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HARVESTING LOW-VOLUME PINE STANDS IN THE WILLIAMS LAKE TIMBER SUPPLY AREA, BRITISH COLUMBIA

Björn Andersson, M.Sc.FE, P.Eng.

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Technical Report

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Abstract

In the early 1980s, forest companies in the Williams Lake Timber Supply Area in the Interior of British Columbia began to harvest low-volume lodgepole pine stands previously considered as unmerchantable. What began as a salvage operation of insect-infested stands is now an important source of wood fibre for several forest companies in the area. However, information on productivity and costs is limited, thus making it difficult to determine the economics of harvesting these stands. The objectives of a study initiated by the Forest Engineering Research Institute of Canada (FERIC) in 1988 were to provide forest companies with cost and productivity data associated with mechanical harvesting of low-volume pine stands.

The study examines the performance of feller-bunchers, grapple skidders, and roadside processors in two operations west of Williams Lake. Productivities and costs are presented for a variety of stand conditions typical for the low-volume lodgepole pine stands in the area. Operating factors influencing machine performance, and simple models for predicting productivity are also presented.

Author

Björn Andersson obtained B.Sc.FE (1973) and M.Sc.FE (1989) degrees from University of New Brunswick. He worked for Eddy Forest Products Ltd. from 1973 to 1974 as a harvesting supervisor, and for Great Lakes Forest Products Ltd. from 1975 to 1981 as a harvesting supervisor and as a project engineer. He also spent three years in Sweden operating a private woodlot. Björn joined FERIC in 1988 as a researcher in the Harvesting Operations Group. He is a Registered Professional Engineer in British Columbia.

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Table of Contents

List of Tables

List of Figures

Summary

In the fall and winter of 1988/89, the Forest Engineering Research Institute of Canada (FERIC) studied the performances of feller-bunchers, grapple skidders, and roadside processors in two harvesting operations (A and B) in the Williams Lake Timber Supply Area in the Interior of British Columbia. During the study, the two operations harvested six cutblocks of low-volume, insect-infested, lodgepole pine stands. The average gross volume of these cutblocks ranged between 92 and 165 m^3/ha.

The objectives of the study were to determine machine productivity levels, identify operating factors affecting machine performance, estimate harvesting costs, and develop simple prediction models for felling, skidding, and roadside processing operations in low-volume lodgepole pine stands in the Williams Lake TSA.

Felling was done by four different feller-bunchers: Case 1187B/Rotosaw 2100, John Deere 693D/Rotosaw 1800, John Deere 693C/Harricana CS5000, and John Deere 693C/Bradeco. Their short-term productivities ranged between 116 and 228 trees/PMH (25.5 and 44.5 m^3/PMH). However, these productivities include those stems that were lost, broken, or discarded in the subsequent skidding and processing operations; hence, the "realized production" of the feller-bunchers was less than recorded in the short-term studies. The long-term productivity (based on delivered volume and total operating time) for the Case/Rotosaw feller-buncher was found to range between 19.1 and 26.6 m^3/OMH.

The differences in the short-term productivities of the feller-bunchers were related to the tree-severing speed of their respective saw heads, and/or to the average number of trees being accumulated in the felling heads (trees/cycle) prior to bunching. The productivity was found to be affected by the number of merchantable trees per hectare and by the ratio of unmerchantable-to-merchantable trees in the stand. The performance of the Harricana-equipped feller-buncher was found to be more sensitive to the stand conditions than the other feller-bunchers.

Stems were skidded to roadside with John Deere 648D grapple skidders. Two of the skidders had extended grapple tongs, and were able to take bigger loads per turn than the skidders with standard grapples. The short-term skidder productivity ranged between 202 and 348 stems/PMH (44.4 and 66.1 m^3/PMH). However, the realized skidder production was lower due to volume losses that occurred during the subsequent processing phase. The long-term productivity of the grapple skidder in Operation A was found to range between 34.4 and 44.6 m^3/OMH.

Differences in the average skidding distances and the number of bunches loaded per turn were the main reasons for variations in the short-term skidder productivity. Variations in the number of bunches loaded per turn could not be correlated to either the original stand or the felled conditions. Differences in grapple sizes, skidding distances, and operators' work habits likely influenced the number of bunches per load.

In four of the six test blocks (Operation A), the stems at roadside were processed into 5.2-m and 7.6-m logs by a Case 1187B/Denis stroke delimber-slasher. The short-term productivity ranged between 59 and 149 stems/PMH (net 12.2-24.6 m^3/PMH). The low end of this range was recorded with inexperienced machine operators who had been hired only days prior to the start of the study. Long-term productivity was not established for the Denis delimber-slasher.

Operator skill and stem size were the main reasons for the variation in the productivity of the Denis stroke delimber-slasher. The number of stems processed per hour decreased as the average stem size increased. This occurred because small stems were more often processed in multiples and yielded, on the average, fewer logs per stem than did large stems.

In two of the test blocks (Operation B), the stems at roadside were processed into five different log lengths (between 3.8 and 6.2 m) by Steyr KP40 processors mounted on excavator carriers. The short-term productivity of the processors ranged between 119 and 227 stems/PMH (net 24.2-38.0 m^3/PMH). Productivity was influenced by operator experience, stem size, number of logs manufactured per stem, and stem quality (frequency of long-butting). Stem quality did not significantly affect the number of stems processed per hour, but had a major adverse impact on the machines' net production (logs/h and net volume/h). Long-term productivity was not established for the Steyr processors.

The study recorded little difference in the ability of the Denis and the Steyr KP40 to accurately measure the length of logs. For the Denis and Steyr KP40 respectively, 34% and 39% of the logs were within 2 cm of the target lengths, and 85% and 92% were within 10 cm of the target lengths.

The estimated overall productivity of the harvesting systems, including road construction, felling, skidding, processing, cutover clearing, and debris piling, ranged between 44 and 60 m^3/man-day. The total system cost was found to be in the magnitude of \$10-15/m^3. Cost and productivity were found to be adversely affected by small tree size and high losses of merchantable fi-

bre, especially when the losses occurred in the processing phase.

The wood cost was also shown to be affected by the operational utilization of individual machines, and by the ratio of the machines' production capacity to the operation's annual production quota. Under-utilizing machines, for either reason, increases the cost per m^3.

Sommaire

Au cours de l'automne et de l'hiver 1988-89, l'Institut canadien de recherches en génie forestier (FERIC) étudia les performances d'abatteuses-groupeuses, de débardeurs à grappin et de façonneuses en bordure de route dans deux exploitations (A et B) situées dans l'aire d'approvisionnement forestier (TSA) de Williams Lake en Colombie-Britannique intérieure. Durant l'étude, la récolte fut effectuée dans six blocs de coupe contenant des peuplements de pin lodgepole de faible volume, infestés d'insectes. Le volume brut moyen de ces blocs de coupe variait entre 92 et 165 m^3/ha.

L'étude avait pour objectifs d'établir les niveaux de productivité des machines, de déterminer les facteurs opérationnels qui en affectent la performance, d'estimer les coûts d'exploitation et de développer des modèles simples de prévision pour les opérations d'abattage, de débardage et de façonnage en bordure de route dans les peuplements de pin lodgepole de faible volume situés dans l'aire d'approvisionnement de Williams Lake.

Quatre abatteuses-groupeuses différentes procédaient à l'abattage: Case 1187B/Rotosaw 2100, John Deere 693D/Rotosaw 1800, John Deere 693C/Harricana CS5000 et John Deere 693C/Bradeco. Les productivités à court terme variaient entre 116 et 228 arbres/HMP (25,5 et 44,5 m^3/HMP). Cependant, ces productivités tiennent compte des tiges qui étaient perdues, brisées ou mises de côté au cours des phases subséquentes de débardage et de façonnage; par conséquent, la production réelle des abatteuses-groupeuses était inférieure à celle enregistrée durant les études de courte durée. La productivité à long terme (basée sur le volume de bois livré et sur le temps total de fonctionnement) de l'abatteuse-groupeuse Case/Rotosaw se situait entre 19,1 et 26,6 m^3/HMF.

Les différences dans les productivités à court terme des abatteuses-groupeuses étaient liées à la vitesse avec laquelle chacune des têtes à scie sectionnait les arbres et au nombre moyen d'arbres conservés dans la tête d'abattage (arbres/cycle) avant le groupage. La productivité était affectée par le nombre d'arbres marchands par hectare et par le ratio d'arbres non marchands par rapport aux arbres marchands dans le peuplement. La performance de l'abatteuse-groupeuse équipée d'une tête Harricana se révéla plus sensible aux conditions du peuplement que celle des autres abatteuses-groupeuses.

Les arbres étaient débardés en bordure de route au moyen de débardeurs à grappin John Deere 648D. Deux des débardeurs étaient dotés d'un grappin à dents allongées; ils étaient donc capables de prendre de plus grosses charges par voyage que les débardeurs à grappin standard. La productivité à court terme des débardeurs variait entre 202 et 348 arbres/HMP (44,4 et 66,1 m^3/HMP). Cependant, la production réelle des débardeurs était plus faible, étant donné les pertes de volume subies durant la phase subséquente de façonnage. La productivité à long terme du débardeur à grappin dans l'exploitation A variait entre 34,4 et 44,6 m^3/HMF.

Les différences dans la distance moyenne de débardage et le nombre de piles chargées par voyage étaient les principales raisons qui expliquaient les variations dans la productivité à court terme des débardeurs. Les variations dans le nombre de piles par voyage ne pouvaient être mises en corrélation ni avec le peuplement d'origine ni avec les conditions d'abattage. Les différences dans les dimensions des grappins, la distance de débardage et les habitudes de travail des opérateurs influençaient sans doute le nombre de piles par charge.

Dans quatre des six blocs d'essai (exploitation A), les tiges en bordure de route étaient façonnées en billes de 5,2 m et de 7,6 m au moyen d'une ébrancheuse-tronçonneuse à flèche Case 1187B/Denis. La productivité à court terme variait entre 59 et 149 arbres/HMP (volume net de 12,2 et 24,6 m^3/HMP). Les productivités les plus basses furent enregistrées avec des opérateurs inexpérimentés qui avaient été engagés quelques jours seulement avant le début de l'étude. La productivité à long terme de l'ébrancheuse-tronçonneuse Denis ne fut pas établie.

L'habileté de l'opérateur et les dimensions des tiges étaient les principales raisons de la variation dans la productivité de l'ébrancheuse-tronçonneuse Denis. Le nombre de tiges façonnées par heure diminuait à mesure que leurs dimensions moyennes augmentaient. En effet, les petites tiges étaient plus souvent façonnées plusieurs à la fois et produisaient, en moyenne, moins de billes par tige que les plus grosses.

Dans deux des blocs d'essai (exploitation B), les tiges en bordure de route étaient façonnées en cinq longueurs de billes différentes (entre 3,8 et 6,2 mètres) par des façonneuses Steyr KP40 montées sur des châssis d'excavatrices. La productivité à court terme des

façonneuses variait entre 119 et 227 tiges/HMP (volume net de 24,2 et 38,0 m^3/HMP). La productivité était influencée par l'expérience de l'opérateur, les dimensions des arbres, le nombre de billes par tige et la qualité des tiges (nécessité plus ou moins fréquente d'enlever une section de la bille de pied). La qualité des tiges n'affectait pas de façon significative le nombre d'arbres façonnés par heure, mais elle avait un important effet négatif sur la production nette des machines (billes/h et volume net/h). La productivité à long terme des façonneuses Steyr ne fut pas établie.

