THE ALBERTA LOGGING COST SURVEY:
DATA FOR 1996–1998

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INFORMATION REPORT NOR-X-375

Canadian Forest Service
Northern Forestry Centre
2002

Catalogue no. Fo46-12/375E
ISBN 0-662-
ISSN 0704-7673

This publication is available at no charge from:

Natural Resources Canada
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton, Alberta T6H 3S5

A microfiche edition of this publication may be purchased from:

Micromedia Ltd.
240 Catherine Street, Suite 305
Ottawa, Ontario K2P 2G8

National Library of Canada cataloguing in publication data

Kuhnke, D.H.

The Alberta logging cost survey: data for 1996–1998

(Information report, ISSN 0831-8247 ; NOR-X-375)
Includes an abstract in French.
Includes bibliographical references.
ISBN 0-662-33273-3
Cat. no. Fo46-12/375E

1. Logging -- Economic aspects -- Alberta.
2. Forests and forestry -- Economic aspects — Alberta.
I. White, William Alexander.
II. Bohning, R.A.
III. Northern Forestry Centre (Canada)
IV. Title.
V. Series: Information report (Northern Forestry Centre (Canada)) ; NOR-X-375.

SD538.3C3K86 2002 634.98’097123 C2002-980341-1

This report has been printed on Canadian recycled paper.

Kuhnke, D.H.; White, W.A.; Bohning, R.A. 2002. *The Alberta Logging Cost Survey: data for 1996–1998.* Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-375.

ABSTRACT

A logging cost survey was conducted in Alberta in 1997 and 1998. The two objectives of the survey were to determine the average cost of logging in Alberta and to develop models for predicting logging productivity on the basis of forest and logging characteristics. The survey gathered information on timber harvest, characteristics of harvested areas, machine productivity, and fixed and variable costs on 239 pieces of logging and road-building machinery covering all phases of logging operations. Twenty-nine firms responded to the survey, and together they harvested 5.2 million m^3 of timber over an area of almost 25 000 ha. The average cost of logging in Alberta was $14 / m^3. The average productivity for the felling, skidding, and processing phases was 39.1, 34.0, and 27.6 m^3 / productive machine hour, respectively.

RÉSUMÉ

Une enquête sur les coûts de l’exploitation forestière a été effectuée en Alberta en 1997 et 1998. Elle avait deux objectifs : déterminer les coûts de la récolte forestière en Alberta et construire des modèles de prévision de la productivité de la récolte à partir des caractéristiques de la forêt et de la récolte. Cette enquête a recueilli des renseignements sur la récolte de bois, les caractéristiques des superficies récoltées, la productivité de l’équipement et les coûts fixes et variables de 239 pièces d’équipement de récolte et de construction de chemins servant dans les différentes phases de l’exploitation des forêts. Vingt-neuf entreprises ont répondu à l’enquête; ensemble, elles avaient récolté 5,2 millions de mètres cubes (m^3) de bois sur une superficie atteignant près de 25 000 ha. D’après leurs réponses, le coût moyen de l’exploitation forestière en Alberta s’élèverait à 14 $ / m^3. La productivité moyenne pour les phases d’abattage, de débusquage / débardage par traînage et de transformation serait de 39,1, de 34,0 et de 27,6 m^3 / heure-machine productive, respectivement.

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NOTE

The exclusion of certain manufactured products does not necessarily imply disapproval nor does the mention of other products necessarily imply endorsement by Natural Resources Canada.

This report was completed using data collected between 1996 and 1998. Unavoidable delays, including our reluctance to release this potentially sensitive data during the recent countervail negotiations, have resulted in the results being slightly dated. Costs that impact on logging costs have increased over the period. For example, manufactured goods have increased by 7.6% since 1997. Raw energy prices have fluctuated but are up 67% over the same period. Wages and insurance costs have also increased since data was collected for this report. As this report describes, these goods and services are only a subset of materials and activities that influence logging costs, and we can not provide a definitive figure on exactly how the results should be adjusted to allow for these changes.

EXECUTIVE SUMMARY

Forestry represents a significant component of the Canadian economy and as such strongly influences the economic welfare of the nation. The well-being of the forestry sector hinges on competitiveness, both locally and internationally, and on sustainable forest management practices. The Alberta Logging Cost Survey, conducted in 1997 and 1998, had two objectives. First, it allowed the determination of the average cost of logging in Alberta, thus providing a reference against which logging companies can gauge their own competitiveness. Second, the data from the survey were used to develop models for predicting logging productivity on the basis of forest and logging characteristics. These models can then be used by loggers, researchers, and forest managers alike to estimate logging productivity and the associated costs of logging areas of commercial forest. They would also provide valuable input into financial analyses of forest management practices that may be integrated into broader strategic land use planning exercises.

The survey gathered information on timber harvest, characteristics of harvested areas, machine productivity, and fixed and variable costs on 239 pieces of logging and road-building machinery covering all phases of logging operations. The survey was conducted in cooperation with an independent association of logging, trucking and equipment supply companies. The twenty-nine firms that responded to the survey harvested 5.2 million m^3 of timber over an area of almost 25 000 ha. The average cost of logging in Alberta was $14 / m^3.

The average productivity for the felling, skidding, and processing phases was 39.1, 34.0, and 27.6 m^3 / productive machine hour, respectively. The regression models for these three phases explained a significant amount of the variation in productivity (goodness-of-fit $R^2 = 0.88$, 0.79, and 0.82, respectively). Tree size was an important factor affecting productivity in all phases of the logging operation, a result consistent with trials of logging machinery performed in Canada and elsewhere.

A model to predict productivity in constructing roads was also developed (in terms of productive machine hours per hectare). The goodness of fit was lower than for the other models ($R^2 = 0.69$), because information about the length and type of roads constructed was not collected. However, several logging characteristics, including total area harvested and sorting requirements, were reasonable proxies for road information.

Despite the limitations of the study, primarily related to the resources available on the part of both researchers and logging firms, the general strength of the models suggests their validity for predicting logging productivity in Alberta.

INTRODUCTION

Forestry is big business in Canada. The country's balance of trade in forest products in 1997 was $31.7 billion, more than farm products, fish products, and energy combined (Statistics Canada 1998a, b). One in 16 people was employed directly or indirectly in the forestry sector in that year (Natural Resources Canada 1998). The well-being of the forestry sector, which strongly influences the economic welfare of the nation, hinges to a great extent on its competitiveness, from the local level of the logging contractor to the global market for forest products such as newsprint.

Competitiveness, however, is not the only criterion that determines the success of the forestry sector. Forest companies must demonstrate that they practice forest management within the larger framework of sustainable development. On a broad landscape scale, achieving sustainable development implies finding the right balance between the jobs and economic prosperity associated with the manufacture of forest products and the demand for nontimber benefits like clean air and habitat for wildlife.

Logging costs constitute a fundamental component in a financial analysis of forest management practices that must be conducted in any economic modeling that seeks to balance the benefits of forest management with nontimber values. At present the weak link in the financial analyses of forest management practices is the absence of models that will estimate logging costs.

The purpose of the Canadian Forest Service (CFS) Alberta Logging Cost Survey (LCS) was twofold. The survey was conducted to determine the average costs of logging, and the variation in the various aspects of logging, to serve as a reference against which logging companies could gauge their competitiveness within the industry as logging companies are the first link in the chain of competitiveness leading to the global level. The LCS was also meant to serve as the basis for models developed to estimate logging productivity, given a set of forest and logging characteristics.

Performance trials of logging equipment that include cost breakdowns have been performed by other Canadian agencies. However, these have usually been restricted to specific sites for specific machines. The scope of the LCS was broader. The LCS was meant to sample firms across the province to cover the full range of logging methods, logging equipment, and site conditions.

It is anticipated that the models that estimate logging productivity can be used by loggers, researchers, and forest managers. These models should also provide valuable input into financial analyses of forest management practices, for eventual integration into broader strategic exercises for land-use planning. Because of limitations in personnel and funding, an Alberta-only focus was adopted. The LCS was conducted entirely out of the Northern Forestry Centre.

METHODS AND APPROACH

Most forest product firms in Alberta contract with independent logging companies to perform most or all logging operations to supply their sawmills, pulp mills, and other wood-processing facilities. Given that these companies actually perform the logging and bear the costs of all or most aspects of logging operations, we sought their cooperation for the survey. Initially, we consulted published directories of logging companies to identify logging firms; however, we subsequently approached the Alberta Logging Association (ALA, now known as the Forest Industry Suppliers and Loggers Association), an association of independent logging companies and logging equipment supply firms, for assistance in persuading its member logging firms to participate in the LCS.

The initial round of the survey was designed to obtain detailed information on a per-cutblock basis, including per-machine cost information for each cutblock. That approach was quickly abandoned because, given the large number of blocks harvested by most logging companies, the process proved too time consuming and costly for everyone involved. A much shorter survey form (Appendix 1), which struck a more appropriate balance between brevity and completeness, was developed to reflect the effort that logging company owners could devote to the survey and the limited resources that the CFS could devote to the survey.

The design of the shorter survey form was based on comments made by member companies of the ALA during the first round of the survey and on published literature. The design of the form was finalized after a multiday interview and completion of the form by a member company of the ALA that generously contributed its time and effort.

The method of conducting the survey—personal interviews with logging company owners, rather than mailed surveys or telephone interviews—was also based on experience garnered during the initial round of the survey. The chief reasons for adopting this method were the need to explain the purpose of the survey to the owners of the logging companies and the need to assure them about the confidentiality of their information, given the high degree of competitiveness in the logging industry.

Because of the brevity of the form, detailed information regarding the nature of all forest and site characteristics thought pertinent to logging could not be obtained. For example, information concerning slope was obtained by asking owners to report the number of cutblocks (or the percentage of cutblocks) that fell into three general slope categories, rather than by asking for the actual percent slope of each cutblock. This classification injected a high degree of subjectivity into the determination of the slope index, but did provide an indication of the slope conditions under which each logging company conducted its operations. However, the survey form did include a section for detailed information on the fixed and variable costs of operating each of the firm's logging and road-building machines.

This report presents descriptive overviews and average data from the survey, as well as models that predict logging productivity on the basis of a number of forest characteristics. Because logging consists of distinct phases, the modeling section examines the productivity of each phase separately. Other aspects of operating a logging company that apply to many types of businesses are also discussed.

RESULTS

General Overview

Twenty-nine logging companies agreed to participate in the survey, which was conducted from spring 1997 to summer 1998. The logging season for which most firms provided information extended from fall 1996 to spring 1997. However, because of the circumstances involved in arranging the interviews, it was easier for some firms to base their responses on their 1997–1998 logging season. Sixteen firms conducted a portion of their logging operations during the summer months. Many firms operated some of their machinery during other times of the year for nonlogging purposes, especially for building roads. Separating the costs of operating machinery for lease work (work not related to logging) from logging costs was difficult for some firms, and some of the resulting figures for productive machine hours (PMHs) and costs were approximate. Most of the logging firms interviewed were contracted by major forest product firms to conduct operations on land leased through forest management agreements; however, several firms conducted all or most of their operations on private land for private landowners. An effort was made to interview firms in all forested regions of the province.

General Logging and Hauling Data

Number of Cutblocks and General Areas

The 29 logging firms processed timber from a total of 1206 cutblocks; the number of cutblocks per firm ranged from 10 to 171 (average 42). Cutblock size ranged from 6.2 to 42.1 ha (average 24.1 ha). Most respondents conducted logging operations for one or two mills or clients, although five respondents conducted logging for five or more mills. On average, respondents harvested 21.1 cutblocks per mill or per client. Respondents were not asked to specify the forest product companies for which they conducted logging.

On average, the cutblocks were distributed among two or three general areas. Because obtaining descriptions of the locations of all cutblocks would have been too time consuming and because maps were not always available, the interpretation of the number of general areas in which a firm conducted logging operations was left to the discretion of the individual firms. Usually, a distance between groups of cutblocks that warranted moving logging machinery on trailers was the criterion used to identify the general areas. Large differences between general areas in terms of distance to the mill could suggest a greater dispersion of logging operations, which might in turn affect overall logging and hauling costs.

Hauling

Although the LCS was not intended to survey log hauling operations, hauling is an integral part of the operations of many logging firms, and therefore the LCS included a section on hauling. Eleven firms conducted some form of hauling. Some firms performed hauling entirely on their own, others paid subcontractors to do all of the hauling, and some used a combination of their own hauling and subcontractors. Data for the latter group had to be reviewed carefully to sort out what was hauled by each entity and at what cost. Care was also taken during interviews to account for any of the total harvest that was left behind for hauling after the logging season.

