forwarders in hand-felled wood, as a function of average forwarding distance.

ground-bearing capacity and gentle slopes (Figure 10). However, skidder operability on soft ground can be improved by mounting wide tires on rubber-tired skidders (Mellgren and Heidersdorf 1984) or by using tracked skidders. Line skidders have a wider range of operating conditions than grapple and clambunk skidders because line skidders do not need to be in the immediate vicinity of the logs to be hooked. They are also more suited to extract scattered logs and logs in broken terrain, than are grapple skidders.

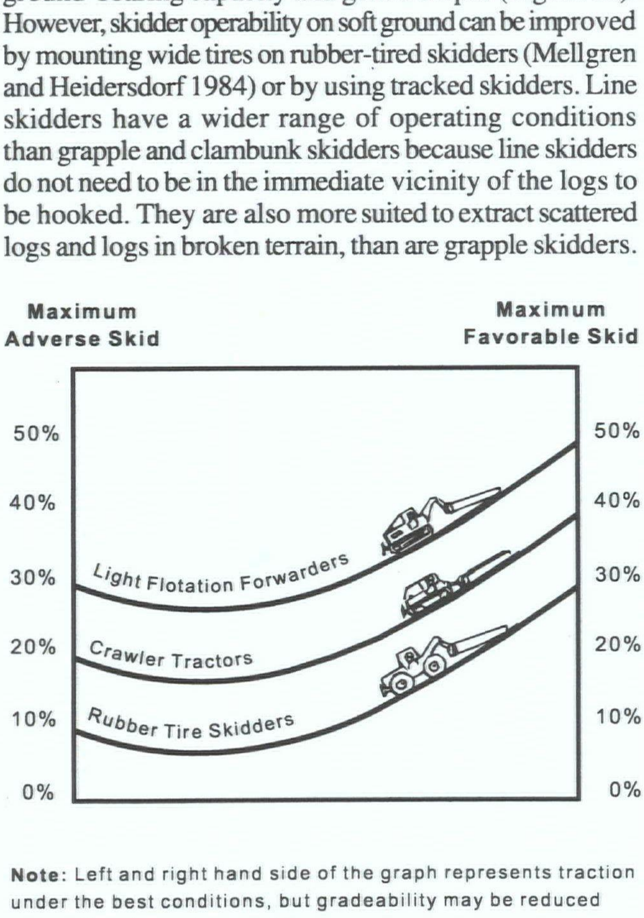

Figure 10. Maximum favourable and adverse gradeability for some skidder types under good conditions (Johnston and Wellburn 1976).

However, line skidders are less suitable for night-shift operations, because the operators must leave the cab in order to set and release the turn.

Recorded productivity of skidders in coastal second-growth operations range from 16 to 32 m³/PMH, while skidders in interior operations average from 47 to 64 m³/PMH (Table 5). The information from coastal second-growth operations is for line skidders in hand-felled wood, while most data from interior operations are for grapple skidders in feller-bunched wood. These differences explain some of the variation in the productivity between coastal and interior operations. Differences in skidding distance, ground conditions, and tree size, are other contributing factors.

No productivity data were found for clambunk or tracked skidder operations in second-growth timber. Tracked skidders are expected to have a slightly lower productivity than wheeled skidders when operating in similar stand and terrain conditions (Rogers and MacDonald 1989). Clambunk skidders typically have longer turn times, but also higher payloads than line or grapple skidders, and would therefore be better suited to settings with long skidding distances (McMorland 1977).

Grapple skidders have shorter loading and unloading times than line skidders, and therefore faster cycle times. In a coastal second-growth, mechanically-felled setting with a 100-m average skidding distance, Peterson (1986) recorded an average turn time of 5.8 min for grapple skidders and 10.0 min for line skidders.

The load size of skidders is believed to vary with merchantable piece size, but no data were found to

Table 5. Productivity of Ground-Skidding Operations: Summary

Felling method, machine type	Average operating conditions [a]				Machine performance [a]			Study type [a]	Reference [b]
	Stand vol. (m^3/ha)	Stem vol. (m^3)	Slope (%)	Distance (m)	MU (%)	Productivity (m^3/PMH)	Productivity (m^3/shift)		
Coastal second-growth operation									
Feller-bunched									
Grapple/line skidders [c]	610	0.9	12	100	71	32	181	dt	26
Hand-felled									
Caterpillar 518/line	580	1.4	<12	160	84	27	180	sl	35
Caterpillar D4H/line [d]	580	1.4	>12	160	94	16	117	sl	35
Caterpillar 518/line	580	1.1	-	160	-	29	-	dt	35
Interior operation									
Feller-bunched									
Caterpillar 528 grapple	340	0.4	8	100	75	58	347	sl	16
John Deere 740A grapple	250	0.3	11	100	80	54	344	sl	14
FMC 220 grapple	340	0.5	30	60	83	64	430	dt	10
Caterpillar D6D grapple	340	0.4	30	55	90	47	336	dt	10

[a] Definitions in Appendix III.
[b] Numbers correspond to items in the References section.
[c] Study did not specify all skidder types, but consisted of two grapple skidders (at least one was a Clark 667 grapple skidder) and four line skidders.
[d] Caterpillar D4H worked on steeper slopes than the Caterpillar 518, and was often used to skid oversized logs. However, differences in operating conditions between the skidders were not identified in the report.

establish such a relationship. Peterson (1986) recorded an average payload of 3.7 m^3/turn for a fleet of four grapple and two line skidders operating in a setting with an average piece size of 0.9 m^3, while Rogers and MacDonald (1989) recorded a payload of 4.9 m^3/turn for a Caterpillar 518 line skidder operating in a setting with an average piece size of 1.1 m^3. Information on differences in payloads between grapple and line skidders in coastal operations was not found. Theoretically, the payload of grapple skidders should be less than that of line skidders of similar size, because of the extra weight of the grapple (about 1.5 tonnes), while in reality, the payloads are also influenced by hooking conditions and operator's preference. Therefore, line skidders should be more competitive with grapple skidders at long distances where large turn size is more important in achieving high productivity than are fast loading and unloading.

Figure 11 shows the projected productivity of rubber-tired grapple and line skidders as a function of external skidding distance (Appendix I). The production functions are based on the relationship between turn time and skidding distance developed by Rogers and MacDonald (1989), and on the principle that the turn size of line skidders ought to be larger than that of grapple skidders.

Grapple Yarding. Most second-growth stands can be grapple yarded provided there is adequate deflection and clearance for the line and the log load (Figure 12). Maximum yarding distance is usually in the 150–200 m range. Compared to ground-based systems, grapple yarding typically results in less site disturbance. However, on sites where both ground-based and cable systems can be used, grapple yarding will likely have higher costs than ground-based extraction methods.

Information on grapple yarding productivity in second-growth stands ranges from 62 to 108 m^3/PMH in feller-bunched wood, and from 35 to 118 m^3/PMH in hand-felled wood (Table 6). The variation in yarder productivity is attributed to differences in falling method, piece size, and yarding distance.

MacDonald (1988b) identified that the larger turn size when yarding feller-bunched wood compared to hand-felled wood was the main reason for the higher grapple-yarder productivity in mechanically felled and bunched wood (Figure 13).

While several factors influence grapple-yarder productivity, only the impact of yarding distance has been analyzed in detail (e.g., Peterson 1986; MacDonald 1988b). Piece size and felling method have also been shown to influence grapple-yarder productivity, and FERIC has attempted to incorporate these factors into the productivity estimate of grapple yarders. Thus, Figure 14 shows the projected productivity of grapple yarders rigged with mobile backspars in hand-felled and feller-bunched wood for different piece sizes, as a function of average yarding distance (Appendix I).

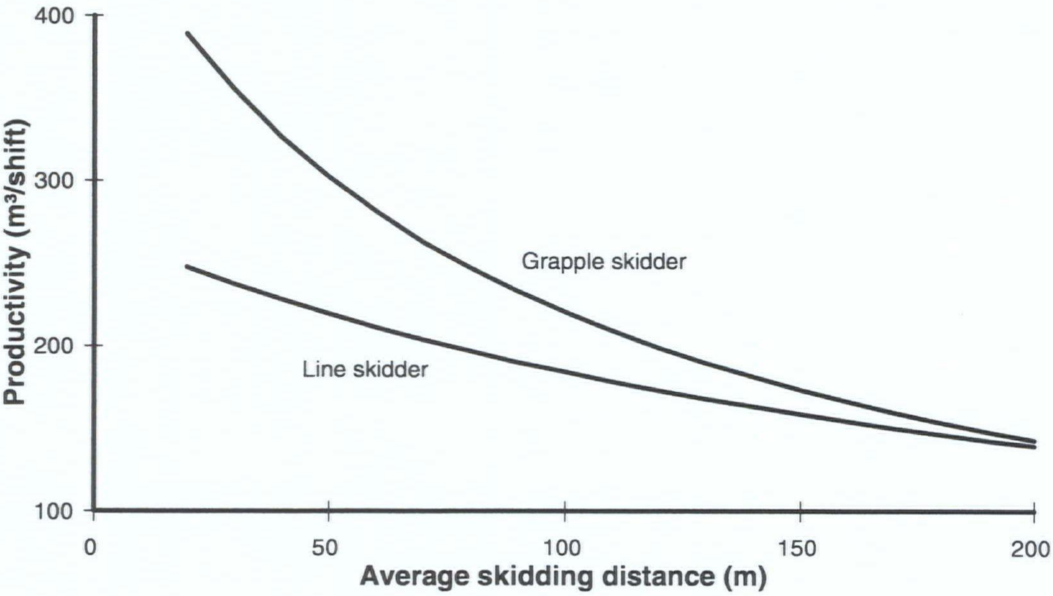

Figure 11. Projected productivity of rubber-tired line and grapple skidders, as a function of average skidding distance.

Figure 12. Grapple yarder extracting hand-felled wood in a second-growth stand.

Cable Yarding with Chokers. Chokers can be used with a variety of machines (e.g., swing yarders and yarding towers) and rigging configurations (e.g., highlead, running skyline, standing skyline, with or without intermediate support) (Figure 15). Because productivity data for these systems in second-growth stands are limited, this report uses 'cable yarding with chokers' as a generic term for all systems using chokers to hook the logs.

Like grapple yarding, cable yarding with chokers can be done in most second-growth stands, and performance is generally affected by the same factors as grapple yarding. Yarding distances can be longer with these systems, but the system generally requires a larger crew than for grapple yarding. As the logs are hooked manually with chokers, hook-up and unhooking times are longer than for grapple yarding. However, the turn size of yarders using chokers is normally larger than for grapple yarders because several pieces are hooked per turn.

