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Björn Andersson, M.Sc.FE, P.Eng.

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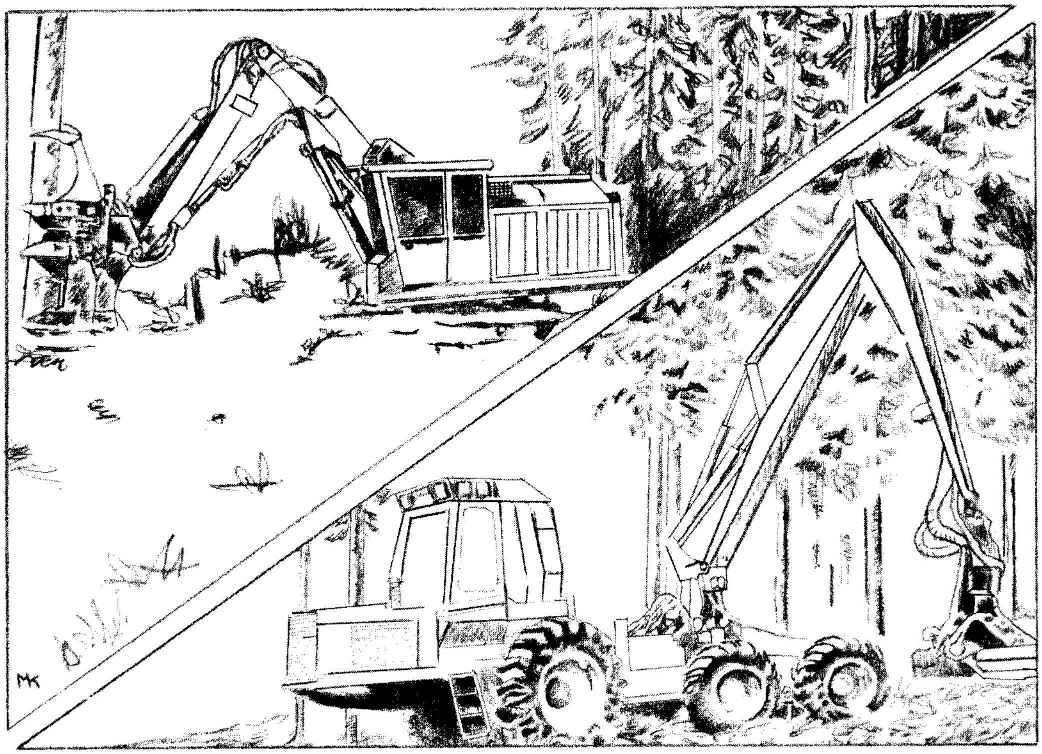

Technical Report

TR-108

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Abstract

In the fall and winter of 1990/91, the Forest Engineering Research Institute of Canada (FERIC) evaluated the relative advantages and disadvantages of cut-to-length and tree-length harvesting systems clearcutting stands of small-diameter softwood in Central Alberta.

FERIC monitored the performance of Koehring 618 feller-bunchers, Timberjack 480 grapple skidders, and Denis 2000 stroke delimbers in a tree-length operation, as well as Rottne single- and double-grip harvesters, and Rottne forwarders working in a cut-to-length operation. The field data provided the input for determining the projected costs of these harvesting systems in stands where merchantable tree volume averaged between 0.10 to 0.40 m^3/tree.

The report examines the influence of the harvesting system on machine productivity and fibre recovery, and identifies key factors influencing the choice of system. Cost and productivity of two truck delivery systems—tree-length trucks with separate log loaders, and self-loading cut-to-length trucks—are also discussed.

Author

Björn Andersson obtained B.Sc.FE (1973) and M.Sc.FE (1989) degrees from the 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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Disclaimer

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Summary

In the fall of 1990, the Forest Engineering Research Institute of Canada (FERIC) undertook a project to compare cut-to-length and tree-length harvesting systems clearcutting stands of small-diameter conifer in Central Alberta. The objective of the study was to provide FERIC's members with cost and productivity information pertinent to selecting a harvesting system. It included evaluations of both the harvesting and the transportation phases, as well as post-harvest site assessments.

Field data were collected on Millar Western Industries' operations north of Swan Hills, Alberta. Differences in the stand characteristics of the tree-length and cut-to-length study sites reflected the company's policy to allocate stands of larger diameter trees for tree-length harvesting, and stands of smaller diameter trees for the cut-to-length method. The difference in stand characteristics necessitated the extrapolation of field data beyond the observed range in the analytical comparison of systems.

In the tree-length system, trees were felled by Koehring 618 feller-bunchers equipped with Koehring saw heads, and skidded to roadside with Timberjack 480 grapple skidders. Delimbing was done by Denis 2000 stroke delimbers mounted on Komatsu LC200 carriers. The tree-length stems were then delivered to the mill at Whitecourt by 5-axle tractor/pole trailer configurations. Loading and unloading were done by separate log loaders.

In the cut-to-length system, trees were felled and processed into short logs by Rottne Rapid EGS 85 single-grip and Rottne/Snoken 860 double-grip harvesters. The short logs were forwarded to roadside with Rottne 10-t and 14-t forwarders. Self-loading 5- and 6-axle tractor/semi-trailers, and self-loading 7-axle Swedish-style truck/full-trailer configurations delivered cut-to-length logs to the mill.

The tree-length harvesting system averaged 137 m^3/man-day while operating in a stand averaging 0.52 m^3/tree and 428 m^3/ha. The machines in the tree-length operation were utilized between 79 and 87% of their scheduled work time. The productivities of the feller-bunchers and the delimbers increased with an increase in average tree size (m^3/tree), but at different rates; the delimbers, which processed most stems individually, were more affected by tree size than the feller-bunchers, which utilized their accumulating capability in small trees. Consequently, the difference in productivities of the feller-bunchers and the delimbers increased with tree size. The productivity of the grapple skidders was primarily influenced by average extraction distance, but also by tree size; average load size per turn increased with an increase in tree size.

The cut-to-length harvesting system averaged 40.6 m3/man-day in a stand averaging 0.22 m^3/tree, and 234 m^3/ha. The machines were operationally utilized between 69 and 74% of their scheduled work time. Harvester productivity varied with average tree size (m^3/tree), and the ratio of unmerchantable-to-merchantable trees in the stand, while forwarder productivity was influenced by average extraction distance and the volume of wood in the log piles (m^3/pile) created by the harvesters.

The lower level of fibre utilization in the tree-length operation compared to the cut-to-length operation occurred because fewer bonus trees (as defined by FERIC) were recovered in the former operation. This result is attributed to a difference in payments to operators, and the impact of short stems on the subsequent log-hauling operations between the tree-length and cut-to-length systems. Consequently, most bonus trees (dbh 10-13 cm) were discarded by the delimber, although a substantial amount of such trees had been felled and bunched, and skidded to roadside. Therefore, neither the feller-bunchers nor the grapple skidders were credited with all the wood they actually produced in small-diameter stands.

On the other hand, the Rottne EGS 85 and Rottne/Snoken 860 harvesters working in the cut-to-length operation recovered most of the bonus trees. As a result, the cut-to-length system had a higher fibre recovery level than the tree-length system, but at the expense of reduced machine productivity and higher operating cost; a high level of bonus tree recovery reduces average tree size handled, and thus machine productivity.

FERIC's baseline harvesting analysis assumed an annual quota of 100 000 m^3; average tree sizes of 0.10, 0.20, 0.30, and 0.40 m^3/tree; and a 100-m average extraction distance. The systems were assumed to operate on a single-shift basis, 180 days/year. The analysis projected that the tree-length system would produce *tree-length stems* at roadside for less cost than the single-grip and the double-grip harvester systems would produce *short logs* at roadside. Higher extraction costs associated with the cut-to-length systems especially in small wood, was a major contributing factor to the overall cost difference. The cut-to-length system with the double-grip harvester generally fared more poorly in FERIC's analysis. However, the impact on system cost from factors such as wood fibre recovery, number of operating days per year, and extraction distance, differed between systems. Therefore, it is difficult to make general statements on system suitability that cover all harvesting conditions. Instead, system comparison must be made for each situation.

At a 200-m average skidding distance, the cost of the single-grip harvester system was projected to be lower than that of the tree-length system because productivity

of the forwarders is influenced less by the extraction distance than are the grapple skidders.

Results from the post-harvest site assessments showed that the tree-length sites contained more logging residue and merchantable wood fibre, and had higher road density and site disturbance than did the cut-to-length sites. However, assessment data were too limited to draw general conclusions about the differences.

Delivery of tree-length stems with 5-axle tractor/trailers and separate log loaders for loading and unloading was found to be more cost effective than delivery of cut-to-length logs (3.6-5.0 m) with self-loading 5- and 6-axle tractor/semi-trailers. Higher payloads of the tree-length trucks were the main reason, but faster loading and unloading times with separate log loaders also contributed to the difference.

The high payload capacity of the self-loading 7-axle truck/full-trailer units made these units very cost competitive with tree-length trucks for delivering shortwood from stands averaging 0.22 m^3/tree.

Besides tree size, the cost of the tree-length haul was found to be affected by the truck-to-loader ratio.

While the study was able to identify some operating factors that either adversely or favourably affected the cut-to-length and tree-length 'stump-to-mill' operations, more information is needed to determine the operating conditions under which each system best performs.

Sommaire

À l'automne 1990, l'Institut canadien de recherches en génie forestier (FERIC) entreprit un projet dans le but de comparer des systèmes de récolte en bois tronçonnés et en troncs entiers, pour la coupe rase de peuplements résineux de faible diamètre dans le centre de l'Alberta. L'étude avait pour objectif de fournir aux membres de FERIC des données de coût et de productivité en vue de la sélection d'un système de récolte. Elle comprenait des évaluations des phases de récolte et de transport ainsi que des conditions du site après coupe.

Les données de terrain furent recueillies dans les opérations forestières de Millar Western Industries au nord de Swan Hills, Alberta. Les différences dans les caractéristiques des peuplements, entre les sites récoltés par troncs entiers et ceux qui étaient récoltés en bois tronçonnés, reflètent la politique de la compagnie d'allouer les peuplements d'arbres de plus grand diamètre pour la récolte en troncs entiers, et les peuplements d'arbres de plus faible diamètre pour la coupe en bois tronçonnés. La différence dans les caractéristiques des peuplements a nécessité l'extrapolation des données de terrain au-delà de la gamme observée, lors de l'analyse comparative des systèmes.

Dans la méthode de récolte en troncs entiers, les arbres étaient abattus par des abatteuses-groupeuses Koehring 618 équipées de têtes d'abattage à scie Koehring, et débardés en bordure de route par des débardeurs à grappin Timberjack 480. L'ébranchage était effectué par des ébrancheuses à flèche Denis 2000 montées sur des châssis porteurs Komatsu LC200. Les troncs entiers étaient ensuite livrés à l'usine de Whitecourt par des ensembles grumiers à 5 essieux constitués d'un tracteur routier et d'une remorque à poutre télescopique. Des chargeuses séparées procédaient au chargement et au déchargement.

Dans la méthode de récolte en bois tronçonnés, les arbres étaient abattus et façonnés en bois courts par des abatteuses-façonneuses à tête multifonctionnelle Rottne Rapid EGS 85 et des abatteuses-façonneuses à deux têtes Rottne-Snoken 860. Les bois courts étaient acheminés en bordure de route au moyen de porteurs Rottne de 10 et de 14 tonnes. Ils étaient ensuite livrés à l'usine par des ensembles autochargeurs tracteur semi-remorque à 5 et à 6 essieux et par des ensembles autochargeurs à 7 essieux de style suédois, constitués d'un camion porteur et d'une remorque classique.

Le système de récolte en troncs entiers produisait en moyenne 137 m^3/jour-homme, dans un peuplement, présentant en moyenne 0,52 m^3/arbre et 428 m^3/ha. Dans cette opération, les machines étaient utilisées entre 79 et 87 % du temps de travail prévu. La productivité des abatteuses-groupeuses et celle des ébrancheuses augmentaient avec l'accroissement du volume moyen des arbres (m^3/arbre), mais à des taux différents; les ébrancheuses, qui façonnaient la plupart des tiges une à la fois, étaient plus affectées par le volume des arbres que les abatteuses-groupeuses, qui avaient recours à leur fonction collectrice dans les arbres de faible diamètre. Par conséquent, la différence entre la productivité des abatteuses-groupeuses et des ébrancheuses augmentait avec le volume des arbres. La productivité des débardeurs à grappin était d'abord influencée par la distance moyenne de débardage, mais aussi par le volume des arbres; en effet, le volume moyen de la charge par voyage augmentait avec l'accroissement du volume par arbre.

Le système de récolte en bois tronçonnés produisait en moyenne 40,6 m^3/jour-homme dans un peuplement présentant en moyenne 0,22 m^3/arbre et 234 m^3/ha. Les machines étaient utilisées de façon opérationnelle entre 69 et 74 % du temps de travail prévu. La productivité des abatteuses-façonneuses variait avec le volume moyen

des arbres (m^3/arbre) et le rapport entre les arbres non marchands et les arbres marchands dans le peuplement, alors que la productivité des porteurs était influencée par la distance moyenne de débardage et le volume de bois dans les piles de billes (m^3/pile) formées par les abatteuses-façonneuses.

Le taux inférieur d'utilisation de la fibre dans l'opération de récolte en troncs entiers comparativement à l'opération de récolte en bois tronçonnés provenait du fait que, dans le premier cas, on récupérait un moins grand nombre d'arbres-primes (tels que définis par FERIC). C'était là le résultat d'une différence dans les salaires payés aux opérateurs et dans l'effet des bois courts sur les opérations subséquentes de transport, entre les méthodes par troncs entiers et par bois tronçonnés. Par conséquent, la plupart des arbres-primes (10-13 cm au dhp) étaient rejetés par l'ébrancheuse même si un nombre substantiel de ces arbres avaient été abattus et groupés, puis débardés en bordure de route. Les abatteuses-groupeuses et les débardeurs à grappin ne recevaient donc pas le crédit pour tout le bois qu'ils avaient réellement produit dans les peuplements de faible diamètre.

Par ailleurs, les abatteuses-façonneuses Rottne EGS 85 et Rottne/Snoken 860 qui travaillaient dans l'opération de coupe en bois tronçonnés récupéraient la plus grande partie des arbres-primes. La méthode de coupe en bois tronçonnés avait donc un rendement en fibre supérieur à la méthode en troncs entiers, mais au prix d'une baisse de productivité des machines et d'un coût de fonctionnement plus élevé; la récupération d'un grand nombre d'arbres-primes contribue à réduire le volume moyen des arbres traités et, par suite, la productivité des machines.