Distance to the mill or mills from general logging areas ranged from 15 to 400 km (average 111.4 km). For the 11 firms that hauled timber, the average hauling distance was 103.2 km. The hauling cost for firms that hauled timber ranged from $0.0177 to $0.1100 / t-km (average $0.0354 / t-km). The wide range in costs is a function of distance and road quality (and therefore of total travel times from loading to unloading and the return trip). Assuming an average speed of 60 km / h for logging trucks, the average hauling cost would be $2.12 / t-h. Hauling costs for each firm are reported in Table 1.

Conversion Factors

All logging firms interviewed were asked to provide the weight-to-volume conversion factors used for coniferous and deciduous timber for each mill. Although most firms recorded their harvest in cubic metres, some firms reported a portion of their harvest in tonnes (reporting the remainder in cubic metres), whereas others recorded their harvest entirely in tonnes. Conversion factors facilitated the conversion of the timber harvest recorded in tonnes to cubic metres to enable productivity and cost analyses across all firms. The conversion factor for coniferous timber ranged from 0.71 to 0.91 t / m^3 (average 0.83 t / m^3). The corresponding range for deciduous timber was 0.86 to 1.07 t / m^3 (average 0.97 t / m^3). Conversion factors were also necessary to convert tree sizes given in trees per tonne to the more commonly used trees per cubic metre. Conversion factors are presented in Appendix 2.

Bucking of Pulpwood Logs and Sawlogs

Respondents were asked to state the ranges of lengths into which pulpwood logs and sawlogs were bucked, if bucking was performed. Most firms that harvested sawlogs performed no bucking (i.e., they performed tree-length harvesting). Pulpwood logs of both species groups (coniferous and deciduous timber) were generally bucked to various lengths (i.e., cut-to-length harvesting), although eight firms performed tree-length harvesting for pulpwood logs. Several firms used a slasher to buck deciduous logs. Bucking characteristics by log type and species group for each logging firm are presented in Appendix 3. A bucking index was developed to measure the degree of bucking applicable to each firm for use in productivity analyses.

Logging Method

The survey included a section on the logging methods used by the firms. Eighteen firms used feller–bunchers, skidding to roadside, and delimbing at roadside (method A, roadside [AR]) as their sole logging method, whereas five others used this method in conjunction with feller–bunchers and delimbers for at-the-stump processing, and then skidded the timber to roadside (method B, roadside [BR]). Only two firms conducted significant amounts of hand felling (method C), although most firms performed some hand felling, usually for oversize trees. Only two firms skidded to landing (method A or B, landing [AL or BL]) in addition to skidding to roadside. The most notable variation in logging method occurred with the seven firms that used multipurpose harvesters or processors for cut-to-length harvesting for all or part of their logging operations (method ER). Logging methods for each firm are shown in Appendix 4, and Table 2 summarizes the many combinations of logging methods and machine types reported.

At-the-stump processing is well suited to large timber or difficult terrain where mechanized felling equipment is unable to operate; such terrain is therefore often associated with hand felling (MacDonald 1999). Two of the firms that conducted at-the-stump processing also conducted significant

Table 1. Hauling distances, weight of timber hauled, and hauling expenditures for 11 logging firms that hauled timber

Firm	No. of general areas	Total one-way distance to mill[a] (km)	Total weight hauled (t)	Total hauling expenditure[b] ($)	Average hauling cost[c] ($/t-km)
1	2	150	40 000	162 000	0.027 0
2	4	564	190 218	2 047 166	0.019 1
3	1	75	160 215	1 322 000	0.110 0
4	9	1 249	232 115	3 020 961	0.010 4
5	3	250	106 383	950 000	0.035 7
6	2	170	147 559	1 030 052	0.041 1
7	3	245	81 250	736 000	0.037 0
8	3	396	88 000	968 000	0.027 8
9	6	465	185 000	1 522 000	0.017 7
10	4	340	182 850	1 950 000	0.031 4
11	3	224	211 015	1 531 428	0.032 4
Total	40	4 128	1 624 605	15 239 607	0.035 4[d]

[a] Sum of the distances from each general area to the mill.

[b] Includes payments to subcontractors.

[c] Based on total one-way distance.

[d] Mean of the average hauling costs.

Table 2. Summary of logging methods by harvesting system and machine combinations

Harvesting system	Machine combinations	Method designation in the LCS	No. of firms[a]
Full-tree or tree-length harvesting	Feller–buncher with delimber at roadside	AR, AL	25
At-the-stump processing	Feller–buncher with delimber at the stump	BR, BL	6[b]
Hand felling	Hand felling with hand delimbing (Method C) or with a delimber (Method D)	CR, CL, DR, DL	2
Cut-to-length harvesting	Harvester (also called harvester–processor or feller–processor), or feller–buncher in tandem with processor	ER	7

[a] The sum of the number of firms exceeds the number of firms in the LCS because many firms performed more than one logging method. See Appendix 4 for details on logging method by firm.

[b] Includes one firm that performed felling, delimbing, and topping using a harvester but did not cut to length.

Note: LCS = Logging Cost Survey, AR = method A at roadside, AL = method A at landing, BR = method B at roadside, BL = method B at landing, CR = method C at roadside, CL = method C at landing, DR = method D at roadside, DL = method D at landing, ER = use of multipurpose harvesters.

hand felling and hand delimbing. At-the-stump processing is also employed for silvicultural reasons, including improvement of regeneration success, or for other considerations such as reducing the cost of managing debris that would otherwise accumulate at the roadside or on landings.

Cut-to-length harvesting can take two forms. Usually, a harvester (also called a harvester–processor or feller–processor) fells and processes the trees (delimbs, tops, and cuts to length); however, a cut-to-length operation might employ feller–bunchers for felling and processors working at the stump to process the felled trees. Two firms responding to the LCS used the latter form of cut-to-length harvesting. Firms that used processors to process all timber at roadside (in which case full trees were skidded to roadside) were not considered to have conducted cut-to-length harvesting.

Loading and Loading Productivity

Only six firms conducted their own loading (two of which also hired subcontractors to perform some of their loading), with a total of eight machines. Another firm hired subcontractors for all loading. For the other 22 respondents, loading was conducted by forest products firms or their subcontractors. Loading productivity averaged 95 m^3/PMH. Downtime for each machine was calculated as PMH divided by total operator hours; this variable averaged 0.86. Most firms conducted loading at roadside with a boom-type loader (method BR). The number of firms that conducted their own loading operations was too low to develop a sound model based on independent variables to predict loading productivity.

Slope

Slope conditions should ideally be given as measured percent slope or degrees of incline for each cutblock, to allow an overall assessment of the slope conditions with which each logging firm had to contend. However, this level of detail was beyond the resources available. Instead, each firm was asked to estimate the number of cutblocks (or the percentage of cutblocks) that fell into three general slope categories. The actual percent slope applicable to each category depended on the interpretation of the slope categories by each firm. Sixty-one percent of the cutblocks harvested across the LCS were considered generally flat, 26% were considered moderately steep, and only 13% were considered steeper than usual. Slope conditions per firm are presented in Appendix 5. A slope index was developed to provide a single measure of the overall slope conditions applicable to each firm; this index was used in the productivity analyses.

Tree Size

Tree size, or piece size, is a crucial variable in determining the productivity of logging machines. Tree size (in cubic metres per tree) is the variable usually used to determine productivity baselines or reference points from which to develop relationships that quantify deviations from the baseline under different, nonideal conditions (Mellgren 1990). Larger trees mean more volume processed for any particular machine function (e.g., felling, processing), which translates into higher productivity and lower cost per PMH. Logging firms were asked to specify the average piece size of their deciduous and coniferous harvest in terms of volume or weight per tree and to rate the average piece size as smaller than usual, about normal, or larger than usual. Some firms gave piece size in terms of trees per tonne, but most used trees per cubic metre; in the former situation the values had to be converted to trees per cubic metre using the conversion factors (Appendix 2). Several firms reported a range of piece sizes, in which case the midpoint of the range was used in analyses involving the effect of piece size on productivity. Average piece sizes in trees per cubic metre are summarized in Appendix 6. Piece sizes varied from 2.0 trees/m^3 to 7.5 trees/m^3 for coniferous species and from 1.7 trees/m^3 to 6.0 trees/m^3 for deciduous species (Appendix 6; Appendix 7 has the same figures in cubic metres per tree). Some overlap in the subjective rating of piece sizes occurred such as one firm's smaller than usual piece size was another firm's about-normal piece size. Average survey piece sizes were 3.57 and 2.78 trees/m^3 for coniferous and deciduous tree species, respectively. Two tree size indexes were developed to measure the overall piece size applicable to each firm in the LCS for use in productivity analyses.

Subcontractors

Fifteen firms hired a total of 39 subcontractors for logging operations, and 5 of these firms also hired 32 subcontractors to conduct all or part of their hauling operations. Payments to subcontractors totaled almost $13.2 million. Some firms hired as many as four subcontractors for their logging operations. Subcontractors usually owned their own machines, but sometimes operated some of the logging firm's machines under a leasing arrangement.

(Cost information for these machines was recorded because they were owned by the logging firms; therefore, they were considered part of the firm's operations and were included in all cost analyses.) Most subcontractors' operations seemed well integrated with the firm's overall operations (according to comments made during interviews), and the subcontractors relied on the logging firms for services such as fuel provision and delivery and machine repairs. Knowledge about subcontractor activities (i.e., what they did, their production, and payments made to them) was essential to determine the productivity and cost of the logging firm's own operations in relation to their harvest, given that, because of time and funding limitations, characteristics of machines used by subcontractors could not be determined to the same level of detail as for machines used by the logging firms. Subcontractor production and services were an essential component of the operations of the firms that hired them, and their contribution could not be ignored in developing overall estimates of the cost of logging. Subcontractor activities are summarized in Table 3.

Harvested Volumes and Areas by Forest Type and Species Group

Information on harvested volumes and areas by forest type (predominantly softwood, predominantly mixed wood, or predominantly hardwood) and by species group was requested of each firm. Forest type in particular was thought to be a factor in logging productivity. Harvested volumes in the predominantly mixed wood forest type were separated into spruce and aspen, as these are the species most often associated with commercial harvesting of mixed wood forests in Alberta. The total harvest processed by the 29 firms was 5 226 871 m^3 over an area of 24 989 ha, equally divided between coniferous and deciduous species. Volumes per area harvested averaged 209 m^3/ha (both species groups and all forest types combined), and the mixedwood forest type had the highest volume per area, 238 m^3/ha. Harvested volumes and area of harvest are summarized in Table 4, and detailed harvest information is presented in Appendix 8.

Machine Costs and Other Costs Associated with Logging

Detailed information concerning the operating costs and productivity of all logging machines was requested from the firms. Operating costs included fixed costs (insurance and loan payments) and variable costs (repairs and alterations, operator wages and benefits, and fuel and oil). Productivity was captured through total PMHs. Downtime, calculated as PMHs divided by total operator hours, was obtained for all machines as well. Every firm was able to report or estimate total productive times (in PMHs) for each machine during their logging season; however, for each cost category, only fifteen of the firms were able to provide cost information for each machine. All firms provided totals for all machines in all of the fixed and variable cost categories. Fixed and variable costs per machine for those firms that were able to provide only totals for all machines were estimated by means of several methods. The validity of these methods was tested by comparing estimated costs per machine with actual costs per machine for the firms that were able to provide per-machine costs. Fixed costs were necessarily based on each firm's fiscal year (encompassing the logging season), whereas operating costs were based on the logging season when the machinery was active. All firms provided the purchase prices (before taxes) of their machines. A total of 184 pieces of logging machinery and 55 pieces of road-building machinery were recorded in the LCS (Appendix 9).

The various machine cost factors are discussed below, and descriptive statistics are presented for each factor. The remaining cost factors obtained in the survey (camp costs, depreciation, and overhead) are also discussed.

Loan Payments

Loan payments represented the annual payments made to service outstanding debt on logging machinery. Because of limited resources, no effort was made to separate the proportions of annual loan payments attributable to principal and interest. Loan payments by the 29 logging firms totaled $11.8 million for 167 pieces of machinery (Table 5). Twenty firms, representing 58% of all machinery, were able to provide per-machine loan payments. Seventy percent of the machines in this group that were over 4 years of age had no loan payments, i.e., the machines had been paid off. Loan payments averaged $0.22 per dollar of purchase price. Loan payments were the second-highest machine cost factor in the LCS (operator wages and benefits represented the highest machine cost factor).