Information on cable yarding with chokers includes different size yarders, rigging configurations, and felling methods. The productivity of a large machine (Madill 044) in coastal second-growth feller-bunched wood ranged from 61 to 75 m^3/PMH, while the productivity of a medium machine (Washington SLH78) in coastal second-growth hand-felled wood ranged from 23 to 26 m^3/PMH (Table 7). As with grapple yarders, the difference in the productivity is attributed to a combination of machine size, yarding distance, piece size, and falling method. The number of chokers and crew size also affect the productivity.

Studies by Kooistra et al. (1990) in coastal old-growth stands show that turn size generally increases with piece size for a given rigging configuration (Figure 16). A similar trend is expected for second-growth yarding operations. Also, the relationship of piece size to turn size will likely be different between hand-felled and feller-bunched wood, and between sizes of yarders.

Figure 17 shows the projected productivities of medium and large yarders as a function of average yarding distance. The medium yarder is assumed to be operating in hand-felled and bucked wood, and rigged with four chokers. The turn size is assumed to be 3 m^3. The large yarder is assumed to be operating in feller-bunched wood, and rigged with one (4 m^3/turn) or two chokers (6 m^3/turn) that are long enough to be wrapped around whole bunches of stems (Appendix I).

Table 6. Productivity of Grapple-Yarding Operations: Summary

Felling method, machine type	Average operating conditions [a]				Machine performance [a]			Study type [a]	Reference [b]
	Stand vol. (m^3/ha)	Stem vol. (m^3)	Slope (%)	Distance (m)	MU (%)	Productivity (m^3/PMH)	Productivity (m^3/shift)		
Coastal second-growth operation									
Feller-bunched									
Washington 118A	380	1.1	5	80	83	62	414	sl	14
Washington 118A	380	1.5	-	80	-	82	-	dt	14
Madill 044	-	1.0	-	100	83	64	423	dt	15
Madill 044	-	0.8	-	80	83	108	718	dt	15
Washington 118A	380	0.8	-	70	-	94	-	dt	14
Madill 084	566	0.6	-	70	77	64	390	dt	26
Hand-felled									
Madill 122	343	0.8	5	80	83	35	232	sl	12
Madill 044 [c]	1300	1.4	15	70	-	118	-	dt	3
Cypress 720B	550	0.9	26	130	71	46	261	dt	32
Madill 084	713	0.9	-	75	72	59	342	dt	26
Madill 122	343	0.8	5	75	-	43	-	dt	12
Madill 123	690	0.7	-	-	-	-	-	dt	Appendix IV
Coastal old-growth operation									
Hand-felled									
Cypress 720B	630	2.4	46	120	87	96	673	dt	32
Interior operation									
Feller-bunched									
Washington 108	330	0.5	20	-	80	50	320	sl	24
Washington 108	330	0.5	-	80	-	55	-	dt	24

[a] Definitions in Appendix III.
[b] Numbers correspond to items in the References section.
[c] Pre-aligned by a John Deere 992 log loader.

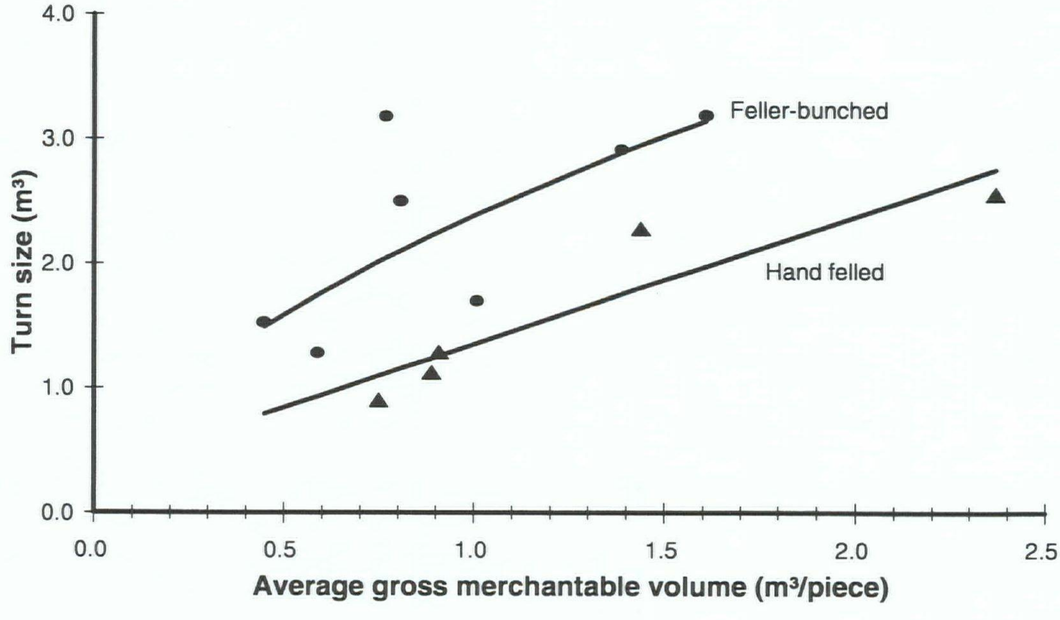

Figure 13. Relationship between grapple yarder turn size and average piece size for hand-felled and feller-bunched wood in coastal second-growth timber.

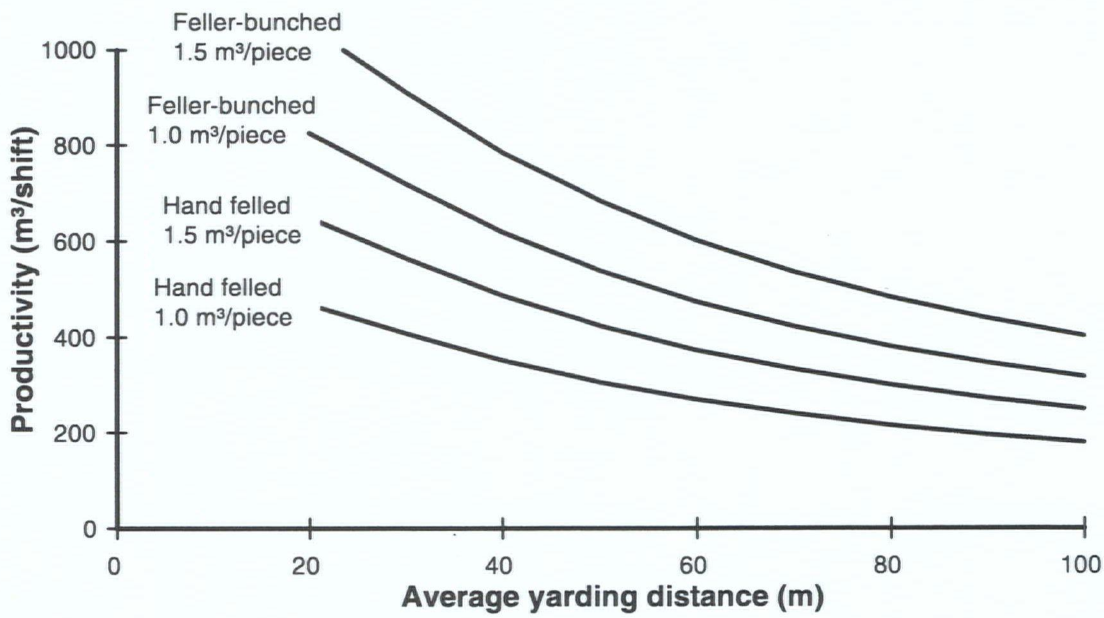

Figure 14. Projected productivity of grapple yarding of hand-felled and mechanically-bunched wood of different piece sizes, as a function of average yarding distance.

Figure 15. Madill 122 yarder working in a second-growth stand.

Super Snorkeling. Super snorkels can be used to extract wood from a relatively narrow strip along haul roads. Because of their great weight[7] they are generally restricted to well-built roads (Figure 18). Although a super snorkel boom can be up to 50 m long (measured from the centre of the machine), its effective yarding range is less than the maximum reach when downhill yarding or when obstacles or high road banks block the operator's view. However, a wider strip can be extracted in settings where the timber is yarded uphill (i.e., the machine is sitting higher than the yarding area) because the grapple can be thrown further than 50 m from the road.

The productivity of a Madill 075 super snorkel ranged from 152 to 352 m^3/PMH in three studies (Table 8). The variation in productivity is attributed primarily to differences in piece size, wood concentration, log alignment, and yarding distance. FERIC observed that in aligned wood, the super snorkel could grapple more pieces per turn, and thus average turn volume was higher than in as-felled wood of similar piece size (Andersson and Jukes 1995). As the machine operates along roads, traffic on the road will affect productivity if the machine is required to move to allow traffic to pass. Also, super snorkel productivity is very much affected by operator experience, as these machine are very difficult to operate.

Based on the limited data available, FERIC estimates that super snorkels yard about 1000 m^3/shift, but could potentially produce up to 2500 m^3/shift.

Log Aligning with Hydraulic Log Loaders. The productivity of cable yarders and super snorkels in hand-felled wood can be improved by aligning and semi-bunching the logs prior to yarding. This operation, referred to as log alignment, can be done with the same

[7] The Madill 075 super snorkel weighs approximately 100 tonnes.

Table 7. Productivity of Cable Yarding with Choker Operations: Summary

Felling method, machine type	Average operating conditions [a] Stand vol. (m^3/ha)	Stem vol. (m^3)	Slope (%)	Distance (m)	Machine performance [a] MU (%)	Productivity (m^3/PMH)	Productivity (m^3/shift)	Study type [a]	Reference [b]
Coastal second-growth operation									
Feller-bunched									
Madill 044									
with 2 chokers	420	1.3	-	130	-	75	-	dt	13
with 1 choker	420	1.2	-	110	-	61	-	dt	13
with 2 choker	420	1.0	-	100	-	71	-	dt	13
Hand-felled									
Washington SLH78									
with 4 chokers	830	0.7	15	90	82	23	149	sl	4
with 4 chokers	830	0.6	10	110	-	26	-	dt	4
with 2 chokers	830	0.7	10	80	-	23	-	dt	4
Coastal old-growth operation									
Hand-felled									
Madill 009 highlead	670	3.4	50	150	89	58	418	dt	11
Madill 009 highlead	1 030	2.1	45	110	83	45	296	dt	11
Madill 009 highlead	690	1.8	45	140	93	26	195	dt	11

[a] Definitions in Appendix III.
[b] Numbers correspond to items in the References section.