Les hypothèses posées par FERIC pour l'analyse des données de récolte étaient les suivantes: un volume annuel de coupe de 100 000 m^3; des arbres ayant un volume moyen de 0,10, 0,20, 0,30 et 0,40 m^3/arbre; et une distance moyenne de débardage de 100 mètres. Le travail devait se faire à raison d'un seul poste par jour, 180 jours/an. Les résultats de l'analyse prévoyaient que la production de troncs entiers en bordure de route par le système de récolte en troncs entiers coûterait moins cher que la production de bois courts en bordure de route par les systèmes utilisant des abatteuses-façonneuses à tête multifonctionnelle et à deux têtes. Les coûts d'extraction plus élevés liés aux systèmes de récolte en bois tronçonnés, particulièrement dans le petit bois, étaient un facteur majeur qui contribuait à la différence globale de coût. Le système de coupe en bois tronçonnés avec l'abatteuse à deux têtes donnait généralement de moins bons résultats dans l'analyse de FERIC. Cependant, l'effet sur le coût des systèmes de facteurs tels que le rendement en fibre ligneuse, le nombre de jours de travail par année et la distance d'extraction, différaient d'un système à l'autre. Il est par conséquent difficile de faire des affirmations générales sur l'acceptabilité des systèmes, qui couvrent toutes les conditions de récolte. On doit plutôt comparer les systèmes dans chaque situation.

À une distance moyenne de débardage de 200 mètres, l'analyse prévoyait que le coût du système utilisant une abatteuse-façonneuse à tête multifonctionnelle serait inférieur à celui du système de récolte en troncs entiers parce que la productivité des porteurs est moins influencée par la distance d'extraction que ne le sont les débardeurs à grappin.

Les résultats des évaluations du site après coupe montraient que les sites récoltés en troncs entiers contenaient plus de résidus d'exploitation et de fibre marchande, et que la densité des routes et la perturbation du site y étaient plus élevées que sur les sites de coupe en bois tronçonnés. Cependant, les données d'évaluation étaient trop limitées pour permettre de tirer des conclusions générales au sujet de ces différences.

La livraison de troncs entiers au moyen de tracteurs-remorques à 5 essieux et de chargeuses séparées pour le chargement et le déchargement se révéla plus rentable économiquement que la livraison de billes tronçonnées (3,6-5,0 m) au moyen de tracteurs semi-remorques autochargeurs à 5 et à 6 essieux. La charge utile plus élevée des camions de troncs entiers en était la principale raison, mais les temps de chargement et de déchargement plus rapides avec des chargeuses séparées contribuaient aussi à la différence.

La capacité élevée de charge utile des ensembles autochargeurs à 7 essieux, camion porteur et remorque classique, rendait ces unités très compétitives au point de vue du coût avec les camions de troncs entiers, pour la livraison des bois courts provenant de peuplements ayant un volume moyen de 0,22 m^3/arbre.

Outre le volume, on constata que le coût du transport des troncs entiers était affecté par le rapport camion-chargeuse.

Bien que l'étude ait permis de reconnaître certains facteurs opérationnels qui affectent positivement ou négativement les opérations directes de récolte en troncs entiers et en bois tronçonnés entre le parterre de coupe et l'usine, de plus amples renseignements sont requis pour déterminer les conditions de fonctionnement dans lesquelles chaque système donne les meilleurs résultats.

INTRODUCTION

In the fall of 1990, the Forest Engineering Research Institute of Canada (FERIC) undertook a study to compare tree-length and cut-to-length forest operations clearcutting conifer stands in Central Alberta. The tree-length operation employed feller-bunchers, grapple skidders, roadside stroke delimbers, hydraulic log loaders, and 5-axle tractor/trailer logging trucks, while the cut-to-length operation used Scandinavian-type single-grip and double-grip harvesters, forwarders, and self-loading log trucks of different axle configurations.

The study originated from increasing interest among FERIC's Western members in using cut-to-length systems to harvest stands with small-diameter trees, as an alternative to the predominately used tree-length systems. Advocates of cut-to-length harvesting systems point to claims of increased fibre recovery, more efficient long-distance off-road extraction, and reduced site disturbance in comparison to tree-length systems. On the other hand, processing stems into short logs at the stump area reduces piece size of the wood to be handled in the subsequent extraction and delivery phases of the operation, thereby potentially increasing the direct operating costs.

The objectives of the study were to: measure and present data on productivity, cost, fibre recovery, and post-harvest site impact of tree-length and cut-to-length forest operations; identify factors influencing machine performances; quantify the systems' relative advantages and disadvantages; and present results of a cost analysis for harvesting stands of small- to medium-sized trees.

The project was partially funded by the Forest Industry Development Division of the Alberta Department of Forestry, Lands and Wildlife, and carried out in cooperation with Millar Western Industries Ltd., L & M Custom Log Works, and Rocan West, all of Whitecourt, Alberta.

Millar Western was the first forest company in Alberta to introduce Scandinavian-type cut-to-length harvesters and forwarders to its timber supply operations in an effort to reduce wood cost and improve fibre recovery in stands with trees averaging <0.25 m^3/tree (Wakelin 1991). Initially, harvesting was done by a contractor with experience in Sweden and Eastern Canada, but the company also gradually set up its own cut-to-length operation. In 1990, the company and the contractor operations, together employing seven harvesters and four forwarders, harvested 17% (150 000 m^3) of Millar Western's annual cut; the remaining volume, 750 000 m^3, was harvested by tree-length contractors employing a total of six feller-bunchers, seven grapple skidders, and ten roadside delimbers.

SITE DESCRIPTIONS

The study was carried out at three locations in Central Alberta (Figure 1). At House Mountain, FERIC monitored a contractor tree-length harvesting operation and the subsequent delivery of the tree-length stems to Millar Western's mill yard in Whitecourt. At Deer Mountain, FERIC monitored a company cut-to-length harvesting operation and the subsequent delivery of the short (cut-to-length) logs to the mill yard. Also monitored at Deer Mountain was a tree-length delivery operation from a cutblock adjacent to the cut-to-length study site. At Goose Mountain, FERIC collected short-term productivity data on single-grip and double-grip harvesters at a contractor operation, and monitored the delivery of short logs to Whitecourt.

Table 1 shows the average stand characteristics at the study sites. The tree-length harvesting site at House Mountain contained larger merchantable trees, more volume per hectare, and proportionally fewer saplings than the cut-to-length block at Deer Mountain. In addition, the relationship of tree heights to tree dbh was different; trees at House Mountain were taller, and hence contained more merchantable fibre per tree for any given dbh class. The differences in the stand characteristics of the House Mountain and Deer Mountain sites reflect the

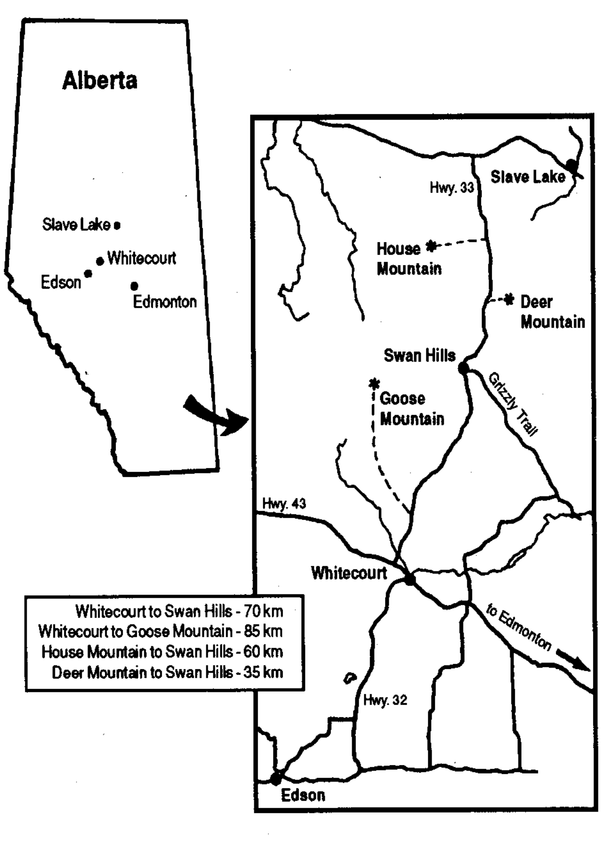

Figure 1. Locations of study sites.

Table 1. Average Stand Characteristics of the Cutblocks

	Harvesting system and location			
	Tree-length		Cut-to-length	
	House Mountain	Deer Mountain[a]	Deer Mountain	Goose Mountain
Area (ha)	50.1	55.7	69.2	52.8
Species composition	$Pl_6Sb_2At_1$	Pl_6Sb_4	Pl_6Sb_4	Sb_8Bf_2
Merchantable tree dbh (cm)	25.5	20.6	20.2	20.5
Total tree height (m)	23.6	18.8	18.2	16.4
Merchantable tree height (m)	18.0	13.3	12.6	10.2
Trees/ha (no.)	820	1050	1060	720
Snags/ha (no.)	120	130	140	80
Volume				
m^3/tree	0.52	0.24	0.22	0.18
m^3/ha [b]	428	252	234	131

[a] Only the log-hauling operation was monitored.
[b] Does not include potential volume from snags.

company's policy to primarily allocate stands of larger diameter trees for tree-length harvesting, while stands of smaller diameter trees are harvested with the cut-to-length method.

Terrain conditions were similar on all cutblocks; i.e. mostly flat or slopes <10%, but sections of steep ground up to 25% slope occurred. All blocks had small areas of soft ground; but, because most of the cut-to-length sites were harvested when the ground was frozen, operating on soft ground conditions was not an issue in the cut-to-length studies.

Gravelled all-weather roads, owned by oil-exploration companies, provided access to the vicinity of the harvesting sites. Single-lane access roads to, and on, individual cutblocks were built by Millar Western, using mainly local material. These access roads were scheduled to be reclaimed after the timber had been removed.

SYSTEM DESCRIPTIONS

Tree-Length Harvesting and Transportation

The tree-length harvesting operation consisted of two identical machine groups, each with one Koehring 618 feller-buncher equipped with a Koehring continuous high-speed saw head, one Timberjack 480 grapple skidder, and one Denis 2000 stroke delimber mounted on a Komatsu LC200 carrier. The groups worked independently of each other, and the wood produced by each group was scaled separately at roadside. The tree-length operation also included one Komatsu bulldozer for removing stumps from haul road right-of-ways, and one standby Clark 667 grapple skidder that was used when one of the Timberjack skidders was mechanically unavailable or when skidder production fell behind that of the feller-bunchers or delimbers.

Cutblock boundaries and future haul roads were marked prior to harvesting. The feller-buncher operators informally divided the block into two sides—one for each machine group. Typically, felling started along a cutblock boundary with the felling passes in an orientation parallel to the closest haul road. The felled stems were bunched with their butts facing the road. This felling pattern left the area for the haul roads free from stems, allowing the road area to be 'stumped' before skidding commenced.

The time lag between the felling and grapple skidding phases was about one week. Full-tree stems could be decked along almost any portion of the haul road, and consequently, most skidding was done in straight lines to the closest haul road (Figure 2). Stems bunched near haul roads were often not skidded; rather, they were just pushed together by the skidder. However, the volume of these stems was included in the skidders' production.

The time lag between the skidding and delimbing phases was about one week. The delimbers worked on the road surface, processing stems first along one side of the road; they then turned around, and processed the stems on the other side. Full-tree stems were picked up, delimbed, and decked on top of the slash on the same side of the road. Most stems, even small ones, were delimbed individually, as the company insisted on good delimbing quality and minimum merchantable fibre losses.

Figure 2. Tree-length harvesting site.

The machines in the tree-length harvesting operation worked on a single-shift basis, five or six days per week. The crew of six machine operators and a 'ground man' was usually at the work site for about 10 h/day; scheduled work time included machine start-up, meal/coffee breaks, daily machine services, and fuelling. Major services and repairs were done by a mechanic/foreman, often during non-scheduled work time. Payments to the operators were based on volume delivered to the mill.

The tree-length delivery operation employed two Caterpillar 235C log loaders for loading trucks in the bush, a logging truck fleet of about thirty 5-axle tractor/trailers for transporting tree-length stems to the mill at Whitecourt, and two overhead Krano Portal cranes for unloading trucks and for feeding the tree-length merchandising deck in the mill yard. An on-site grader maintained roads, and removed snow on the bush roads.

The company's annual hauling period was about 70 days during the winter, during which hauling was under way 24 h/day from noon on Sunday until Friday evening. Hauling was not possible on weekends because the Portal cranes were scheduled for service at this time.

The two Caterpillar 235C loaders each served about half the truck fleet. The loaders usually operated well apart from each other to minimize traffic congestion on the single-lane roads to and from the loading sites. However, the loaders were close enough that log trucks could quickly be redirected from one loading site to the other.

Cut-to-Length Harvesting and Transportation

The company operation at Deer Mountain consisted of two Rottne Rapid EGS 85 single-grip harvesters, one Rottne Rapid Snoken 860 double-grip harvester, and two Rottne Rapid forwarders—one with a payload capacity of 10 t and the other 14 t.

Cutblock boundaries and future haul roads were marked prior to harvesting, but no formal operating boundaries existed inside the cutblock between the areas felled with the single- and double-grip harvesters; the decision was left to the operators. Usually, though, the double-grip harvester cut the areas with the biggest trees.

Typically, the harvesters first cut a section of the road right-of-way, then moved to cut the area at the side of the road. The direction of the harvesters' felling passes, relative to the nearest road, varied from perpendicular to parallel. The trees were felled and processed into fixed-length saw logs (target lengths were 3.78 m, 4.47 m, and 5.02 m) with a minimum diameter of 10 cm, and random-length pulpwood bolts (3.6 to 5.1 m) with a minimum diameter of 5 cm. Generally, the harvesters and forwarders did not sort saw logs from pulpwood bolts.

The forwarders generally travelled along the same trail created by the harvesters, and loaded logs from only one side of the machine. The wood was, therefore, not always forwarded the shortest distance to the road, nor was the distance the loaded forwarders had to travel minimized. Also, most roads had not been built or stumped prior to forwarding, so the operators decked the logs where they assumed the edge of the future road to be (Figure 3).

The machines at the company operation at Deer Mountain worked on a single-shift basis, five days per week. The crew, consisting of five machine operators, a trainee (on the forwarder), and a mechanic, was on the site for approximately 10 h/day; scheduled work time included machine start-up, coffee/meal breaks, daily machine service, and fuelling. Most equipment repairs were done during the regular scheduled shifts, while major services often were done on non-scheduled work days (weekends). Crew members were paid on an hourly basis.