Per-machine loan payments for firms that were able to provide only total loan payments were estimated by prorating the total amount spent to service loans among all machines (for both logging

Table 3. Subcontractor activities of the 15 firms that engaged subcontractors

Logging phase	No. of subcontractors[a]	Production (m^3)	Total payments to subcontractors ($)	Average cost ($/$m^3$)
Felling	8	438 410	1 453 999	3.32
Skidding	9	580 450	1 584 076	2.73
Delimbing or processing	11	524 855	1 621 583	3.09
Loading	9	386 519	655 379	1.70
Slashing	2	202 981	568 000	2.80
Hauling	32	734 496[b]	7 294 127	9.93
Total	71	NA	13 177 164	NA

[a] Three subcontractors performed more than one phase; however, breakdowns of production and cost by phase were not available. Production and cost were divided among the applicable phases according to volumes processed in the firm's own operations in each phase.

[b] Equivalent to 702 795 t.

Note: NA = not applicable.

Table 4. Summary of volume and area harvested

Forest type and species group	Harvest volume (m^3)	Area harvested (ha)
Predominantly softwoods		
Coniferous species	1 914 745	8 488
Deciduous species	85 135	
Predominantly mixed woods		
Coniferous species	508 161	6 180
Deciduous species	962 807	
Predominantly hardwoods		
Coniferous species	195 972	10 321
Deciduous species	1 560 051	
All forest types		
Coniferous species	2 618 878	
Deciduous species	2 607 993	
Both species groups	5 226 871	24 989

Table 5. Annual loan expenditures for logging and road-building machinery

Type of machine	No. of machines[a]	Sum of all purchase prices ($)	Loan expenditures ($) Total	Average[b]	Minimum[b]	Maximum[b]	Standard deviation[b]
Feller–bunchers, harvesters, and processors	43 (57)	17 773 642	3 884 420	0.22	0.02	0.54	0.09
Skidders and forwarders	49 (61)	11 229 812	2 550 907	0.23	0.02	0.70	0.13
Delimbers	48 (58)	18 394 146	4 000 077	0.22	0.02	0.54	0.08
Loaders	7 (8)	1 910 000	467 405	0.24	0.09	0.37	0.11
All logging machines	147 (184)	49 307 600	10 902 809	0.22	0.02	0.70	0.11
Road-building machines	20 (55)	3 391 200	904 433	0.27	0.04	0.65	0.16
All machinery	167 (239)	52 698 800	11 807 242	NA	NA	NA	NA

[a] The first figure represents the number of machines with nonzero loan payments. These machines form the basis for all other figures in the table. The figures in parentheses represent the total number of machines in the Logging Cost Survey.

[b] Figures in this column are expressed per dollar of purchase price.

Notes: NA = not applicable.

Table 6. Annual expenditures on repairs and alterations for logging and road-building machinery

Type of machine	No. of machines[a]	Average purchase price ($)	Expenditure for repairs and alterations ($) Total	Average
Feller–bunchers	24	402 135	894 960	37 290
Harvesters and processors	7	367 143	230 654	32 951
Skidders and forwarders	35	196 012	786 679	22 477
Delimbers	33	347 280	1 044 311	31 646
Loaders	7	298 000	145 546	20 792
Road-building machines	34	136 452	628 174	18 476
All above machines	140	NA	3 730 324	NA
All machines in the Logging Cost Survey	239	NA	7 200 015	NA

[a] Machines owned by firms that were able to provide per-machine costs for repairs and alterations, except in the last row. Includes machines with zero costs for repairs and alterations during the logging season.

Note: NA = not applicable.

and road-building machines) according to the proportion that each machine's purchase price represented of the total of all purchases. This method assumes that loan payments are a function of purchase price alone. The amount of any down payments, arising from the sale or trade-in of an older machine or a cash lump sum, was not requested in the survey and therefore could not be factored directly into the estimation of loan payments for specific machines. A further assumption of this prorating method was that machines over 4 years of age had no loan payments.

Actual and estimated per-machine loan payments were compared on the basis of this prorating method for the 138 machines for which per-machine loan payment expenditures were available. A paired-difference *t*-test and a nonparametric Wilcoxon signed-rank test showed that there was no significant difference at the 95% level of confidence between the actual and estimated per-machine loan payments (Appendix 10). The prorating method was therefore adopted for the firms that were able to provide only total figures for loan payments.

Repairs and Alterations

Expenditures for repairs and alterations totaled just over $7.2 million for all firms (Table 6). These expenditures averaged 10.8% of the purchase price of all logging and road-building machines, 9.4% for logging machines only (based on the 106 logging machines for which per-machine costs for repairs and alterations were available), and 13.5% for road-building machines (based on 34 machines). Of the 140 logging and road-building machines for which individual data were available, 131 had nonzero costs for repairs and alterations. On the basis of repair and alteration costs incurred by firms that were able to provide per-machine costs, a number of methods were attempted to estimate per-machine costs for repairs and alterations for the remaining firms. However, no method resulted in nonsignificant differences between estimated and actual per-machine costs, probably because repairs and alterations occur randomly. Therefore, the LCS's single-season snapshot of logging costs was insufficient to support conclusions about the cost of repairs and alterations based on parameters such as machine type and manufacturer. With a longer time series of data tracking the cost of repairs and alterations, it might be possible to draw such conclusions. It was noted, however, that expenditures for repairs and alterations rose substantially for machines over 2 years of age, which reflects the existence of warranties which typically cover the first 3000 to 5000 h of operation on new machines. The average cost of repairs and alterations for all machines up to 2 years of age was $20 521 (or 6.0% of the purchase price); the average cost rose to $30 193 (or 13.4% of the purchase price) for machines over 2 years of age. Repair costs for logging machines, expressed as a percentage of the purchase price, averaged 6.2% for machines up to 2 years of age (48 machines) and 12.7% for machines over 2 years of age (58 machines). The average cost of repairs and alterations for the 38 logging machines over 3 years of age, expressed as a percentage of purchase price, was 13.8%. This percentage rose to 15.4% for the 27 machines over 4 years of age.

Figures for road-building machines were an average of $5755 (or 2.3% of the purchase price) for machines up to 2 years of age (4 machines) and $20 172 (or 16.5% of the purchase price) for machines over 2 years of age (30 machines). There was little change in this percentage for machines between 3 and 9 years of age. The percentage rose to 18.8% for the 23 machines that were more than 8 years of age.

Insurance

Insurance rates incorporate many factors, starting with the base rate, which depends on the claims history of the logging industry in general and factors in the cost of the insurance firm's overhead. The base rate is then adjusted to reflect a number of considerations pertinent to the insured firm, including the age, use, and condition of the equipment being insured, the past claims history of the firm, and the experience of the firm's owners. Expenditures for insurance totaled $921 677 for all firms (Table 7) and averaged $3.11 per $100 of residual value. Fourteen firms were able to provide per-machine insurance costs for a total of 104 pieces of machinery. Per-machine insurance payments for the remaining firms were estimated by prorating the total amount spent on insurance for all logging and road-building machines according to the proportion that each machine's residual value represented of the total of all residual values. Residual values were determined using rates of depreciation and the age of the machine. The mathematics of depreciation result in a residual value that approaches zero as the age of a machine increases. However, in reality, residual value levels off at some market-determined level based on salvage value. The Forest Engineering Research Institute of Canada (FERIC) sets salvage value at 20% of

Table 7. Annual expenditures on insurance for logging and road-building machinery

Type of machine	No. of machines	Insurance expenditure ($) Total	Average	Minimum	Maximum	Standard deviation
Feller–bunchers, harvesters, and processors	57	312 393	5 481	435[a]	11 446	3 330
Skidders and forwarders	61	193 887	3 178	610[a]	13 282	2 569
Delimbers	58	296 776	5 117	478	14 117	3 437
Loaders	8	23 007	2 876	1 989	5 875	1 198
All logging machines	184	826 063	4 489	435	14 116	3 243
Road-building machines	55	95 614	1 000[a]	0	14 077	420–1825[b]
All machinery	239	921 677	NA	NA	NA	NA

[a] This figure represents the median expenditure. Several machines had zero insurance costs.

[b] Because of the skewed distribution, the interquartile range (25–75%) is presented.

Note: NA = not applicable.

the purchase price, a value based on empirical observations over time. Salvage values were not specifically discussed during the course of interviews for the LCS (although some interviewees expressed their estimates of the salvage value or worth of some of their older machines); therefore, 20% of the purchase price was used for machines of sufficient age that their calculated residual value was below 20% of the purchase price. This usually occurred for machines 10 or more years old. Thirty-eight machines were at least 10 years old, and 29 of these were road-building machines.

Most firms were able to provide the rate of depreciation used in their accounting practices. The rates of depreciation ranged from 20% to 30%; some firms adopted a 15% rate of depreciation for a machine's first year of operation, using a higher rate of depreciation in all subsequent years. Depreciation rates averaged 23.5%, and this rate was used for firms that did not provide per-machine insurance breakdowns or a rate of depreciation.

Actual and estimated per-machine insurance payments were compared using the above prorating method for the 104 machines from firms that were able to provide per-machine insurance expenditures. A paired difference *t*-test and a nonparametric Wilcoxon signed-rank test showed that there was no significant difference at the 95% level of confidence between the actual and estimated per-machine insurance costs (Appendix 11). This prorating method was therefore adopted for the firms that were able to provide only total insurance payment expenditures.

Operator Wages and Benefits

Expenditures for operator wages and benefits (including Canada Pension Plan, Workers' Compensation, Unemployment Insurance [now known as Employment Insurance], medical benefits, and vacation pay) totaled $14.2 million, the highest machine cost factor in the LCS (Table 8). For the firms that were unable to provide per-machine costs for operator wages and benefits, total expenditure for this item was prorated among the firm's individual machines according to the percentage of total PMHs represented by each machine. The validity of this approach was tested by comparing actual per-machine operator wages and benefits from firms that were able to provide the data in this form with wages and benefits estimated in this manner. A paired-difference *t*-test and a nonparametric Wilcoxon signed-rank test showed that there was no significant difference at the 95% level of confidence between the actual and estimated per-machine operator wages and benefits (Appendix 12). This prorating method was therefore adopted for the firms that were able to provide only total expenditures for operator wages and benefits. Information on whether operators were paid on a piece-rate basis or on an hourly basis was not recorded; however, comments made during the course of interviews indicated that most firms paid their operators on an hourly basis.

Table 8. Annual expenditures on operator wages and benefits for logging and road-building machinery

Type of machine	No. of machines	Total no. of PMHs	Total no. of SMHs	Total expenditure ($)	Expenditure ($/PMH) Average	Minimum	Maximum	Standard deviation
Feller–bunchers	46	106 805	127 822	3 099 435	29.02	13.54	51.23	8.11
Harvesters and processors	11	19 576	25 877	601 281	30.72	13.25	40.00	6.48
Skidders and forwarders	61	127 141	147 512	3 579 114	28.15	13.53	51.23	10.04
Delimbers	57[a]	157 324	191 153	4 697 138	29.86	13.53	52.67	8.76
Loaders	8	13 931	16 870	408 295	29.31	22.87	35.24	4.50
All logging machines	183	424 777	509 234	12 385 263	29.16	13.25	52.67	8.76
Road-building machines	54[b]	61 086	72 605	1 791 579	29.33	13.53	51.23	6.43
All machinery	237	485 863	581 839	14 176 842	NA	NA	NA	NA

[a] One delimber was idle for the logging season and was not included in the analysis.

[b] One crawler had negligible productive machine hours and was not included in the analysis.

Note: PMH = productive machine hours, SMH = scheduled machine hours, NA = not applicable.

Fuel and Oil

Expenditures for fuel and oil totaled $4.6 million for the survey total of almost 486 000 PMHs (Table 9). For firms that were unable to provide per-machine estimates of fuel and oil costs, total expenditure for fuel and oil was prorated among individual machines according to the percentage of total PMHs represented by each machine. The validity of this approach was tested by comparing actual per-machine fuel and oil costs from firms that were able to provide the data in this form with fuel and oil costs estimated in this manner. A paired difference *t*-test and a nonparametric Wilcoxon signed-rank test showed that there was no significant difference at the 95% level of confidence between actual and estimated per-machine fuel and oil costs (Appendix 13). This prorating method was therefore adopted for the firms that were able to provide only total expenditures for fuel and oil. However, for some of these firms, the total expenditure for fuel and oil included the cost of fuel and oil for various service and support vehicles; in these cases, it was not possible to separate the costs for logging machinery from those for service and support vehicles.

Other Costs

The survey form also requested information concerning other costs incurred by the firm, including hauling costs incurred by the firm's own hauling operations (i.e., independent of subcontractors), costs of operating a logging camp or costs incurred for the use of another firm's camp, total depreciation of logging machines over the fiscal year, and overhead. Hauling costs have already been discussed.