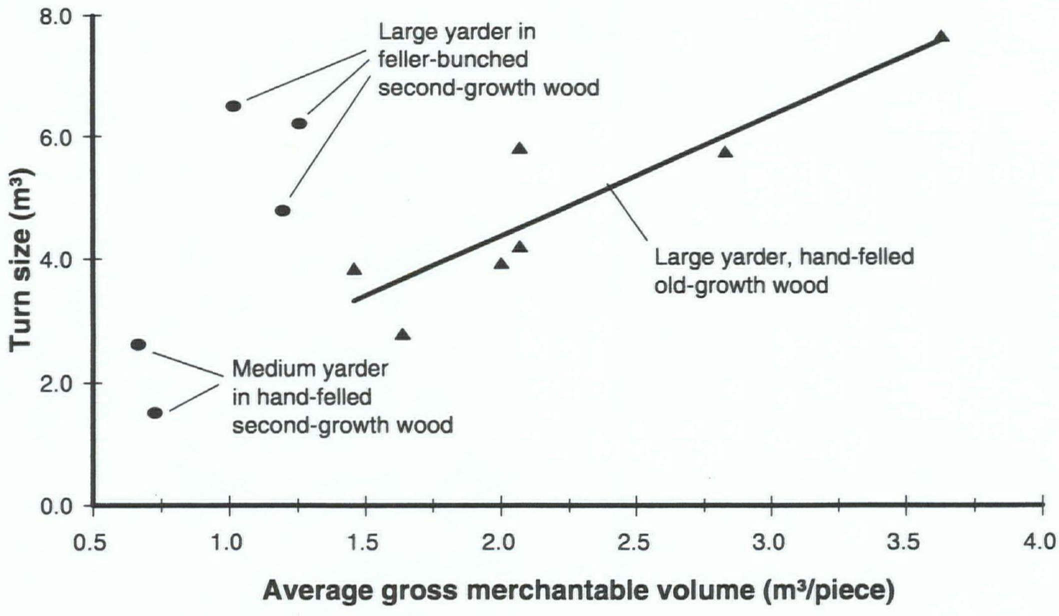

Figure 16. Examples of the relationship between turn size and average piece size for yarder operations with chokers in old-growth and second-growth operations.

type of hydraulic log loaders as used for loader-forwarding. A study by FERIC found that a John Deere 992D log loader aligning logs averaged 99 m^3/PMH or 700 m^3/shift (Andersson and Jukes 1995). Because of the soft ground conditions on the study site, 28% of the machine's operating time was spent on corduroying its travel path and removing the puncheon material after its use. Had the ground been firmer and corduroying not required, it is estimated that machine productivity would have been 970 m^3/shift.

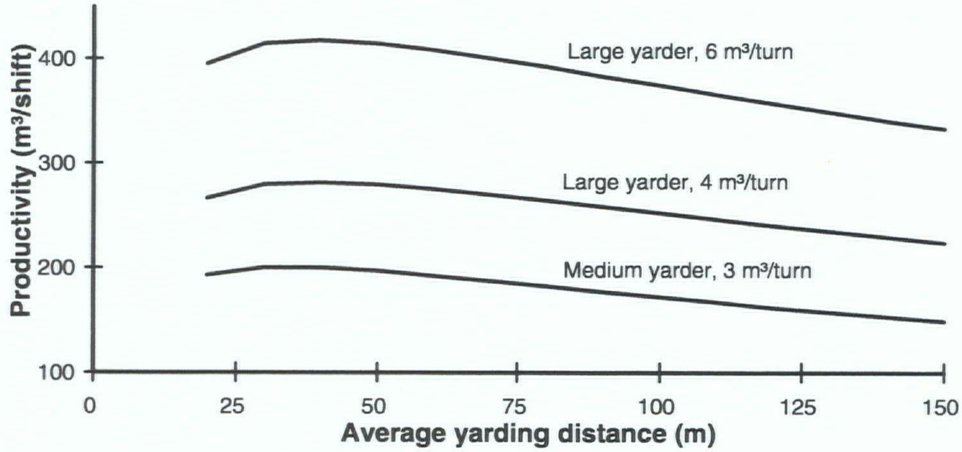

Figure 17. Predicted productivity of cable yarding with chokers, as a function of average yarding distance.

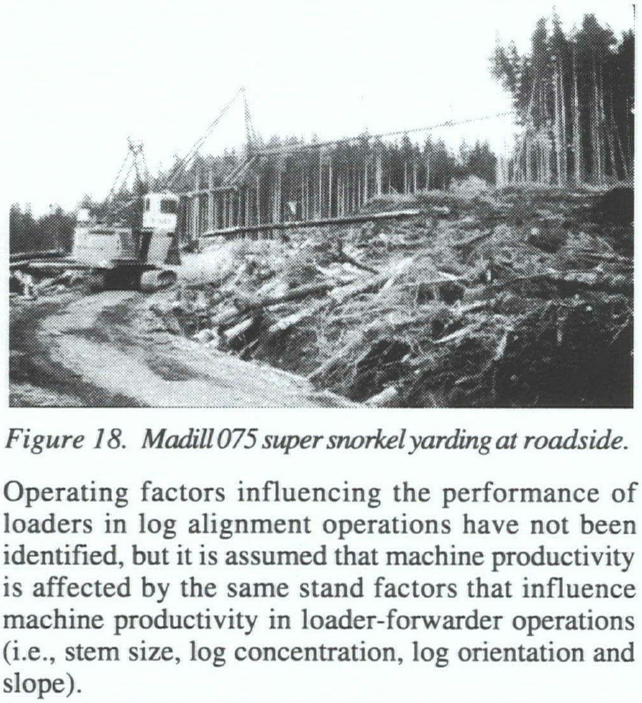

Figure 18. Madill 075 super snorkel yarding at roadside.

Operating factors influencing the performance of loaders in log alignment operations have not been identified, but it is assumed that machine productivity is affected by the same stand factors that influence machine productivity in loader-forwarder operations (i.e., stem size, log concentration, log orientation and slope).

Manual Processing at Roadside Landings. In manual processing, one or two buckers usually work with a log loader that places full-length stems on the road or landing, and removes the logs following bucking. The loader can assist the buckers either full-time or intermittently while loading trucks.

Information on manual processing operations show productivities ranging from 95 to 209 m^3/shift, depending on stem size, bucking specifications, number of buckers, and loader availability (Table 9). However, the impact of individual factors on productivity could not be quantified. As a result, FERIC established a base value for manual bucking operations of 140 m^3/shift, assuming an average of 1.5 buckers, assisted by a hydraulic log loader for 31% of its scheduled time.

Mechanical Processing at Roadside Landings. Several types of mechanical processors, such as stroke boom (e.g., Denis and Lim-mit), dangle head (e.g., Steyr), or deck mounted (e.g., Hahn) are available for processing second-growth timber. Processors can

Table 8. Productivity of Madill 075 Super Snorkel with 50-m Boom: Summary

Felling method, machine type	Average operating conditions [a]				Machine performance [a]			Study type [a]	Reference [b]
	Stand vol. (m^3/ha)	Stem vol. (m^3)	Slope (%)	Distance (m)	MU (%)	Productivity (m^3/PMH)	Productivity (m^3/shift)		
Coastal second-growth operation									
Hand-felled									
Madill 075	1300	1.4	10	35	80	152	973	sl	3
Madill 075 (aligned wood)	1300	1.9	15	28	-	352	-	dt	3
Madill 075 (as-felled wood)	1300	1.8	15	33	-	211	-	dt	3

[a] Definitions in Appendix III.
[b] Numbers correspond to items in the References section.

Table 9. Productivity of Manual Processing: Summary[a]

Buckers (no.)	Stem volume (m^3)	Loader availability (%)	Productivity (m^3/PMH)	Productivity (m^3/shift)
1	0.5	27	44	95
2	0.5	27	60	129
1	0.8	35	47	130
2	0.8	35	75	209

[a] Data derived from Peterson (1986).

work either alone (i.e., processing cold decks of stems at roadside) or with skidders, yarders, or loaders (Figure 19). The processing can also be combined with sorting, but may require a loader to deck the different log products (depending on the number of sorts and the available decking space). The application of mechanical processors is limited by tree size, both in terms of stem diameter and stem weight, and thus some over-sized stems may be processed manually. Processors can be equipped with computer-assisted bucking devices to ensure proper log lengths, or to optimize value recovery during processing.

Productivity data on processors in second-growth timber are limited, but information from non-coastal operations is useful to estimate processor productivity for coastal second-growth operations. Because the processing is done at roadside or at landings, the influence of stand characteristics is basically reduced to only the stem size.

Published information on processors shows that productivity ranges from 35 to 84 m^3/PMH in coastal second-growth operations, and from 43 to 86 m^3/PMH in interior operations with piece sizes similar to coastal ones (Table 10). While variation in productivity is attributed primarily to stem size (Figure 20), other factors (e.g., type of processor, sorting requirements,

Figure 19. Keto 1000/Timbco processor.

and the logistics of supplying stems and removing logs at the landing) also affect processor performance.

Processors working in combination with other machines (e.g., yarders, skidders, and loaders) are expected to have lower productivity than processors working independently of other machines. MacDonald (1988a) observed that a John Deere 740A grapple skidder supplying stems to a Steyr KP40 processor was unable to supply sufficient stems to keep the processor working at all times. Similarly, a Keto 1000 processor working with a yarder and a loader was observed to spend nearly one-fifth of its scheduled time waiting for wood (Appendix IV). Delays may also occur where a loader is required to remove processed logs. The length of delay will vary between operations, depending on the system and size of the landing.

Information on the effect of sorting is limited. McMorland (1984) estimated a 10% productivity reduction due to sorting for a stroke delimber producing three sorts at a processing yard.

Figure 21 shows the projected productivity, as a function of average stem volume, of generic processors (combination of all types) working independently and integrated with other machines at roadside. FERIC assumes that machine utilization will differ between the two operations (Appendix I).

Loading. Either hydraulic (knuckle-boom) or front-end loaders can load trucks, or log trucks can be self-loading. Hydraulic loaders can be used either at roadside or on landings, while front-end loaders are better suited to landings.

The effective loading time often varies with stem size (Andersson 1994). However, when loaders are not fully utilized (i.e., constantly loading trucks), the availability of trucks generally becomes the key factor determining the loader's daily productivity. Table 11 summarizes the results of studies by Peterson (1986) in a coastal second-growth operation, and by Powell (1981) in an interior operation.

Table 10. Productivity of Mechanical Processors: Summary

Machine type	Average operating conditions [a]		Machine performance [a]			Study type [a]	Reference [b]
	Stand vol. (m^3/ha)	Tree vol. (m^3)	MU (%)	Productivity (m^3/PMH)	Productivity (m^3/shift)		
Coastal second-growth operations							
Integrated operation [c]							
Hahn processor	570	0.5	73	67	392	dt	26
Hahn processor	710	0.8	80	84	535	dt	26
Hahn processor	610	0.6	68	60	328	dt	26
Keto 1000/Timbco	715	0.6	65	35	182	dt	Appendix IV
Hahn II processor	570	0.5	55	44	193	dt	26
Hahn II processor	710	0.8	31 [d]	65	163	dt	26
Coastal old-growth operations							
Independent operations							
Tanguay EC 200	690	1.5	53	39	163	dt	28
Interior operations							
Integrated operation							
Steyr KP40	-	0.7	89	86	612	dt	13
Denis D3000	330	0.5	82	43	282	sl	23
Denis D3000	330	0.5	-	45	-	dt	23
Independent operations							
Steyr KP40	-	0.5	93	72	539	dt	16
Lim-mit LM 2200	400	0.9	58	80	373	sl, dt	29
Lim-mit (prototype)	340	0.6	63	78	393	sl	13
Denis DP550	250	0.5	79	62	394	sl	5
Lim-mit LM2200	-	0.5	80	45	286	sl	6

[a] Definitions in Appendix III.
[b] Numbers correspond to items in the References section.
[c] Stems supplied or removed by skidders, yarders, or loaders.
[d] Low machine utilization due to waiting for loader to remove processed logs.