L'étude enregistra peu de différence dans la capacité des façonneuses Denis et Steyr KP40 à mesurer avec précision la longueur des billes. Avec la Denis et la Steyr KP40 respectivement, 34 % et 39 % des billes obtenues étaient à moins de 2 cm des longueurs désirées, alors que 85 % et 92 % en étaient à moins de 10 cm.

La productivité estimée pour l'ensemble des systèmes d'exploitation, y compris la construction des routes, l'abattage, le débardage, le façonnage, le nettoyage de la coupe et l'empilage des résidus variait entre 44 et 60 m^3/jour-personne. Le coût total du système était de l'ordre de 10 à 15 \$/m^3. Le coût et la productivité se révélèrent affectés négativement par les arbres de faibles dimensions et par les pertes élevées de fibre marchande, particulièrement quand ces pertes se produisaient durant la phase de façonnage.

Le coût du bois se montra aussi affecté par le taux d'utilisation des machines individuelles, ainsi que par le ratio de la capacité de production des machines par rapport au volume annuel total de production. Une sous-utilisation des machines, pour l'une ou l'autre de ces raisons, augmente le coût par m^3.

INTRODUCTION

Since the early 1980s, forest companies in the Williams Lake Timber Supply Area (TSA) in the Interior of British Columbia have been harvesting insect-infested, low-volume, lodgepole pine (*Pinus contorta* Dougl.) stands. Harvesting has proceeded under Emergency Forest Licences for the purpose of controlling the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) population and salvaging the damaged stands. As the beetle population is now under control and the Emergency Forest Licences will soon expire, the forest companies are looking for replacement wood to supplement their current normal Allowable Annual Cut. The only large source of uncommitted timber consists of other low-volume lodgepole pine stands, previously considered unmerchantable, and locally known as marginal pine stands.

In 1987, the Forest Engineering Research Institute of Canada (FERIC) was asked by its member companies in the Williams Lake area to determine the cost of harvesting low-volume pine stands. In FERIC's initial marginal pine study, Peterson and Giles (1988) surveyed the potential fibre resources of these stands and interviewed forest company staff and timber-harvesting contractors. Respondents felt that operating in low-volume pine stands increased harvesting costs and lowered equipment productivities. Although the industry provided average cost and productivity figures, little information was available on how variations in stand conditions affect the cost and productivity of harvesting. Peterson and Giles recommended that detailed harvesting studies be undertaken to provide information for developing a stand-by-stand strategy for harvesting low-volume pine stands.

In 1988/89 FERIC undertook further studies on two mechanized harvesting operations in the low-volume pine stands in the Williams Lake TSA to provide information to the forest industry in that region (Figure 1).

BACKGROUND

Objectives and Methodology

The objectives of this study were to determine machine productivity levels, identify operating factors affecting machine performance, estimate harvesting costs, and develop simple prediction models for felling, skidding, and roadside processing operations in low-volume lodgepole pine stands in the Williams Lake TSA. Field data were obtained through shift-level reports and detailed-timing studies of feller-bunchers, grapple skidders, and roadside processors operating at two different harvesting operations in the Williams Lake TSA. The relationships between machine performance and the operating conditions were determined through simple and multiple regression analyses using the detailed-timing data (definitions in Appendix I).

Harvesting costs for each test block were calculated using the average stand data from the company cruise summaries, the productivity prediction models, and the machine rental rates estimated using the standard FERIC machine costing format (Appendix II).

Description of Study Sites and Harvesting Operations

Field studies were carried out in low-volume lodgepole pine stands in six separate cutblocks identified as Blocks A:1 to A:4, and B:1 and B:2. Average stand characteristics of the cutblocks are presented in Table 1.

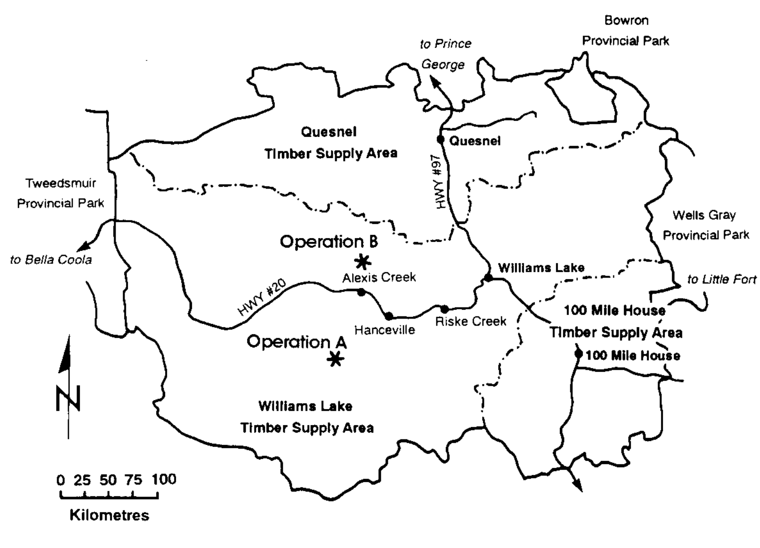

Figure 1. Locations of study areas.

Terrain conditions were generally uniform and favourable in all blocks. The ground was typically flat, firm, and free from obstacles (Figure 2). Some areas in Block B:2, however, had slopes up to 30% and/or had slightly uneven ground.

In Operation A (Blocks A:1 to A:4), the trees were felled by a Case 1187B/Rotosaw 2100 feller-buncher and skidded to roadside with a John Deere 648D grapple skidder. At roadside, a Case 1187B/Denis stroke delimber-slasher (Figure 3) processed the stems into logs 5.2-m and 7.6-m long and sorted them by length. All major defects were removed during processing, while cat faces and minor butt rot were normally not removed.

The harvesting equipment in Operation B (Blocks B:1 and B:2) varied throughout the study period, but the core equipment consisted of three feller-bunchers (a John Deere 693D/Rotosaw 1800, a John Deere 693C/Harricana CS5000, and a John Deere 693C/Bradeco); three John Deere 648D grapple skidders, two of which had their grapple tongs extended for accumulating larger payloads; and three Steyr KP40 processors mounted on different carriers, including a Caterpillar 225, Caterpillar EL 180, and Linkbelt L-2800 (Figure 4).

Figure 3. Case 1187B/Denis stroke delimber-slasher.

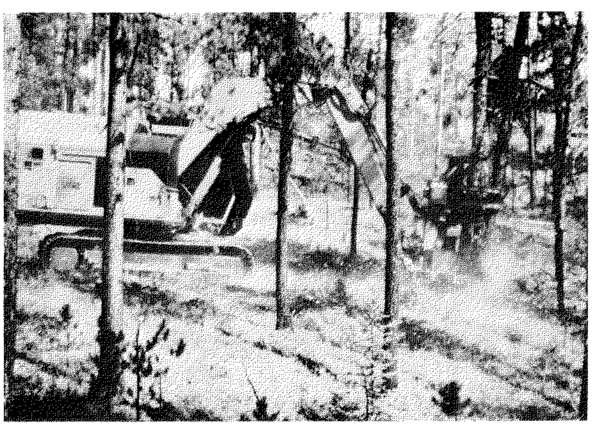

Figure 2. Feller-buncher operating in typical terrain conditions in low-volume pine stands.

Figure 4. Steyr KP40 processors operating at roadside.

Table 1. Average Stand Characteristics of Cutblocks [a]

	Cutblock					
	A:1	A:2	A:3	A:4	B:1	B:2
Tree dbh						
Merchantable (cm)	18.0	20.4	20.5	20.6	21.6	20.0
Snags (cm)	18.1	25.4	21.6	21.6	18.2	19.7
Tree height						
Total (m)	15.2	15.5	15.5	16.2	16.3	16.8
Merchantable (m)	9.7	10.9	11.0	11.7	12.2	12.1
Gross merchantable volume/tree (m^3)	0.15	0.21	0.21	0.22	0.24	0.21
Trees/ha						
Merchantable (no.)	749	465	440	755	380	531
Snags (no.)	625	194	381	30	39	51
Gross merchantable volume/ha (m^3) [b]	114	96	92	165	92	111

[a] From company cruise summaries.

[b] Does not include volume of snags.

The stems in Operation B were normally processed into five different log lengths—3.8 m, 4.4 m, 5.0 m, 5.6 m, and 6.2 m—each with a minimum 10-cm top diameter. All visual defects were removed during processing. Sorting by length was not required.

FELLER-BUNCHER STUDIES

Machine Utilization

The Servis recorders used in the study were not set up to differentiate between the time the machines travelled to and from work sites (machine travel time) and the time the machines harvested trees (productive machine hours, PMH). Therefore, the expression "operating machine hours" (OMH) is used to denote all time for which the machines were in motion. Delays less than 5 min in duration are also included in the OMH.

Operational utilization of the feller-bunchers ranged between 58 and 82% (Table 2). Variation in utilization levels was caused by differences in machine scheduling, the mechanical condition of the machines, machine maintenance support, organization of the operations, and amount of supervision. The highest utilization was recorded for the Case/Rotosaw feller-buncher when it worked one shift per day, but utilization dropped when the machine was rescheduled to work two shifts per day because more in-shift wait-for-parts and wait-for-repair times occurred during its double-shift operation. The low utilization of both the John Deere/Harricana and the John Deere/Bradeco feller-bunchers was primarily related to major mechanical failures of the undercarriers and engine components.

Productivity

Long-Term Productivity. The gross stand volume and the delivered volume for the individual cutblocks in the study showed considerable differences (Table 3). These volumes differed because of variations in stand quality and fibre recovery.

Based on the delivered volume, the long-term productivity of the Case/Rotosaw feller-buncher in the four cutblocks ranged from 19.1 to 26.6 m^3/OMH (Table 3). No correlation of feller-buncher performance to stand characteristics (Table 1) could be found.

Short-Term Productivity. Productivities of the feller-bunchers determined from the detailed-timing studies are presented in Table 4. In several studies, the average diameter of standing merchantable trees and the

Table 2. Shift-Level Utilization: Feller-Bunchers

	Operation A		Operation B		
	Case 1187B/ Rotosaw	Case 1187B/ Rotosaw	JD 693D/ Rotosaw	JD 693C/ Harricana	JD 693C/ Bradeco
Machine age (yr)	3.5	3.5	0.5	2.5	2.5
Normal shifts/day (no.)	1	2 [a]	2	2	2
Shifts with available data (no.)	38	29	179	135	148
Shifts with missing data (no.)	0	0	2	52	33
Average shift composition [b]					
Scheduled (h)	10.4	11.4	12.0	12.0	12.0
Operating (h)	8.5	8.3	8.6	7.1	7.0
Repair and service (h)	0.7	1.5	1.7	2.0	1.9
Operational delay (h)	0.9	0.5	0.4	0.8	0.8
Unknown delays (h)	0.3	1.1	1.3	2.1	2.3
Operational utilization (%)	82	73	72	59	58
Mechanical availability (%) [c]	90-93	77-87	75-86	66-83	65-84

[a] One shift/day when working Saturdays and Sundays.
[b] Based on shifts with available data.
[c] Expressed as a range, due to unknown delays.

Table 3. Long-Term Productivity: Case 1187B/Rotosaw Feller-Buncher

	Test block					
	A:1	A:2	A:3	A:4	All blocks	Road[a]
Gross stand volume, excluding snags (m^3)	1 683	3 866	962	6 437	12 948	n/a
Delivered volume to mill (m^3)	1 450	5 117	1 322	4 678	12 567	606
Volume difference (%) [b]	-14	+32	+37	-27	-3	n/a
Size of cutblock (ha)	14.8	40.3	10.5	39.0	104.6	n/a
Operating machine hours (OMH)	76.0	197.7	49.7	241.9	565.3	27.8
Feller-buncher productivity based on:						
Gross stand volumes, excluding snags (m^3/OMH)	22.1	19.6	19.4	26.6	22.9	n/a
Delivered volume (m^3/OMH)	19.1	25.9	26.6	19.3	22.2	21.8
Cutblock size (ha/OMH)	0.19	0.20	0.21	0.16	0.19	n/a

[a] Approximately 1.5 km long, built to access Block A:4.
[b] (delivered - gross stand) • 100/gross stand.