Twenty-one firms operated a logging camp, with an average total cost of $67 250 for the logging season. The costs of operating a logging camp ranged from $0.06 to $1.16 / m^3 (average $0.37 / m^3). No correlations existed between the use or cost of operating a logging camp and the total volume harvested or the number of general areas in use during the logging season; because employment data were not collected, they cannot be used to predict logging camp usage or cost. This finding suggests that the use of a logging camp depends to a great extent on the proximity of logging operations to the residences of the firm's equipment operators and on-site supervisors.

Each firm was asked to report the annual depreciation of its logging machinery during the fiscal year in which the logging season occurred. However, most firms provided an overall figure for the depreciation of all assets (including buildings and service vehicles) because the overall figure was most readily at hand. Nonetheless, because of their high purchase costs, logging and road-building machinery would account for the bulk of a logging firm's total depreciation (based on the depreciation of logging and road-building machinery determined during calculation of residual value for insurance estimation procedures). The average rate of depreciation was 23.5%.

Depreciation totaled $10 322 482. The larger firms generally incurred higher depreciation because they owned more machinery, although this

Table 9. Annual expenditures on fuel and oil for logging and road-building machinery

Type of machine	No. of machines	Total no. of PMHs	Total expenditure ($)	Expenditure ($ / PMH) Average	Minimum	Maximum	Standard deviation
Feller–bunchers	46	106 805	1 063 464	9.96	4.55	27.78	4.67
Harvesters and processors	11	19 576	171 186	8.74	4.55	16.89	3.30
Skidders and forwarders	61	127 141	1 055 544	8.30	4.55	27.78	4.53
Delimbers	57[a]	157 324	1 514 462	9.63	4.44	27.78	5.13
Loaders	8	13 931	142 958	10.26	5.50	27.78	6.63
All logging machines	183	424 777	3 947 614	9.29	4.44	27.78	4.83
Road-building machines	54[b]	61 086	686 009	11.23	4.55	27.78	4.91
All machinery	237	485 863	4 633 623	NA	NA	NA	NA

[a] One delimber was idle for the logging season and was not included in the analysis.

[b] One crawler had negligible productive machine hours and was not included in the analysis.

Note: PMH = productive machine hours, NA = not applicable.

relationship was influenced by the mix of ages and purchase prices of each firm's complement of machinery. Depreciation certainly has to be factored into the cost of doing business to lessen the cost of future purchases because depreciation can be used to lower taxable corporate income. Depreciation averaged \$0.58 / m^3. This figure was calculated as the total depreciation of all firms divided by the sum of volumes processed in all logging phases and the volume felled by firms that built roads.

Overhead was determined by subtracting all costs, including depreciation, from the firm's total revenue from logging. The total revenue earned by all firms sampled was \$82 735 699. In the LCS overhead represents a catchall figure for any other costs incurred that could not be itemized. It thus includes a myriad of items, such as the costs of running an office or operating a shop for the repair and maintenance of logging and other equipment, the costs associated with building roads that are not reflected in the cost of operating road-building equipment (such as the purchase of culverts), the costs of operating a fleet of service vehicles such as trucks for transporting fuel and heavy equipment and pick-up trucks, on-site supervisory costs, and, of course, taxes. Overhead also includes any profit the firm generated. Nine firms had negative overhead. Overhead ranged from \$0.16 to \$10.2 / m^3 (average \$2.35 / m^3).

Summary of Logging Costs

Table 10 summarizes the average costs of operating logging machinery and operating a logging firm in general. The average cost of logging in Alberta by the 29 firms was \$14.00 / m^3 and the average cost of hauling was \$0.0354 / t-km (Table 1).

Estimation of Machine Productivity

Whether a researcher is investigating the potential financial return of an intensive forest-management regime over a large land area or a logger is contemplating rate negotiations with a forest products firm for the coming season, advance estimates of the potential productivity of logging operations, based on the nature of the forest to be logged, are valuable. One of the objectives of the LCS was to investigate the development of models that could, with reasonable accuracy, predict the productivity of logging operations on the basis of forest and machine characteristics. The cost of logging the forest would flow from these productivity estimates, according to the cost averages outlined earlier in this report (in the case of the researcher) or from in-depth knowledge of the hourly costs of operating the machinery and the overhead costs of operating the business (in the case of the logger).

In the analysis of the LCS data, regression equations were developed to predict the productivity of each phase of logging in terms of cubic metres of harvest per PMH (the dependent variable) in relation to a number of forest and machine characteristics (the independent variables). Before regression models could be developed, however, a number of forest and logging characteristics had to be quantified in a manner that permitted their incorporation into a multiple-regression analysis.

Table 10. Average cost of logging in Alberta[a]

Cost factor	Average logging cost ($/m^3) Felling[b]	Skidding[c]	Processing[d]	Loading	Average road-building costs ($/m^3)	Total average cost[e] ($/m^3)
Fixed machine costs						
Insurance	0.07	0.05	0.06	0.03	0.02	0.23
Loan payments	0.86	0.62	0.85	0.73	0.22	3.28
Subtotal	0.93	0.67	0.91	0.76	0.24	3.51
Variable machine costs						
Repairs and alterations	0.48[f]	0.36[g]	0.42[h]	0.23[i]	0.29[j]	1.78
Operator wages and benefits	0.82	0.86	0.99	0.63	0.44	3.74
Fuel and oil	0.27	0.25	0.32	0.22	0.17	1.23
Subtotal	1.57	1.47	1.73	1.08	0.90	6.75
Total machine costs	2.50	2.14	2.64	1.84	1.14	10.26
Subcontractors[k]	3.32	2.73	3.00[l]	1.69	NA[m]	1.12[n]
Camps	NA	NA	NA	NA	NA	0.27[o]
Overhead	NA	NA	NA	NA	NA	2.35[p]
Total	NA	NA	NA	NA	NA	14.00

[a] Average hauling cost for the 11 logging firms that hauled timber was $0.0354/t-km (*see* Table 1).

[b] Feller–bunchers and harvesters. All harvester costs were attributed to felling.

[c] Skidders and forwarders.

[d] Delimbers and processors.

[e] Sum of average cost for each logging phase plus average road-building costs.

[f] Based on the volume felled by the 31 machines for which repair and alteration costs were available. Includes machines that had zero costs for repairs and alterations.

[g] Based on the volume skidded and forwarded by the 35 machines for which repair and alteration costs were available. Includes machines that had zero costs for repairs and alterations.

[h] Based on the volume processed by the 33 machines for which repair and alteration costs were available. Includes machines that had zero costs for repairs and alterations.

[i] Based on the 7 machines for which repair and alteration costs were available.

[j] Based on the 34 machines for which repair and alteration costs were available. Includes machines that had zero costs for repairs and alterations. Volume based on the total volume felled, including felling by subcontractors, by the firms that owned these 34 machines.

[k] All costs, except the total average cost, are based on the volumes processed by subcontractors in each logging phase.

[l] Includes slashing.

[m] No subcontractors built roads.

[n] Represents the average costs of subcontractors (per cubic metre) over the whole survey, including firms that did not employ subcontractors. Figure is based on total volume of timber felled.

[o] Includes firms with zero camp costs. Based on total volume felled, including felling by subcontractors.

[p] Negative overheads were treated as positive, because they represent legitimate costs that firms must meet.

Note: NA = not applicable.

Slope Index

Indexes are generally used to indicate changes in the status or quantity of several measurable items, that have some degree of commonality among them, with respect to a reference level or reference date. The Consumer Price Index is a well-known example. In the LCS, the reference level for slope is a logging area with no slope or generally flat conditions. An index can assume any numerical denomination; the important characteristic is that changes in the value of the index must be consistent with the denomination if the index is to be used in statistical analyses that incorporate the variance or distribution of the variables being analyzed.

The slope index was determined by multiplying the percentage of the total number of cutblocks within each slope class by an arbitrarily assigned point score for that slope class. The generally flat slope class was assigned two points, the moderately steep slope class was assigned four points, and the steeper-than-usual slope class was assigned six points. In this type of index, the interval between consecutive pairs of classes must be consistent (in this case, the interval was two points). Inconsistent intervals falsely skew the distribution of the indexes; for example, assigning a value of seven to the steeper-than-usual slope class would skew the distribution toward steeper slopes than actually existed.

The higher the slope index, the steeper the conditions in which the firm had to operate. A firm with 50% of cutblocks rated as generally flat and 50% of cutblocks rated as moderately steep would be assigned an index of 300. The average slope index for firms in the LCS was 285 (Fig. 1), only four firms had an overall slope index greater than 400, i.e., moderately steep (Appendix 4).

Tree Size Indexes

Two tree size indexes were developed to reflect a firm's average piece size. One index, termed the modified proportional timber size index, integrated subjective piece size ratings with numeric tree sizes, whereas the other index, the quantitative timber size index, was based on numeric tree sizes only.

The modified proportional timber size index can be determined in one or more steps. The first step is to multiply the percentage of total volume harvested in any timber size rating by its points score times the actual timber size (in trees per cubic metre) for that timber size rating. This is repeated for all timber size ratings (usually no more than two corresponding to the coniferous and deciduous harvest), with the resultant indexes summed to come up with the overall index for that firm. The larger-than-normal rating was arbitrarily assigned two points, the about-normal rating was assigned four points, and the smaller-than-usual rating was assigned six points. The larger the index, the smaller the timber harvested, and therefore the higher the cost of harvesting. For example, a firm with 15% of its total harvest from coniferous forests rated smaller than usual with 4.5 trees/m^3, and 85% of its total harvest from deciduous forests rated about normal in size, with 2.75 trees/m^3, would have an index of 1340 $(15 \times 6 \times 4.5) + (85 \times 4 \times 2.75)$.

The quantitative timber size index was determined by multiplying the percentage of total volume represented by each species group by the respective timber size (in trees per cubic metre) and summing each species group's index to arrive at the overall quantitative timber size index for a firm. This index differs from the modified proportional timber size index because it omits the subjective rating of timber sizes made by the firms' owners. Again, the larger the index, the smaller the timber harvested, and therefore the higher the cost of harvesting. For example, a firm with a 15% coniferous harvest with 4.5 trees/m^3 and an 85% deciduous harvest with 2.75 trees/m^3 would have an index of 301.25 $(15 \times 4.5) + (85 \times 2.75)$. The maximum possible value of this index was 650.

The modified proportional timber size index ranged from 485 to 3276 (average 1473) (Fig. 2). The quantitative timber size index ranged from 202 to 650 (average 348) (Fig. 3 and Appendix 4).

Sorting and Bucking Indexes

Sorting and bucking are significant cost factors in logging operations. Logging contractors often harvest for different forest product firms that require different species or log lengths. Timber is commonly sorted by species group. Another common requirement is sorting by log type (pulpwood logs and sawlogs) for various kinds of forest products. Deciduous logs are largely used in pulp mills and oriented strand-board plants. A species group may also be sorted by species (balsam fir, for example, is sometimes separated from other coniferous species); however, species-level information was not collected in the LCS. Logging operations

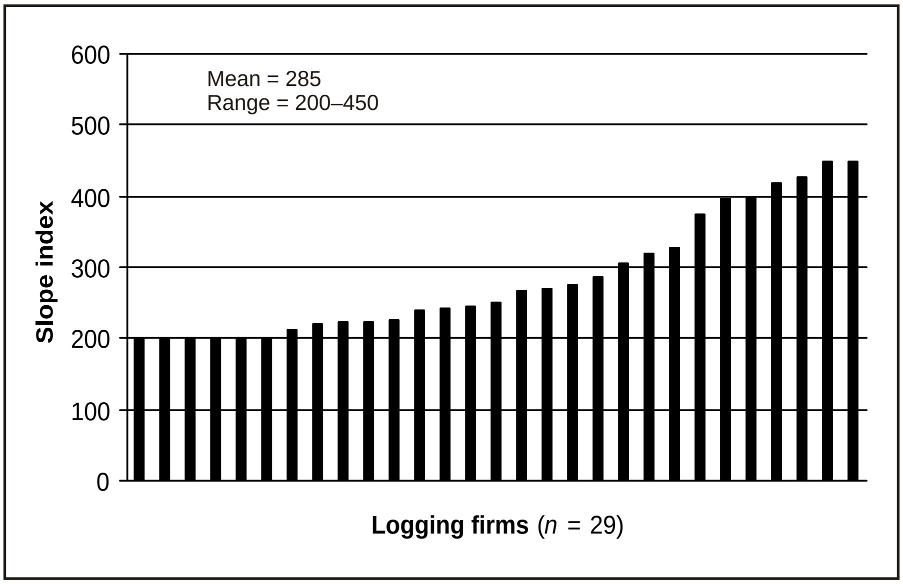

Figure 1. Distribution of slope index among all firms (minimum possible value = 200, maximum possible value = 600).