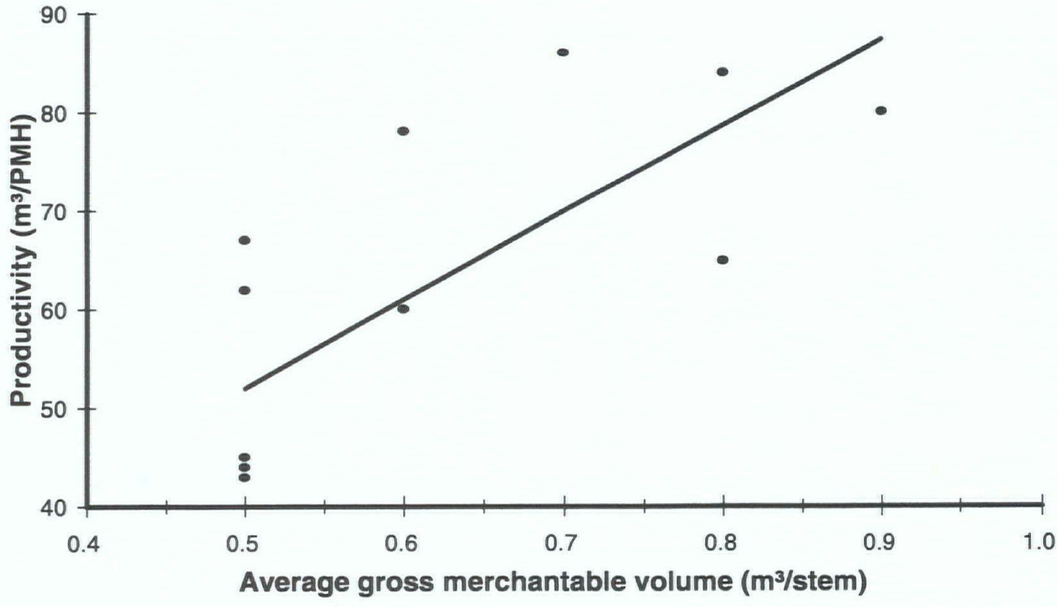

Figure 20. Impact of average stem volume on processor productivity.

Costing of Harvesting Systems

The cost of harvesting timber can vary considerably among operations even when the same harvesting system is used. The reasons are many and may include: differences in operating conditions; wear and tear on the machines; and repair and maintenance programs. Also, the cost of individual harvesting phases must be considered relative to quality of work done, and how well they perform with other phases in a complete 'stump-to-dump' harvesting operation. The harvesting costs presented in this report are examples based on FERIC's standard costing methodology (Appendix II) and the projected harvesting productivities (Figures 2, 4, 9, 11, 14, 17, and 21). As the productivity data were collected from operations with different conditions, a direct comparison of the harvesting costs between systems may not be representative in every situation.

Falling Costs. FERIC's analysis shows little difference in the direct falling costs between large feller-bunchers and fall-only hand fallers (Figure 22). As the degree of log processing increases in hand-falling operations, the cost of falling increases. Operations with medium feller-bunchers appear to be more expensive than fall-only and fall-selective buck hand-falling, presumably because these feller-bunchers have to be complemented with hand-falling of oversized trees.

Extraction Costs. Large loader-forwarders appear to be cost competitive with grapple skidders in feller-bunched wood at extraction distances up to 100 m (Figure 23). Data on medium loader-forwarders suggest this size of machine is best suited to relatively short extraction distances. Line skidders become more cost competitive than grapple skidders at long skidding distances because they can skid more volume per turn than grapple skidders.

The costs of cable-yarding operations (Figures 24 and 25) are typically higher than those of ground-based systems, but the two methods are not likely to be used in the same terrain. At shorter distances, grapple yarding is more cost effective than yarding with chokers. However, the cost of grapple yarding increases with yarding distance at a higher rate than does yarding with chokers due to smaller turn size. The yarding costs of feller-bunched wood are generally lower than for hand-felled wood for both grapple and choker yarders.

The cost of extracting wood with super snorkels is estimated as approximately \$1.50/m^3, and thus super snorkel operations are cost competitive with both ground-based and cable systems working within 50 m of haul roads.

Processing Costs. FERIC's data suggest that a mechanical processor working independently of other machines will result in the lowest processing costs. However, if a loader is needed to sort the manufactured logs or to remove them from the processing area, there is little difference between manual or mechanical processing costs (Figure 26).

Loading Costs. As the productivity of log loaders is greatly influenced by the number of trucks being served by the loaders, the loading cost is difficult to estimate. If shift-level productivity is 300–600 m^3/shift, and the loader performs no other tasks (e.g., assisting landing buckers), the loading cost would range from \$2.08 to 4.15/m^3.

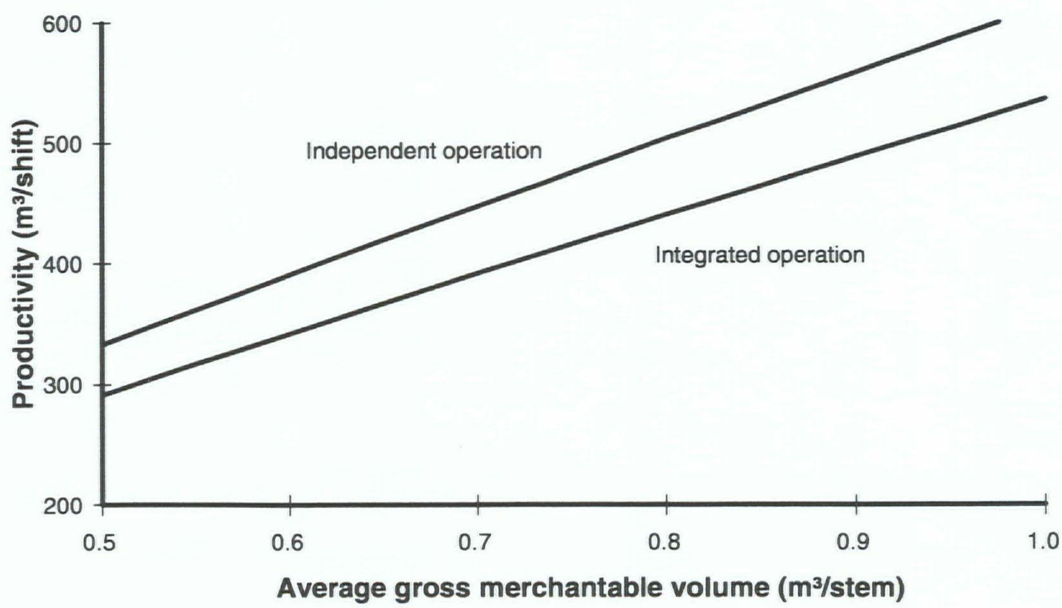

Figure 21. Predicted productivity of processors as a function of average stem volume.

Table 11. Productivity of Log Loading: Summary

Machine type	Average operating conditions [a]			Machine performance [a]			Study type [a]	Reference [b]
	Form	Location	Stem (m³)	MU (%)	Productivity (m³/PMH)	Productivity (m³/shift)		
Coastal second-growth operations								
Poclain HC 300	logs	roadside	0.5	37	102	299	dt	26
Poclain HC 300	logs	roadside	0.6	36	102	290	dt	26
Poclain HC 300	logs	roadside	0.7	29	139	328	dt	26
Barko 250	logs	roadside	0.5	57	124	570	dt	26
Barko 250	logs	roadside	0.6	46	112	412	dt	26
Interior operations								
Barko 450	full trees	roadside	0.3	80	79	502	sl	34
Barko 450	full trees	roadside	0.8	79	74	464	sl	34

[a] Definitions in Appendix III.
[b] Numbers correspond to items in the References section.

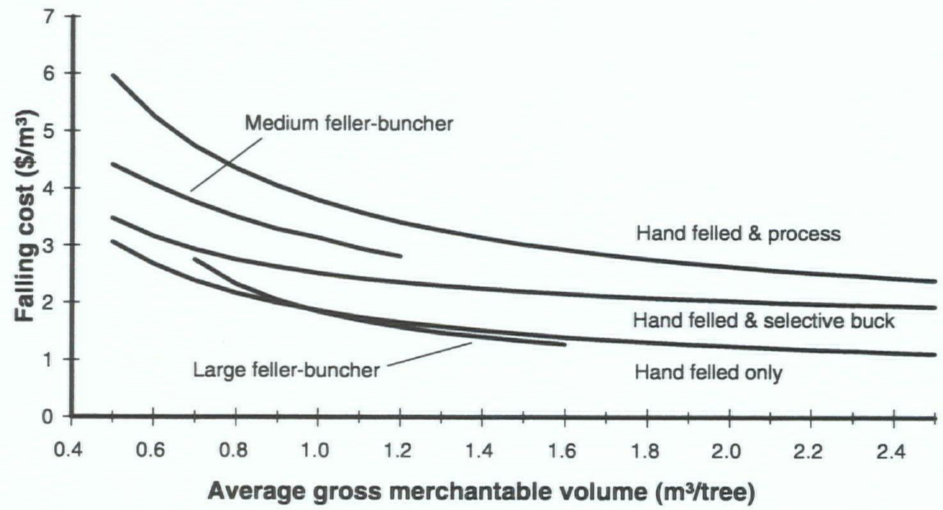

Figure 22. Projected falling costs of mechanical and hand-falling operations, as a function of average tree volume.