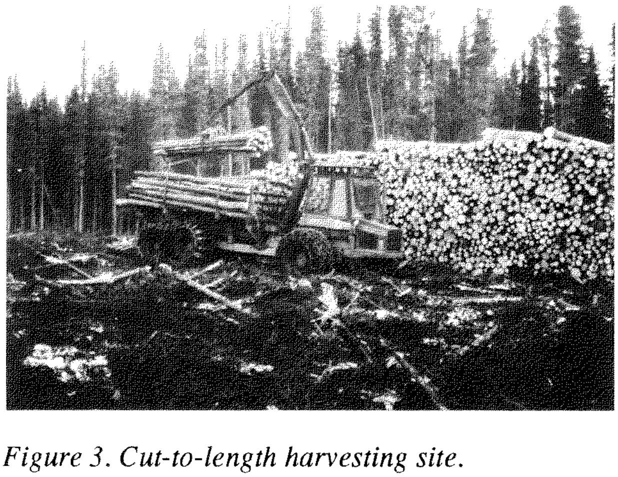

Figure 3. Cut-to-length harvesting site.

Logs from the cut-to-length operations were delivered to Millar Western's Whitecourt mill by a small fleet (4-6 units) of contractor-owned self-loading trucks. Configurations included 5-axle and 6-axle tractor/semi-trailers (highboys) with the loader mounted at the mid-section of the trailers, and 7-axle Swedish-style truck/full-trailers (Cox 1992) with the loader mounted on the rear section of the truck frame (Figure 4). The work schedule and the number of shifts per day of the shortwood trucks depended on whether one or two drivers were assigned to the trucks. However, they worked independently of the unloading equipment at the mill yard, and thus could deliver wood to the mill any day of the week.

STUDY METHODS

All data were collected on Millar Western's regular operations. No changes were made to normal layout patterns, cutblock selections, fibre recovery standards, or operator work habits to accommodate the studies.

Road Development. All roads were traversed using a compass and a hip-chain after harvesting had been completed. Locations of roadside log decks were also recorded. The data were then transferred to the cutblock maps for analysis.

Harvesting Studies. Field data on the tree-length and cut-to-length harvesting operations were collected during September/October 1990, and during October 1990 to February 1991, respectively. Productivity data on the cut-to-length harvesters from a pilot study in July 1989 near Swan Hills were also included in the reporting of study results.

Figure 4. Self-loading Swedish-type truck/full-trailer.

Servis Recorders were used to record in-shift operating and non-operating times of the machines in the tree-length and cut-to-length operations at House Mountain and Deer Mountain, respectively. Because the Servis Recorders used do not differentiate between productive time and non-productive time,[1] the term Operating Machine Hours (OMH) was used to denote the total time the machines were in motion. OMH also included all delays that were <15 min/occurrence.

Reasons for major delays (>15 min/occurrence) were obtained from the operators. In addition, all operators (except those on the grapple skidder) reported their daily production; tree counts for feller-bunchers, delimbers, and harvesters, and load counts for forwarders.

Detailed-timing studies were done on all machines at the House Mountain and Deer Mountain operations, and on cut-to-length harvesters at the Goose Mountain contractor operation. Each study consisted of three parts; a pre-harvest assessment to determine the operating conditions; a detailed timing study that included timing various machine activities, and a tally of stems that were recovered, discarded, and broken; and, a post-study assessment of the site to determine the quality of work performed, the size and volume of recovered stems (or logs), and the conditions created for the subsequent phase in the operation.

The machine productivities determined in the detailed-timing studies are based on the of volume of recovered logs (cut-to-length system), or stems (tree-length system), and expressed in m^3/productive machine hour (PMH). PMH includes all activities required for the machine to fulfil its task, but excludes delays and non-essential activities.

Wood volume was separated into two components: merchantable and bonus wood. Merchantable wood was defined according to the standards of the Alberta Forest Service[2] (1987), which for coniferous trees included those with a minimum of 13.6-cm dbh, top diameter of 10 cm, and length of 4.9 m. Bonus wood was defined by FERIC as the additional fibre recovered from trees with a minimum dbh of 10 cm, top diameter of 5 cm, and length of 3.5 m.

Log-Hauling Studies. Data on the log-hauling phases were collected in January 1991 from tree-length and cut-to-length operations, and in January/February 1992 from

[1] Non-productive time includes moving to/from the actual working sites, and assisting other machines.

[2] Now called Alberta Environmental Protection, Land and Forest Services Division.

cut-to-length operations.[3] Information on load size and cycle times were obtained from the company's weigh-scale records and from tachograph cards, while detailed-timing techniques were used to establish times for the loading and unloading phases.

Post-Harvest Assessment. Post-harvest wood waste and site disturbance assessments of all the study sites were undertaken in May 1991 based on survey guidelines published by the British Columbia Ministry of Forests (1989).[4] In addition, a tree-length cutblock adjacent to the cut-to-length site at Deer Mountain was included in the assessment because its pre-harvest stand characteristics and time of harvest were similar to the cut-to-length site.

System Comparison. The cost and productivity of the tree-length and cut-to-length harvesting systems were analytically determined for harvesting stands with average tree volumes of 0.10, 0.20, 0.30, and 0.40 m^3/tree. The baseline analysis assumed an annual harvesting quota of 100 000 m^3, an operating period of 180 days/y and an average extraction distance of 100 m. A sensitivity analysis was used to test the impact on overall system cost by varying machine utilization, annual production, number of operating days per year, and average extraction distance.

The machine productivities used in the analysis are based on mathematical relationships of merchantable tree size (m^3/tree) and machine productivity as established from detailed-timing studies (Appendix I). Similar relationships were also developed to determine the impact on fibre recovery for stands with different tree sizes. However, FERIC extrapolated these mathematical relationships beyond the range in which field data were collected. Great care was exercised in making the projected results as probable as possible, but the fact remains that extrapolation reduces prediction accuracy.

The analysis of the tree-length and short log (cut-to-length) delivery systems used actual recorded data for average payload, and loading and unloading terminal times, but assumed values for truck driving speeds.

Hourly machine ownership and operating costs for the equipment used in tree-length and cut-to-length harvesting, and log-hauling systems were determined analytically. These costs do not include supervision, profit, and overhead, and are not the actual costs of the operations.

[3] About 82% (10 280 m3) of the volume felled during the 1990/91 harvesting study was transported to the mill during the 1991/92 hauling season.

[4] A new edition has since been published.

RESULTS

Road Development

The amount of road constructed per hectare on the tree-length blocks (93 m/ha) was more than double that on the cut-to-length block (44 m/ha). This resulted in higher road construction costs, more site disturbance, and, where applicable, road-reclamation costs. Road-construction and road-reclamation costs were estimated by Millar Western to be \$3000 and \$380/km, respectively. Thus, the cost of roads was \$314 and \$149/ha in the tree-length and the cut-to-length operations, respectively.

Harvesting Operations

Wood Fibre Recovery. Wood fibre recovery was determined in two categories—loss of merchantable wood, and gain of bonus wood—and expressed in percent of total gross merchantable wood. FERIC concluded that, overall, the cut-to-length operation recovered considerably more bonus wood than did the tree-length operation, but that little difference existed between the systems in terms of lost merchantable wood.

The lower level of bonus wood recovered by the tree-length system occurred not because tree-length machines were incapable of felling or processing small trees, but rather because many of these trees were deliberately discarded by the operators, particularly in the delimbing phase. These small stems were discarded because stems with a butt diameter <16 cm were not credited to the operation (i.e. no monetary remuneration). In addition, large quantities of stems shorter than 9 m were undesirable for tree-length log hauling.[5] On the other hand, any tree in the cut-to-length operation that could be processed into a 3.6-m log with a minimum top diameter of 5 cm was a 'recoverable' tree, and credited to the operation.

Figure 5 shows the projected fibre recovery of the tree-length systems. Loss of wood from merchantable stems increased with tree size, primarily because large stems tended to break more frequently than did small stems. Overall, the amount gained from bonus wood exceeded the amount of merchantable fibre loss when the average stem size was <0.37 m^3/stem.

FERIC's fibre analysis does not, however, include fibre losses during the skidding operation, or losses from very short sections of merchantable stems that were discarded

[5] During the winter, maximum legal GVW for the tractor/trailers hauling tree-length stems required a 7-m distance between the rear-most axle of the truck and the first axle of the trailer; a reduction in axle spacing by 1 m reduces GVW by 5000 kg; thus, log lengths shorter than 9 m were shorter than the inter-bunk spacing on the tractor/trailers.

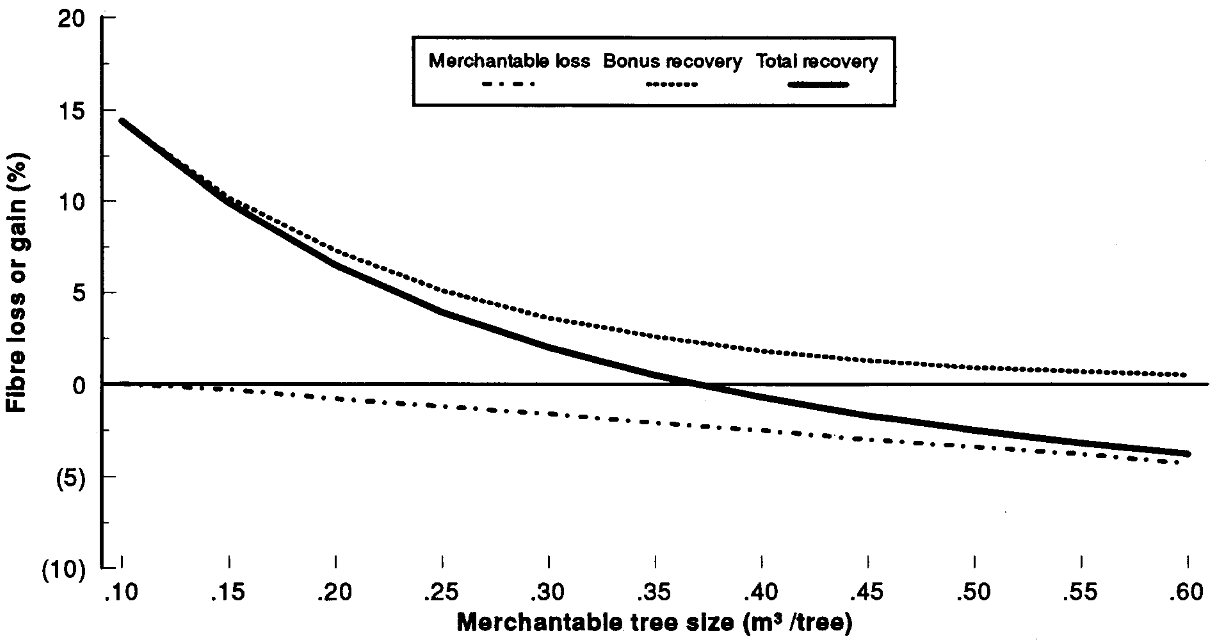

Figure 5. Projected fibre recovery of the tree-length system, as a function of merchantable volume/tree.

by the delimber. About 2% of the stems in the full-tree deck were broken sections, attributed mainly to skidders decking stems.

Harvesters determined the level of fibre recovery in the cut-to-length operations. FERIC found no evidence of fibre losses in the subsequent forwarding phase, except for logs being forgotten on the site. In the felling-processing phase, FERIC compared the number of stems recovered to the total number of standing trees, and concluded that the cut-to-length harvesters recovered substantially more trees than the total number of merchantable trees in the stand. Although FERIC could not determine what size trees were recovered and discarded, it assumed that larger trees were more likely to be recovered than smaller trees. Consequently, FERIC concluded that the harvester recovered most (>90%) of the bonus trees. However, FERIC could not quantify the added volume from bonus trees, because the origin of small logs (upper portion of merchantable trees or bonus trees) could not be determined during the post-timing sampling.

Some merchantable wood loss did occur in the cut-to-length operation, primarily from trees being topped at diameters >10 cm. FERIC estimated that 10-12% of the recovered trees were topped at diameters >10 cm, but could not quantify the loss of merchantable wood.

Machine Availability and Utilization. Machine availability and operational utilization were higher with the tree-length machines (Table 2) than with the cut-to-length machines (Table 3) mainly because more scheduled shift time was spent maintaining the cut-to-length equipment than the tree-length equipment. However, longer start-up time of the cut-to-length machines (average 37 min/shift/machine) compared to that of the tree-length machines (average 20 min/shift/machine) also contributed to the difference.

Overall System Productivity. A direct comparison of the overall productivities of the tree-length and the cut-to-length operations is not appropriate because of the difference in stand characteristics of the two harvesting sites. Also, the cut-to-length operation produced manufactured logs ready for the saw mill, while the stems produced by the tree-length operation had to be merchandised into short logs before entering the saw mill. However, overall, the tree-length operation at House Mountain produced tree-length stems at roadside at an average rate of 137 m^3/man-day or 20.6 m^3/OMH (derived from Table 2), while the cut-to-length operation at Deer Mountain produced short logs at roadside at an average rate of 40.6 m^3/man-day or 7.2 m^3/OMH (derived from Table 3). The higher production of the tree-length system is partly attributed to the larger tree size and higher road density (i.e. shorter extraction distance) of the tree-length site.

Individual Machine Productivity. The Koehring 618 feller-bunchers had the highest productivity of all ma-

Table 2. Shift-Level Performance of Tree-Length Harvesting Machines at House Mountain [a]

	Feller-bunchers	Grapple skidders [b]	Delimbers
Total shifts (no.)	31	36	42
Monitored shifts (no.)	28	28	42
Average shift time			
Scheduled (h)	9.2	8.9	9.8
Operating (h)	7.7	7.0	8.6
Major delays			
Repair (h)	0.3	0.5	0.4
Daily service (h)	0.7	0.6	0.6
Major service (h)	0.1	0.1	0.0
Nonmechanical (h)	0.4	0.7	0.2
Other/unknown (h)	<0.1	<0.1	0.0
Total major delays (h)	1.5	1.9	1.2
Machine availability [c] (%)	88	87	90
Machine utilization [d] (%)	84	79	87
Machine productivity			
Trees/OMH (no.) [e]	185	n/a	100
Trees/man-day (no.) [e]	1239	n/a	629
Delivered volume/OMH (m^3)	74.5	68.9	48.6
Delivered volume/man-day (m^3)	498.0	433.0	341.0

[a] Differences due to rounding.
[b] Includes operating time of stand-by skidder (Clark 667).
[c] Machine availability (%) = $\frac{\text{Operating + Nonmechanical + Other}}{\text{Scheduled}} \times 100.$
[d] Machine utilization (%) = $\frac{\text{Operating}}{\text{Scheduled}} \times 100.$
[e] Based on operators' daily tree count.