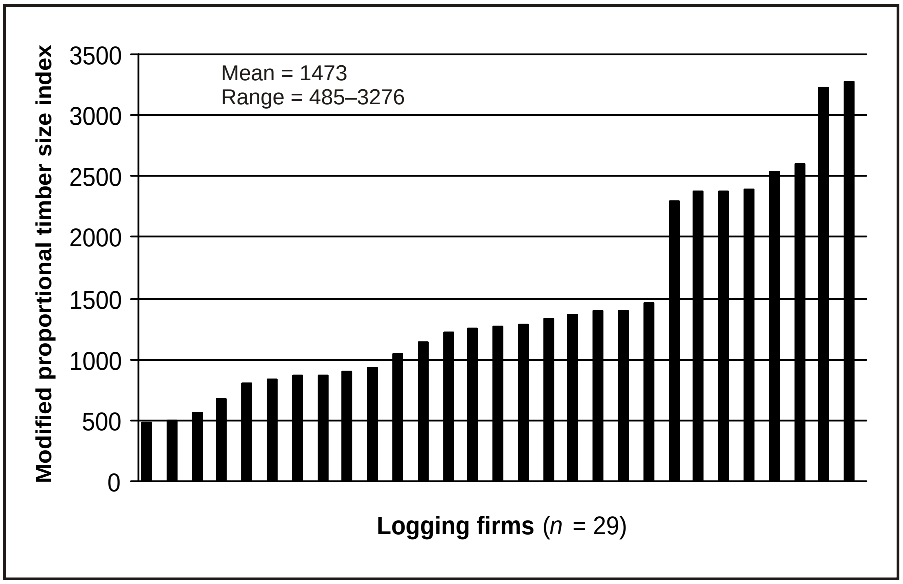

Figure 2. Distribution of modified proportional timber size index among all firms.

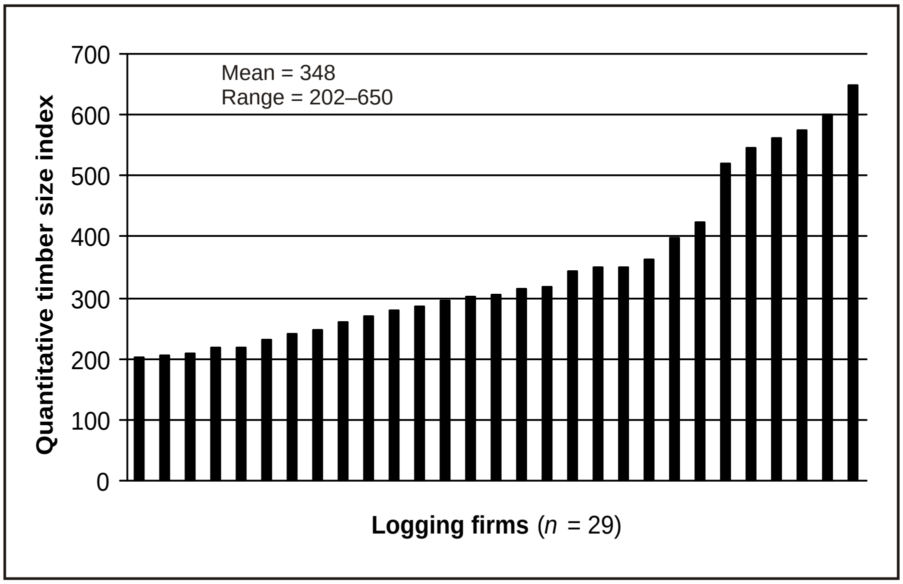

Figure 3. Distribution of quantitative timber size index among all firms.

conducted in mixed-wood forests were not considered to involve any sorting if a coniferous harvest was performed in one area and a deciduous harvest in another area.

Although some firms claimed an additional sort for oversize timber, comments made during the interviews indicated that many firms contended with oversize timber in their operations but did not view this as a distinct sorting procedure. Therefore, for consistency, sorts based on oversize timber were not used in the sort index. The types of all sorts were summed to determine the total number of sorts performed (Table 11). Appendix 4 presents the sorting indexes for the LCS.

The bucking index was assigned a value of 0 if tree-length harvesting was performed and a value of 1 if cut-to-length harvesting was performed. Shortwood harvesting was also assigned a value of 1 because it can be considered a form of cut-to-length harvesting. Although some firms supplied the distribution of harvest volume among the various lengths generated in their cut-to-length operations, other firms did not. Therefore, it was not possible to assign a value to the bucking index to reflect this distribution. The bucking index simply indicates whether bucking was performed. However, this index also reflects whether bucking was done for one or both species groups for pulpwood logs. The index was incremented to a maximum value of 3 if sawlogs and both species groups for pulpwood logs were bucked (Table 11).

Slashing was not assumed to be equivalent to bucking. Slashing is a separate function from felling and cutting-to-length (using delimbers or processors) for which the bucking index was developed. Appendix 4 displays the values of the bucking index for all firms.

Species Diversification Index

Sorting becomes an increasingly significant cost factor as the proportion of total volume processed that requires sorting increases. The species diversification index (SDI) was therefore developed to complement and enhance the sorting index. The SDI was simply the percentage of the firm’s total harvest volume (in cubic metres) represented by the more common species group. The smaller the SDI, the greater the effort devoted to sorting. Values of the SDI ranged from 50 to 100. Species diversification index values are presented in Appendix 4.

It was not possible to create another sorting index to indicate the amount of sorting required by species group for each log type, because the firms were not asked to provide this level of detail. However, in Alberta generally, pulpwood logs can be either deciduous or coniferous timber, whereas sawlogs are almost entirely coniferous timber.

Table 11. Summary of sorting and bucking conditions used to determine sorting and bucking indexes

Conditions	Index value[a]
Sorting	
No sorting	0–2
Sorting by log type	
Sorting by species group for pulpwood logs	
Bucking	
Tree-length harvesting for both log types and species groups	0–3
Cut-to-length harvesting for coniferous pulpwood logs	
Cut-to-length harvesting for deciduous pulpwood logs	
Cut-to-length harvesting for sawlogs	

[a] Index is determined on the basis of the number of conditions met (e.g., if one condition met, index = 0).

Seasonal Index

Sixteen firms conducted a portion of their operations in the summer months; however, the proportion of their timber volume processed during summer was not requested. The seasonal index therefore merely indicates whether logging occurred in both summer and winter (index = 2) or in winter only (index = 1) (Appendix 4).

Logging Methods Index

This index was used to indicate whether a portion of a firm's operations involved cut-to-length harvesting or at-the-stump processing. Ten of the firms surveyed performed at-the-stump processing (method BR) or cut-to-length harvesting (method ER) and two of these firms performed both at-the-stump processing and cut-to-length harvesting (Appendix 4). However, the proportion of total volume processed that was cut to length or processed at the stump was not requested. This index was coded 1 if tree-length harvesting only was performed and 2 if some cut-to-length harvesting or at-the-stump processing was performed (Appendix 4).

Felling Productivity

Information on 54 pieces of felling machinery from the 27 firms that conducted felling operations were sampled in the LCS. Forty-six of these machines were feller–bunchers, and the remainder were multifunction harvesters. Unlike feller–bunchers, harvesters perform felling and cut-to-length or processing functions at the stump. Processing consists of delimbing, topping, and bucking or cutting to length. Cut to length logs are cut into shorter, more precise lengths than when they are bucked, a similar term. Bucking is usually performed by a delimber or, on occasion, with a chainsaw. Bucking can also be performed by cut-to-length machinery. Processors usually perform cut-to-length functions at the stump or at roadside. Processed logs are picked up by a forwarder to be carried to roadside, although a number of firms used skidders (including clam-bunk skidders) for this purpose. Therefore, before a model could be developed to predict felling productivity according to forest and machine characteristics, the total productive time of harvesters had to be weighted by a factor estimating the number of PMHs actually devoted to felling. Felling includes the selection or picking of the next tree following the one just felled or processed, and may involve moving the whole machine, positioning the cutting head on the tree and cutting it, and finally piling the trees in a bunch on the ground (feller–bunchers) or re-positioning the tree for take-up by the processing unit (for harvesters).

Weighting factors were not collected in the LCS; consequently, general weighting factors were derived from Sauder (1992), which reported on conventional logging equipment and Scandinavian cut-to-length harvesters and forwarders as they harvested two-story mixed-wood stands in central Alberta. The study was conducted at three sites, and at two of these sites, harvesters were used. Weighting factors used in the present report are based on the average percentages of total productive time devoted to felling and processing (Tables

11 and 17 in Sauder [1992]). The resulting average weighting factors were 38.85% for felling and 47.05% for processing. The factors included move-to-cut and move-to-process machine functions. The remaining 14.1% was devoted to general brushing functions and delays of less than 15 min because of operational and mechanical reasons. The total productive time (in PMHs) for each harvester in the LCS was first multiplied by 38.85% to estimate the number of PMHs devoted to felling before the overall felling productivity was determined for the firm.

The variation in felling rates among firms was considerable, ranging from 22.5 to 56.7 m^3/PMH (average 39.1 m^3/PMH). Downtime for all felling machines ranged from 0.55 to 0.95 (average 0.83). Downtime for feller–bunchers only ranged from 0.63 to 0.95 (average 0.84). Felling rates were compared against data for forest and site variables, as well as against data for logging operation variables such as average age of the felling machines and sorting index, to determine how much of the variation in felling rates could be explained by the independent variables. Ordinary least-squares multiple regression was used for these comparisons, with the aim of developing a model to predict felling productivity.

The independent variables that were significant in explaining the variation in felling rates (at the 0.05% level of significance) are presented below. The quantitative timber size index explained more of the variation than the modified proportional timber size index, which suggests that firms' subjective ratings of timber size are less important to logging productivity than actual tree sizes. This result may have been due in part to some overlap in numerical tree sizes between subjective size ratings.

Forest types in the regression analyses were initially coded as 1 for the predominantly coniferous forest type, 2 for the predominantly mixed-wood forest type, and 3 for the predominantly hardwood forest type. Coding for firms that conducted operations in more than one forest type were assigned on the basis of the forest type in which the majority of the firm's total volume was harvested. Subsequently, firms that conducted the bulk of their operations in the predominantly mixed-wood forest type were assigned to either the softwood or hardwood forest type, according to which species group represented the larger portion of the total harvest because this resulted in a better model (higher R^2). In this situation, the hardwood forest type was coded as 2.

The goodness-of-fit statistic (R^2) was high, at 0.88. Goodness-of-fit statistics were even better when separate regression analyses were performed for each forest type; however, the numbers and types of significant independent variables were somewhat different in each model, because of the lower number of observations (lower number of firms) for each forest type.

The resulting regression-based model for felling productivity is presented below, and the complete analysis, including confidence limits for predicted productivities, is presented in Appendix 14.

For the regression model predicting felling productivity (in cubic metres per PMH), $n = 26$, $R^2 = 0.88$, and level of significance = 0.05%. Initial regression models developed with data for the 27 firms that conducted felling revealed that one firm had a productivity that was highly improbable in relation to the values of the independent variables, as evidenced by high values of Student residuals and Cook's D. This outlier firm was dropped from the final analysis shown in Appendix 14.

Felling rate = !102.663 + (0.199 × QUANT) ! (0.246 × Q2) ! (7.925 × VQ) ! (0.0549 × SLOPE2) ! (6.748 × AVAGE) + (0.483 × AV2) + (13.428 × FTYPE) + (2.559 × SDI) ! (14.082 × SDI2) + (4.839 × SUMWIN) + (2.529 × SOBUCK) ! (6.447 × STUCK) + (7.531 × STUMP)

where

QUANT = quantitative timber size index;
Q2 = quantitative timber size index squared divided by 1000;
VQ = quantitative timber size index divided by average volume (in cubic metres per hectare);
SLOPE2 = square of slope index divided by 1000;
AVAGE = average age (in years) of all felling machines owned by the firm;
AV2 = average age (in years) of all felling machines owned by the firm squared;
FTYPE = forest type;
SDI = species diversification index;
SDI2 = species diversification index squared divided by 1000;
SUMWIN = seasonal index;
SOBUCK = sort index + bucking index;
STUCK = logging methods index + bucking index; and

STUMP = logging methods index.

In addition to a high value of R^2 and the inclusion of independent variables, at the 0.05% level of significance, that were expected to influence felling rates, the soundness of the model is reinforced by the sign of most of the variables. The coefficient of the VQ variable is negative, for example, which is consistent with the expectation that, for a derived variable involving piece size, smaller piece sizes (i.e., higher values of the index for a given volume per hectare) are associated with lower felling productivity. The QUANT, Q2, and VQ variables were collectively more powerful predictors of felling productivity than was the quantitative timber size index alone (overall R^2 dropped to 0.79 when the quantitative timber size index was used alone), which highlights the interrelatedness of volume per area and tree size. Similarly, the net coefficient of the AVAGE and AV2 variables is negative, which indicates that productivity declines as machines age. The average age of a firm's felling machines ranged from 1.0 year to 11.0 years (overall mean 3.35 years). The influence of at-the-stump processing or cut-to-length harvesting on felling productivity was best captured by the logging methods index (STUMP) in combination with the derived SOBUCK and STUCK variables. Ten firms employed at-the-stump processing and/or cut-to-length harvesting for all or part of their operations.