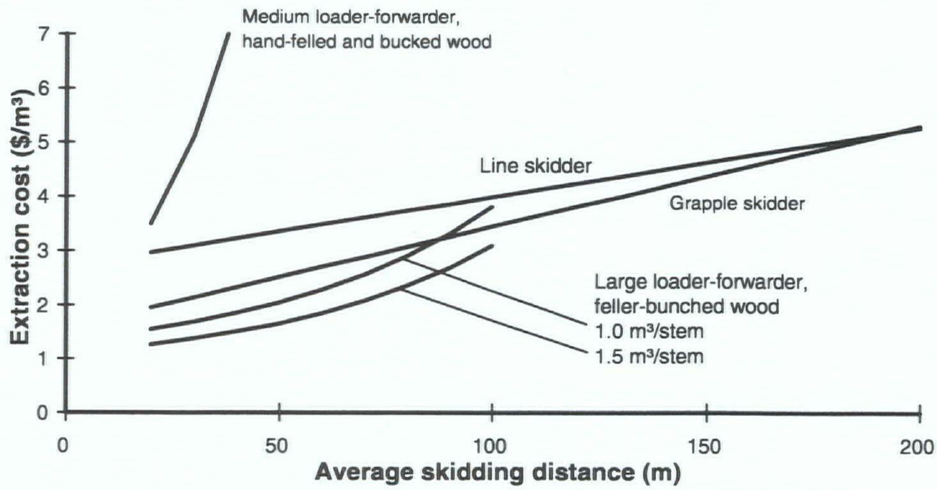

Figure 23. Projected extraction cost using ground-based systems, as a function of average skidding distance.

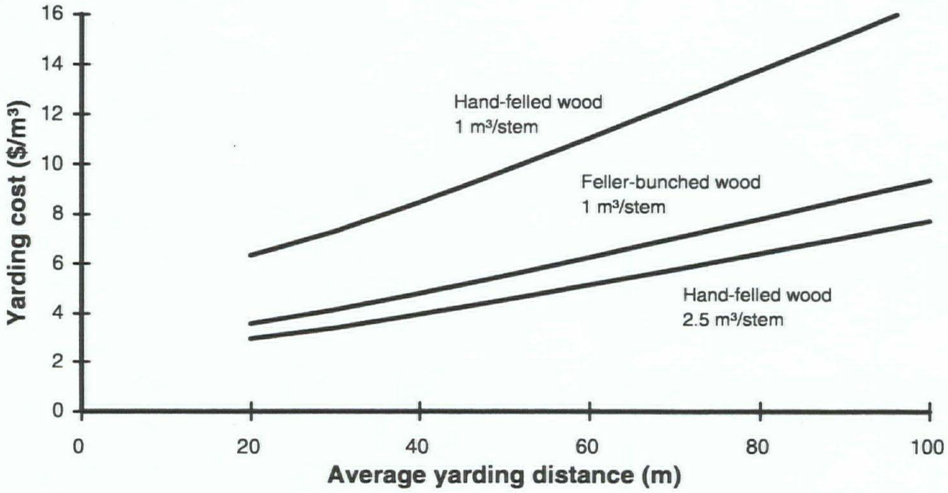

Figure 24. Projected costs of grapple yarding, as a function of average yarding distance.

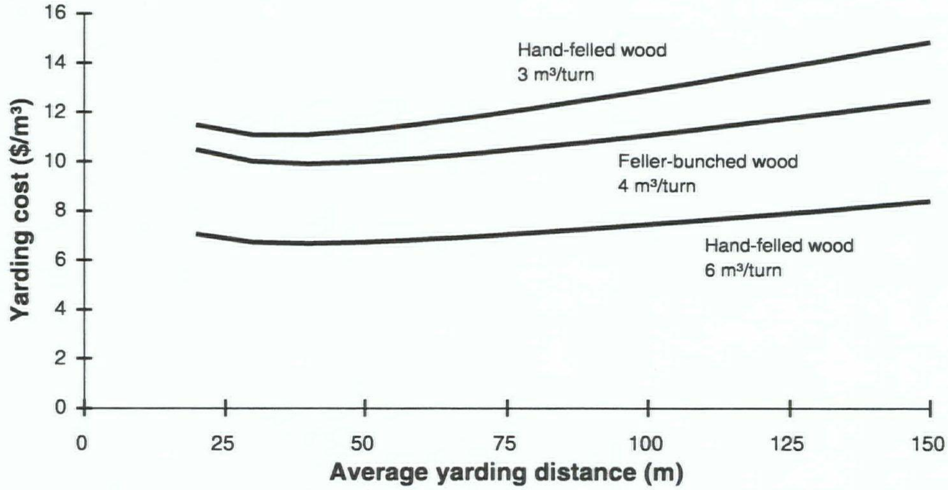

Figure 25. Projected costs of yarding with chokers, as a function of average yarding distance.

Total System Cost. FERIC compiled the total direct cost for ten different harvesting systems to produce manufactured logs at roadside (or landing) in coastal second-growth stands with an average tree size of 1.0 m^3, and at a 100-m average extraction distance (Figure 27). The summary shows that the cost of harvesting coastal second-growth forests can vary greatly (in this example from \$5.70 to \$16.72/m^3) depending on system selection, operating conditions, and harvesting criteria (e.g., sorts produced). As the impacts of differences in operating conditions and harvesting criteria on cost are not quantified, Figure 27 is not intended as a direct cost comparison of these harvesting systems.

Predicting Fibre Yield and Value

As the value of the logs produced from second-growth timber varies considerably with stem quality and size, predicting the volume by sorts (and therefore value) is necessary when conducting economic analyses of future timber harvesting operations. The B.C. Ministry of Forests has established standards for timber cruising and data compilation to determine stand volume and volume by statutory grades; however, the method has limitations for economic analyses. The current methodology cannot be used to determine the volume of specific company sorts, nor does it consider differences in stem breakage, level of fibre recovery, and value loss from sub-optimal bucking that may exist among harvesting systems. Therefore, FERIC developed a modified method of compiling cruise data which provides the information needed for pre-harvest economic analyses of coastal second-growth timber operations.[8] FERIC identified four components needed for this analysis:

[8] Andersson, B., Young, G., and Pavel, M. Design and validation of a decision support model for predicting net revenue of harvesting second-growth forests. FERIC, Vancouver. Report in progress.

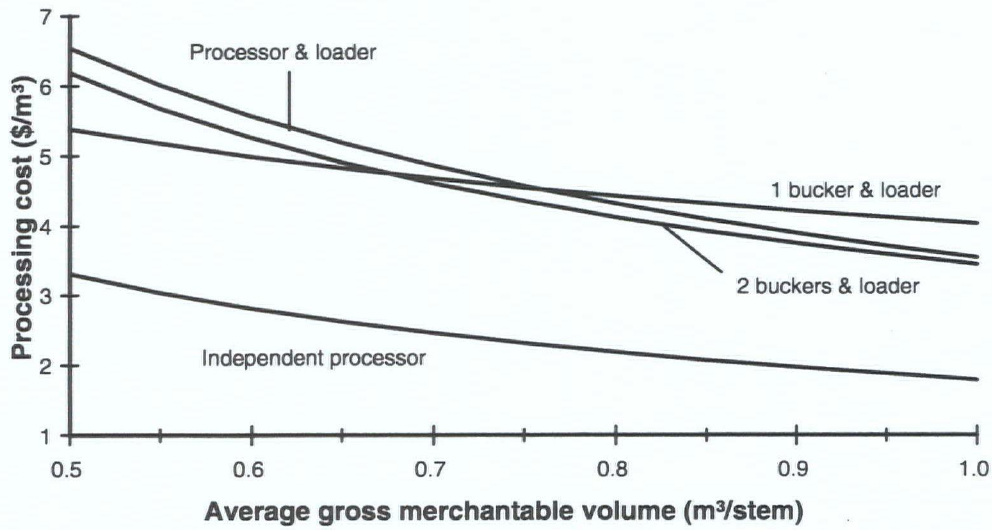

Figure 26. Projected costs of mechanical and manual processing, as a function of average stem volume.

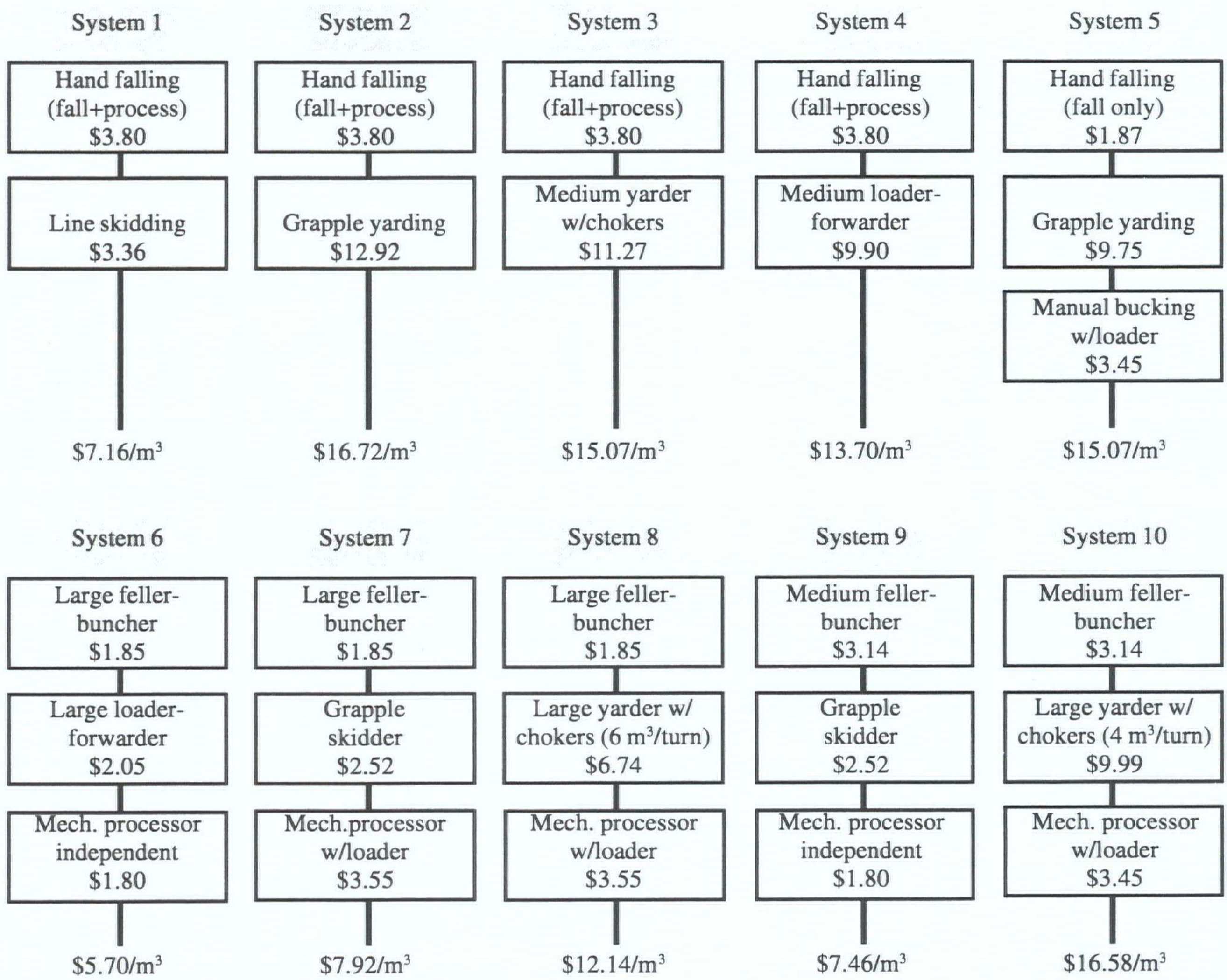

Figure 27. Examples of direct harvesting cost to produce manufactured logs at roadside or landings.

tree characteristics data that include exact location and extent of defects and knot sizes; specification (dimensions, allowed defects, and knots) and value of sorts; a bucking optimization model; and information on the ability of a harvesting system to produce and recover different log sorts.