Table 3. Shift-Level Performance of Cut-to-Length Harvesting Machines at Deer Mountain [a]

<table>
<tr><th></th><th colspan="2">Harvesters</th><th colspan="2">Forwarders</th></tr>
<tr><th></th><th>Single-grip</th><th>Double-grip</th><th>10-t</th><th>14-t</th></tr>
<tr><td>Total shifts (no.)</td><td>148</td><td>74</td><td>72</td><td>68</td></tr>
<tr><td>Monitored shifts (no.)</td><td>133</td><td>65</td><td>63</td><td>60</td></tr>
<tr><td>Average shift time</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Scheduled (h)</td><td>9.3</td><td>9.3</td><td>9.3</td><td>9.3</td></tr>
<tr><td>Operating (h)</td><td>6.4</td><td>6.5</td><td>6.7</td><td>6.9</td></tr>
<tr><td>Major delays</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Repair (h)</td><td>1.5</td><td>0.8</td><td>0.6</td><td>0.6</td></tr>
<tr><td>Daily service (h)</td><td>1.0</td><td>1.2</td><td>1.2</td><td>1.0</td></tr>
<tr><td>Major service (h)</td><td>0.2</td><td>0.5</td><td>0.4</td><td>0.4</td></tr>
<tr><td>Nonmechanical (h)</td><td>0.3</td><td>0.3</td><td>0.4</td><td>0.3</td></tr>
<tr><td>Other/unknown (h)</td><td><0.1</td><td><0.1</td><td><0.1</td><td>0.1</td></tr>
<tr><td>Total major delays (h)</td><td>2.9</td><td>2.8</td><td>2.6</td><td>2.4</td></tr>
<tr><td>Average out-of-shift time</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Repair (h)</td><td><0.1</td><td>0.1</td><td>0.1</td><td>0.1</td></tr>
<tr><td>Major service (h)</td><td>0.4</td><td>0.4</td><td>0.2</td><td>0.2</td></tr>
<tr><td>Machine availability (%) [b]</td><td>71</td><td>72</td><td>77</td><td>79</td></tr>
<tr><td>Machine utilization (%) [c]</td><td>69</td><td>70</td><td>72</td><td>74</td></tr>
<tr><td>Machine productivity</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Trees/OMH (no.) [d]</td><td>96</td><td>46</td><td></td><td></td></tr>
<tr><td>Trees/man-day (no.) [d]</td><td>530</td><td>257</td><td></td><td></td></tr>
<tr><td>Loads/OMH (no.) [d]</td><td></td><td></td><td>1.5</td><td>1.7</td></tr>
<tr><td>Loads/man-day (no.) [d]</td><td></td><td></td><td>8.6</td><td>10.1</td></tr>
<tr><td>Delivered volume/OMH (m³)</td><td colspan="2">11.7</td><td colspan="2">18.4</td></tr>
<tr><td>Delivered volume/man-day (m³)</td><td colspan="2">65.0</td><td colspan="2">108.0</td></tr>
</table>

[a] Differences due to rounding.
[b] See footnote c in Table 2.
[c] See footnote d in Table 2.
[d] Based on operators' daily tree or load count.

chines in the study. Its overall productivity at the House Mountain site, in terms of delivered volume[6], was 74.5 m^3/OMH (Table 2). In seven detailed-timing studies, feller-buncher productivity, expressed in terms of bunched volume at the stump[7], ranged from 56.4 to 113.5 m^3/PMH[8] (Table 4). However, the bunched volume included bonus wood, much of which was discarded in the subsequent delimbing operation, and not credited to the feller-bunchers. Consequently the net productivity of the feller-bunchers would be somewhat lower than that recorded in the detailed-timing studies.

Feller-buncher productivity was influenced by the stand's average tree size (merchantable volume/tree). The presence of unmerchantable trees in the stand had little effect on the productivity because most were knocked down when the felling head was positioned around a merchantable tree.

At an estimated average skidding distance of 50 m, the overall productivity of the Timberjack 480 grapple skidders on the House Mountain site, in terms of delivered volume, was 68.9 m^3/OMH (Table 2). In five detailed timing studies, skidder productivity, in terms of decked full-tree stems at roadside, ranged from 45.4 to 129.4 m^3/PMH (Table 5). But, as in the case of the feller-bunchers, net productivity is less, due to fibre losses during the subsequent delimbing operation. Average skid distance in these studies ranged from 30 to 80 m, and are considered to be representative of the operation.

Productivity recorded in the detailed-timing studies varied because of the combined influences of skidding distance, average tree size, and ground conditions. Skidding distance was found to be the prime factor affecting productivity, because skidders' loading and unloading times were relatively short compared to their travel times.

The skidders seldom picked up more than one bunch of full-tree stems per turn; hence skidder load volume was primarily influenced by the size of the bunches created by the feller-bunchers. Typically the volume per bunch increased with an increase in the average tree size of the harvested stand. As a result, at a fixed skidding distance, grapple-skidder productivity was found to increase proportionally as the average tree size increased.

The Denis 2000 delimbers had the lowest productivity of all the machines working in the tree-length system

[6] Net volume delivered to the mill and credited to the operation.

[7] Gross merchantable and bonus volume of trees placed in bunches.

[8] Productive machine hour (PMH) excludes all delays and nonproductive machine activities.

Table 4. Detailed-Timing Studies: Koehring 618 Feller-Bunchers [a]

	Study number						
	FB 1	FB 2	FB 3	FB 4	FB 5	FB 6	FB 7
Average stand characteristics							
Merchantable trees							
Tree dbh (cm)	17.6	18.0	18.5	19.2	22.7	25.3	26.1
Total height (m)	17	17	18	20	20	21	21
Volume (m^3/tree)	0.19	0.20	0.22	0.28	0.41	0.53	0.59
Trees/ha (no.)	1630	1400	1600	1300	1140	820	600
Volume (m^3/ha)	310	280	356	364	466	435	353
Bonus trees [b] (no./ha)	780	650	890	350	180	110	210
Machine productivity [c]							
Trees/PMH (no.)	331	326	355	294	225	181	189
Bunched volume							
Merchantable (m^3/PMH)	46.4	45.6	66.4	67.7	90.7	93.0	111.7
Bonus (m^3/PMH)	11.2	10.8	7.1	8.8	2.5	3.0	1.8
Total (m^3/PMH)	57.6	56.4	73.5	76.5	93.2	96.0	113.5
Decked net volume [d] (m^3/PMH)	49.7	48.6	70.0	69.5	89.9	90.3	107.6
Average trees/cycle (no.)	4.1	4.0	2.8	2.0	1.9	1.4	1.2

[a] Differences due to rounding.
[b] Sound conifers with 10-13 cm dbh.
[c] Productive machine hours (PMH) exclude all delays and nonproductive machine activities.
[d] Estimated volume of delimbed, topped, and decked tree-length stems at roadside.

Table 5. Detailed-Timing Studies: Timberjack 480 Grapple Skidders [a]

	Study number				
	GS 1	GS 2	GS 3	GS 4	GS 5
Operating conditions					
Full-tree bunches					
Stems/bunch (no.)	17.1	4.8	5.0	5.5	4.9
Tree dbh (cm)	16.6	24.1	26.2	27.5	28.8
Volume/tree (m^3)	0.15	0.48	0.61	0.67	0.72
Average skid distance (m)	30	40	80	30	60
Average travel speed					
Empty (m/min)	77	50	59	51	68
Loaded (m/min)	71	31	55	43	66
Average load size (m^3/min)	2.0	2.2	2.9	3.8	3.7
Average turn time (min)	1.45	2.89	3.31	1.76	2.76
Machine productivity					
Stems/PMH (no.)	769	98	91	197	114
Gross volume					
Merchantable (m^3/PMH)	66.9	45.4	52.2	129.4	80.4
Bonus (m^3/PMH)	16.1	0.2	0.3	0.2	0.1
Total (m^3/PMH)	83.0	45.6	52.5	129.6	80.5
Decked net volume (m^3/PMH)	73.5	44.1	50.0	123.4	76.3

[a] Differences due to rounding.

(Table 2). On the House Mountain site, the machines averaged, in terms of delivered volume, 48.6 m^3/OMH. In areas with smaller timber, the difference in productivities between the delimbers and the feller-bunchers was proportionally higher than in areas with larger timber. This is attributed to the delimbers' tendency to consistently process single stems, while the feller-bunchers utilized their stem-accumulation capability. Consequently, proportionally more delimbing hours are needed in small timber than in large timber to balance the production of the feller-bunchers.

The delimbers' productivity in six detailed-timing studies, in terms of decked tree-length volume at roadside, ranged from 32.5 to 91.8 m^3/PMH (Table 6). The studies showed that the volume productivity of the delimbers was strongly influenced by the average merchantable volume/tree. Stem length also affected delimbing time; but, except for extreme differences in average stem length (e.g. 10 m versus 20 m), the impact of stem length on productivity was minor.

At the Deer Mountain site, the overall productivity of the Rottne Rapid harvesters, in terms of delivered volume, was 11.7 m^3/OMH (Table 3). Because the wood produced by the two types of harvesters was not scaled separately, overall productivity per harvester type could not be determined. The productivity of the Rottne Rapid EGS 85 single-grip and the Rottne Rapid/Snoken 860 double-grip harvesters, in terms of volume of processed logs at the stump, ranged from 9.1 to 24.6 m^3/PMH, and 9.1 to 19.3 m^3/PMH, respectively (Tables 7 and 8). Productivity was found to be influenced primarily by average tree size, but was also affected by the length of logs being manufactured, and by the ratio of unmerchantable-to-merchantable trees in the stand. Volume productivity (i.e. m^3/PMH) increased both with an increase in the average merchantable volume/tree, and with an increase in the average manufactured log length, but decreased with an increase in the machine time spent discarding unmerchantable trees (fell-to-waste).

The productivity of the double-grip harvesters was lower than that of the single-grip harvesters because an extra handling step was required by the double-grip harvesters to transfer felled stems to the processor unit. The transfer time typically added 0.10-0.15 min/tree to the processing cycle time. The difference in the machines' productivities should decrease with an increase in tree size, because the transfer time is relatively independent of tree size. However, this was not evident from the study results because the double-grip harvester with the experienced operator was studied only in areas with small-diameter trees.

FERIC also observed the length-measuring accuracy of the harvesters and found that 67% and 62% of the saw logs were within 4 cm of the target length for the single-

Table 6. Detailed-Timing Studies: Denis 2000/Komatsu LC200 Delimbers [a]

	Study number					
	DL 1	DL 2	DL 3	DL 4	DL 5	DL 6
Operating conditions						
Merchantable stems (%)	77	85	91	90	93	99
Bonus stems (%)	23	15	9	10	7	1
Merchantable tree dbh (cm)	18.9	22.7	23.7	24.5	24.7	30.3
Merchantable volume (m^3/tree)	0.23	0.41	0.46	0.49	0.51	0.83
Machine productivity						
Stems/PMH (no.)	143	129	127	117	108	119
Decked volume						
Merchantable (m^3/PMH)	29.9	51.4	57.3	55.2	54.2	91.7
Bonus (m^3/PMH)	2.6	0.5	1.0	0.4	0.1	<0.1
Total (m^3/PMH)	32.5	51.8	58.3	55.6	54.3	91.8
Average stems/delimbing cycle (no.)	1.28	1.00	1.04	1.01	1.05	1.00

[a] Differences due to rounding.

grip and double-grip harvesters, respectively (Figure 6). In general, the more experienced operators produced the most accurate log lengths.

Overall productivity, in terms of delivered volume, of the Rottne Rapid forwarders on the Deer Mountain site was 18.4 m^3/OMH, or about 60% higher than that of the harvesters (Table 3). A fleet of two forwarders and three harvesters therefore allowed the felling and forwarding productivities to be relatively balanced. Average forwarding distance could not accurately be determined. Based on the location of the roads on the harvesting sites, average forwarding distance must have been at least 115 m, but in reality was likely longer, because the wood was not always forwarded the shortest distance to the road.

In the detailed-timing studies, the productivity of the 10-t and 14-t forwarders, in terms of volume of logs decked at roadside, ranged from 16.1 to 25.4 m^3/PMH, and 12.1 to 33.3 m^3/PMH, respectively (Tables 9 and 10). Productivities of the 10-t and 14-t machines were similar, partly because the payload capacity of the 14-t machine was often underutilized, and partly because of the operator of the 10-t machine was more experienced than the operator of the 14-t forwarder.

Forwarder productivity varied directly with the increase in average merchantable volume/tree, and inversely with average forwarding distances. The positive effect of increased tree size on productivity results because the volume in the log piles increased with an increase in tree size, thus reducing the loading time per turn.

Post-Harvest Site Evaluation. Differences in the pre-harvest stand conditions and time of harvest of the study blocks make it difficult to draw conclusions about the impact of the different harvesting systems on post-harvest site conditions. The information presented in Table 11 is, therefore, intended only to show the results of FERIC's post-harvest site evaluation on individual cutblocks, and not to compare the impact of tree-length and cut-to-length harvesting.

The logging residue (slash) from the cut-to-length operation was distributed throughout the cutblock, but typically concentrated in rows created during the felling-processing phase. The slash load averaged 126 m^3/ha, of which 25 m^3/ha was potentially merchantable material (assumed to be any sound piece of wood with a diameter of 10 cm or more, regardless of length). About 2 m^3/ha of merchantable wood is attributed to one pile of manufactured logs not being forwarded.

Approximately half of the slash load on the tree-length sites was at roadside, and had been piled by log loaders following the log-hauling operation. Total slash load at the two tree-length sites was similar, but the Deer Mountain site had a higher content of potentially merchantable material. The latter is attributed to smaller average tree size and a higher content of bonus trees on the Deer Mountain site.

Most of the disturbance on the tree-length blocks was recorded as occurring near the roads, and was assumed to be caused by the skidders. No site disturbance was measured on the cut-to-length site because harvesting occurred when the ground was frozen and covered with snow (about 0.5 m).