Table 4. Short-Term Productivity: Feller-Bunchers

	Feller-buncher studies								
	Case 1187B/Rotosaw			JD 693D/Rotosaw			JD 693C/ Harricana		JD 693C/ Bradeco
	1	2	3	1	2	3	1	2	1
Observed time (PMH)	11.6	8.5	3.3	2.1	6.0	4.3	7.5	2.8	2.9
Average stand characteristics									
Merchantable tree dbh (cm)	17.7	18.3	19.4	17.8	21.2	22.8	18.4	20.9	19.8
Gross merchantable volume/tree (m^3)	0.16	0.18	0.20	0.17	0.26	0.29	0.19	0.25	0.22
Merchantable trees/ha (no.) [a]	1100	950	800	770	650	500	850	550	650
Unmerchantable trees/ha (no.)	900	700	300	600	550	300	550	650	600
Gross merchantable volume/ha (m^3)	176	171	160	131	169	145	162	138	143
Bunch characteristics									
Stems/bunch (no.)	7.2	8.8	8.0	9.0	5.6	5.2	7.0	6.0	6.7
Average dbh of bunched stems (cm)	18.3	18.8	20.2	18.3	21.9	22.8	18.6	20.9	19.8
Bunched merchantable volume/stem (m^3)	0.17	0.19	0.21	0.18	0.28	0.29	0.19	0.25	0.22
Gross merchantable volume/bunch (m^3)	1.2	1.7	1.7	1.6	1.6	1.5	1.3	1.5	1.5
Machine productivity [b]									
Trees/PMH (no.)	161	180	164	161	155	138	228	178	116
Merchantable volume (m^3/PMH)	27.5	34.2	34.4	30.0	43.4	40.0	43.3	44.5	25.5
Area (ha/PMH)	0.16	0.20	0.22	0.25	0.26	0.30	0.27	0.32	0.18
Average trees/cycle (no.)	1.6	1.8	1.5	2.0	1.3	1.4	2.5	1.8	2.3
Work element distribution									
Fell and bunch (min/tree)	0.30	0.29	0.30	0.26	0.30	0.28	0.20	0.24	0.36
Fell-to-waste (min/tree)	0.02	0.01	0.02	0.05	0.02	0.02	0.01	0.02	0.02
Move (min/tree)	0.05	0.03	0.05	0.06	0.06	0.11	0.05	0.07	0.12
Other work (min/tree)	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	0.01
Minor delay (min/tree)	<0.01	0.00	<0.01	0.00	<0.01	0.02	<0.01	0.01	0.01
Total time (min/tree)	0.37	0.33	0.37	0.37	0.39	0.43	0.26	0.34	0.52

[a] Merchantable stems per hectare includes all snags with firmly attached bark.
[b] Machine productivity is based on the number and volume of bunched stems.

average diameter of bunched stems was significantly different. These differences occurred because a portion of the smaller merchantable trees (13-15 cm dbh) were not recovered by the feller-bunchers.

The short-term productivity established for the Case/Rotosaw feller-buncher is considerably higher than its long-term productivity (Table 3) because the short-term productivity is based on the gross merchantable volume bunched at the felling site and because PMH does not include machine travel time to and from the actual felling sites.

Despite differences in the operating conditions among the feller-buncher studies, results clearly show that the trees/PMH differs considerably between machines equipped with different saw heads. The Harricana-equipped feller-buncher recorded the highest productivity (average 203 trees/PMH), followed by the Rotosaw-equipped machines (average 160 trees/PMH), and the Bradeco-equipped feller-buncher (116 trees/PMH). The variation in the feller-bunchers' productivity levels resulted mainly from differences in their respective fell-and-bunch time per tree (Table 4). The fell-and-bunch time per tree was affected not only by the speed of actually felling trees, but also by the number of trees being accumulated in the felling head (trees/cycle) prior to bunching (Table 5). Analysis showed that the number of trees accumulated by the Harricana varied inversely with the number of stems per hectare[1] while the other heads were not influenced by this factor.

The productivity of the feller-bunchers was also affected by the ratio of unmerchantable to merchantable trees per hectare, and the number of merchantable trees per hectare. The machines' fell-to-waste times increased in stands with a high content of unmerchantable trees, while the moving time per tree decreases with an increase in the number of trees per hectare. All feller-bunchers in the study were equally affected by these stand factors.

Models for Estimating Productivity of Feller-Bunchers. Figure 5 presents simple models for predicting productivity of medium-sized excavator-type feller-bunchers in low-volume pine stands. The models use only the stand characteristic found to have the strongest influence on machine performance and, for that reason, caution must be exercised when applying these models to other operations.

GRAPPLE SKIDDER STUDIES

Machine Utilization

Although the mechanical availability of the John Deere 648D grapple skidder in Operation A exceeded 86% during the study period, the skidder was utilized only 67% of its scheduled working time (Table 6). The skidder's production capacity was considerably higher than that of the feller-buncher and processor and thus allowed the operator to take longer breaks or perform other tasks.

Productivity

Long-Term Productivity. The overall long-term productivity of the grapple skidder in Operation A (Table 7) was about 90% higher than that of the feller-buncher (Table 3).

Short-Term Productivity. The short-term productivity in the six skidder studies ranged from 44.4 to 66.1 m^3/PMH (Table 8). The short-term productivity was approximately 30% higher than that determined in the long-term studies (Table 7). But the data from these two different study methods cannot be directly compared

Table 5. Average Fell-and-Bunch Time per Tree

	Case 1187B/Rotosaw		JD 693D/Rotosaw		JD 693C/Harricana		JD 693C/Bradeco	
No. trees/cycle	Frequency of occurrence (%)	Time (min/tree)	Frequency of occurrence (%)	Time (min/tree)	Frequency of occurrence (%)	Time (min/tree)	Frequency of occurrence (%)	Time (min/tree)
1	39	0.35	66	0.32	27	0.30	23	0.45
2	59	0.27	28	0.25	38	0.22	31	0.37
3	2	0.24	5	0.23	25	0.19	36	0.35
4	0	-	1	0.22	10	0.16	10	0.31

[1] Typically, the average tree diameter in the stand also decreased as the number of trees per hectare increased.

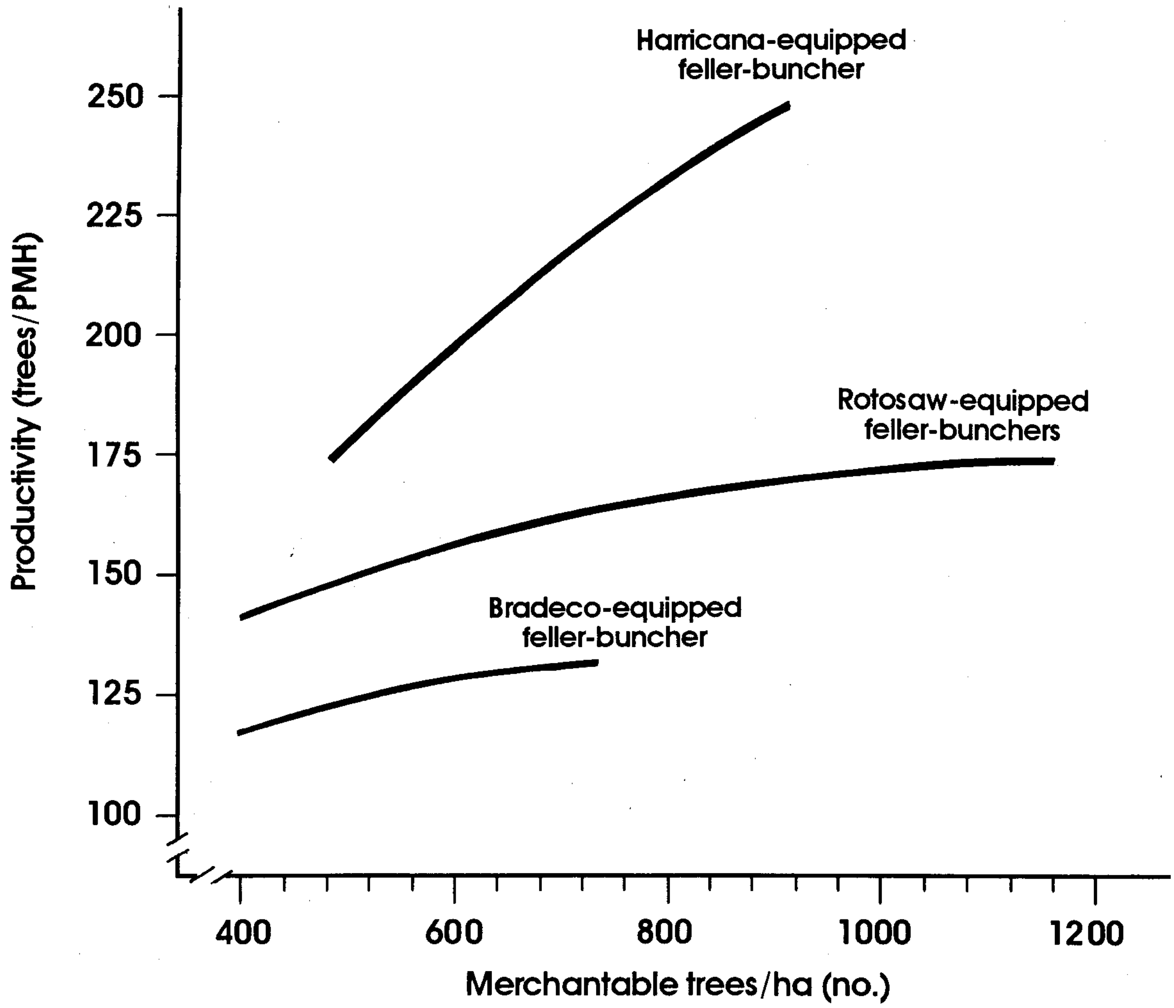

Figure 5. Estimated productivity: medium-sized, excavator-type feller-bunchers.

Table 6. Shift-Level Utilization: John Deere 648D Grapple Skidder, Operation A

Normal shifts/day (no.)	1
Shifts with available data (no.)	50
Shifts with missing data (no.)	0
Average shift composition	
Scheduled (h)	9.1
Operating (h)	6.1
Repair and service (h)	0.5
Operating delay (h)	1.7
Unknown delays (h)	0.8
Operational utilization (%)	67
Mechanical availability [a] (%)	86-95

[a] Expressed as a range, due to unknown delays.

for the same reasons discussed regarding the feller-buncher in Operation A.

Differences in the skidding distances and the average number of bunches loaded per turn explain most of the variations in the short-term grapple skidder productivity. However, variations in the number of bunches per load could not be correlated with either the original or the post-felling stand conditions. Differences in grapple size, skidding distance, and operators' work habits likely influenced the number of bunches per load. Terrain conditions were similar in all studies.