Data for many sources of variation could not be collected, which limits the accuracy and predictive power of this model. The missing factors include tree size ranges (the midpoint of the range was used in all analyses), actual productive time for each machine (these data were often approximate or estimated), harvester weighting factors (which varied from one firm to the next), operator experience, ground roughness or stoniness, and ecological concerns such as the degree of understory protection practiced during felling and the degree of partial harvesting.

Skidding Productivity

Data for the 23 firms that performed skidding operations represented information for 56 skidders and 5 forwarders. Because forwarders are single-purpose machines that work in conjunction with feller–bunchers or harvesters, no weighting factors were applied to them. Richardson and Makkonen (1994) noted that forwarders are generally used for longer extraction distances than skidders, and that forwarder productivity is strongly affected by the duration of loading and unloading. Productivity for skidders and forwarders ranged from 15.0 to 65.5 m^3/PMH (average 34.0 m^3/PMH). The average age of a firm's skidders and forwarders ranged from 1.0 to 12.5 years (overall mean 3.60 years). The distribution of age was highly skewed, with 16 of 20 firms used in the analysis possessing an average machine age less than the survey average. Downtime for skidders ranged from 0.70 to 0.98 (average 0.87), whereas downtime for forwarders ranged from 0.55 to 0.95 (average 0.80).

Skidding rates were compared against data for forest and site variables, as well as against data for logging operation variables such as average age of the skidders and sorting index, to determine how much of the variation in skidding rates could be explained by the independent variables. Ordinary least-squares multiple regression was used for these comparisons, with the aim of developing a model to predict skidding productivity.

The independent variables that were significant in explaining the variation in skidding rates (at the 0.05% level of significance) are presented below. A derived variable, VQ, determined by dividing the quantitative timber size index by volume (in cubic metres per hectare), explained more of the variation in skidding productivity than either of these variables alone. The quantitative timber size index was also significant in explaining variation in skidding productivity. Another derived variable, AV2 (square of average machine age), was also significant. Although it was not possible to determine total or average per-firm skidding distances or average skidder speeds, average cutblock size was anticipated to be a proxy for skidding distance, on the assumption that larger average cutblock sizes would be associated with longer skidding distances. Average cutblock size (AVCUT) was significant in explaining variation in skidding productivity. However, the positive value of the coefficient of the AVCUT variable suggests that larger cutblocks result in higher productivity. This may be because larger cutblocks result in more repeated use of skid trails that equate to higher skidder or forwarder speeds that more than offset longer skidding distances. The total volume harvested by each firm (VOLUME) and the total number of cutblocks that underwent cutting during the logging season (TOTB) were also significant in explaining variation in skidding productivity. There was a trend towards larger average cutblock sizes as the volume harvested increased among the firms in the LCS. The negative coefficient of the TOTB variable may indicate that roadside conditions in some cutblocks were unsuitable for logging operations, which would necessitate the transport of logs to other cutblocks. These three variables (average cutblock size, total number of cutblocks, and total volume harvested) served as a better proxy for skidding speeds and distances than average cutblock size alone. Slope was also significant in explaining skidder productivity, which suggests that overall skidder speed and productivity are sensitive to slope.

The goodness-of-fit statistic (R^2) was moderately high, at 0.79. The resulting regression-based model for skidding productivity is presented below, and the complete analysis, including confidence limits for predicted productivities, is presented in Appendix 15.

For the regression model predicting skidding productivity (in cubic metres per PMH), $n = 20$, $R^2 = 0.79$, and level of significance = 0.05%. Initial regression models developed with data for the 23 firms that conducted skidding revealed that 3 firms had productivities that were highly improbable in relation to the values of the independent variables, as evidenced by high values of Student residuals and Cook's D. These outlier firms were dropped from the final analysis shown in Appendix 15.

$$\text{Skidding rate} = !13.243 + (0.151 \times \text{QUANT}) ! (0.0516 \times \text{SLOPE}) + (6.749 \times \text{AVAGE}) + (0.41 \times \text{SDI}) + (0.277 \times \text{AVCUT}) ! (0.33 \times \text{TOTB}) ! (15.842 \times \text{STUMP}) ! (0.497 \times \text{AV2}) ! (18.821 \times \text{VQ}) + (0.000154 \times \text{VOLUME})$$

where
QUANT = quantitative timber size index;
SLOPE = slope index;
AVAGE = average age of machines in years;
SDI = species diversification index;
AVCUT = average cutblock size in hectares;
TOTB = total number of cutblocks;
STUMP = logging methods index;
AV2 = square of average age of all skidding machines owned by the firm;
VQ = quantitative timber size index divided by average volume (in cubic metres per hectare); and
VOLUME = total volume harvested in cubic metres.

Data for many sources of variation could not be collected, which limits the accuracy and predictive power of this model. The missing factors include tree size ranges (the midpoint of the range was used in all analyses), actual productive time for each machine (these data were often approximate or estimated), operator experience, ground roughness or stoniness, whether skid trails were used repeatedly to increase average skidder speeds and minimize the area of soil compaction and rutting (to address silvicultural concerns), and, in particular, average skidding distance.

Processing Productivity

Information was obtained for 68 pieces of processing machinery owned by 28 firms. Fifty-seven of these machines were dedicated delimbers, and the remainder were multifunction harvesters or processors. Therefore, before a model could be developed to predict processing productivity according to forest and machine characteristics, the total productive time of harvesters had to be weighted by a factor estimating the number of PMHs actually devoted to processing. (Processing at this stage consists of delimbing, topping, cutting to length, and depositing the processed log in bunches at the stump or onto a log deck at roadside. Dedicated delimbers perform the same functions except for cutting to length. Delimbers may also perform bucking.) The weighting factor used was 47.05% (see earlier discussion on weighting factors in the section on felling productivity). Actual weighting factors probably vary widely, depending to a great degree on the number of different lengths called for in a cut-to-length operation. The total productive time (in PMHs) for each harvester in the LCS was first multiplied by 47.05% to estimate the number of PMHs devoted to processing before the overall processing productivity was determined for the firm.

Rates of productivity ranged from 14.1 to 49.3 m^3/PMH (average 27.6 m^3/PMH). Downtime ranged from 0.55 to 0.95 (average 0.82). Downtime for delimbers only ranged from 0.70 to 0.98 (average 0.88). The average age of processing machines ranged from 1.5 to 9.0 years (mean 3.70 years). Processing rates were compared against data for forest and site variables, as well as against data for logging operation variables such as average age of processing machines and sorting index, to determine how much of the variation in processing rates could be explained by the independent variables.

Various forest and machine characteristics were regressed against processing productivity to determine which factors were significant in explaining variation in productivity. The strength of the model—the degree to which the significant independent variables explain the variation in rates of productivity—was quite high ($R^2 = 0.82$). The resulting regression-based model for processing productivity is presented below, and the complete analysis, including confidence limits for predicted productivities, is presented in Appendix 16.

For the regression equation predicting processing productivity (in cubic metres per PMH), $n = 27$, $R^2 = 0.82$, and level of significance = 0.05%. Initial regression models developed with data for the 28 firms that conducted processing revealed that 1 firm had a productivity that was highly improbable in relation to the values of the independent variables, as evidenced by high values of the Student residual and Cook's D. This outlier firm was dropped from the final analysis shown in Appendix 16.

$$\text{Processing rate} = -156.05 + (0.173 \times \text{QUANT}) + (0.527 \times \text{SLOPE}) - (4.732 \times \text{AVAGE}) - (2.027 \times \text{SORT}) - (0.05 \times \text{VOLHA}) + (3.027 \times \text{SDI}) - (4.626 \times \text{SUMWIN}) - (12.105 \times \text{STUMP}) + (0.365 \times \text{AV2}) - (0.0008 \times \text{SLOPE2}) - (7.837 \times \text{VQ}) - (0.0002 \times \text{Q2}) + (0.261 \times \text{SB2}) - (0.017 \times \text{SDI2})$$

where
QUANT = quantitative timber size index;
SLOPE = slope index;
AVAGE = average age (in years) of all processing machines owned by the firm;
SORT = sorting index;
VOLHA = average volume (in cubic metres per hectare);
SDI = species diversification index;
SUMWIN = seasonal index;
STUMP = logging methods index;
AV2 = square of average age of all processing machines owned by the firm;
SLOPE2 = square of slope index;
VQ = quantitative timber size index divided by average volume (in cubic metres per hectare);
Q2 = square of quantitative timber size index;
SB2 = square of sorting index + bucking index; and
SDI2 = square of species diversification index.

The derived variable STUCK, the sum of the logging methods index and the bucking index, was not significant in explaining variation in the model. Its inclusion in the felling model suggests that the weighting factor attributed to the felling portion of a harvester's work cycle may have included a higher component attributed to processing. The logging methods index, STUMP, was significant, suggesting cut-to-length harvesting and at-the-stump processing have lower productivity than tree-length harvesting. The strength of the model was higher ($R^2 = 0.87$) when the significant factors listed above were regressed against the productivity of delimbers only. Twenty firms used delimbers only for their delimbing and bucking operations (total 44 machines), including firms that conducted at-the-stump processing as well as tree-length harvesting. However, the logging methods index was not significant in that model.

The processing model was another model in which the derived variable Q2, the square of the quantitative timber size index, explained a significant proportion of the variation in processing productivity. This reflects the sensitivity of processing machinery to tree sizes (Richardson and Makkonen 1994; Gingras 1994). Harvested volume per area (VOLHA) was significant in this analysis, although it was not significant in the felling model. Clearly, tree size and harvested volume per area are related, as evidenced by the inclusion of the derived VQ variable.

The model for processing productivity has the highest total number of variables and the highest number of independent variables for any of the logging-phase models. Other factors not examined in the LCS, including the distribution of a harvester's work cycle among various functions, clearly have major roles in determining processing productivity. In particular, the number of log lengths and the associated distribution of volume per length class, as well as branchiness, live crown ratio, and the degree of defects and rot in the bole, may be major factors in determining productivity, in conjunction with the higher complexity of delimbers and harvesters or processors relative to other types of logging machines, which places even greater emphasis on the skill of the operator.

Road-Building Productivity

The construction of logging roads to provide access for logging trucks and equipment is an essential complement to logging. Twenty of the firms constructed access roads to connect cutblocks with one another or to connect cutblocks to the nearest haul road. Some firms also built roads for other logging firms or as lease work; in this case, the firms were asked to estimate the degree to which road-building was associated with their own logging operations. Information was obtained for 55 pieces of road-building equipment, including bulldozers, crawlers, excavators, graders, and backhoes. Road-building equipment tended to be older than logging machinery (average age 12.0 and 3.5 years, respectively). Road-building costs varied widely, depending not only on soil conditions, season, the nature of the terrain, and the class of road being built (the five classes of logging roads in Alberta are based on degree of permanence, season of use, and expected term of life), but also on the number and type of bridges and culverts that must be put in place. The number of firms that were able to provide data on length of roads built was insufficient to develop sound estimates of road-building costs on a per-kilometre basis. However, a number of variables related to the logging operation, such as the total area harvested and average cutblock size, were anticipated to be reasonable proxies for length of roads built, based on an assumed correlation between average cutblock size, for example, and the number of PMHs required to build the roads. Slope, quantified by the slope index, was thought to be a rough indication of the slope conditions under which road-building machinery would be operated, given that the slope of roads would be similar to the slope of the cutblocks to be accessed. The resulting regression-based model for road-building productivity is presented below, and the complete analysis is presented in Appendix 17.

For the regression model predicting road-building productivity (in PMH per hectare), $n = 20$, $R^2 = 0.69$, and level of significance = 0.05%.

$$\text{Number of PMHs per hectare} = -17\,618.389 + (140.419 \times \text{SLOPE}) - (2335.342 \times \text{FTYPE}) + (1.5 \times \text{HA}) - (1455.4 \times \text{SORT}) + (1115.081 \times \text{SUMWIN}) - (0.205 \times \text{SLOPE2})$$

where

SLOPE = slope index;
FTYPE = forest type;
HA = total area harvested (in hectares);
SORT = sorting index;
SUMWIN = seasonal index; and
SLOPE2 = square of slope index.