Table 7. Detailed-Timing Studies: Rottne EGS 85 Single-Grip Harvesters [a]

	Study number						
	SGH 1	SGH 2	SGH 3	SGH 4	SGH 5	SGH 6	SGH 7
Average stand characteristics							
Merchantable trees							
Tree dbh (cm)	17.2	16.5	18.6	17.3	18.1	22.3	22.1
Total height (m)	14	13	15	14	14	16	17
Volume (m^3/tree)	0.14	0.12	0.19	0.15	0.16	0.33	0.34
Trees/ha (no.)	1270	1000	940	1100	1410	980	640
Volume (m^3/ha)	178	120	177	166	226	323	218
Bonus trees (no./ha)	630	1300	630	680	480	140	60
Machine productivity							
Trees/PMH (no.)	132	129	106	123	93	84	75
Logs/PMH (no.)	220	185	193	216	172	198	168
Merchantable volume (m^3/PMH)	14.7	7.8	12.9	14.5	13.7	24.4	22.2
Bonus volume (m^3/PMH)	1.1	1.3	0.8	1.1	0.5	0.4	0.2
Total (m^3/PMH)	15.8	9.1	13.7	15.6	14.2	24.6	22.4
Average logs/tree (no.)	1.67	1.43	1.82	1.75	1.85	2.36	2.24

[a] Differences due to rounding.

Table 8. Detailed-Timing Studies: Rottne/Snoken 860 Double-Grip Harvesters [a]

	Study number				
	DGH 1	DGH 2	DGH 3	DGH 4	DGH 5
Average stand characteristics					
Merchantable trees					
Tree dbh (cm)	17.0	22.1	17.3	19.0	21.5
Total height (m)	14	17	13	15	16
Volume/tree (m^3)	0.14	0.32	0.14	0.20	0.30
Trees/ha (no.)	1710	640	960	1340	1110
Volume/ha (m^3)	239	205	134	268	333
Bonus trees (no./ha)	1080	140	500	220	220
Machine productivity					
Trees/PMH (no.)	75	62	92	73	63
Logs/PMH (no.)	125	161	180	174	160
Merchantable volume (m^3/PMH)	8.8	19.0	12.1	14.8	17.7
Bonus volume (m^3/PMH)	0.3	0.3	0.9	0.5	0.5
Total volume (m^3/PMH)	9.1	19.3	13.0	15.3	18.2
Average logs/stem (no.)	1.66	2.61	1.95	2.40	2.54

[a] Differences due to rounding.

Cost Analysis of Harvesting Systems. For stands with average tree sizes between 0.10 to 0.40 m^3/tree, the tree-length system produces tree-length stems at roadside at a lower cost than the cut-to-length system produces short logs at roadside (Table 12). The cost of processing tree-length stems into logs is, however, not included in the tree-length system cost. The cooperating company estimated its merchandising cost to be \$0.45/m^3,[9] but no data were available on how this cost would vary with tree size. The cost difference between the tree-length and the single-grip harvester systems increases with larger tree size, while the difference with the double-grip harvester system decreases with larger tree size. The latter was expected because double-grip harvesters are intended to harvest larger trees than single-grip harvesters.

[9] K. Murray, Area Supervisor, Millar Western Industries Ltd., Whitecourt; personal communication, 1992.

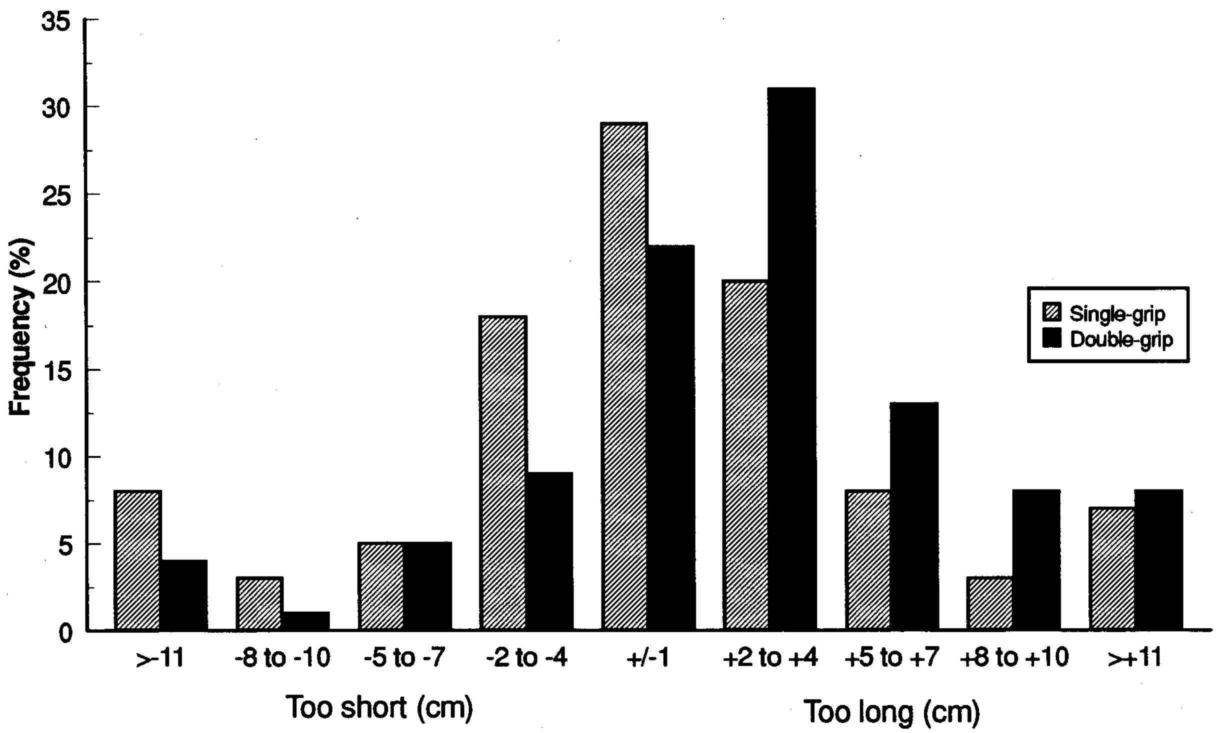

Figure 6. Length-measuring accuracy: Single- and double-grip harvesters.

Table 9. Detailed-Timing Studies: Rottne 10-t Forwarder [a]

	Study number				
	F10 1	F10 2	F10 3	F10 4	F10 5
Operating conditions					
Log piles at stump area					
Logs/pile (no.)	24.7	22.6	30.3	16.7	n/a
Volume (m^3/pile)	1.06	1.38	2.15	1.84	1.92
Merchantable tree volume (m^3/tree) [b]	0.10	0.13	0.15	0.27	0.35
Average forwarding distance					
Empty (m)	280	85	100	70	60
Loaded (m)	180	55	85	90	220
Average travel time					
Empty (m/min)	35	40	38	34	31
Loaded (m/min)	30	24	33	31	29
Average load size (m^3/turn)	8.8	10.5	9.9	9.2	12.3
Average turn time (min)	33.00	30.89	27.59	21.68	34.00
Machine productivity					
Logs (no./PMH)	374	336	303	231	169
Merchantable volume (m^3/PMH)	14.1	18.7	20.0	24.9	21.6
Bonus volume (m^3/PMH)	2.0	1.8	1.5	0.5	0.1
Total volume (m^3/PMH)	16.1	20.5	21.5	25.4	21.7

[a] Differences due to rounding.
[b] Estimated volume/tree, prior to felling.

Table 10. Detailed-Timing Studies: Rottne 14-t Forwarder [a]

	Study number							
	F14 1	F14 2	F14 3	F14 4	F14 5	F14 6	F14 7	F14 8
Operating conditions								
Log piles at stump								
Logs/pile (no.)	20	17.9	19.4	14.1	12.6	6.8	17.6	17.2
Volume (m^3/pile)	1.80	1.02	1.57	1.24	1.78	0.24	1.53	1.67
Merchantable tree volume (m^3/tree) [b]	0.20	0.12	0.17	0.19	0.43	0.08	0.19	0.22
Average forwarding distance								
Empty (m)	55	55	115	110	140	60	80	35
Loaded (m)	65	70	95	80	90	125	100	80
Average travel time								
Empty (m/min)	36	38	40	43	44	46	44	43
Loaded (m/min)	26	38	36	34	41	45	41	37
Average load size (m^3/turn)	12.6	14.2	11.0	11.5	16.0	9.2	13.6	12.2
Average turn time (min)	36.48	40.00	37.42	29.96	28.87	45.49	28.90	26.90
Machine productivity								
Logs (no./PMH)	230	375	218	261	236	346	324	281
Merchantable volume (m^3/PMH)	19.8	19.4	16.7	21.9	33.3	10.3	26.9	26.3
Bonus volume (m^3/PMH)	0.9	2.0	1.0	1.0	0.0	1.8	1.3	0.9
Total volume (m^3/PMH)	20.7	21.4	17.7	22.9	33.3	12.1	28.2	27.2

[a] Differences due to rounding.
[b] Estimated volume/tree, prior to felling.

Table 11. Post-Harvest Site Evaluation

	Harvesting system and location		
	Tree-length		Cut-to-length
	House Mountain	Deer Mountain	Deer Mountain
Harvest period	Sept/Oct	Dec	Jan/Feb
Delivered volume (m^3)	17600	10881	10281
Cutblock size (ha)	50.1	42.8	40.9
Post-harvest merchantable volume [a]			
At stump (m^3/ha)	6	10	25
At roadside (m^3/ha)	29	31	0
Total (m^3/ha)	35	41	25
Total cutblock (m^3)	1755	1738	1022
% of delivered volume	9.9	16.0	9.9
Post-harvest slash load			
At stump (m^3/ha)	112	111	126
At roadside (m^3/ha)	114	110	0
Total (m^3/ha)	226	221	126
Site disturbance[b]			
Disturbed (%) [c]	3.1	0.2	0.0
Undisturbed (%)	57.4	84.8	100.0
Other (%) [d]	39.5	15.0	0.0

[a] Assumed to be any sound piece of wood with a diameter of 10 m or more, regardless of length.
[b] Does not include road right-of-ways.
[c] Any abrupt change in the physical, chemical, or biological properties of the soil.
[d] Evidence of disturbance, but not enough to be classified as disturbance according to BCMOF guidelines (1989).

Table 12. Baseline Productivity and Cost Analysis [a]

	Harvesting system		
		Cut-to-length	
	Tree-length	Single-grip harvester	Double-grip harvester
Annual harvest (m^3)	100 000	100 000	100 000
Operating days/y (no.)	180	180	180
Shifts/day (no.)	1	1	1
Target SMH/shift (h)	10	10	10
Average extraction distance (m)	100	100	100
System man-day productivity			
- @ 0.10 m^3/tree (m^3/man-day)	35	31	27
- @ 0.20 m^3/tree (m^3/man-day)	61	50	45
- @ 0.30 m^3/tree (m^3/man-day)	76	62	56
- @ 0.40 m^3/tree (m^3/man-day)	89	70	63
Felling and processing cost			
- @ 0.10 m^3/tree ($/$m^3$)	20.07	16.74	22.63
- @ 0.20 m^3/tree ($/$m^3$)	9.28	9.30	12.27
- @ 0.30 m^3/tree ($/$m^3$)	6.13	7.39	10.02
- @ 0.40 m^3/tree ($/$m^3$)	5.50	6.89	8.36
Extraction cost @ 100 m			
- @ 0.10 m^3/tree ($/$m^3$)	5.26	8.64	8.64
- @ 0.20 m^3/tree ($/$m^3$)	4.51	6.16	6.16
- @ 0.30 m^3/tree ($/$m^3$)	4.21	4.98	4.98
- @ 0.40 m^3/tree ($/$m^3$)	3.91	4.72	4.72
Road development and reclamation cost [b]			
- @ 0.10 m^3/tree ($/$m^3$)	0.34	0.34	0.34
- @ 0.20 m^3/tree ($/$m^3$)	0.34	0.34	0.34
- @ 0.30 m^3/tree ($/$m^3$)	0.34	0.34	0.34
- @ 0.40 m^3/tree ($/$m^3$)	0.34	0.34	0.34
Total system cost			
- @ 0.10 m^3/tree ($/$m^3$)	25.67	25.72	31.61
- @ 0.20 m^3/tree ($/$m^3$)	14.13	15.80	18.87
- @ 0.30 m^3/tree ($/$m^3$)	10.68	12.71	15.34
- @ 0.40 m^3/tree ($/$m^3$)	9.75	11.95	13.42

[a] See Table II-A for detailed example of cost calculations.
[b] Based on road-building costs of $3000/km, road reclamation costs of $380/km, and recovered volume of 250 m^3/ha.

The extraction cost, especially for small tree sizes, was the major contributing factor to the differences in the overall unit wood cost between the tree-length and single-grip harvester systems. The single-grip harvesting cost was actually lower than the tree-length felling and delimbing costs for tree sizes <0.20 m^3.

To determine how the different input variables in the analysis affected harvesting costs, a sensitivity analysis was performed by varying the value of each individual variable (Table 13). As expected, an increase in machine utilization reduced the harvesting cost. The magnitude of cost reduction appeared to be highest for low-production machines, i.e. it affected the cut-to-length machines more than the tree-length machines. However, the analysis shows that even if the utilization of the cut-to-length machines were the same as the tree-length machines, the wood cost from the cut-to-length system would still be higher. Therefore, the recorded difference in machine utilization for these systems only partly contributed to the difference in harvesting cost.

The number of operating days per year (assuming fixed daily production) directly affects harvesting cost. Also, its effect on cost appears to be greatest for the smallest wood. Therefore, if the cut-to-length systems can operate twelve months and the tree-length systems for nine months per year (as is done by Millar Western), the single-grip system is cost competitive with the tree-length systems in stands with average tree sizes <0.20 m^3/tree.