When operating at an average skidding distance of 70 m, the average turn-around times for the skidders with extended grapples were between 1.1 and 1.5 min

Table 7. Long-Term Productivity: John Deere 648D Grapple Skidder, Operation A

	Cutblock					
	A:1	A:2	A:3	A:4	All blocks	Road[a]
Gross stand volume, excluding snags (m^3)	1 683	3 866	962	6 437	12 948	n/a
Delivered volume (m^3)	1 450	5 117	1 322	4 678	12 567	606
Size of cutblock (ha)	14.8	40.3	10.5	39.0	104.6	n/a
Operating machine hours (OMH)	42.2	117.8	30.1	104.9	295.0	11.7
Average skidding distance (m) [b]	75	75	75	75	75	50
Skidder productivity based on:						
Gross stand volume, excluding snags (m^3/OMH)	39.9	32.8	32.0	61.4	43.9	
Delivered volume (m^3/OMH)	34.4	43.4	43.9	44.6	42.6	51.8
Cutblock size (ha/OMH)	0.35	0.34	0.35	0.37	0.35	

[a] Approximately 1.5-km long, built to access Block A:4.
[b] Visually estimated, based on the locations of roads and roadside decks.

Table 8. Short-Term Productivity: John Deere 648D Grapple Skidders

	Grapple skidder studies					
	Standard grapple					Extended grapple
	1	2	3	4	5	1
Observed time (PMH)	4.3	3.1	2.2	4.3	2.0	2.4
Average operating conditions						
Stem dbh in bunch (cm)	18.8	19.7	19.6	18.9	19.3	22.4
Bunched merchantable volume/stem (m^3)	0.19	0.20	0.20	0.19	0.22	0.28
Stems/bunch (no.)	6.1	6.7	5.8	8.9	6.2	6.0
Merchantable volume/bunch (m^3)	1.16	1.34	1.16	1.69	1.36	1.68
Skidding distance (m)	75	75	70	65	135	75
Machine productivity						
Stems/PMH (no.)	271	243	240	348	202	236
Gross merchantable volume/PMH (m^3)	51.5	48.6	48.0	66.1	44.4	66.1
Area (ha/PMH)	0.36	0.32	0.48	0.43	0.40	0.67
Load characteristics						
Stems/load (no.)	12.3	11.4	12.2	15.7	13.8	16.5
Bunches/load (no.)	2.02	1.70	2.10	1.76	2.23	2.75
Gross merchantable volume/load (m^3)	2.34	2.28	2.44	2.98	3.04	4.62
Work element distribution						
Travel empty (min/turn)	0.76	0.79	0.82	0.65	1.07	0.99
Load (min/turn)	0.53	0.48	0.51	0.44	0.90	0.93
Other work at stump (min/turn)	0.02	0.01	0.01	0.03	0.14	0.09
Travel loaded[a] (min/turn)	0.96	1.00	1.08	0.94	1.45	1.46
Unload and manoeuvre (min/turn)	0.15	0.19	0.16	0.18	0.12	0.14
Decking (min/turn)	0.28	0.31	0.30	0.25	0.42	0.58
Other work at roadside (min/turn)	0.02	0.01	0.05	0.08	0.00	0.00
Minor delays (min/turn)	<0.01	0.02	0.12	0.14	0.00	0.00
Total turn-around time (min/turn)	2.72	2.81	3.05	2.71	4.10	4.19

[a] Includes travel between bunches during the loading phase.

longer than those for skidders with standard grapples (Table 8). The time difference translates into 25% more skidder turns per hour in Operation A (20 turns versus 15 turns). In spite of this, the productivity of skidders with standard grapples was generally lower than that for skidders with extended grapples due to the differences in load sizes.

Models for Estimating Productivity of Grapple Skidders. Figure 6 presents simple models for estimating the productivity of grapple skidders operating in low-volume pine stands as a function of average skidding distance. The predicted productivity is shown in m^3/PMH for skidders with standard and extended grapples, respectively.

STROKE DELIMBER-SLASHER STUDIES: OPERATION A

Machine Utilization

Because only 50 Servis recorder charts from a total of 136 shifts could be used to calculate the operational utilization of the Case 1187B/Denis stroke delimber-slasher, the accuracy of the results presented in Table 9 as a measure of long-term utilization is uncertain.

Productivity

Short-Term Productivity. The productivity of the machine is expressed in terms of both gross and net volumes (Table 10). Gross volume is based on the average gross volume of the stems in the deck and the

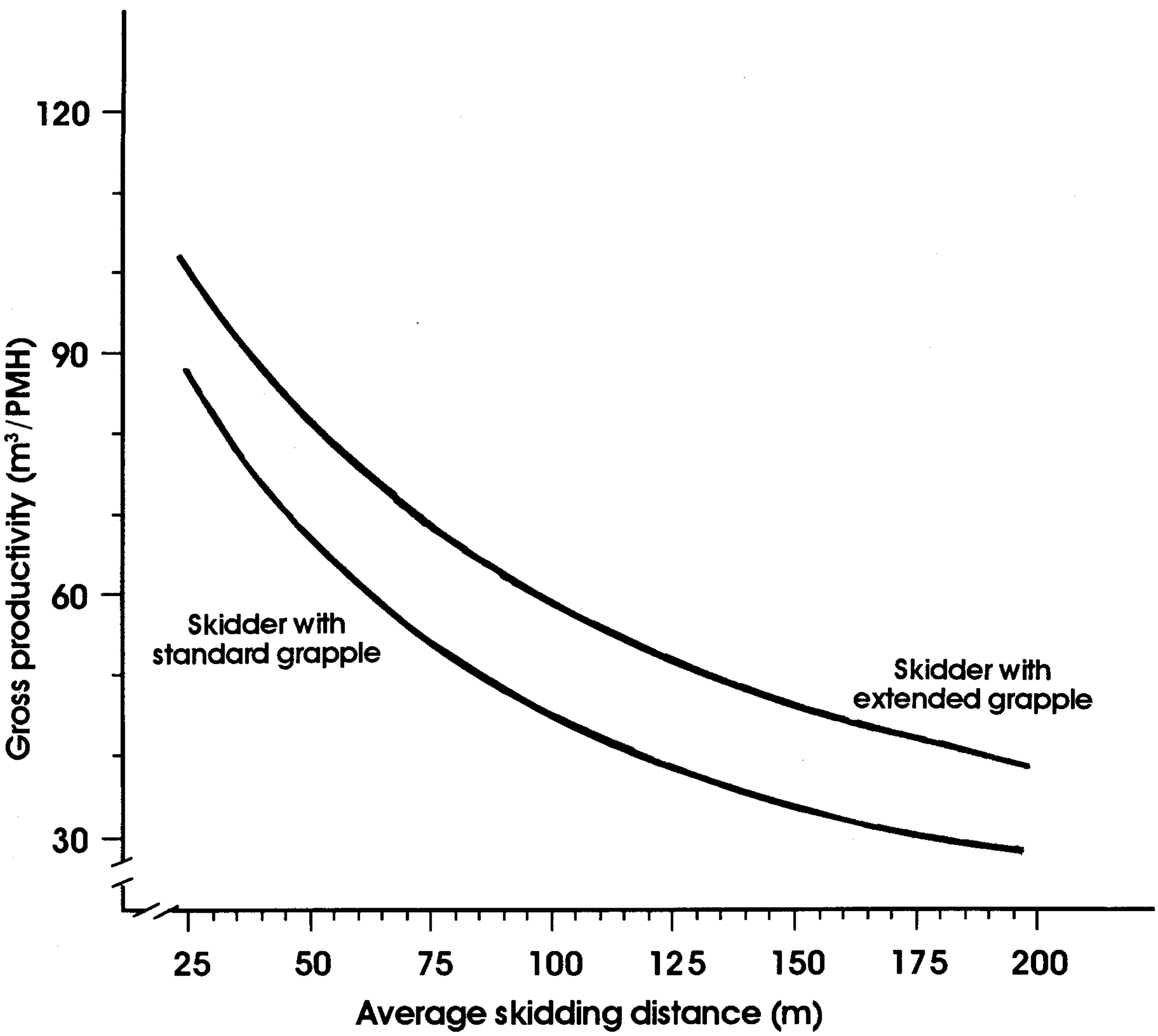

Figure 6. Predicted productivity: John Deere 648D grapple skidders.

Table 9. Shift-Level Utilization: Case 1187B/Denis Stroke Delimber-Slasher

	Study period		
	Oct-Nov '88	Feb '89	Total
Normal shifts/day (no.)	2 or 3[a]	2	2 or 3
Shifts with available data (no.)	25	25	50
Shifts with missing data (no.)	73	13	86
Average shift composition [b]			
Scheduled (h)	8.4	10.8	9.6
Operating (h)	6.4	8.0	7.2
Repair and service (h)	0.7	0.7	0.7
Operational delay (h)	0.3	0.5	0.4
Unknown delays (h)	1.0	1.6	1.3
Operational utilization (%)	76	74	75
Mechanical availability (%) [c]	80-92	79-94	79-93

[a] Monday to Friday, 3 shifts/day; Saturday and Sunday, 2 shifts/day.
[b] Based on shifts with available data.
[c] Expressed as a range, due to unknown delays.

Table 10. Short-Term Productivity: Case 1187B/Denis Stroke Delimber-Slasher

	Delimber-slasher studies					
	1	2	3	4	5	6
Observed time (PMH)	3.7	7.2	2.2	2.0	3.6	1.7
Average operating conditions						
Merchantable stem dbh (cm)	20.2	18.5	21.4	19.8	19.6	21.7
Total stem length (m)	15.2	15.2	15.7	15.7	16.2	16.2
Gross merchantable volume/stem (m^3)	0.21	0.17	0.24	0.21	0.21	0.26
Snag content in deck (%)	74	63	64	56	22	6
Broken stem content (%)	1	7	8	8	8	3
Machine productivity						
Merchantable stems/PMH (no.)	59	109	76	109	149	121
Gross merchantable stem volume/PMH (m^3)	12.4	18.5	18.2	22.9	31.3	31.5
Logs/PMH (no.)	94	127	112	145	173	166
Net log volume/PMH (m^3)	12.2	16.2	16.8	19.5	24.6	21.7
Stems/process cycle (no.)	1.1	1.4	1.1	1.2	1.2	1.2
Logs/merchantable stem (no.)	1.58	1.17	1.50	1.33	1.16	1.38
Utilized stem length (m)	9.3	7.6	8.9	8.3	6.2	6.1
Log-length distribution						
5.2-m logs (%)	71	34	67	58	78	63
7.6-m logs (%)	29	66	33	42	22	37
Work elements						
Stem pickup (min/stem)	0.28	0.21	0.24	0.20	0.13	0.16
Process (min/stem)	0.62	0.24	0.46	0.29	0.22	0.27
Move (min/stem)	0.02	0.02	0.01	0.01	0.01	0.01
Other work (min/stem)	0.08	0.06	0.07	0.05	0.04	0.04
Minor delay (min/stem)	0.01	0.02	0.01	<0.01	<0.01	0.02
Total time (min/stem)	1.01	0.55	0.79	0.55	0.40	0.50

number of stems processed. Net volume is based on the average volume of sampled logs and the number of logs produced.

Overall, the machine's short-term gross productivity ranged between 59 and 149 stems/PMH. However, the results from earlier studies (1-3 in Table 10) are below the expected production level because the machine was operated by inexperienced workers who had been hired only days before the study began. As the study progressed the operators became more proficient; productivity increased and stem pickup and process times decreased (Table 10). Therefore, the results from the February studies are more representative of the machine's productive capability.

The process time increased with stem size, primarily because the average number of logs produced per stem increased, and because multistem processing of smaller stems occurred more frequently than with larger stems.

Long-butting[2] typically increased the total cycle time by 0.20-0.25 min per stem. However, only about 5% of the stems in Operation A were long-butted; therefore, the impact of long-butting on the overall productivity of the Denis stroke delimber-slasher was minimal. However, had the machine worked in an operation with more frequent long-butting, the machine's productivity would most likely have been significantly lower than recorded in this study.