Fibre Losses. On the eight sites where FERIC conducted post-harvest wood residue surveys, the amount of merchantable fibre, as defined in this study, ranged from 18 to 101 m^3/ha, or 2.2% to 7.8% of the cruised stand volume. On some of the sites the amount of fibre along roadside or near landings was considerable, suggesting that the recorded variation in residual fibre between sites may have depended not only on different harvesting techniques and stand conditions, but also on how well the sites were cleaned up during the log-loading phase. Thus, evaluating the fibre-recovery efficiency for different harvesting systems based on this data was not possible.

While the revenue from harvesting is affected to some degree by the amount of fibre recovered from the site, maximum fibre recovery does not necessarily result in maximum revenue. Sub-optimal bucking and stem breakage will reduce timber revenue even when all merchantable wood is recovered. Timber revenue may be equally, or more, influenced by the way the equipment is used than by the type of equipment used. Consequently, quantifying the effect of different harvesting techniques and machines on timber revenue in various stand and terrain conditions requires a substantial amount of data from controlled operations, and was beyond the scope of this project. The limited information on fibre yield and value recovery collected during this study is intended primarily to illustrate possible trends and important concepts of fibre/value recovery.

The opportunity to maximize revenue from harvesting is optimized when there is no operational damage to the merchantable stems or loss of merchantable fibre. Therefore, FERIC hypothesized that harvesting practices that result in higher frequencies of stem damage are more likely to yield lower timber revenue than techniques with low stem damage frequency. Figure 28 shows the stem breakage frequency by diameter classes for three harvesting operations: a feller-buncher/loader-forwarder operation, a hand faller/loader-forwarder operation, and a hand faller/grapple yarder operation. The predominate species in the loader-forwarder operations was Douglas-fir, while western hemlock and amabilis fir dominated the site in the grapple yarder operation.

FERIC found a lower occurrence of stem breakage in the feller-buncher/loader-forwarder operation, and that stem breakage generally occurred at a smaller stem diameter than for the other two operations. Most of the stem breakage in the feller-buncher/loader-forwarder operation occurred during the forwarding phase, while in the hand-falling operations it occurred during

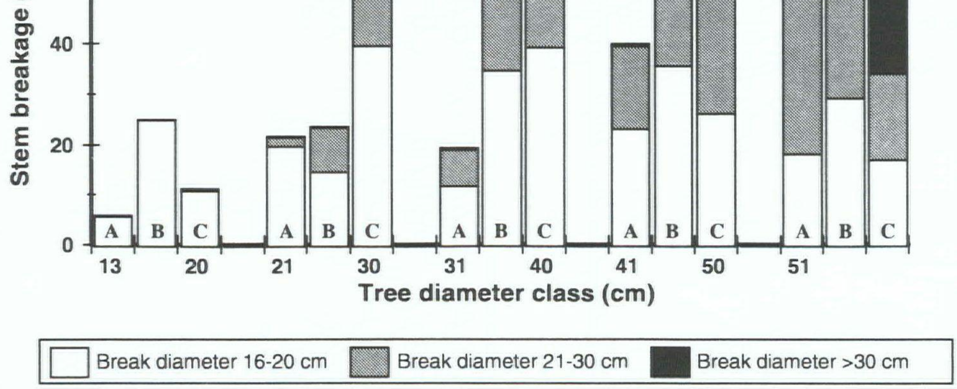

Figure 28. Frequency of stem breakage, by tree dbh class, for three second-growth harvesting operations.

falling. However, the differences were not in all cases statistically significant at the 95% level of confidence. Differences in species composition and terrain conditions may also have contributed to the differences.

The impact of breakage on timber revenue is potentially more severe on high value trees. However the full impact can only be determined with specific information on the characteristics of the stem, location of the break, and log specification and value.

POST-HARVEST SITE DISTURBANCE AND SOIL COMPACTION

Table 12 summarizes the results of the site-disturbance surveys conducted on eight sites harvested with three different systems. The survey did not differentiate between detrimental and non-detrimental disturbance. The site disturbance, as defined in this study, varied greatly among sites, even for sites harvested with the same harvesting system. Overall, the hand-felled and cable-yarded sites had the lowest site disturbance, while there was little difference among the sites harvested by the two ground-based systems. More data are needed to assess if any significant differences exist in the amount of site disturbance caused by different harvesting systems.

Table 13 summarizes the results of the soil compaction surveys conducted on seven of the eight sites surveyed[9] for site disturbance. The bulk density of disturbed soil was, on average, 8–19% higher than the bulk density of undisturbed soil, and in most cases, statistically significant at the 95% level of confidence. However, the soil bulk density readings varied within a short distance, due to natural variation in the soil structure (e.g., rocks and organic matter). As a result, differences (or lack of differences) in bulk density readings between paired disturbed and undisturbed sites may not be entirely the result of compaction (or lack of compaction) from harvesting activities. The study found no correlation between the depth of disturbance and the increase in total soil bulk density.

CONCLUSIONS AND RECOMMENDATIONS

A wide variety of harvesting equipment and systems, both mechanical and manual, has been used to harvest coastal second-growth stands. Information on the performance of these harvesting systems shows that both equipment productivity and wood costs vary greatly. Consequently, harvest planners must correctly match the harvesting system(s) to operating conditions and other criteria (e.g., log quality, site disturbance, and fibre recovery) to realize the best possible net revenue from harvesting coastal second-growth stands. Because of the complexity of such analyses, the process can be facilitated with the use of interactive computer-assisted decision models. However, appropriate prediction models can be developed only when sufficient data on an individual system's performance are available.

[9] The data of disturbed soil are more representative of the worst case scenario than of the average disturbance on the site.

Table 12. Summary of Post-Harvest Site Disturbance for Various Harvesting Systems

	Feller-bunched			Hand felled				
	Loader-forwarded			Loader-forwarded			Cable yarded	
Machine type	Site 1 (%)	Site 2 (%)	Site 3 (%)	Site 4 (%)	Site 5 (%)	Site 6 (%)	Site 7 [a] (%)	Site 8 (%)
Disturbance								
Organic layer >15-cm depth	1.7	1.7	4.2	10.5	9.8	8.9	10.1	0.0
Exposed mineral soil	5.6	19.5	33.8	8.9	16.5	17.8	9.6	7.7
Backspar trail	-	-	-	-	-	-	-	0.3
Total	7.3	21.2	38.0	19.4	26.3	26.7	19.7	8.0
Undisturbed	89.5	76.3	60.2	59.4	71.6	70.9	65.2	81.4
Slash covered	1.2	0.0	0.0	16.0	0.0	0.0	11.5	6.8
Others (stumps, rock, creek)	2.0	2.5	1.8	5.2	2.1	2.4	3.6	3.8
Total [b]	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[a] A hydraulic log loader was used to align the stem on the site prior to yarding.
[b] Excludes area covered by haul road (rehabilitated or not rehabilitated) and ditches.

Table 13. Bulk Density Assessment on Disturbed and Undisturbed Sites: Summary

	Feller-bunched			Hand felled			
	Loader-forwarded			Loader-forwarded			Cable yarded
Machine type	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7 [a]
Average bulk density, 0–10 cm depth							
Undisturbed site (g/cm^3)	1.25	1.30	1.18	0.71	1.15	1.18	0.70
Exposed mineral soil	1.37 [a]	1.52	1.28 [a]	0.82 [a]	1.33 [a]	1.28	0.77
Average bulk density, 0–20 cm depth							
Undisturbed site (g/cm^3)	1.33	1.44	1.26	0.74	1.19	1.20	0.73
Disturbed site (g/cm^3)	1.44 [a]	1.60	1.39 [a]	0.85 [a]	1.42 [a]	1.39 [a]	0.79
Average depth of disturbed plots (cm) [b]	-	18	25	-	18	20	-

[a] Bulk density of disturbed and undisturbed sites statistically different @ 95% level of confidence.

[b] The depth of depression was measured in relation to adjacent undisturbed area, and is more representative of the maximum depression than of the average depression of the disturbed sites.

This study provides an insight into coastal second-growth harvesting operations, although, in general, information on second-growth harvesting is still relatively limited. Most productivity data are for harvesting systems operating in relatively favourable terrain conditions, while information on quality of work (e.g., conditions created for subsequent harvesting phases, fibre losses, stem breakage, and site disturbance) is sparse. Thus, only a few factors with the potential to influence the performance of harvesting systems were evaluated. Consequently, the various predictive models presented in this report may not be representative of each harvesting system's performance in all types of coastal second-growth forests.

Tree size and forwarding (yarding) distance are two factors that often significantly influence the productivity and costs of individual phases. Equally important to overall harvesting costs are the conditions that individual harvesting phases create for the subsequent phases. For example, several FERIC studies showed that yarding productivity increases if wood is bunched. Thus, cost-effective harvesting operations of coastal second-growth forests require not only that the individual harvesting machines be suitable for their specific task, but also that they work well as a complete harvesting system.

Lack of data prevented FERIC from evaluating the impact of different harvesting systems on fibre and log-value recovery, soil disturbance, and soil compaction. Observations made during the project suggest that these results may be as dependent on how harvesting is done as with what it is done. Therefore, future fibre/value recovery and site impact studies must differentiate between causes attributed to different operating techniques, cutblock layout pattern, and equipment hardware. Such information would reduce the risk of selecting or eliminating harvesting systems based on wrong criteria.

The findings of this project are intended to assist harvest planners in selecting an appropriate harvesting system for a particular coastal second-growth stand. However, because the available information is limited to specific sites and operating conditions, harvest planners must exercise their own judgment when using this information for sites or operations different than those described. As more information on coastal second-growth harvesting operations become available it will be necessary to re-assess the findings and conclusions presented in this report.