Table 13. Sensitivity Analysis: Changes in Total Wood Cost from Baseline Cost by Varying the Values of Individual Input Variables [a]

	Average tree size											
	0.10 m³/tree			0.20 m³/tree			0.30 m³/tree			0.40 m³/tree		
	TL ($/m³)	SGH ($/m³)	DGH ($/m³)	TL ($/m³)	SGH ($/m³)	DGH ($/m³)	TL ($/m³)	SGH ($/m³)	DGH ($/m³)	TL ($/m³)	SGH ($/m³)	DGH ($/m³)
Machine utilization												
- 10%	0.87	2.26	2.53	1.00	1.52	1.72	0.42	2.12	2.30	0.34	0.77	1.82
-5%	0.41	1.38	1.57	0.24	0.30	1.33	0.20	0.55	0.58	0.16	0.21	1.24
Baseline data	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
+ 5%	-2.76	-1.71	-1.90	-0.20	-0.67	-0.70	-0.16	-0.22	-0.25	-0.15	-1.07	-0.21
+ 10%	-3.08	-2.39	-2.63	-2.27	-2.08	-2.26	-0.29	-0.41	-1.46	-0.76	-1.64	-0.80
Operating days/y												
- 60 days/y	5.73	5.87	7.43	3.07	3.58	4.39	2.13	2.80	3.54	2.12	2.79	3.04
- 30 days/y	2.29	2.35	2.97	1.23	1.43	1.75	0.85	1.12	1.41	0.85	1.12	1.22
Baseline data	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
+ 30 days/y	-1.66	-1.69	-2.14	-0.87	-1.03	-1.26	-0.60	-0.80	-1.02	-0.61	-0.80	-0.87
+ 60 days/y	-2.88	-2.95	-3.73	-1.53	-1.80	-2.20	-1.05	-1.40	-1.78	-1.06	-1.41	-1.53
Extraction distance [b]												
-50 m	-2.08	-0.47		-1.47	-0.74		-1.34	0.16		-1.22	-0.40	
Baseline data	0.00	0.00		0.00	0.00		0.00	0.00		0.00	0.00	
+100 m	3.62	0.90		3.92	0.81		3.15	1.15		2.86	0.73	
+300 m	12.06	3.75		11.37	3.16		10.16	3.29		8.88	2.49	
Forwarder productivity												
Baseline data		0.00			0.00			0.00			0.00	
+ 10%		-0.82			-0.70			-0.26			-0.24	
+ 20%		-1.49			-1.26			-0.48			-0.84	
+ 30%		-2.20			-1.48			-1.06			-1.01	

[a] TL=tree-length. SGH=single-grip harvester. DGH=double-grip harvester. [b] Includes effect on road-building cost ($/m³) caused by changes in extraction distance.

Extending the average extraction distance beyond 100 m will increase the cost of the tree-length operation considerably more than it will the cut-to-length operation, thus making cut-to-length harvesting more cost effective. At average extraction distances of 200 m or more, the unit wood cost of the single-grip harvesting system is lower than that of the tree-length system.

Because of the concern that productivity levels recorded in the detailed-timing studies of the forwarders did not reflect the machines' expected performance, the impact on cost of potentially higher forwarder productivities were also tested in the analysis. The results show that even at 30% higher productivity levels for the forwarder, the cost of cut-to-length systems will be higher than that of the tree-length system.

Transportation Operations

The results from the tree-length delivery operations at House Mountain and Deer Mountain showed that tree size had a significant effect on truck payload and consequently also on truck productivity (Table 14). The smaller load size from Deer Mountain resulted in lower truck productivity from this area than from the House Mountain area despite the shorter average truck trip time from Deer Mountain.

Loader productivity was similar for both areas, although FERIC observed that the effective loading time of individual loads increased with a decrease in tree size. However, long-term loader productivity is also influenced by the frequency of trucks arriving at the loading site. The shorter truck trip times at Deer Mountain likely compensated for the smaller tree size.

Table 15 shows the time distribution for trucks and loaders at the House Mountain loading site, based on four days of detailed-timing studies. The loaders actively loaded trucks 48% of the observed time, but loading time of individual trucks varied considerably. Tree-length decks with small stems typically increased loading time because the loaders spent more time arranging the stems on the log trailers.

Table 16 shows the performance of the self-loading shortwood log trucks hauling wood from cut-to-length sites at Goose Mountain and Deer Mountain. Poor driving conditions during several days in the Goose Mountain hauling period adversely affected the truck trip time. In addition, one of the drivers on the 5-axle tractor/semitrailer was new to self-loading trucks, and had no previous experience operating the log loader. The truck/full-trailer unit (Figure 4) was also new at the time, and the

Table 14. Log Transportation: Tree-Length System [a]

	5-axle tractor/pole-trailer	
	House Mountain	Deer Mountain
Monitoring period (h)	204	120
Average tree size (m^3/tree) [b]	0.52	0.22
Haul distance (km)	150	135
Truck payload		
Total loads (no.)	763	341
Average mass (t)	40.2	33.7
Average volume (m^3)	49.4	41.4
Total trucks (no.)	28	28
Average trucks/12-h shift (no.)	24.9	17.3
Average trips/12-h shift (no.)	50.1	37.8
Loaders in bush (no.)	2	1
Average truck trip time (h)	5.6	5.2
Loader productivity		
Mass (t/h)	84	85
Volume (m^3/h)	101	104
Trucks/h (no.)	2.1	2.5
Truck productivity		
Mass (t/h)	7.2	6.6
Volume (m^3/h)	8.9	8.1

[a] Differences due to rounding.
[b] From company cruise summary; merchantable trees >13 cm dbh.

driver was still somewhat unfamiliar with its operation.

FERIC observed no differences in the actual loading rate, expressed in min/t, between a 5-axle tractor/trailer and a 7-axle truck/full-trailer (Swedish unit) when loaded by the same operator. Overall, the actual loading time averaged 0.65 min/t. However, the combined time to position the truck for loading and to secure its load after loading was slightly longer for the Swedish unit (18 min verses 14 min) (Appendix III, Table III-B).

The actual unloading time at the millyard did not differ significantly between truck configurations, and averaged 23 min/load (Appendix III, Table III-B). Occasionally, even the self-loading trucks were unloaded by the Portal cranes, which reduced unloading time to about 8 min/load. Weigh-scaling, driving in the millyard, and other activities related to the unloading cycle typically added 15 min/trip.

Table 17 summarizes the productivity and cost analysis of the tree-length and shortlog delivery systems (Appendix III). For tree-length log delivery (\$/t-h), cost increased 19% when the average tree size was reduced from 0.50 to 0.22 m^3/tree. The analysis concludes that delivering short logs with self-loading trucks is cost competitive with the delivery of tree-length stems with trucks

Table 15. Loading Times: Tree-Length System [a]

Machine	Average (min/load)	Average (% of time)	Range (min/load)
Log loader			
Activities			
Wait-for-trucks	11.8	4	0.0 - 45.0
Prepare to load	2.3	8	1.4 - 5.6
Active load	13.4	48	7.2 - 30.9
Truck clears loader	0.5	2	0.3 - 1.2
Total time/load	28.0	100	9.5 - 63.8
Productivity			
Truck loads (no./h)	2.1		
Mass (t/h)	86		
Volume (m^3/h)	106		
Log truck			
Activities			
Wait-for-loader	4.5	15	0.0 - 20.4
Prepare to load	2.3	8	1.4 - 5.6
Active load	13.4	47	7.2 - 30.9
Truck clears loader	0.5	2	0.3 - 1.2
Secure and trim load	8.1	28	4.2 - 16.8
Total time/load	28.7	100	15.7 - 48.8

[a] Differences due to rounding.

Table 16. Log Transportation: Cut-to-Length System [a]

	Site and study					
	Goose Mountain			Deer Mountain		
Average tree size[b] (m^3/tree)	0.18			0.22		
Haul distance (km)	85			135		
Truck/trailer configuration	5-axle tractor/ semi-trailer	6-axle tractor/ semi-trailer	7-axle truck/ full-trailer	5-axle tractor/ trailer	6-axle tractor/ trailer	7-axle truck/ full-trailer
No. of units	2	2	1	2	2	2
Truck payload						
Total loads (no.)	30	22	16	64	81	70
Average mass (t)	26.2	30.4	35.6	28.4	32.8	39.8
Average volume (m^3)	34.2	39.6	46.2	36.9	40.6	51.0
Truck trip time (h)	7.2	5.2	6.9	6.2	5.7	6.3
Truck productivity						
Mass (t/h)	3.6	5.9	5.2	4.6	5.8	6.3
Volume (m^3/h)	4.8	7.6	6.9	6.0	7.1	8.1

[a] Differences due to rounding.
[b] From company cruise summary; merchantable trees >13 cm dbh.

Table 17. Log Transportation: Cost and Productivity Comparison

	Tree-length trucks		Cut-to-length trucks		
	Tractor/pole trailers		Tractor/semi-trailers		Truck/full-trailer
	5-axle		5-axle	6-axle	7-axle
Tree size (m^3/tree)[a]	0.50	0.22	0.22	0.22	0.22
Payload (t)	40.2	33.7	28.0	31.9	39.3
Average truck trip time					
- @ 50 km (h)	2.5		3.1	3.1	3.3
- @ 100 km (h)	3.9		4.7	4.7	4.9
- @ 150 km (h)	5.2		6.2	6.3	6.5
- @ 200 km (h)	6.6		7.8	7.9	8.1
Operating costs					
Log trucks ($/t-h)[b]	1.73	2.06	2.60	2.32	2.06
Loaders ($/t)	1.47	1.74			
Off-loaders ($/t)	0.56	0.67			
Total delivery cost					
- @ 50 km ($/t)	6.36	7.56	8.06	7.19	6.80
- @ 100 km ($/t)	8.78	10.44	12.22	10.90	10.09
- @ 150 km ($/t)	11.03	13.12	16.12	14.62	13.39
- @ 200 km ($/t)	13.45	16.01	20.28	18.33	16.69

[a] Gross volume per tree from pre-harvest stand data.
[b] Calculations in Appendix IV.

and separate loaders, providing that the payload capacity of shortlog trucks is higher than that of the tree-length trucks. Delivery distance also appears to influence the competitiveness of the two systems; short distances favour self-loading shortlog trucks, and long distances favour tree-length trucks.

DISCUSSION

The study could not determine a clear 'winner' between the tree-length and cut-to-length systems for clearcutting stands with small-diameter trees. Some results suggest the tree-length system is the better choice, others favour the cut-to-length system with single-grip harvesters. Furthermore, differences in the performances of the systems could also, to some degree, be attributed to differences in operator skill and method of payment, machine maintenance strategy, and climatic conditions; none of which was unique to either system.

The ability of the feller-bunchers and delimbers to handle multiple small-diameter stems makes these machines potentially more suitable than the cut-to-length harvesters—which fell and process trees individually—for harvesting small-diameter low-value trees. Results from detailed-timing studies on individual machines also support this notion, while results of the cost analysis are to the contrary. The reason is that small trees were undesirable in the tree-length delivery operation; therefore, many were deliberately discarded in the delimbing phase. Consequently, neither the feller-bunchers nor the grapple skidders were credited for the total volume of wood they actually handled. However, had the delimbers opted to process all small stems, their productivity would likely have been reduced, because of the smaller average stem size handled.

The level of fibre utilization when operating in a small-diameter stand also affected the results in the cut-to-length operation, but in a different manner. Here, the harvesters felled and processed a substantial number of unmerchantable trees (i.e. trees <13.6 cm dbh); in effect, the harvesters actually operated in stands with much smaller average tree size than indicated by pre-harvest cruise data. This increased the amount of wood fibre recovered by the operation, and decreased the amount of productive time the machines spent discarding unmerchantable stems (fell-to-waste). However, reducing machine fell-to-waste time by increasing the recovery of gradually smaller (unmerchantable) trees only increases machine productivity in terms of trees/PMH, but not necessarily in terms of m³/PMH. While the level of small tree recovery for optimum volume productivity was not addressed in this study, FERIC suspects that in most of the detailed-timing studies harvester productivity and wood cost were adversely affected by the high level of small tree recovery.

The cost analysis projected a higher wood cost for harvesting small wood with single-grip harvesters and forwarders than with systems employing feller-bunchers, grapple skidders, and roadside stroke delimbers. The cost difference resulted primarily from the higher cost of short-distance (average 100 m) wood extraction with forwarders than with grapple skidders. Felling and processing costs were lower in the cut-to-length system, particularly when the cost of tree-length slashing (assumed $0.45/m³) is included. Therefore, operating conditions that favour grapple skidding over forwarding would probably also favour the tree-length systems over the cut-to-length systems, and vice versa.

Results from FERIC's studies suggest that the productivity of grapple skidders is affected more than the forwarders by extraction distance, ground bearing capacity, and roadside decking space. The cost analysis showed that by doubling the extraction distance (e.g. from 100 to 200 m), skidder productivity decreased by about 45%, while forwarder productivity decreased only 20-25% (Appendix I). The impact on the total system cost was significant; at 200-m average extraction distance, the cut-to-length system with single-grip harvesters typically had the lowest wood cost.

During the field studies FERIC observed that soft ground conditions reduce the travel speed of the grapple skidders more than that of forwarders. In addition, site disturbance increased due to wheel slippage. The impact on forwarder travel speed by various ground conditions could not be assessed in this study. However, observations on other operations visited by FERIC in Central Alberta suggest that forwarder travel speeds vary little with changing ground conditions. This is attributed to forwarders travelling on a bed of slash created by the harvesters, which reduced the impact of soft or rough ground conditions, as well as reducing site disturbance.

The cost analysis showed that in small wood, double-grip harvesters are not cost competitive with either the single-grip harvester or with tree-length systems. Double-grip harvesters are designed to work primarily in final clearcuttings where average tree dbh is >30 cm. This machine could be considered for use in larger wood as an alternative to the tree-length harvesting system if conditions are such that the site favours forwarding over grapple skidding. However, additional studies would be needed before such a recommendation can be made.

The small sample size in the post-harvest site evaluation makes it difficult to determine advantages and disadvantages of the two systems. However, there was an added cost of roadside slash disposal. Both systems would incur cost of slash treatment at the stump area. However, this cost may not be noticeably different between the systems because the amount of slash at the stump differed surprisingly little for the cut-to-length blocks and the tree-length blocks.

The choice between cut-to-length and tree-length harvesting systems is also influenced by the cost of delivering wood to the mill yard. As well, the choice of truck configuration can influence the performance of the harvesting operation. This was observed in the tree-length operation at House Mountain, where small stems were discarded because of their adverse impact on tree-length delivery cost.

The use of the 7-axle truck/full-trailer units in the cut-to-length operation also had an impact on the harvesting operation. To be able to load three tiers of logs on the truck, logs could not be manufactured longer than about 5 m. Shorter logs mean more pieces to process and handle, less flexibility of log products, and likely lower fibre recovery. The other truck configurations used in the cut-to-length haul were also at a potential disadvantage. These trucks must carry only two tiers of logs, but have room for logs at least 6.3 m long.

For log-hauling systems requiring independent log loaders, the overall delivery cost is also influenced by the ratio of trucks-to-loader. Figure 7 shows the theoretical cost of delivering tree-length stems, based on an average payload size of 49.4 m³/load (i.e. the average load size from the House Mountain site) (Table 14), different haul distances (50, 100, 150, and 200 km) and number of trucks per loader. For minimizing the cost, the optimum number of trucks per loader is more critical at short distances than at long haul distances. Also, exceeding the optimum number of trucks per loader affects the haul cost more adversely than having less than the optimum number. The optimum number of trucks also varies with distance, but not with load size (because loading and unloading times per truck load are assumed constant).