The model was reasonably strong ($R^2 = 0.69$) and verified that cutblock and forest characteristics are reasonable predictors of the productive machine time required for the construction of roads associated with logging. In contrast to the models for logging phases, the average age of road-building machinery was not a factor. As expected, average cutblock size was not significant in explaining variation in the model; however, the significance of total area harvested verifies that longer roads are required as the area harvested increases. The inclusion of the sorting index in the model was unexpected. This suggests that more roads are required as sorting requirements increase, probably because of the need for more space, in the form of wider roads or more clearings adjacent to roads, for logging machinery to maneuver.

DISCUSSION

What does it cost to conduct logging in Alberta? According to the LCS, the average cost of logging in the period studied was $14/m^3 (Table 10), a value that factors in all costs associated with running a logging firm. However, this figure is based on average productivity and average fixed and variable costs. Costs can vary widely depending on forest conditions and logging characteristics, as well as machine characteristics.

Only seven firms conducted cut-to-length harvesting, of which four of these also conducted full-tree harvesting (Table 2); consequently, it was not possible to directly separate the costs of cut-to-length harvesting from full-tree harvesting. Comparisons of costs between one harvesting system and another are most valid when all systems operate under essentially similar conditions. For the seven firms that conducted cut-to-length harvesting the average quantitative timber size index was 411, whereas the overall average was 348 (Fig. 3). Any cost comparisons would be influenced by the negative effect on productivity resulting from the smaller timber handled by firms employing cut-to-length systems rather than by any inherent cost differences between harvesting systems. Costs may also fluctuate because of market conditions and a firm's financial situation at a given time.

An approach to isolate costs may be to use the models developed for the various phases of logging, which predict productivity (in terms of cubic

Felling rate in m^3 per PMH = $-102.663 + (0.199 \times \text{QUANT}) - (0.246 \times \text{Q2}) - (7.925 \times \text{VQ}) - (0.0549 \times \text{SLOPE2}) - (6.748 \times \text{AVAGE}) + (0.483 \times \text{AV2}) + (13.428 \times \text{FTYPE}) + (2.559 \times \text{SDI}) - (14.082 \times \text{SDI2}) + (4.839 \times \text{SUMWIN}) + (2.529 \times \text{SOBUCK}) - (6.447 \times \text{STUCK}) + (7.531 \times \text{STUMP})$ [$n = 26$, $R^2 = 0.88$]

Skidding rate in m^3 per PMH = $-13.243 + (0.151 \times \text{QUANT}) - (0.516 \times \text{SLOPE}) + (6.749 \times \text{AVAGE}) + (0.41 \times \text{SDI}) + (0.277 \times \text{AVCUT}) - (0.33 \times \text{TOTB}) - (15.842 \times \text{STUMP}) - (0.497 \times \text{AV2}) - (18.821 \times \text{VQ}) + (0.000154 \times \text{VOLUME})$ [$n = 20$, $R^2 = 0.79$]

Processing rate in m^3 per PMH = $-156.05 + (0.173 \times \text{QUANT}) + (0.527 \times \text{SLOPE}) - (4.732 \times \text{AVAGE}) - (2.027 \times \text{SORT}) - (0.05 \times \text{VOLHA}) + (3.027 \times \text{SDI}) - (4.626 \times \text{SUMWIN}) - (12.105 \times \text{STUMP}) + (0.365 \times \text{AV2}) - (0.0008 \times \text{SLOPE2}) - (7.837 \times \text{VQ}) - (0.0002 \times \text{Q2}) + (0.261 \times \text{SB2}) - (0.017 \times \text{SDI2})$ [$n = 27$, $R^2 = 0.82$]

Number of PMHs per ha for road-building = $-17\,618.389 + (140.419 \times \text{SLOPE}) - (2\,335.342 \times \text{FTYPE}) + (1.5 \times \text{HA}) - 1\,455.4 \times \text{SORT}) + (1\,115.081 \times \text{SUMWIN}) - (0.205 \times \text{SLOPE2})$ [$n = 20$, $R^2 = 0.69$]

Figure 4. Summary of models predicting logging and road-building productivity. Variables are defined in Table 12.

metres per PMH) on the basis of forest and logging characteristics, as well as machine characteristics. Actual PMHs were available for all machines in the survey and were not affected by variation in the fixed costs of operating logging equipment. The models developed for the logging phases and for building roads are summarized in Figure 4, with all but the road-building model featuring strong goodness-of-fit statistics. A summary of the independent variables that were significant in explaining variation in productivity in each model is presented in Table 12. The road-building model, with an R^2 of 0.69, can be characterized as only moderately strong. The productivities predicted by the models, once the various characteristics of the forest to be harvested and the intended logging operation have been determined, represent the mean of a confidence interval of upper and lower estimates, within which there is a 95% chance that the actual productivity will fall. Models with higher R^2 values will have narrower confidence intervals, whereas those with lower R^2 values will have wider confidence intervals, given the same level of significance.

Roughly half of the firms in the LCS were unable to provide fixed and variable costs for their logging equipment on a per-machine basis. These quantities, namely the fixed costs of insurance and loan payments and the variable costs of operator wages and benefits, and fuel and oil, were estimated from totals of these quantities by means of various prorating methods, which were tested for validity with data from the firms that were able to provide per-machine cost information. However, total costs for repairs and alterations could not be prorated among individual machines, presumably because of the random nature of repairs and alterations. Estimation or prediction of costs of repairs and alterations would require a longer time frame than one season.

Once the estimated productive machine time required to harvest a given area of forest has been determined from the models, the cost of logging the area can be predicted on the basis of the logger's knowledge of the costs of operating his or her machinery. Using the LCS for strategic planning purposes implies using average costs of operating logging machinery or selecting costs within the known cost range on the basis of justifiable reasons pertinent to the planning exercise. Forest managers or researchers using the LCS may also wish to use a subset of the various types of costs in their endeavors. Table 10 summarizes the average costs of logging in Alberta as determined in the LCS. Past studies of logging machinery in Canada have used a fixed set of assumptions concerning the cost of operating logging machinery as a means of comparing different logging machinery and comparing such machinery between operating sites. The

Table 12. Summary of independent variables found to be significant in models that predict logging and road-building productivity

Variable name	Logging phase			
	Felling	Skidding	Processing	Road-building
AVAGE	✓	✓	✓	
AVCUT		✓		
FTYPE	✓			✓
HA				✓
QUANT	✓	✓	✓	
SDI	✓	✓	✓	
SLOPE		✓	✓	✓
SORT			✓	✓
STUMP	✓	✓	✓	
SUMWIN	✓		✓	✓
TOTB		✓		
VOLHA			✓	
VOLUME		✓		
AV2[a]	✓	✓	✓	
Q2	✓		✓	
SB2			✓	
SDI2	✓		✓	
SLOPE2	✓		✓	✓
SOBUCK	✓			
STUCK	✓			
VQ	✓	✓	✓	

[a] Variables in italics denote derived variables.

Variable definitions:
AVAGE = Average age in years of logging machines
AVCUT = Average cutblock size in hectares
FTYPE = Forest type (softwood or hardwood)
HA = Total area harvested
QUANT = Quantitative timber size index
SDI = Species diversification index
SLOPE = Slope index
SORT = Sorting index
STUMP = Logging methods index
SUMWIN = Seasonal index
TOTB = Total number of cutblocks accessed during the logging season
VOLHA = Average volume in cubic metres per hectare
VOLUME = Total volume harvested in cubic metres
AV2 = Average age in years of logging machines squared
Q2 = Quantitative timber size index squared
SB2 = Square of sorting index + bucking index
SDI2 = Species diversification index squared
SLOPE2 = Slope index squared
SOBUCK = Sorting index + bucking index
STUCK = Logging methods index + bucking index
VQ = Quantitative timber size index divided by average volume per hectare

Forest Engineering Research Institute of Canada (Mellgren 1990), for example, assumes that salvage value is 20% of the purchase price of machinery (an assumption also used in this report to calculate minimum residual value of machinery for per-machine determinations of insurance cost) and that insurance and licensing costs are 5% per year of the purchase price.

No model can predict logging productivity exactly, because it is not possible to account for all sources of variability that influence productivity. The LCS was hindered, in the number and level of detail of forest and site characteristics that could be examined and the number of firms that could be interviewed, by the limitations in resources that the CFS could devote to the survey and, to some extent, by the time and effort that logging company owners could reasonably be expected to volunteer, given the demands of running their businesses in a highly competitive industry. Forest and site characteristics that have been included in trials of logging machinery in Canada that were not covered in the LCS include ground roughness, the ratio of unmerchantable to merchantable stems, and the density of underbrush. In addition, the forest and site characteristics used in the LCS are general estimates or averages of these quantities, which introduces a degree of imprecision. The quantitative timber size index, for example, was based on the average tree size of one or two species groups. A measure that reflects the range of tree sizes, in addition to the average, might be a better factor for modeling productivity.

One of the most significant factors in logging productivity is difficult to quantify or measure: the skill and motivation of the equipment operators and logging crews. The importance of skilled operators to the success and profitability of a firm, particularly in light of increasingly stringent demands arising from environmental concerns and the adoption of cut-to-length processing methods, was a common theme voiced by many of the owners interviewed. One study found that operator experience can account for a 35% difference in total cut-to-length harvesting costs (Favreau and Gingras 1998). Logging company owners often mentioned the increasing time and effort required for supervision of field operations to ensure that they meet stringent demands by forest products companies or the provincial government to minimize damage to advanced regeneration or to stand understories and to retain biodiversity. Another factor that could not be assessed in the LCS is the degree to which machine productivity was affected by organizational delays. The machines in a logging system must be chosen to complement one another's capacity and productivity, because overall productivity is usually determined by the capacity of one phase (MacDonald 1990).

CONCLUSION

The goal of the LCS was to determine the range and average costs of logging in Alberta to serve as a reference against which logging companies can gauge their competitiveness within their industry and, secondarily, to develop models to predict logging productivity according to forest and site conditions in Alberta. It is anticipated that these models will provide valuable information for input into financial analyses of forest management practices for eventual integration into broader strategic land use-planning essential to finding the right balance between the economic prosperity associated with the manufacture of forest products and the demand for nontimber benefits.

In spite of the LCS's limitations, the general strength of the models, as reflected by the goodness-of-fit measures, suggests that they are reasonable predictors of average logging productivity under forest and site conditions in Alberta. Cost predictions can be made by loggers, researchers, and forest managers alike, given the costs of operating logging machinery, and running a logging business in general, that this survey has determined.

ACKNOWLEDGMENTS

The authors, on behalf of the Canadian Forest Service, express their most sincere gratitude and appreciation to the Alberta Logging Association, and particularly to the participating member and nonmember logging companies, for their cooperation and support in conducting this survey. Special mention and thanks must be extended to Les Kerik of Kerik Brothers Enterprises Ltd., who generously contributed his time and effort toward the design and completion of the survey form that was subsequently used for all interviews. The authors also express their gratitude to the reviewers of this manuscript: Earl Marsh, TREES Consulting (formerly with an ALA logging company); Bonnie McFarlane (review chair), Canadian Forest Service; Derek Sidders, Canadian Forest Service; and Sen Wang, Canadian Forest Service.

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APPENDIX 1
Survey form used in the Logging Cost Survey

Alberta Logging Association &
Canadian Forest Service

Logging Cost Survey

ALBERTA
LOGGING ASSOCIATION

CONFIDENTIAL

1. Please define your past logging season (for example October 1996 to April 1997).

____

2. What was the total number of cutblocks you harvested per mill in the past logging season?

__________ ________ ________ ________

3. How many general areas were the cutblocks you harvested in the past logging season grouped into?

____

4. What was the average distance to the mill for each of the above general areas of cutblocks you harvested over the past logging season?

__________ km __________ km _________ km ________ km

5. Please fill in the weight to volume conversion factor for coniferous and deciduous trees for each mill if measures of weight were used at the scale.

Coniferous	Deciduous
____	______________________________________
____	______________________________________

6. If logs were bucked, what were the ranges of lengths they were bucked into (for example, 15 - 40 ft. for pulpwood logs)?

Pulpwood logs ______________ m (T) ____ or ft. (T) ___ Sawlogs _________________ m (T) ___ or ft. (T) ___

7. What logging methods did your firm use in the past logging season? Please check (T)all that apply.

A. Falling with feller-buncher, skid to landing _______ or roadside ________ , delimb at landing ______ or roadside ________

B. Falling with feller-buncher, delimb at stump, skid to landing _______or roadside _____

C. Hand falling, skid to landing ______ or roadside ______ , delimb at landing _____or roadside _________ by hand ______ or with a delimber _______

D. Hand falling, delimb by hand ______ or with a delimber _______ , skid to landing ______ or roadside _____

E. Falling, delimbing, and transport to landing _______ or roadside ______ with processor-forwarder

F.Other harvest equipment combination (please specify):________________________________

____

8. What was the breakdown of the average slope of the cutblocks you harvested in the past logging season (for example, 10 of the 30 cutblocks I harvested in the past logging season were steeper than usual, the remaining 20 cutblocks were generally flat)?