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Appendix I

Summary of Statistical Analysis and Productivity Formulas [a]

Hand-Falling Operations

Falling cycle times (min/tree)

Fall-process: $FT = 1.772 + 1.016 \bullet [m^3/tree] - 0.075/[m^3/tree]$
$r^2 = 0.73$, *s.e.e.* $= 1.27$, $n = 329$ *trees*

Fall-selective buck: $FT = 0.690 + 1.07 \bullet [m^3/tree]$
$r^2 = 0.53$, *s.e.e.* $= 0.70$, $n = 180$ *trees*

Fall only: $FT = 0.904 + 0.444 \bullet [m^3/tree] - 0.015/[m^3/tree]$
$r^2 = 0.47$, *s.e.e.* $= 0.78$, $n = 506$ *trees*

Fuel/file time (%): FF = 12.4 % of FT

Minor delay (%): DEL = 7.3 % of FT

Shift length (h): SHIFT = 6.5 SMH @ 90% utilization

Productivity (m^3/shift) $P_{SHIFT} = (60/(FT + FF + DEL)) \bullet SHIFT \bullet [m^3/tree]$

Feller-Buncher Operations

Productivity (m^3/PMH)

Large machine $P_{PMH} = 118.80 + 252.96 \bullet \log[m^3/tree]$
$r^2 = 0.81$, *s.e.e.* $= 16.74$, $n = 11$ *studies*

Medium machine $P_{PMH} = 24.36 + 22.4 \bullet [m^3/tree]$

Minor delay (%): DEL is included in PMH

Shift length (h): SHIFT = 8.0 SMH @ 75% utilization

Productivity (m^3/shift) $P_{SHIFT} = P_{PMH} \bullet SHIFT$

Hand-Falling Operations of Oversized Trees (combined with medium feller-buncher operations)

Hand-felled volume (% of total) $V_{HAND} = -25.4 + 64 \bullet [m^3/tree]$

Productivity (m^3/shift): $P_{SHIFT} = 137.8 + 22 \bullet [m^3/tree]$

Loader-Forwarding Operations

Large machines in feller-bunched wood

Out-pass time (min/turn): $T_o = -2.45 + 0.216 \bullet [Distance, m]$
$r^2 = 0.73$, *s.e.e.* $= 5.76$, $n = 72$ *turns*

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[a] Square brackets [ ] indicate independent variables (predictors). r^2 = coefficient of determination. s.e.e. = standard error of estimate (for the equation). N = number of observations. **NOTE**: Equations with no r^2 value were not developed statistically, but are merely the best mathematical relationship based on very limited data.

In-pass time (min/turn):	$\log(T_I) = 0.2775 + 0.0047 \cdot [\text{Distance, m}] + 0.4890 \cdot \log[\text{Distance,m}]$ $r^2 = 0.89$, *s.e.e.* $= 0.170$, $n = 69$ *turns*
Total turn time (min):	$TT = T_O + T_I$
Minor delay (%):	DEL = 5.5 % of turn time
Wood forwarded to roadside	
Grapples with stems (no):	$G = 1.946 + 0.289 \cdot [\text{Distance, m}]$ $r^2 = 0.79$, *s.e.e.* $= 8.05$, $n = 14$ *studies*
Volume/grapple (m^3):	$\log(V_G) = 0.3180 + 0.1796 \cdot [m^3/\text{stem}]$ $r^2 = 0.53$, *s.e.e.* $= 0.076$, $n = 14$ *studies*
Volume/turn (m^3):	$V_{TURN} = G \cdot V_G$
Shift length (h):	SHIFT = 8.0 SMH @ 85% utilization
Productivity (m^3/shift):	$(60/(TT + DEL)) \cdot V_{TURN} \cdot SHIFT$

Medium machines in hand-felled wood

Productivity (logs/PMH)	$\log(P_{PMH}) = -2.0331 - 0.0083 \cdot [\text{Distance, m}]$ $r^2 = 0.52$, *s.e.e.* $= 0.146$, $n = 21$ *turns*
Minor delay (%):	DEL is included in PMH
Shift length (h):	SHIFT = 8.0 SMH @ 85% utilization
Productivity (m^3/shift):	$P_{SHIFT} = P_{PMH} \cdot SHIFT$

Rubber-Tired Skidding Operations

Travel time (min/turn):	$T_{TVL} = 0.46 + 0.0166 \cdot [\text{Distance, m}]$ $r^2 = 0.43$, *s.e.e. = n/a, n = n/a*
Fixed turn time (min/turn)	
Line skidders:	$T_F = 6.55$
Grapple skidders:	$T_F = 2.35$
Total turn time (min):	$TT = T_{TVL} + T_F$
Minor delay (%):	DEL = 5.0% of TT
Turn size (m^3)	
Line skidders:	$V_{TURN} = 4.9$
Grapple skidders:	$V_{TURN} = 3.7$
Shift length (h)	
Line skidders:	SHIFT = 8.0 SMH @ 85% utilization (single-shift operations)
Grapple skidders:	SHIFT = 8.0 SMH @ 80% utilization (double-shift operations)
Productivity (m^3/shift):	$P_{SHIFT} = (60/(TT+DEL)) \cdot SHIFT \cdot V_{TURN}$

Grapple Yarder Operations

Out/In-haul time (min/turn):	$T_{o+I} = 0.048 + 0.0080 \cdot$[Distance, m]
	$r^2 = 0.87$, s.e.e. = 0.084, n = 315 turns
Load time (min/turn):	$T_L = 0.038 + 0.0031 \cdot$[Distance, m]
	$r^2 = 0.05$, s.e.e. = 0.366, n= 315 turns
Fixed turn (min/turn):	$T_F = 0.069$
Total turn time (min):	$TT = T_{o+I} + T_L + T_F$
Minor delay (%):	DEL = 3.9% of TT
Move yarder (min/turn):	
Within corridor:	$M_{IN} = 0.18$
New corridor: [b]	$M_{NEW} = 20.50/(2.55 \cdot$[Distance, m])
Total (min/turn):	$M = Min + M_{NEW}$
Turn size (m^3)	$V_{TURN} = V_{HF}$ or V_{FB}
Hand-felled wood:	$V_{HF} = 0.330 + 1.024 \cdot (m^3/log)$
	$r^2 = 0.92$, s.e.e. = 0.325, n = 5 studies
Feller-bunched wood:	$\log(V_{FB}) = 0.3771 + 0.5847 \cdot \log(m^3/log)$
	$r^2 = 0.48$, s.e.e. = 0.129, n = 7 studies
Shift length (h):	SHIFT = 8.0 SMH @ 75% utilization
Productivity (m^3/shift):	$(60/(TT + M + DEL)) \cdot V_{TURN} \cdot SHIFT$

Yarding Operations with Chokers

Large yarder in feller-bunched wood

Out/In-haul time (min/turn):	$T_{o+I} = 0.20 + 0.00818 \cdot$[Distance, m] $+ 0.0293 \cdot [m^3/turn]$
	$r^2 = 0.64$, s.e.e. = n/a, n = 207 turns
Fixed turn time (min/turn):	$T_F = 2.93$
Total turn time (min):	$TT = T_{o+I} + T_F$
Minor delay (%):	DEL = 4.7% of TT
Move yarder (min/turn): [c]	$M = 24.70/(0.26 \cdot$[Distance, m])
Turn size (m^3):	V_{TURN} = Variable
Shift length (h):	SHIFT = 8.0 SMH @ 80% utilization
Productivity (m^3/shift):	$(60/(TT + DEL + M)) \cdot V_{TURN} \cdot SHIFT$

[b] FERIC assumes 225 yarding turns per 100-m length of yarding corridor.

[c] FERIC assumes 26 yarding turns per 100-m length of yarding corridor.

Medium yarder in hand-felled wood

Out/In-haul time (min/turn):	$T_{o+I} = 0.310 + 0.0106 \bullet$[Distance, m] $r^2 = 0.42$, *s.e.e.* $= 0.644$, $n = 414$ *turns*
Hook-up time (min/turn):	$T_L = 1.593 + 1.240 \bullet \log$[No. of pieces] $r^2 = 0.09$, *s.e.e.* $= 0.703$, $n = 414$ *turns*
Unhook time (min/turn):	TU = 0.326 + 0.107•[No. of pieces] $r^2 = 0.13$, *s.e.e.* $= 0.318$, $n = 383$
Fixed time (min/turn):	$T_F = 0.021$
Total turn time (min):	$TT = T_{o+I} + T_L + T_U + T_F$
Minor delay (%):	DEL = 4.2% of TT
Move yarder (min/turn): [d]	M = 24.70/(0.47•[Distance, m])
Turn size (m^3):	$V_{TURN} = 3.0$
Shift length (h):	SHIFT = 8.0 SMH @ 80% utilization
Productivity (m^3/shift):	$(60/(TT + M + DEL)) \bullet V_{TURN} \bullet SHIFT$

Roadside or Landing Processing Operations
Mechanized operations

Productivity (m^3/PMH):	$P_{PMH} = 118.80 + 252.96 \bullet \log[m^3/\text{tree}]$ $r^2 = 0.55$, *s.e.e.* $= 0.82$, $n = 12$ *studies*
Minor delay (%):	DEL in included in PMH
Shift length (h) (single-shift operation) (double-shift operation)	Integrated operations: SHIFT = 8.0 SMH @ 70% utilization Independent operations: SHIFT = 8.0 SMH @ 80% utilization
Productivity (m^3/shift):	$P_{SHIFT} = P_{PMH} \bullet SHIFT$

Hand-bucking operations with loader

Productivity (m^3/shift)	1 bucker: $P_{SHIFT} = 38.7 + 116.7 \bullet [m^3/\text{stem}]$ 2 buckers: $P_{SHIFT} = -4.3 + 266.7 \bullet [m^3/\text{stem}]$
Loader requirement (h):	$TIME = 8.0 \bullet (14.7 + 26.7 \bullet [m^3/\text{stem}])/100$

[d] FERIC assumes 225 yarding turns per 100-m length of yarding corridor.