Models for Estimating Productivity of the Denis Stroke Delimber-Slasher. Figure 7 presents a simple model for predicting the productivity of the Denis de-

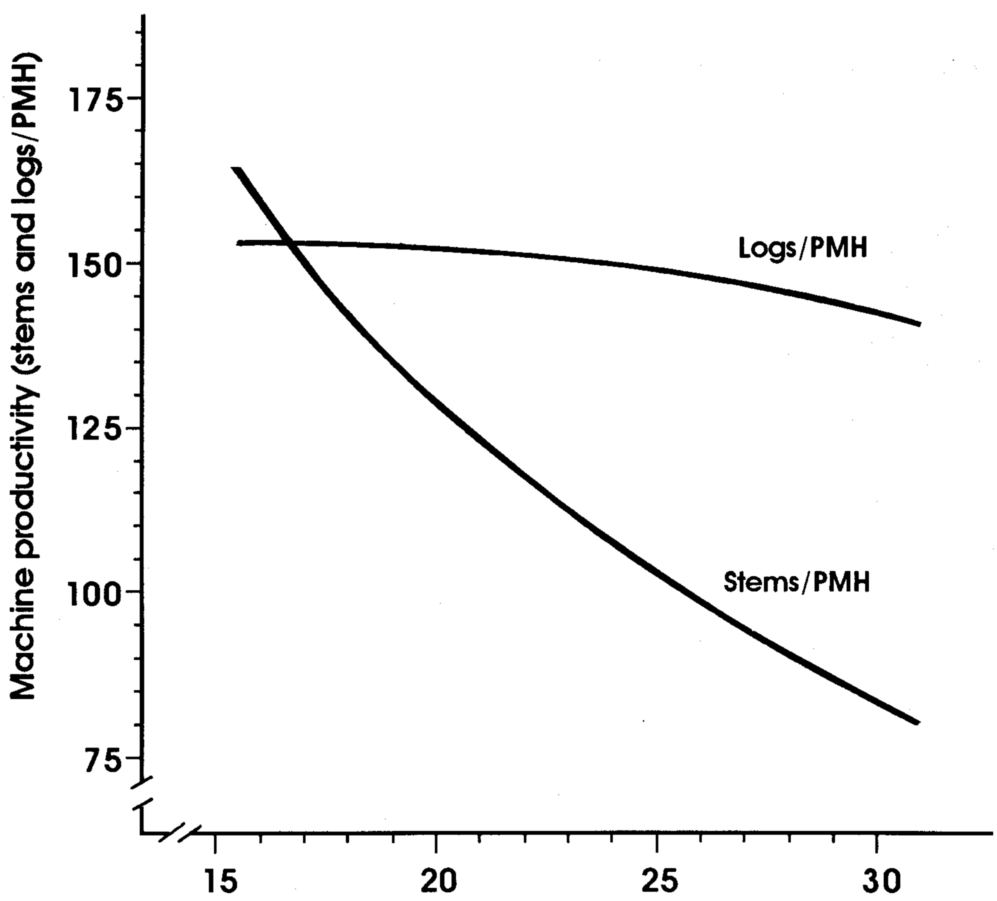

Figure 7. Estimated Productivity: Case 1187B/Denis stroke delimber-slasher.

[2] Long-butting is a term that refers to cutting off the butt end of the stem to eliminate defect (e.g. rot, cat face, butt flare, stump pull).

limber-slasher when operating in low-volume pine stands. The model is based only on the results from the latter part of the project (November to February). The model is assumed to be valid *only* for processing 15- to 16-m long stems into logs 5.2-m and 7.6-m in length, and sorting by length. The model shows that stem size significantly influences the stems/PMH, not the logs/PMH.

Log Length: Measuring Accuracy

Analysis of 494 logs sampled for length-measuring accuracy showed that 34%, 64%, and 85% of the logs were within 2 cm, 6 cm, and 10 cm of the target length, respectively. The distribution of length errors around the target lengths (Figure 8) indicate the machine's length-measuring system functioned well, and the deviation from the target length most likely related to the operator's selection of the bucking location.

STEYR KP40 PROCESSOR STUDIES: OPERATION B

Machine Utilization

The operational utilization of the Steyr KP40 processors ranged from 68 to 76% of the scheduled machine time (Table 11).

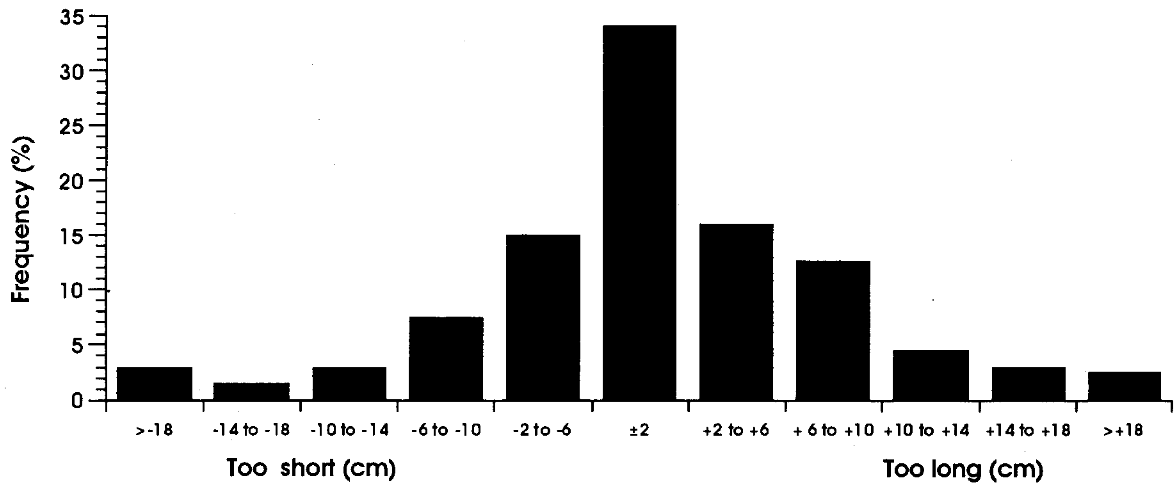

Figure 8. Length-measuring accuracy: Case 1187B/Denis stroke delimber-slasher.

Table 11. Shift-Level Utilization: Steyr KP40 Processors

	Carrier		
	Caterpillar 225	Linkbelt L-2800	Caterpillar EL 180
Normal shifts/day [a] (no.)	2	2	2
Shifts with available data (no.)	69	76	73
Shifts with missing data (no.)	39	39	40
Average shift composition [b]			
Scheduled (h)	11.2	11.4	11.4
Operating (h)	7.6	7.9	8.7
Repair and service (h)	1.8	2.2	1.5
Operational delay (h)	1.3	0.9	1.0
Unknown delays (h)	0.5	0.4	0.2
Operational utilization (%)	68	69	76
Mechanical availability (%) [c]	79-84	77-81	85-87

[a] Generally only one shift/day operating on Saturday and Sunday.
[b] Based on shifts with available data.
[c] Expressed as a range, due to unknown delays.

Productivity

Short-Term Productivity. The machine's productivity is expressed in terms of both gross and net volumes. Gross volume is based on the average gross volume of the stems in the deck, and the number of stems processed. Net volume is based on the average volume of sampled logs and the number of logs produced. Overall, the machines' short-term gross productivity ranged between 28.6 and 51.2 m³/PMH (Table 12). Their net productivity ranged between 24.2 and 38.0 m³/PMH.

The wide range of productivities, and the variation in the gross and net production ratios, reflect not only differences in the size and quality of stems but also differences in the processing criteria and the operator skill levels.

The studies show differences in stems/PMH because the process time per stem varied with stem size (Table 12). All other work element times were fairly constant in all studies, with the exception of the stem pickup time which was influenced only by level of operator experience.

The process time per stem was found to be influenced by stem diameter, primarily because the number of logs per stem also changed with stem diameter. Long-butted stems often took longer to process than sound stems. However, the difference in processing times did not have a significant effect on the overall stems/PMH production. Long-butting, however, had an adverse effect on the net productivity in terms of logs per hour (Figure 9).

Models for Estimating Productivity of the Steyr KP40 Processor. Figure 10 shows the predicted productivity of the Steyr KP40 when producing short logs from trees in low-volume pine stands. It shows that the machine's stems/PMH productivity decreases with an increase in stem diameter, while the productivity in

Table 12. Short-Term Productivity: Steyr KP40 Processors

	Processor studies								
	1	2	3	4	5	6	7	8	9
Observed time (PMH)	1.1	1.3	1.0	3.1	2.0	2.9	1.7	0.8	1.5
Average operating conditions									
Merchantable stem dbh (cm)	21.3	22.2	21.7	20.6	20.2	21.0	20.4	24.0	19.9
Total stem length (m)	16.5	16.5	16.5	16.7	16.7	16.7	16.7	16.7	16.7
Gross merchantable volume/stem (m³)	0.25	0.27	0.26	0.24	0.23	0.25	0.24	0.33	0.22
Snag content in deck (%)	46	33	50	15	40	35	21	47	49
Broken stem content (%)	8	0	5	8	11	11	8	12	3
Machine productivity									
Stems/PMH (no.)	136	120	176	119	134	163	176	155	227
Gross merchantable volume/PMH (m³)	34.0	32.4	45.8	28.6	30.8	40.8	42.2	51.2	49.9
Logs/PMH (no.)	206	157	259	175	234	229	254	278	235
Net merchantable volume/PMH (m³)	26.4	24.7	36.8	24.2	29.3	32.1	34.5	38.0	27.5
Logs/stem (no.)	1.52	1.30	1.47	1.47	1.75	1.40	1.44	1.80	1.04
Utilized stem length (m)	8.5	7.4	7.8	8.1	10.3	7.7	8.3	8.3	4.8
Stems long-butted (%)	54	85	64	57	69	51	35	57	66
Log-length distribution									
3.8-m logs (%)	8	5	7	17	6	10	4	31	13
4.4-m logs (%)	12	7	11	6	4	15	13	10	32
5.0-m logs (%)	18	13	36	11	8	20	13	59	55
5.6-m logs (%)	3	16	1	9	7	5	4	-	-
6.2-m logs (%)	59	59	45	59	75	50	66	-	-
Work elements									
Stem pickup (min/stem)	0.09	0.14	0.08	0.11	0.10	0.08	0.07	0.09	0.09
Process (min/stem)	0.28	0.33	0.24	0.34	0.31	0.25	0.23	0.29	0.14
Move (min/stem)	0.02	0.01	<0.01	0.01	0.01	0.01	0.02	0.01	0.01
Other work (min/stem)	0.0	0.02	0.02	0.04	0.03	0.03	0.02	<0.01	0.02
Minor delay (min/stem)	0.02	<0.01	0.00	0.01	<0.01	<0.01	0.00	0.00	<0.01
Total time (min/stem)	0.44	0.50	0.34	0.51	0.45	0.37	0.34	0.39	0.26