CONCLUSION

An increased interest among Western Canadian forest companies in cut-to-length harvesting systems prompted FERIC to initiate a project in 1990 to compare the advantages and disadvantages of cut-to-length and tree-length harvesting systems clearcutting stands of small-diameter softwood in Central Alberta. The project was undertaken in cooperation with Millar Western Industries Ltd., L & M Custom Log Works, and Rocan West, all of Whitecourt, Alberta.

The tree-length harvesting system, which employed Koehring 618 feller-bunchers, Timberjack 480 grapple skidders, and Denis 2000/Komatsu delimbers, averaged 137 m³/man-day while operating in a stand averaging

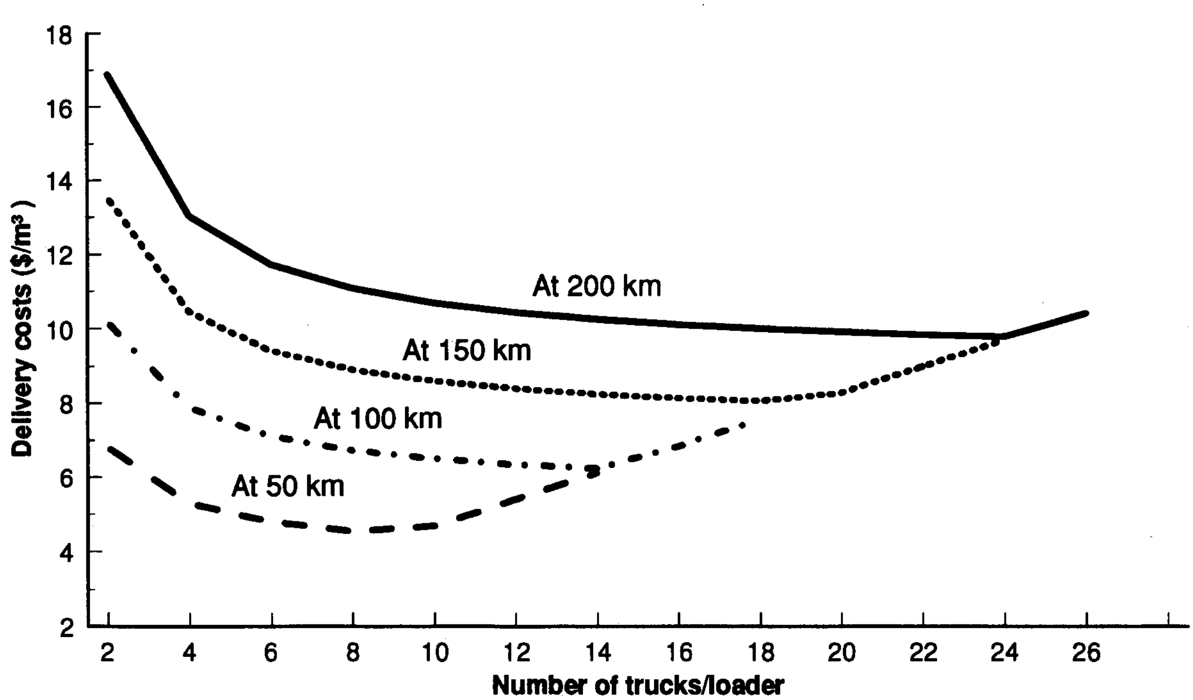

Figure 7. Tree-length transportation costs, as a function of trucks-to-loader ratio.

0.52 m^3/tree and 428 m^3/ha. Machines in the tree-length operation were utilized from 79 to 87% of their scheduled work time. The productivities of the feller-bunchers and the delimbers increased with an increase in average tree size (m^3/tree), but at different rates; the delimbers, which processed most stems individually, were more affected by tree size than the feller-bunchers, which effectively utilized their accumulating capability in small trees. Consequently, the difference in productivities between the feller-bunchers and the delimbers increased with a decrease in tree size. The productivity of the grapple skidders was primarily influenced by average extraction distance, but also by tree size; average load size per turn increased with an increase in tree size.

The cut-to-length harvesting system consisted of Rottne Rapid single- and double-grip harvesters, and forwarders with 10-t and 14-t load capacity. The system averaged 40.6 m^3/man-day in a stand averaging 0.22 m^3/tree, and 234 m^3/ha. The machines were operationally utilized from 69 to 74% of their scheduled work time. Harvester productivity varied with average tree size (m^3/tree), and the ratio of unmerchantable-to-merchantable trees in the stand, while forwarder productivity was influenced by average extraction distance and the volume of wood on the log piles (m^3/pile) created by the harvesters.

The lower level of fibre utilization in the tree-length operation compared to the cut-to-length operation occurred because fewer bonus trees (as defined by FERIC) were recovered in the former operation. This result is attributed to a difference in method of payment to operators, and a difference in the impact of short stems on the subsequent log-hauling operations. FERIC found no evidence that the harvesting equipment in the tree-length operation was incapable of harvesting and processing the bonus trees.

FERIC's cost analysis of tree-length and cut-to-length harvesting was based on machine productivities derived mathematically from detailed-timing data, and machine operation cost ($/OMH) determined by a standard costing method. The baseline analysis assumed an annual harvest quota of 100 000 m^3, 180 operating days/y, and an average extraction distance of 100 m. The results showed that, for average tree sizes of 0.10-0.40 m^3/tree, the tree-length system produces tree-length stems for less cost than the single-grip and double-grip harvester systems can produce short logs at roadside. The higher cost of the cut-to-length systems resulted primarily from higher extraction costs, while felling and processing cost for the single-grip harvester was less than that of the tree-length system for tree sizes <0.20 m^3/tree. The felling and processing cost of the double-grip harvester was in all cases higher than that of the other systems, but decreases with increased tree size.

The number of operating days per year and the extraction distance were two factors having considerable effect on the overall system cost of the tree-length and the cut-to-length systems. Therefore, in regions where operating conditions limit tree-length harvesting to fewer operating months per year, and/or where average extraction distance is 200 m or more, the single-grip harvester system will potentially be cost competitive with the tree-length system in stands averaging $\leq$0.25 m^3/tree.

Overall, the tree-length harvesting sites contained more post-harvest slash and merchantable fibre (as defined by FERIC), and had more site disturbance than did the cut-to-length site. However, no final conclusions were made about the site impacts of the different harvesting systems because of limited data and differences in stand characteristics and harvest seasons.

The analysis of the log-hauling operations concludes that delivering short logs with self-loading trucks is cost competitive with the delivery of tree-length stems with trucks and separate loaders, providing that the payload capacity of the shortlog trucks is higher than that of the tree-length trucks. Delivery distance also appears to influence the competitiveness of the two systems; short distances favour self-loading shortlog trucks, and long distances favour tree-length trucks. The cost of tree-length log hauling was also found to be influenced by stem size; a reduction in tree size from 0.50 to 0.22 m^3 increased the delivery cost by 19%.

The study compared the operating costs of cut-to-length and tree-length harvesting systems, but did not address the issue of the value of the delivered wood to the wood conversion plants. Because net revenue is more appropriate than the operating cost for comparing systems, future evaluation of cut-to-length and tree-length harvesting systems should include data on log value delivered to the mills.

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Appendix I

Mathematical Relationships of Merchantable Tree Size to Harvesting Machine Productivities

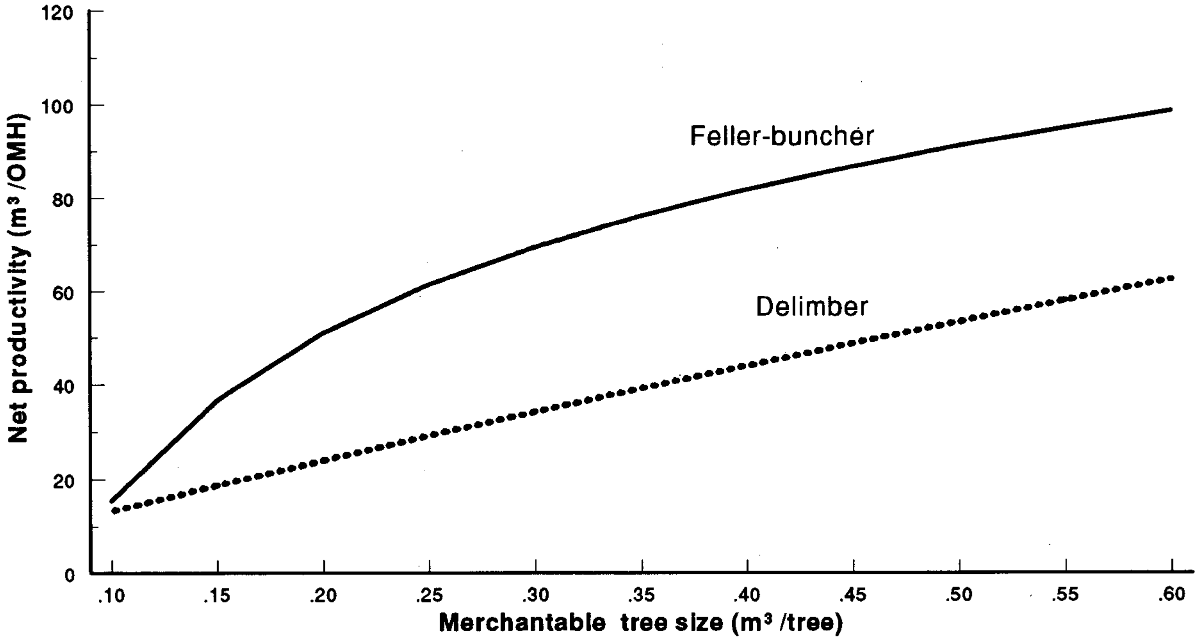

Figure I-A. Feller-buncher and delimber productivities, as functions of tree size.

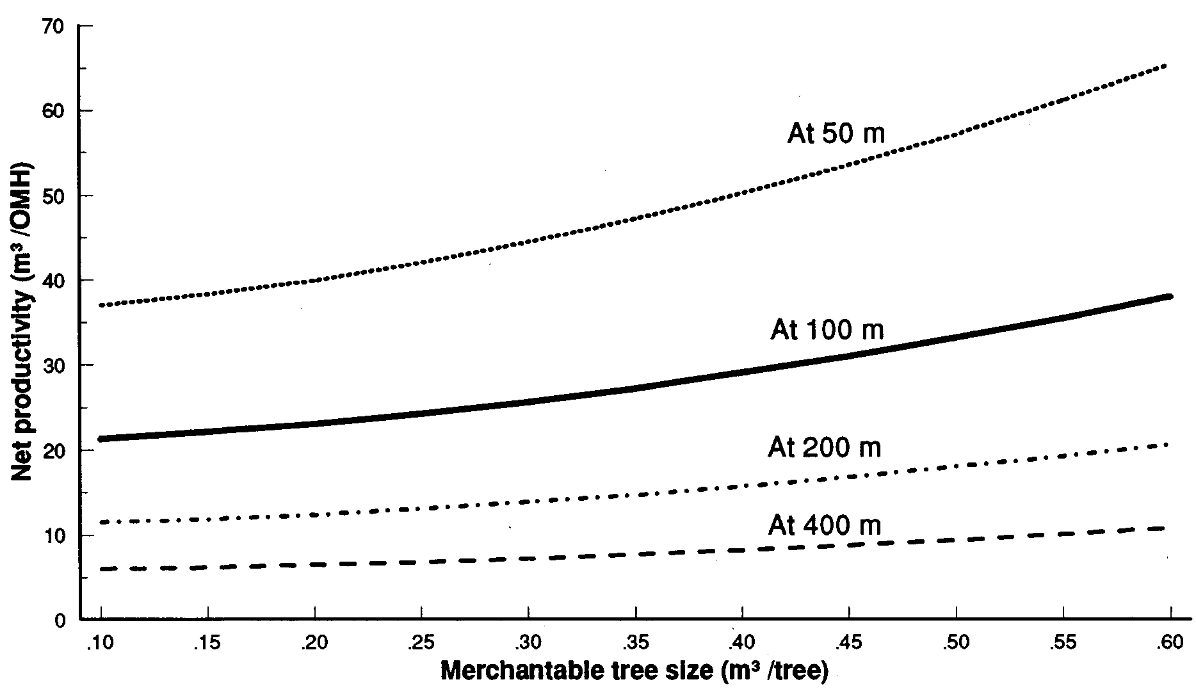

Figure I-B. Grapple skidder productivity, as a function of tree size and distance.

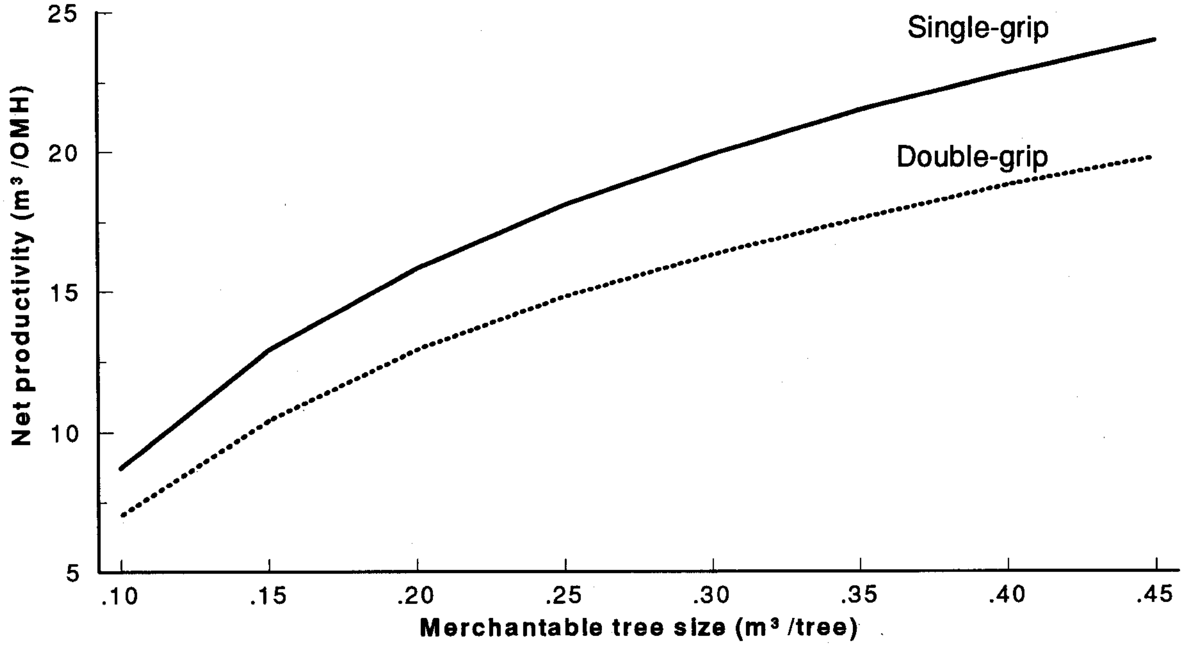

Figure I-C. Harvester productivity, as a function of tree size.