Appendix II

Calculation of Machine Charge-Out Rates

	Feller-bunchers		Feller-	Loader-forwarders		Ground skidders	
	Large	Medium	processors	Large	Medium	Grapple	Line
Machine input variables							
Purchase price (P) ($)	750 000	500 000	600 000	510 000	400 000	250 000	200 000
Salvage value (% of P)	20	20	20	20	20	20	20
Depreciation period (y)	5	5	5	5	5	5	5
Operating days/year (no.)	180	180	180	180	180	180	180
Shifts/day (no.)	2	2	2	2	2	2	1
Scheduled hours/shift (SMH)	8	8	8	8	8	8	8
Machine utilization (%)	75	75	70	85	80	80	85
Productive (PMH) h/y	2 160	2 160	2 016	2 448	2 304	2 304	1 224
Average investment ($/y)	450 000	300 000	360 000	306 000	240 000	150 000	120 000
Interest on investment (%)	9	9	9	9	9	9	9
Insurance rate (%)	3	3	3	3	3	3	3
Fuel consumption (F) (L/PMH)	40	28	28	43	21	19	13
Fuel cost ($/L)	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Oil consumption (% of F)	6	6	6	4	4	4	4
Oil cost ($/L)	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Lifetime repair cost (% of P) [a]	103	103	120	110	110	215	90
Number of operators (no.)	1	1	1	1	1	1	1
Operator wage ($/SMH)	24.04	24.04	24.04	24.04	24.04	21.74	21.34
Fringe benefits (% of wage)	35	35	35	35	35	35	35
Machine operating cost							
Depreciation ($/PMH)	55.56	37.04	47.62	33.33	27.78	17.36	26.14
Interest ($/PMH)	18.75	12.50	16.07	11.25	9.38	5.86	8.82
Insurance ($/PMH)	6.25	4.17	5.36	3.75	3.13	1.95	2.94
Repair/maintenance ($/PMH)	71.53	47.69	71.43	45.83	38.19	46.66	29.41
Fuel ($/PMH)	18.00	12.60	12.60	19.35	9.45	8.55	5.85
Lubrication ($/PMH)	6.00	4.20	4.20	4.30	2.10	1.90	1.30
Direct labour ($/PMH)	32.05	32.05	34.34	28.28	30.05	27.18	25.11
Indirect labour ($/PMH)	11.22	11.22	12.02	9.90	10.52	9.51	8.79
Charge-out rate ($/PMH)	219.36	161.46	203.64	156.00	130.59	118.97	108.36
Operating cost/shift ($) [b]	1 316	969	1 140	1 061	836	761	737

[a] Repair costs of ground-based machines based on Williams 1989.
[b] Rounded to the nearest dollar.

Appendix II

Calculation of Machine Charge-Out Rates

	Super snorkels	Grapple yarders	Choker yarders Large	Choker yarders Medium	Back-spars	Processors	Log loaders
Machine input variables							
Purchase price (P) ($)	950 000	1 200 000	800 000	600 000	150 000	550 000	500 000
Salvage value (% of P)	20	20	20	20	20	20	20
Depreciation period (y)	5	10	10	10	5	5	7
Operating days/year (no.)	180	180	180	180	180	180	180
Shifts/day (no.)	2	1	1	1	1	2	1
Scheduled hours/shift (SMH)	8	8	8	8	8	8	8
Machine utilization (%)	85	75	80	80	90	80	90
Productive (PMH) h/y	2 448	1 080	1 152	1 152	1 296	2 304	1 296
Average investment ($/y)	570 000	720 000	480 000	360 000	90 000	330 000	300 000
Interest on investment (%)	9	9	9	9	9	9	9
Insurance rate (%)	3	3	3	3	3	3	3
Fuel consumption (F) (L/PMH)	35	63	45	23	5	25	27
Fuel cost ($/L)	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Oil consumption (% of F)	4	4	4	4	4	5	5
Oil cost ($/L)	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Lifetime repair cost (% of P)	100	100	100	100	80	130	90
Number of operators (no.)	1	3	5	4	0	1	1
Operator wage ($/SMH)	24.69	22.84	21.74	22.08	0	24.04	24.04
Fringe benefits (% of wage)	35	35	35	35	35	35	35
Machine operating cost							
Depreciation ($/PMH)	62.09	88.89	55.56	41.67	18.52	38.19	44.09
Interest ($/PMH)	20.96	60.00	37.50	28.13	6.25	12.89	20.83
Insurance ($/PMH)	6.99	20.00	12.50	9.38	2.08	4.30	6.94
Repair/maintenance ($/PMH)	77.61	111.11	69.44	52.08	18.52	62.07	49.60
Fuel ($/PMH)	15.75	28.35	20.25	10.35	2.25	11.25	12.15
Lubrication ($/PMH)	3.50	6.30	4.50	2.30	0.50	3.13	3.38
Direct labour ($/PMH)	29.05	91.36	135.88	110.40	0	30.05	26.71
Indirect labour ($/PMH)	10.17	31.98	47.56	38.64	0	10.52	9.35
Charge-out rate ($/PMH)	226.11	437.99	383.18	292.94	48.12	172.39	173.06
Operating cost/shift ($) [a]	1 538	2 628	2 452	1 875	346	1 103	1 246

[a] Rounded to the nearest dollar.

Appendix III

Definitions

Operating Conditions

Stand volume	The gross merchantable volume of the stand, determined from operational cruises or loaded-out volume information, and rounded to the nearest 10 m^3/ha. Information presented is usually the average stand volume for the entire cutblock, even when data on harvesting productivity were collected only in a portion of the cutblock.
Tree volume	The gross merchantable volume of standing trees, determined from operational cruises, loaded-out volume information, or sampled trees; rounded to the nearest 0.1 m^3/tree.
Stem volume	The gross merchantable volume of felled trees (stems), determined from operational cruises, loaded-out volume information, or sampled stems; rounded to the nearest 0.1 m^3/stem. Information presented here may include a small portion of broken stem pieces, or manufactured logs.
Log volume	The gross merchantable volume of felled and bucked trees (logs), determined from loaded-out volume information or sampled logs; rounded to the nearest 0.1 m^3/log. A portion of the logs may be broken stem pieces.
Slope	The average ground slope of the entire cutblock, or of the actual study where data on harvesting productivity were collected only in a portion of the cutblock. The slope is expressed to the nearest 5%.
Distance	The average of the external (maximum) skidding or yarding distance of all turns; rounded to the nearest 10 m.

Machine Performance

SMH	Scheduled machine hours (SMH) is the length of time, in hours, during which the machine (or worker) is scheduled to work.
PMH	Productive machine hours (PMH) is the portion of the scheduled shift length, in hours, during which the machine (or worker) does productive work. However, PMH may in some studies include an unknown portion of non-productive activities that could not be separated from actual productive time, as well as minor delays <15 min/occurrence.
MU	Machine utilization (MU) is that portion of the scheduled shift during which the machine performed productive work, expressed as a percentage of scheduled shift length, i.e., PMH/SMH•100%.
m^3/PMH	Average productivity of machine (or worker) expressed in volume of wood produced per productive machine hour (PMH). However, the productivity data may lack consistency as the data were obtained from several studies in which different volume estimates and definitions of a productive hour may have been used.
m^3/shift	Average productivity of machine (or worker) expressed in volume of wood produced per shift, with a shift of 6.5 SMH for hand falling operations, and 8.0 SMH for all other operations.

Study types

sl	Shift-level study, a study technique using Servis Recorders or daily shift reports to monitor machine and worker activities.
dt	Detailed-timing study, a study technique where machine (worker) activities are visually monitored and timed using a stopwatch or a data logger.

Appendix IV

Summary of Unpublished Equipment Studies

Table IV-1 summarizes the results of two detailed-timing studies conducted in second-growth stands on the Sunshine Coast near Powell River. The Valmet 500T harvester felled and processed trees in an 80-year-old Douglas-fir stand. The manufactured logs ranged in length from 3.5 to 13.4 m. Many of the trees with a dbh of 40 cm or more were not felled because the harvester had difficulty processing them.

The Keto 1000/Timbco operated as a processor in an integrated (hot log) system together with a Madill 122 yarder rigged as a standing skyline and hydraulic log loader on a small landing. The processor worked both between and behind the two machines. The small landing caused traffic congestion while trucks were being loaded, and caused the processor to sit idle while the loading was done.

Table IV-2 summarizes the results of detailed-timing studies of a Madill 123 grapple yarder operating in a 60-year-old stand of Douglas-fir, western hemlock, and western red cedar. The trees had been hand felled and manufactured into logs with an average size of 0.7 m^3.

Table IV-3 summarizes the result of detailed-timing studies of two John Deere 690 hydraulic log loaders used as loader-forwarders in the same cutblock as the Madill 123 yarder. The loader-forwarders worked on the flatter parts of the cutblock.

Table IV-1. Summary of Detailed-Timing Studies: Harvesters and Processors

	Valmet 500T harvester	Keto 1000/Timbco processor
Observed time (h)	5.8	7.0
Average stem volume (m^3)	0.51	0.58
Distribution of machine time		
Grab tree (min/tree)	0.16	0.20
Fell tree (min/tree)	0.13	-
Process (min/tree)	0.32	0.42
Move machine (min/tree)	0.16	0.05
Other work (min/tree)	0.22	0.14
Minor delays (min/tree)	0.04	0.18
Total productive time (min/tree)	1.03	0.99
Major delays (min/tree)	0.10	0.54
Machine productivity		
Stems (no./PMH)	58	61
Volume (m^3/PMH)	29.8	35.3
Average logs/tree (no.)	2.1	1.4
Machine utilization (%)	91	65

Table IV-2. Summary of Detailed-Timing Studies: Madill 123 Grapple Yarder

	Studies 1	2	3	All
Observed time (h)	3.0	2.4	3.3	8.7
Average operating conditions				
Piece size (m^3)	-	-	-	0.7
Yarding distance (m)	80	100	130	110
Slope (%)	20	20	35	30
Distribution of machine time				
Out-haul (min/turn)	0.41	0.44	0.48	0.45
Load (min/turn)	0.24	0.36	0.32	0.30
In-haul (min/turn)	0.33	0.38	0.40	0.37
Deck (min/turn)	0.16	0.26	0.12	0.16
Other work (min/turn)	0.17	0.00	0.00	0.06
Move back spar (min/turn)	0.24	0.15	0.07	0.14
Move yarder (min/turn)	0.00	0.70	0.00	0.15
Minor delay (min/turn)	0.22	0.04	0.12	0.14
Total productive time (min/turn)	1.77	2.33	1.51	1.77
Major delay (min/turn)	-	-	-	-
Turn size (no. of logs)	1.18	1.33	1.30	1.27
Machine productivity				
Logs (no./PMH)	40.2	34.1	51.7	42.9
Volume (m^3/PMH)	-	-	-	-

Table IV-3. Summary of Detailed-Timing Studies: John Deere 690 Loader-Forwarders

	Studies				
	1	2	3	4	All
Observed time (h)	4.6	1.3	1.4	2.8	10.0
Average operating conditions					
Piece size	-	-	-	-	0.7
External distance (m)	55	40	35	30	40
Slope (%)	5	5	10	15	10
Distribution of machine time					
Move out (min/turn)	4.25	2.16	1.86	1.19	1.96
Move in (min/turn)	4.08	1.60	1.44	0.88	1.60
Prepare path (min/turn)	0.14	-	0.91	0.95	0.68
Forward logs (min/turn)	48.25	19.40	8.63	13.54	17.93
Other work (min/turn)	1.62	1.66	0.70	1.22	1.19
Minor delay (min/turn)	1.21	0.40	0.49	0.61	0.63
Total productive time (min/turn)	59.55	25.22	14.03	18.39	23.99
Major delay (min/turn)	32.42	-	-	-	4.63
Turn size					
Logs (no.)	24.0	16.3	14.2	16.6	16.9
Volume (m^3)	-	-	-	-	11.8
Machine productivity					
Logs (no./PMH)	24.2	38.8	60.7	54.2	42.3
Volume (m^3/PMH)	-	-	-	-	29.6

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