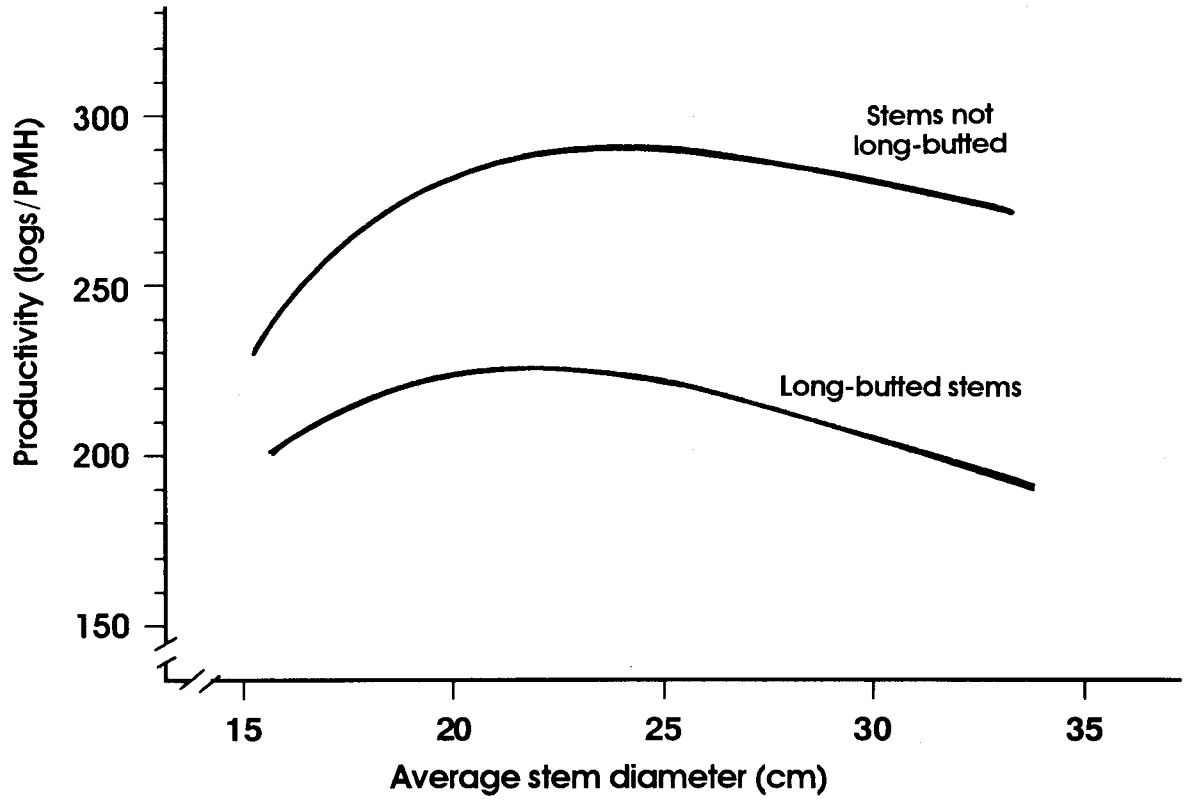

Figure 9. Estimated productivity: Steyr KP40 processors.

terms of logs/PMH initially increased until it reached a maximum at a stem diameter of about 22 cm, after which it began to decrease.

Log Length: Measuring Accuracy

A total of 733 logs were sampled to test the length-measuring accuracy of the Steyr KP40 processors. The results showed that 39%, 79%, and 92% of the logs were within 2 cm, 6 cm, and 10 cm respectively of the target lengths (Figure 11). The majority of logs deviating from the target lengths were too short. FERIC's general observations suggest this was primarily caused by slippage between the stem and the drive track when processing deformed stems and stems with large branches.

SYSTEM PRODUCTIVITY AND COST ANALYSES

The objectives of the system productivity and cost analyses were to determine, as realistically as possible, the machine requirements, productivities, and costs associated with harvesting low-volume pine stands in the Williams Lake TSA. The analyses are based on the equipment used by Operations A and B, and on their respective operating conditions. The results from the field studies were used when deemed appropriate, but certain assumptions about machine shift utilization, scheduling, merchantable fibre losses, and machine operating costs were necessary. Because of these assumptions, the results of the analyses might deviate from what the contractors actually experienced during the study period.

System Analysis Assumptions

Operation A is assumed to consist of one Case 1187B/ Rotosaw 2100 feller-buncher, one John Deere 648D grapple skidder, and one Case 1187B/Denis stroke delimber-slasher. The operation's annual quota is 60 000 m^3, and its daily production requirement is 360 m^3 of sorted 5.2-m and 7.6-m sawlogs.

Operation B is assumed to consist of John Deere 693 carriers equipped with either Rotosaw, Harricana, or Bradeco felling heads; John Deere 648D grapple skidders; and Steyr KP40 processors. The number of machines needed is based upon the timber quota require-

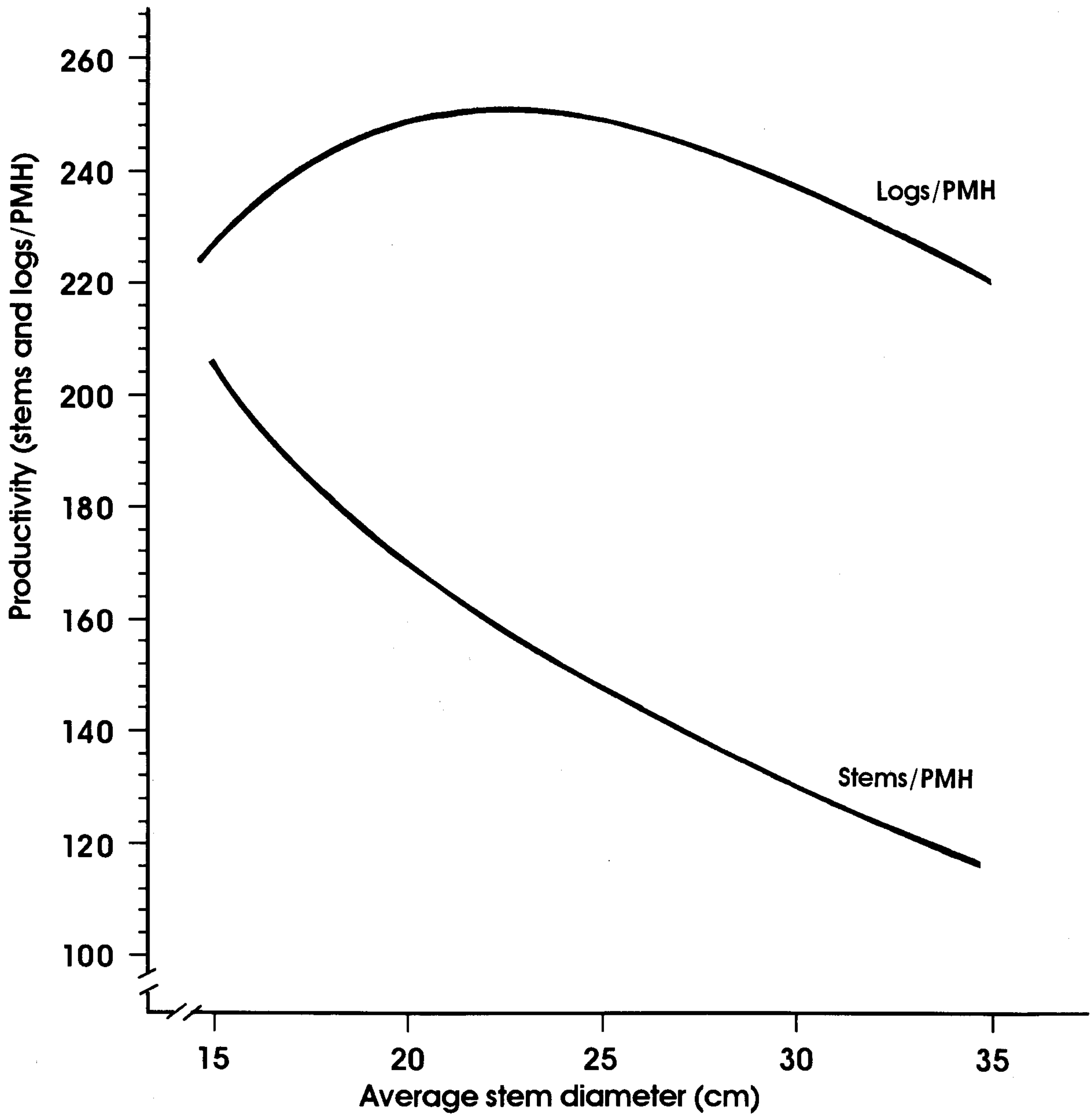

Figure 10. Estimated productivity: Steyr KP40 processors.

ment. Operation B's annual quota is 160 000 m^3, and its daily production requirement is 850 m^3 of unsorted sawlogs, varying in length from 3.8 m to 6.2 m.

The gross productivities (m^3/PMH) for the feller-bunchers, grapple skidders, and processors were obtained from the various prediction models (Figures 5, 6, 7, and 10) for the appropriate average operating conditions in the six different test blocks (Table 1). The analysis assumes that all snags in the cutblocks are usable. The gross productivity was then converted to net productivity by including allowances for the estimated merchantable fibre losses that occurred in the subsequent phases of the operation, and the estimated time the machine spent travelling to and from work sites. The machine costing details are presented in Appendix II.

In both operations, secondary haul roads are assumed to be spaced 300 m apart, resulting in an average skidding distance of 75 m and 1 km of road per 30 ha of

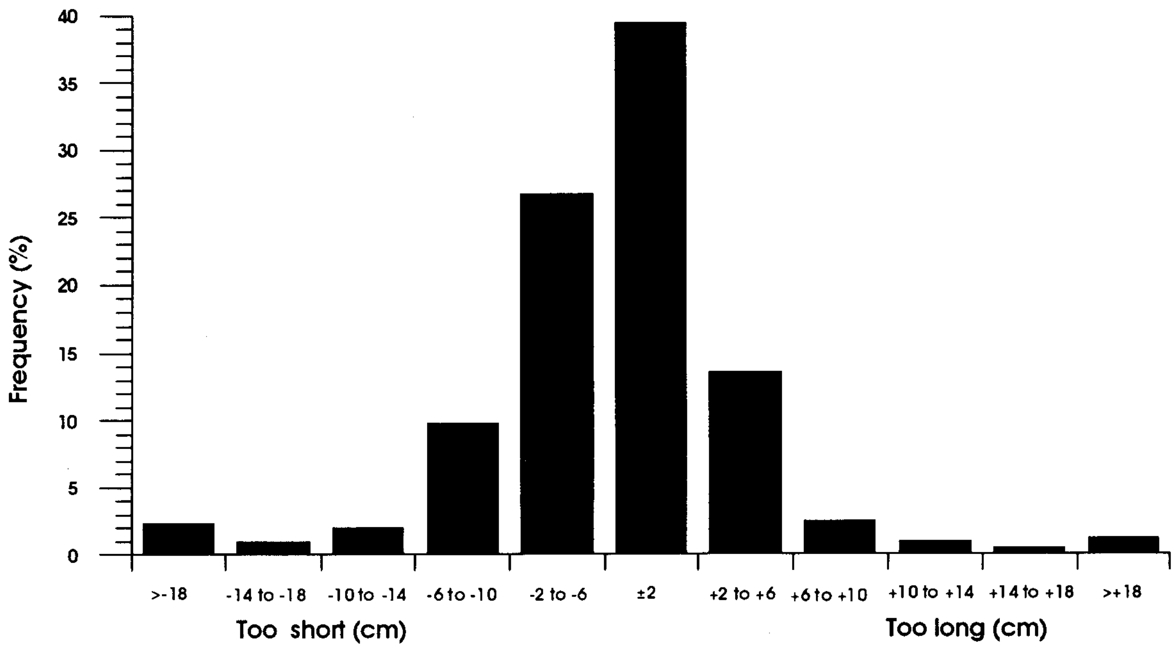

Figure 11. Length-measuring accuracy: Steyr KP40 processors.

harvested area. The roads are built by D7-sized bulldozers, which also build 5 km/yr of access roads to the cutblocks, maintain roads, and pile harvesting debris onto the haul roads for burning following harvesting. The bulldozers are assumed to build 60 m of secondary haul roads per OMH, and road-maintenance time is assumed to be 10% of the road-building time. The piling of harvesting debris is assumed to require 1 OMH/340 m^3 of merchantable wood (based on field studies). Because the bulldozer in Operation A would be required for only 550-600 OMH/year, it is assumed that the purchase of a used machine is adequate for that Operation, while Operation B would require the purchase of a new machine.