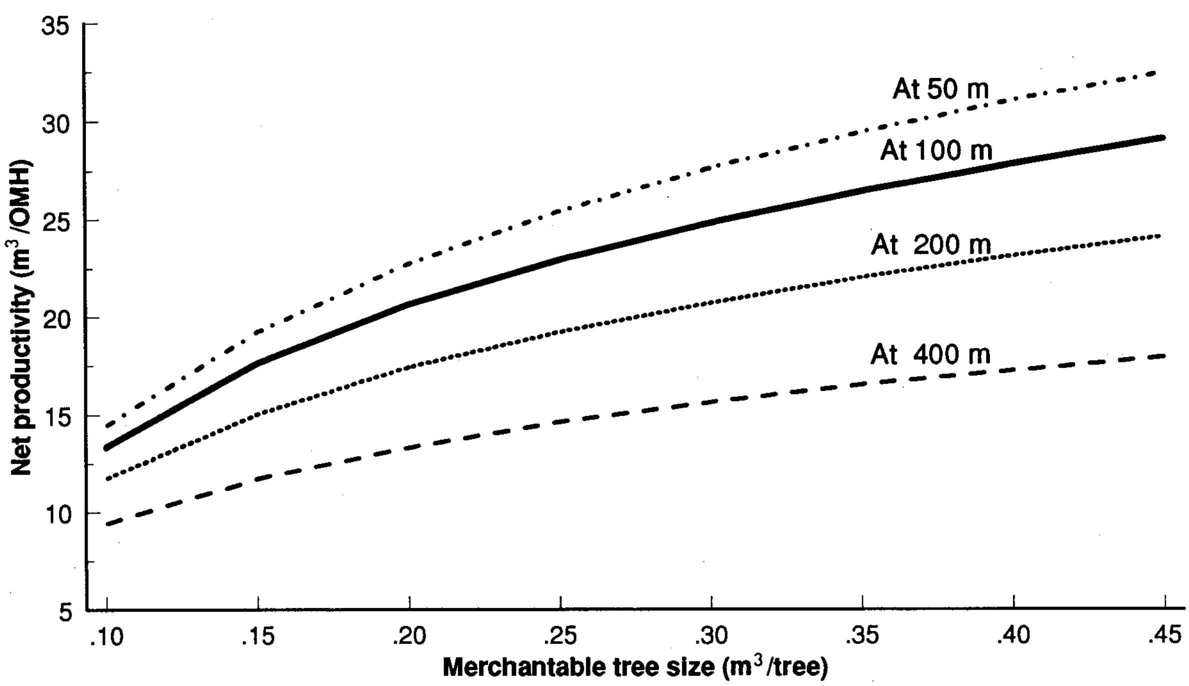

Figure I-D. Forwarder productivity, as a function of tree size and distance.

Appendix II

Example of Baseline Productivity and Cost Comparison Analysis

Table II. Example of Baseline Productivity and Cost Comparison Analysis [a]

	Tree-length system	Single-grip harvester		Double-grip harvester	
		10-t forwarder	14-t forwarder	10-t forwarder	14-t forwarder
Annual harvest (m^3)	100 000	100 000	100 000	100 000	100 000
Volume/ha (m^3)	250	250	250	250	250
Average tree size (m^3)	0.20	0.20	0.20	0.20	0.20
Operating days/y (no.)	180	180	180	180	180
Daily production (m^3)	556	556	556	556	556
Shifts/day (no.)	1	1	1	1	1
Felling phase					
Machine productivity (m^3/OMH)	50.3	15.5	15.5	12.6	12.6
Machine utilization (%)	77	71	71	72	72
Machine productivity (m^3/SMH)	38.7	11.0	11.0	9.1	9.1
SMH required per day (h)	14	50	50	61	61
No. of machines	2	5	5	6	6
SMH/machine-day (h)	7.2	10.1	10.1	10.2	10.2
Extraction phase					
Extraction distance (m)	100	100	100	100	100
Machine productivity (m^3/OMH)	22.6	19.5	20.3	19.5	20.3
Machine utilization (%)	76	74	76	74	76
Machine productivity (m^3/SMH)	17.2	14.4	15.4	14.4	15.4
SMH required per day (h)	32	39	36	39	36
No. of machines	3	4	4	4	4
SMH/machine-day (h)	10.8	9.6	9.0	9.6	9.0
Roadside delimbing phase					
Machine productivity (m^3/OMH)	25.7				
Machine utilization (%)	82				
Machine productivity (m^3/SMH)	21.1				
SMH required per day (h)	26				
No. of machines	3				
SMH/machine-day (h)	8.8				
Total man-days/shift (no.)	9.1	11.1	10.8	12.5	12.2
Man-day productivity (m^3)	61	50	51	45	46
Machine operating costs					
Felling ($/SMH)	145.77	102.31	102.31	112.23	112.23
Extraction ($/SMH)	77.54	81.23	103.19	69.48	103.19
Roadside delimbing ($/SMH)	116.39				
Unit wood cost					
Road development ($/$m^3$)	0.30	0.30	0.30	0.30	0.30
Road reclamation ($/$m^3$)	0.04	0.04	0.04	0.04	0.04
Felling ($/$m^3$)	3.76	9.30	9.30	12.37	12.37
Extraction ($/$m^3$)	4.51	5.63	6.69	5.63	6.69
Roadside delimbing ($/$m^3$)	5.52				
Total system cost ($/$m^3$)	14.13	15.27	16.33	18.34	19.40

[a] Differences due to rounding.

....continued

Table II, continued

	Koehring 618 feller-buncher	Timberjack 480 grapple-skidder	Denis 2000 delimber/ Komatsu LC200	Rottne Rapid EGS 85 single-grip harvester	Rottne Rapid /Snoken 860 double-grip harvester	Rottne Rapid 10-t forwarder	Rottne Rapid 14-t forwarder
Input variables							
Purchase price (P) ($)	420 000	200 000	340 000	350 000	400 000	240 000	320 000
Salvage value (% of P)	20	20	20	20	20	20	20
Depreciation period (y)	5	5	5	5	5	5	5
Scheduling (SMH/day) (h)	7.2	10.8	8.8	10.1	10.2	9.6	9.0
Operating days (no./y)	180	180	180	180	180	180	180
Machine utilization (%)	77	76	82	71	72	74	76
Operating life (OMH)	4 970	7 375	6 485	6 452	6 614	6 410	6 158
Average investment ($)	252 000	120 000	204 000	210 000	240 000	144 000	192 000
Interest on investment (%)	12	12	12	12	12	12	12
Insurance (%)	3	3	3	3	3	3	3
Fuel consumption (L/OMH)	30	20	25	15	15	12	15
Fuel cost ($/L)	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Oil consumption (% of fuel)	6	4	4	6	6	5	5
Oil cost ($/L)	2.40	2.40	2.40	2.40	2.40	2.40	2.40
Repair & maintenance ($/OMH)	33.60	24.00	32.30	31.50	36.00	21.60	28.80
Operator wage ($/SMH)	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Fringe benefits (% of wage)	30	30	30	30	30	30	30
Operating cost/OMH							
Depreciation ($)	67.60	21.70	41.94	43.40	48.38	29.95	41.57
Interest on investment ($)	30.42	9.76	18.87	19.53	21.77	13.48	18.71
Insurance ($)	7.61	2.44	4.72	4.88	5.44	3.37	4.68
Repair & maintenance ($)	33.60	24.00	32.30	31.50	36.00	21.60	28.80
Fuel cost ($)	12.00	8.00	10.00	6.00	6.00	4.80	6.00
Oil & lube cost ($)	4.32	1.92	2.40	2.16	2.16	1.44	1.80
Operator wages ($)	25.97	26.32	24.39	28.17	27.78	27.03	26.32
Fringe benefits ($)	7.79	7.89	7.32	8.45	8.33	8.11	7.89
Charge-out rate ($/OMH)	189.32	102.03	141.94	144.09	155.87	109.78	135.77
Charge-out rate ($/SMH)	145.77	77.54	116.39	102.31	112.23	81.23	103.19

Appendix III

Cost Analysis of Transportation Operations

Table III-A. Costing Analysis of Tree-Length Transportation Operation

1. Input Variables

Delivery distance (km)	50, 100, 150, 200
Operating days/y (no.)	70
Bush loader input data	
No. of loaders	1
Max. scheduled time (h/day)	24
Loader availability (%)	95
Active loading (min/load)	18
Loader @ bush ($/SMH)	101.37
Log truck input data	
No. of trucks	1 to 30
Max. scheduled time (h/day)	24
Truck availability (%)	90
Payload capacity	
For 0.50 m³/tree (t/load)	40.2
For 0.22 m³/tree (t/load)	33.7
Active loading time (min/trip)	24
Travel empty speed (km/h)	80
Travel loaded speed (km/h)	65
Check points (min/trip)	5
Fixed millyard time (min/trip)	20
Queuing time (min/trip)	0.5 • (no. of trucks)
Truck/trailers ($/SMH)	56.64
Mill yard loader input data	
No. of loaders	1
Max. scheduled time (h/day)	24
Fixed unloading (min/load)	4
Unloading ($/m³)	0.45
System productivity	
Volume (m³/shift)	Minimum of loader or truck fleet capacity.

2. Calculation of Machine Charge-Out Rates

	Loader @ bush, Cat 235C butt-n-top	Log trucks, 300 kW, highway	Log trailer, 2-axle pole
Input variables			
Purchase price (P) ($)	435 000	90 000	30 000
Salvage value (% of P)	20	20	20
Depreciation period (y)	5	5	5
Scheduling, SMH/day (h)	24.0	24.0	24.0
Operating days (no./y)	70	70	70
Machine utilization (%)	95	90	90
Operating hours (OMH/y)	1 596	1 512	1 512
Average investment ($)	261 000	54 000	18 000
Interest on investment (%)	12	12	1
Insurance & licensing (%)	3	5	5
Fuel consumption (L/OMH)	30	30	n/a
Fuel cost ($/L)	0.40	0.45	n/a
Oil consumption (% of fuel)	6	4	n/a
Oil cost ($/L)	2.40	2.40	n/a
Repair & maintenance ($/OMH)	14.50	3.00	0.40
Operator wages ($/SMH)	20.00	20.00	n/a
Fringe benefits (% of wage)	30	30	n/a
Operating cost/OMH			
Depreciation ($)	43.61	9.52	3.17
Interest on investment ($)	19.62	4.29	1.43
Insurance ($)	4.91	1.79	0.59
Repair & maintenance ($)	14.50	3.00	0.40
Fuel cost ($)	12.00	13.50	0.00
Oil & lube cost ($)	4.32	2.88	0.00
Operator wages ($)	21.05	22.22	0.00
Fringe benefits ($)	6.32	6.67	0.00
Charge-out rate ($/OMH)	126.33	63.87	5.59
Charge-out rate ($/SMH)	120.00	57.48	5.03

Table III-B. Costing Analysis of Cut-to-Length Delivery Operation

1. Input Variables

Delivery distance (km)	50,100,150,200
Operating days/y (no.)	70
Input data: 5-axle tractor/semi-trailer	
Max. scheduled time (h/day)	24
Availability (%)	90
Payload capacity (t/load)	28.0
Fixed load time (min/trip)	14
Variable load time (min/t)	0.65
Travel empty speed (km/h)	78
Travel loaded speed (km/h)	63
Check points (min/trip)	5
Fixed millyard time (min/trip)	38
Queuing time (min/trip)	5
Queuing time (min/trip)	5
Input data: 6-axle tractor/semi-trailer	
Max. scheduled time (h/day)	24
Availability (%)	90
Payload capacity (t/load)	31.9
Fixed load time (min/trip)	14
Variable load time (min/t)	0.65
Travel empty speed (km/h)	78
Travel loaded speed (km/h)	63
Check points (min/trip)	5
Fixed millyard time (min/trip)	38
Queuing time (min/trip)	5
Input data: 7-axle truck/full-trailer	
Max. scheduled time (h/day)	24
Availability (%)	90
Payload capacity (t/load)	39.3
Fixed load time (min/trip)	18
Variable load time (min/t)	0.65
Travel empty speed (km/h)	78
Travel loaded speed (km/h)	63
Check points (min/trip)	5
Fixed millyard time (min/trip)	38
Queuing time (min/trip)	5

2. Calculation of Machine Charge-Out Rates

	Tractor/semi-trailer		Truck/ full-trailer
	5-axle	6-axle	7-axle
Input variables			
Purchase price (P) ($)	148 000	155 000	190 000
Salvage value (% of P)	20	20	20
Depreciation period (y)	5	5	5
Scheduling, SMH/day (h)	24.0	24.0	24.0
Operating days/y (no.)	70	70	70
Machine utilization (%)	90	90	90
Operating hours (OMH/y)	1 512	1 512	1 512
Average investment ($)	88 800	93 000	114 000
Interest on investment (%)	12	12	12
Insurance & licensing (%)	5	5	5
Fuel consumption (L/OMH)	30	30	30
Fuel cost ($/L)	0.45	0.45	0.45
Oil consumption (% of fuel)	2	2	2
Oil cost ($/L)	2.4	2.4	2.4
Repair & maintenance ($/OMH)	3.45	3.62	4.43
Operator wages ($/SMH)	20.00	20.00	20.00
Fringe benefits (% of wage)	30	30	30
Operating cost/OMH			
Depreciation ($)	15.66	16.40	20.11
Interest on investment ($)	7.05	7.38	9.05
Insurance ($)	2.94	3.08	3.77
Repair & maintenance ($)	3.45	3.62	4.43
Fuel cost ($)	13.50	13.50	13.50
Oil & lube cost ($)	1.44	1.44	1.44
Operator wages ($)	22.22	22.22	22.22
Fringe benefits ($)	6.67	6.67	6.67
Charge-out rate ($/OMH)	72.93	74.31	81.19
Charge-out rate ($/t-h)	2.60	2.32	2.06