The skidder will also be used to knock down residual unmerchantable trees (cutover clearing). While some of the cutover clearing is done during the skidding phase, the field studies showed that an additional 0.1 OMH/ha was required.

Results

Operation A. The overall system productivity in Operation A ranged from 43.9 to 55.4 m^3/man-day, and the unit wood cost was found to range between $11.65 and $15.05/$m^3$ (Table 13). The lowest productivity and the highest cost occurred in Block A:1 because of small tree size and higher-than-average fibre loss. Most adversely affected in this block was the processing phase, because two machines were required to fulfil the daily production of 360 m^3 while in all other A-blocks only one processor was needed.

Although the average stand characteristics in blocks A:2, A:3, and A:4 were relatively similar, the productivity and wood cost in Block A:4 differed. The differences were due to the higher amount of fibre losses observed in this block.

Operation B. The analysis resulted in more favourable productivities and costs in Operation B than in A, largely due to differences in the performances of processors. However, direct comparisons of the two operations are not entirely appropriate because they produced different log products.

The overall system productivity in Operation B ranged from 50.7 to 59.7 m^3/man-day, and the unit wood cost was found to range between $10.10 and $11.86/$m^3$ (Table 13). The two blocks showed only minor differences in cost and productivity, stemming primarily from the type of saw head used on the feller-buncher. The higher cost of using chain-saw type felling heads (Bradeco) resulted partly from the need to use three of these feller-buncher types to fulfil the daily production quota (850 m^3), compared with two units of either Rotosaw- or Harricana-equipped feller-bunchers.

Discussion

The analyses do not address all logistical problems as-

Table 13. Results of System Analyses

	Cutblock					
	A:1	A:2	A:3	A:4	B:1	B:2
Required average SMH/day [a]						
Bulldozer (h)	4.5	4.7	4.4	5.0	13.8	11.3
Rotosaw feller-buncher (h)	22.6	17.4	16.7	19.0	45.7[b]	46.2[b]
Harricana feller-buncher (h)	-	-	-	-	40.7[c]	37.8[b]
Bradeco feller-buncher (h)	-	-	-	-	55.6[c]	55.9[c]
Grapple skidder (h)	11.4	10.1	10.3	12.1	21.2[d]	20.7[d]
Processor (h)	27.1[b]	20.6	20.6	23.2	38.2[b]	46.2[b]
Costs [e]						
Road development ($/m³)	1.18	1.24	1.16	1.29	1.29	1.06
Felling with Rotosaw ($/m³)	4.70	3.82	3.73	4.06	3.95	4.01
Felling with Harricana ($/m³)	-	-	-	-	3.57	3.34
Felling with Bradeco ($/m³)	-	-	-	-	4.92	4.97
Grapple skidding ($/m³)	2.00	1.85	1.85	2.08	1.51	1.51
Roadside processing ($/m³)	6.58	4.30	4.30	4.76	3.24	3.83
Cutover clearing ($/m³)	0.05	0.06	0.05	0.06	0.11	0.08
Debris piling ($/m³)	0.54	0.52	0.54	0.51	0.33	0.41
Harvesting system cost						
With Rotosaw feller-buncher ($/m³)	15.05	11.80	11.65	12.76	10.48	10.90
With Harricana feller-buncher ($/m³)	-	-	-	-	10.10	10.23
With Bradeco feller-buncher ($/m³)	-	-	-	-	11.45	11.86
System productivity [f]						
With Rotosaw feller-buncher (m³/man-day)	43.9	54.5	55.4	48.6	57.2	54.7
With Harricana feller-buncher (m³/man-day)	-	-	-	-	59.7	58.6
With Bradeco feller-buncher (m³/man-day)	-	-	-	-	52.8	50.7

[a] Average total scheduled machine hours for all machines in each phase, assuming five working days per week.
[b] Requires two machines, each operating 2 shifts/day.
[c] Requires three machines, each operating 2 shifts/day.
[d] Requires two machines, each operating 1 shift/day.
[e] Unit wood cost for each phase.
[f] One man-day = 8 SMH.

sociated with the harvesting operations observed in the study. One such problem arises when a particular machine is only periodically needed. For example, the bulldozer in Operation A was required only 550-600 OMH/yr. Although the bulldozer was not used daily, its services were required periodically to build roads as harvesting progressed through the cutblocks. Low machine utilization results in high hourly operating costs. In addition to the higher cost, periodic use of a machine might also make it more difficult to find an operator willing to work part time in a remote location.

A similar problem would exist if a machine is required for more than one shift per day but for less than two shifts. One option is to continue with single-shift operation and let the operator work very long days, including weekends, thereby possibly reducing hourly output and increasing the risk of personal injuries and machine damage. Or, a second option is to change to a double-shift operation and hire another operator on a part-time basis, although this can be difficult in a remote operation.

Annual or daily production quotas will also affect the harvesting cost. Figure 12 shows, simplistically, how the unit wood cost in an operation would vary with annual quotas. As the quota initially increases, the utilization of individual machines will increase and reduce hourly machine costs and wood costs. However, at some point, the quota reaches a level at which the machine(s) in one phase (e.g. the processing phase) cannot handle all the wood, so an additional machine must be purchased. Because the new machine cannot be fully utilized at that quota level, its hourly cost will be high, and total wood cost will increase.

The operational utilization of individual machines also affects the wood cost. Figure 13 is a simplistic presentation of how the processing cost associated with using a Steyr KP40 would change with machine utilization levels, assuming production quota is not limited.[3]

[3] The costs per hour of repairs, fuel, and lubrication are assumed to be constant, while the costs per hour for depreciation, interest on investment, and insurance vary with machine utilization.

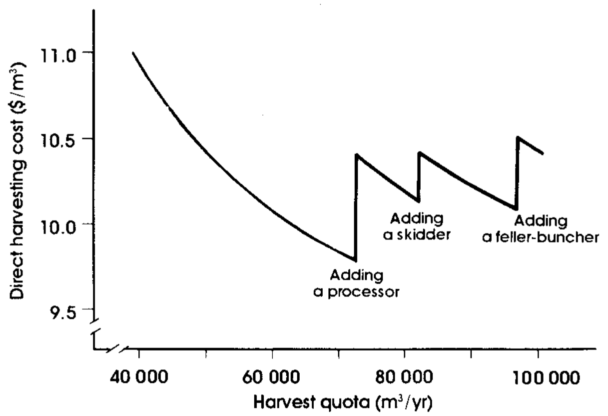

Figure 12. Simplistic relationship of system wood cost to annual harvest quota.

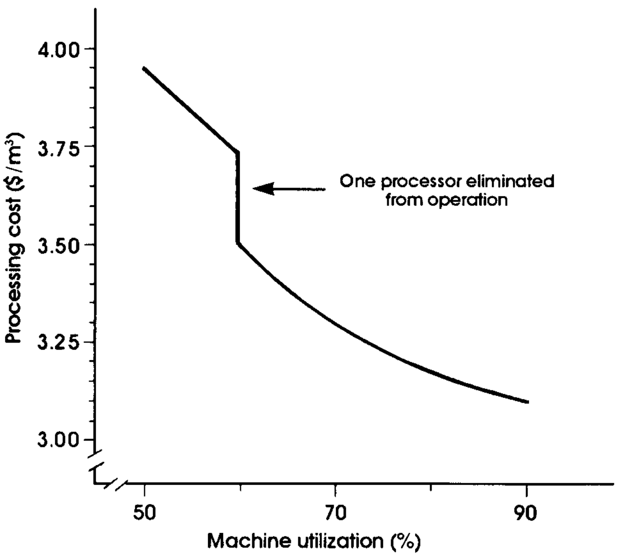

Figure 13. Simplistic relationship of processing cost to machine utilization: Steyr KP40 processor.

CONCLUSION

In the fall and winter of 1988/89, FERIC studied the performances of feller-bunchers, grapple skidders, and roadside processors in two harvesting operations in the Williams Lake TSA, in the Interior of British Columbia. The objectives of the study were to determine machine productivity, harvesting costs, and operating factors affecting machine performances in low-volume lodgepole pine stands. The findings of the study are based on data collected in detailed-timing studies and shift-level studies.

The operational utilization of the feller-bunchers ranged between 59 and 82%. Observations indicated that differences in scheduling, initial mechanical condition of the machines, and work organization were the main reasons for the variations in machine utilization.

Short-term productivity of the feller-bunchers ranged from 116 to 228 trees/PMH (25.5-44.5 m^3/PMH). However, fibre losses in subsequent phases of the operations reduced considerably the volume credited to the feller-bunchers. The long-term productivity, based on delivered volume, ranged in Operation A between 19.1 and 26.6 m^3/OMH.

Productivity of the Rotosaw, Harricana, and Bradeco-equipped feller-bunchers differed, primarily because their felling speeds differ, as does their ability to accumulate trees before bunching. The number of merchantable trees per hectare and the ratio of unmerchantable to merchantable trees had the strongest influences on feller-buncher productivity. Productivity of the Harricana-equipped feller-buncher was highly influenced by stand conditions, while the Rotosaw- and Bradeco-equipped machines were only moderately influenced by stand conditions.

At an average skidding distance of about 75 m, short-term productivity of the John Deere 648D grapple skidders ranged between 44.4 and 66.1 m^3/PMH. However, fibre losses during the subsequent operational phases reduced considerably the volume credited to the skidding operation. The long-term productivity in Operation A ranged between 34.4 and 44.6 m^3/PMH.

Average skidding distance and load size were the main factors associated with variation in skidder production. The number of bunches loaded per turn affected the total turn-around time, but fewer turns per hour with larger loads generally resulted in higher machine productivity.

The objectives of the two operations and their processing criteria were sufficiently different to prevent a direct comparison of the performances of the Denis stroke delimber-slasher and the Steyr KP40 processors. The short-term productivity studies indicate Denis stroke delimber-slashers would be less cost efficient than Steyr KP40 processors in operations where stems are manufactured into several logs per stem, where multistem processing is not feasible, and where frequent long-butting is required. Alternatively, the Steyr KP40 processor would likely be the less cost-efficient machine in operations where sorting logs is required, and where the stems frequently have either large branches or deformities.

The potential performance of the Denis stroke delimber-slasher could not be fully evaluated during the study because inexperienced operators had been hired only days prior to the start of the study. The short-term productivity during the latter part of the study period ranged from 109 to 149 stems/PMH, or 19.5 to 24.6 m^3/PMH net volume, with variations in the stem size and the frequency of multistem handling being the main factors.

Productivity of the Steyr KP40 processor, which was operated by experienced workers, ranged from 136 to 227 stems/PMH, or 26.4 to 38.0 m^3/PMH net volume, when stems are processed into log lengths averaging 5.5 m and not sorted by length. The range in productivity was attributed mainly to variations in stem size and stem quality.

The productivity analyses of the two feller-buncher systems resulted in overall productivities of between 44 and 60 m^3/man-day. These man-day productivity levels included felling, skidding, roadside processing, road building, cutover clearing with skidders, and debris piling (for subsequent burning) with bulldozers. The unit wood cost was found to be \$10-15/m^3. The costs and productivities were adversely affected by small tree size and high levels of merchantable fibre losses. The type of saw head mounted on the feller-buncher also influenced the total harvesting cost.

REFERENCES

Peterson, J.T.; Giles, D.R. 1988. *Economic Utilization Study of Poor-Quality Lodgepole Pine: Phase I.* Vancouver, FERIC. Technical Report TR-86. 28 pp.

APPENDIX I

Definitions

STAND AND TREE CHARACTERISTICS

Merchantable tree. Commercial tree species having a green crown, a minimum diameter at breast height (dbh) of 12.5 cm, and sufficiently tall to produce a log at least 5-m long with a minimum top diameter of 10 cm.

Unmerchantable tree. Noncommercial tree species of any size, or a commercial tree species too small to be classified as a merchantable tree.

Snag. Commercial tree species sufficiently large to be classified as a merchantable tree, but with no green crown.

Stem. Felled tree or snag, before being processed.

Gross merchantable volume. Total stemwood volume of trees, snags, or stems down to a 10-cm top diameter, less the volume of a 30-cm high stump. Gross volume of sampled trees and stems in the detailed-timing studies was calculated with the formula

$$\log(\text{gross volume}) = -4.3495 + 1.82278 \log(\text{dbh}) + 1.108142 \log(\text{total height})$$

less volume of stump and unmerchantable top.

Net merchantable volume. Wood volume of logs processed from merchantable stems.

Delivered volume. Wood volume of logs delivered to mill, based on mill's scale records.

Unmerchantable-to-merchantable tree ratio. The number of trees in the stand expressed as a relationship of unmerchantable to merchantable trees.

Low-volume pine stand. Although there is no clear definition of a low-volume pine stand, woodlands managers in the Williams Lake TSA generally agree that the following criteria apply (Peterson and Giles 1988):

- Tree height less than 12 m, down to a 10-cm top.
- Gross volume per hectare less than 100 m^3.
- Gross volume per tree less than 0.20 m^3.

SHIFT-LEVEL STUDIES

Scheduled working time. That period of the day, week, or year during which a machine is intended to work, regardless of what actually occurs during the scheduled work period. Scheduled work time per shift is expressed in terms of scheduled machine hours (SMH). Where operators are paid hourly, SMH per shift equals the number of hours for which the operators are normally paid. In other operations, SMH per shift equals the number of hours the operator normally spends on the work site.

Operating time. That time of the scheduled work period during which the machine does any type of work or travels by its own power. Operating time per shift is expressed in the number of operating machine hours (OMH).

Repair and service time. That time of the scheduled work period during which the machine does not operate because of mechanical failures (repairs, or wait for parts/mechanics), or regular maintenance activities.

Operational delay time. That time of the scheduled work period during which the machine does not operate because of reasons other than mechanical failure or service.

Unknown delay time. That time of the scheduled work period during which the machine does not operate for reasons that cannot be determined (i.e. information missing).

Mechanical availability (%). That time of the scheduled work period during which the machine is mechanically fit to operate. Expressed as a percentage of scheduled time, and calculated as

$$\text{mechanical availability} = (\text{OMH} + \text{operational delay time}) \cdot 100/\text{SMH}.$$

Operational (or machine) utilization (%). That part of the scheduled work time during which the machine operates. Expressed as a percentage of scheduled time, and calculated as

$$\text{operational utilization} = \text{OMH} \cdot 100/\text{SMH}.$$

DETAILED-TIMING STUDIES

Productive time. That part of the operating time during which the machine does the type of work for which it is intended. Productive time is expressed in terms of productive machine hours (PMH), including all minor delays and machine movements, with durations less than 5.0 min/occurrence. The various activities performed by the machines during productive time are referred to as work elements.

Feller-Buncher Work Elements

Fell and bunch. That time during which the operator actively fells and bunches merchantable trees or snags. The element includes all boom movements needed to fell and bunch trees (grab, fell, swing to bunch, bunch, and swing back). The number of trees accumulated in the felling head prior to bunching, is referred to as trees/(felling) cycle.

Fell-to-waste. That time during which the operator fells or knocks down (unmerchantable) trees with no intention to place them in bunches.

Move. That time during which the operator moves the machine in the stand.

Other work. That time during which the operator performs activities other than those previously described to achieve the desired results in the felling operation.

Minor delay. That time during which the operator does not perform any work with the machine, or when performing a machine activity that is not related to the objectives of the work cycle. Delays exceeding 5.0 min are classified as major delays, and not considered a time element in the productive time.

Grapple Skidder Work Elements

Travel empty. That time during which the machine travels without any load to the area from which stems are to be skidded.

Travel loaded. That time during which the machine travels with a load to the (roadside) unloading area.

Load. That time during which the operator grapples stems in bunches. The time includes preparing to load, moving between adjacent bunches, and securing the load. The number of complete bunches loaded during the same turn is referred to as bunches/load.

Other work at stump. That time during which the machine is at the stump (loading) area, and does other necessary work not directly associated with loading or travelling.

Unload and manoeuvre (at roadside). That time during which the operator drops stems at roadside, secures the grapple, and turns the machine around.

Decking. That time during which the machine pushes stems up or into the deck, or time spent aligning stem butts in the deck.

Other work at roadside. That time during which the machine is at the roadside decking area, and does other necessary work other than unloading, manoeuvring, or decking.

Minor delay. That time during which the operator does not perform any work with the machine, or when performing a machine activity that is not related to the objectives of the work cycle. Delays exceeding 5.0 min are classified as major delays, and not considered a time element in the productive time.

Other Grapple Skidder Terms

Skidding distance. Distance between the spot where the first bunch of each load is grappled and the roadside decking area, measured in a straight line regardless of the skidder's actual travel path.

Turn-around time. Total time of all machine activities during skidding, from the time the skidder leaves the roadside decking area to the time it again leaves the roadside decking area for the next trip.

Processor Work Elements

Stem get. That time during which the operator grabs merchantable stems, and places them in the position required for processing. The number of stems grabbed and processed simultaneously is referred to as stems/(processing) cycle.

Process. That time during which the machine delimbs stems, bucks them into logs, decks the logs, and discharges the remaining unmerchantable stem top. It also includes removing part of the stems unsuitable for manufactured logs (long-butting).

Move. That time during which the operator moves the machine to a new set-up for the purpose of continuing to process stems.

Other work. That time during which the machine performs other necessary activities, such as align logs and clear debris, to achieve the desired results in the processing operations.

Minor delay. That time during which the operator does not perform any work with the machine, or when performing a machine activity that is not related to the objectives of the work cycle. Delays exceeding 5.0 min are classified as major delays, and not considered a time element in the productive time.

Other Processor Terms

Long-butting. Refers to cutting off the butt end of the stem to eliminate defect (e.g. rot, cat face, butt flare, stump pull).

Broken stem content. Percentage of stems in deck that, at the time they are picked up by the processor, are broken at a diameter >> 10 cm; this significantly affects the number or length of logs that can be processed from each stem.

Snag content. Percentage of stems in deck that do not have a green crown when they are picked up by the processor.

OTHER TERMS

Cut-over clearing. Work that involves using the skidder to knock down (mostly unmerchantable) trees left standing on the site following completion of felling and skidding phases.

Debris piling. Work that involves using a bulldozer to push accumulated roadside processing debris onto temporary haul roads for subsequent burning, following completion of loading and hauling phases.

APPENDIX II

Procedures for Calculating Machine Charge-Out Rates

Purchase price. All machines, except the bulldozer in Operation A, are assumed to have been purchased new and operated throughout their respective useful lives. A reconditioned (used) bulldozer is assumed to be sufficient to do the limited work required in Operation A. Machine purchase prices (October 1989) include the cost of transportation from the closest equipment dealer.

Useful life (depreciation period). Useful life in this analysis refers to the economical life of the machine rather than its mechanical life. As loans for purchasing new harvesting equipment are typically paid off over 60 or fewer months, maximum useful life (depreciation period) is assumed to be five years. However, useful life is also assumed to be limited by the machine operating hours, and thus machine life can be shorter than five years when the machine is intensely used.

Salvage value. In reality, a machine's salvage value depends not only on the condition of the machine, but also on the market's demand for used machines. Because it is difficult to estimate true machine salvage values, the analysis simply assumes the salvage value to be 20% of the purchase price.

Average annual investment ($/yr). Average annual investment (AAI) is calculated using the formula below. It is used solely for the purpose of calculating the interest paid on borrowed money and the cost of insuring the equipment. However, it is an approximation and thus may not be the same as calculations made by commercial banks for business loans.

$$AAI = \frac{purchase\ price + salvage\ value}{(2)}$$

Interest on investment. Calculation of interest on investment is based on the average annual investment and an assumed interest rate of 15.5% (prime lending rate + 2%). The rate was obtained from two different commercial banks as the typical rate for small business loans (October 1989).

Insurance on equipment. The analysis assumes the insurance on equipment to be 3% of the average annual investment.

Repair costs (parts and labour). There are no accurate long-term repair costs, nor is there a reliable method for accurately predicting the repair costs of timber-harvesting machines in different operating conditions. The analysis assumes the repair cost to be 80% of the machine purchase price over its full mechanical life (in OMH). As this rule of thumb typically assumes that repairs are done by mechanics (rather than operators or machine owners), calculated repair costs in this analysis may be significantly higher than what actually would occur in a well-run contractor operation where the contractor's own time is not usually considered "chargeable" to the machine.

Fuel consumption and fuel cost. Fuel consumption is assumed to be 0.30 L/kW of average engine output. Average engine output was assumed to be 80% of the continuous engine rating for the feller-buncher and the bulldozer, 75% of the continuous engine rating for the grapple skidder, and 70% of the continuous engine rating for the roadside processor.

The cost of fuel was assumed to be $0.36/L.

Oil/lube consumption and cost. Oil and lube consumption is assumed to be 6% of fuel consumption for the feller-buncher and roadside processor, and 4% of fuel consumption for the grapple skidder and the bulldozer. Oil and lube cost per litre is assumed to be six times that of the fuel cost per litre, i.e. $6 \cdot 0.36 = \$2.16$.

Operator wages. The analysis assumes that all operators are paid an hourly wage of $18/SMH, with no allowance for night shift operations or overtime.

Fringe benefits. The analysis assumes fringe benefits to be 25% of the operator's wage. This is assumed to include the worker's transportation or camp costs.

In-shift utilization. Although in-shift utilization is likely to vary with scheduling (e.g. single-shift operation versus double-shift operation), insufficient data does not allow the analysis to show such differentiation. Therefore, the analysis assumes the following levels of utilizations, regardless of scheduling; feller-bunchers 74%; grapple skidders 81%; road-side processors 76%; used bulldozer 76%; new bulldozer 81%.

Table II-A. Machine Costs: Summary [a]

Cost component	Feller-buncher	Grapple skidder	Denis processor	Steyr KP40 processor	Caterpillar D7 bulldozers New	Caterpillar D7 bulldozers Used
Depreciation ($/OMH)	26.40	17.80	23.90	22.50	36.50	45.00
Interest on investment ($/OMH)	17.40	11.80	15.80	14.70	23.60	24.60
Insurance ($/OMH)	3.40	2.30	3.10	2.80	4.60	4.80
Repair ($/OMH)	20.70	13.10	22.30	20.10	29.20	30.00
Fuel ($/OMH)	8.60	5.80	7.60	7.60	12.10	12.10
Oil and lube ($/OMH)	3.10	1.40	2.70	2.70	2.90	2.90
Operator wages ($/OMH)	24.30	22.20	23.70	23.70	22.50	23.70
Fringe benefits ($/OMH)	6.10	5.60	5.90	5.90	5.60	5.90
Total charge-out rate ($/OMH)	110.00	80.00	105.00	100.00	137.00	149.00

[a] Showing purchase prices and interest rates in effect October 1989.