Generally flat __________ Moderately steep ______________ Steeper than usual ______________

9. What loading methods, if any, did your firm use in the past logging season? Please check (T) all that apply.

A. Loading at landing with front-end loader _______________

B. Loading at roadside with boom-type loader _______________

C. Loading at roadside with self-loading or picker truck ______________

D. Other loading equipment combination - (please specify) __________________________________

____

10. What were the average timber sizes of the wood you harvested in the past logging season, and your subjective rating of these timber sizes? For example, say your average tree size for one mill was 2.5 deciduous trees per cubic metre that you considered smaller than usual, and you harvested 3.0 coniferous trees per tonne for another mill that you considered about normal, the table would be filled out like the following example.

Example table

	Trees per tonne		*Trees per cubic metre*		*Trees per ton*	
Timber size	*Coniferous*	*Deciduous*	*Coniferous*	*Deciduous*	*Coniferous*	*Deciduous*
Smaller than usual				*2.5*		
About normal	*3.0*					
Larger than usual						

	Trees per tonne		Trees per cubic metre		Trees per ton	
Timber size	Coniferous	Deciduous	Coniferous	Deciduous	Coniferous	Deciduous
Smaller than usual						
About normal						
Larger than usual						

11. Please complete the following table on subcontractors you employed in the past logging season, including hauling subcontractors. Use the reverse side of the page if more space is required.

Subcontractor	List what the subcontractor did	Subcontractor's total production	Total payment made to subcontractor ($)
# 1			
# 2			
# 3			

12. Please complete the following table for all of your logging and road-building equipment used over the past logging season. Use the reverse side of the page if more space is required.

Type of machine (include rented machines)	Purchase price ($)	Repairs & alterations ($)	Insurance ($)	Loan or rental payments (include interest) ($)	Estimated total operator wages (**see first footnote**) ($)	Estimated fuel & oil ($)	Productive machine hours	Down time (**see second footnote**) %
TOTALS	▨						▨	╳

Include Canada Pension Plan, Workmen's Compensation, Unemployment Insurance, medical benefits and vacation pay.
Expressed as a ratio of Productive Machine Hours divided by total operator hours.

13. Please complete the following table on volume harvested and area harvested by species group in the past logging season

Species group harvested		Volume (or weight) harvested	Area harvested (hectares)
Predominantly softwoods			
Predominantly mixedwood forests	Aspen harvested		
	Spruce harvested		
Predominantly hardwoods			

14. If you hauled logs to a mill(s) in the past logging season, what was the total cost of hauling the weight or volume you harvested (from Step 13)?

$ ______________________

15. If you ran a camp in the past logging season, what was the cost of running it, including wages?

$ ______________________

16. Please estimate the yearly depreciation of your logging machines. (If you do not have a figure for depreciation, a rule of thumb across the industry is logging machinery depreciates 20% per year of the original purchase price over a 4 year period).

$ ______________________

17. What was your total overhead for the past logging season? Total overhead cost is your company's total revenue **minus**:

a) the sum of all ***TOTALS*** in Step 12 (repairs and alterations+ insurance+ loan or rental payments+ estimated total operator wages+estimated fuel and oil) $ __________________________

b) hauling costs (from Step 14); $ __________________________

c) camp costs (from Step 15); $ __________________________

d) total depreciation of logging machinery (from Step 16);

$ __________________________

e) total payments to subcontractors (from Step 11).

$ __________________________

Total overhead $ ____________________________

ALBERTA
LOGGING ASSOCIATION

APPENDIX 2
Harvest volumes, conversion factors, and harvest weights by species group

Firm	Harvest volume (m^3)		Conversion factors (t / m^3)		Harvest weight (t)		Total harvest	
	Coniferous	Deciduous	Coniferous	Deciduous	Coniferous	Deciduous	In m^3	In t
1	134 000	0	0.801 7	NA	107 428	0	134 000	107 428
2	108 912[a]	62 475	0.817	1.066 5	88 980	66 630	171 387	155 610
3	23 529[a]	36 496[a]	0.85	0.959	20 000	35 000	60 025	55 000
4	80 000	228 000	0.906 4	1.011	72 512	230 508	308 000	303 020
5	86 717[a]	94 346[a]	0.878	0.95	76 138	89 629	181 063	165 767
6	174 375[a]	7 273[a]	0.8	1.1	139 500	8 000	181 648	147 500
7	18 072[a]	178 976[a]	0.83	0.949 8	15 000	170 000	197 048	185 000
8	400	71 600	0.83	1.1	332[b]	78 760	72 000	79 092
9	72 000	8 000	0.85	0.97	61 200	7 760[c]	80 000	68 880
10	170 625[a]	9 474[a]	0.8	0.95	136 500	9 000	180 099	145 500
11	100 000	0	0.812 5	NA	81 250	NA	100 000	81 250
12	260 000	0	0.795	NA	206 700	0	260 000	206 700
13	275 000	0	0.86	NA	236 500	0	275 000	236 500
14	52 087[a]	35 943[a]	0.819 7	0.900 9	42 694	32 381	88 030	75 075
15	165 000	0	0.803	NA	132 495	0	165 000	132 495
16	69 849	400 407	0.879 5	1.0	61 432	400 407	470 256	461 839
17	0	90 722[d]	NA	0.97	0	88 000	90 722	88 000
18	55 000	10 000	0.713 5	0.888	39 243	8 880	65 000	48 123
19	80 000	220 000	0.85	0.9	68 000	198 000	300 000	266 000
20	226 000	14 000	0.81	1.0	183 060	14 000	240 000	197 060
21	80 000	130 000	0.867	0.97	69 360	126 100	210 000	195 460
22	200 000	60 000	0.825	1.0	165 000	60 000	260 000	225 000
23	190 000	30 000	0.8	1.0	152 000	30 000	220 000	182 000
24	30 000	130 000	0.85	0.925	25 500	120 250	160 000	145 750
25	61 958	157 635	0.83	0.925	51 425	145 812	219 593	197 237
26	0	170 000	NA	0.86	0	146 200	170 000	146 200
27	262 000	6 000	0.782 5	1.0	205 015	6 000	268 000	211 015
28	18 000	0	0.83	NA	14 940	0	18 000	14 940
29	80 000	2 000	0.848	0.98	67 840	1 960	82 000	69 800
Total	3 073 524	2 153 347	NA	NA	2 520 045	2 073 277	5 226 871	4 593 242

[a] Volume determined by conversion from weight (in tonnes) using contractor-supplied conversion factors.

[b] Volume converted to weight using the survey average for coniferous timber of 0.83 t / m^3, because contractor was unable to supply a conversion factor.

[c] Volume converted to weight using the survey average for deciduous timber of 0.97 t / m^3, because contractor was unable to supply a conversion factor.

[d] Volume determined by conversion using the survey average for deciduous timber of 0.97 t / m^3, because contractor was unable to supply a conversion factor (all timber from private land).

Note: NA = not applicable.

APPENDIX 3
Bucking by log type and species group

Firm	Pulpwood logs: Coniferous timber	Pulpwood logs: Deciduous timber	Sawlogs (coniferous timber)
1	NA	NA	Tree length
2	15–40 ft.	15–40 ft.	NA
3	NA	101 in.[a]	Tree length
4	Tree length	Tree length	NA
5	NA	Tree length	5 lengths, all <27 ft.
6	20–40 ft.	20–40 ft.	12 ft. to tree length
7	NA	102 in.[a]	Tree length
8	NA	8–30 ft. (90% at 30 ft.)[a]	Tree length
9	NA	Tree length	Tree length
10	15–25 ft.	15–25 ft.[a]	Tree length
11	8–24 ft.	NA	16–24 ft.
12	NA	NA	Tree length
13	NA	NA	Tree length
14	<20–40 ft.	8 ft. to tree length	20 ft. to tree length
15	40 ft.	NA	Tree length
16	NA	8 ft.	Cut to length
17	NA	100 in.	NA
18	12–16 ft.	12–16 ft.	12, 14, 16 ft.
19	30 ft.	30 ft.	34 ft.
20	10–16 ft.	10–16 ft.	10–16 ft. and tree length
21	NA	30 ft.	Tree length
22	NA	Tree length	Tree length
23	NA	Tree length	Tree length
24	30 ft.	NA	Tree length
25	NA	30 ft.	Tree length
26	NA	30 ft.	NA
27	12–40 ft.	Tree length	12 ft. to tree length
28	10, 12, 14, 16 ft.	NA	10, 12, 14, 16 ft.
29	Tree length	Tree length	Tree length

[a] Logs were slashed.

Note: NA = not applicable, 1 in. = 2.54 cm, 1 ft. = 30.48 cm.

APPENDIX 4

Logging phases, logging methods, forest characteristics, and descriptive logging indexes

Firm	Logging phases performed[a]	Logging method[b]	Logging methods index	Average volume (m^3/ha)	Average cutblock size (ha)	Slope index	Quantitative timber size index	Sorting index	Bucking index	Species diversification index	Seasonal index
1	FSL	AR	1	178.67	10.0	418.68	294.80	0	0	100.00	2
2	FSDL	AR	1	190.41	18.2	241.04	270.36	1	2	63.55	1
3	FSD	AR	1	174.73	16.9	276.20	216.81	0	0	66.38	1
4	FSDL	AR	1	210.24	24.4	250.00	206.91	0	0	74.03	1
5	FSD	AR	1	226.33	18.2	427.28	306.53	0	1	52.11	1
6	FSD	AR, BR, CR, ER	2	312.11	13.5	395.36	318.64	2	3	96.00	1
7	FSDL	AR	1	140.75	26.9	328.14	247.25	1	0	90.83	1
8	FD	AR	1	159.11	30.0	226.66	546.00	1	1	99.44	1
9	FD	FR[c]	2	200.00	40.0	240.00	575.00	1	0	90.00	2
10	FSDL	AR	1	190.58	23.6	450.00	201.95	1	1	94.74	2
11	FSDL	ER	2	221.24	37.7	266.68	650.00	1	2	100.00	2
12	FDL	AR, BR	2	173.33	37.5	320.00	520.00	0	0	100.00	2
13	D	AR	1	373.64	17.9	297.56	260.00	0	0	100.00	2
14	FSD	AR	1	598.84	6.4	200.00	209.12	2	3	59.17	1
15	FSD	AR	1	366.67	21.4	400.00	350.00	1	1	100.00	2
16	FSDL	AR, AL, ER	2	213.68	12.9	374.28	300.99	1	2	85.15	2
17	FSDL	AR	1	236.26	24.2	200.00	218.00	0	1	100.00	2
18	FSD	ER	2	250.00	20.0	200.00	242.31	2	3	84.62	1
19	FSD	AR	1	200.00	27.3	200.00	350.00	2	3	73.33	2

Firm	Logging phases performed[a]	Logging method[b]	Logging methods index	Average volume (m^3/ha)	Average cutblock size (ha)	Slope index	Quantitative timber size index	Sorting index	Bucking index	Species diversification index	Seasonal index
20	FSD	AR, ER	2	307.69	6.2	224.00	363.63	2	3	100.00	1
21	FSD	AR	1	143.84	30.4	245.84	342.87	1	1	61.90	2
22	FSD	AR	1	240.30	31.8	270.60	231.54	1	0	76.92	1
23	FSD	AR, BR	2	220.00	40.0	224.00	286.36	1	0	86.36	2
24	FSD	AR	1	115.11	42.1	212.12	562.50	1	1	81.25	2
25	FSD	AR	1	183.45	35.2	305.88	314.69	1	1	71.79	2
26	FSD	AR	1	184.78	23.6	200.00	280.00	0	1	100.00	2
27	FSD	AR, AL, BR, BL, CR, CL, DR, DL, ER	2	205.21	31.1	447.62	398.60	2	2	97.76	2
28	FD	ER	2	234.9[d]	7.7[d]	200.00	600.00	1	2	100.00	1
29	D	AR, BR	2	269.7	23.4	220.00	424.39	2	0	97.56	1

[a] F = falling; S = skidding; D = delimbing; L = loading. Logging phases performed by subcontractors are not included.

[b] Method A = use of feller–bunchers, skidding to roadside (R) or landing (L), and delimbing at roadside or landing;
Method B = use of feller–bunchers, at-the-stump processing, and skidding to roadside (R) or landing (L).;
Method C = hand felling, skid to roadside (R) or landing (L), delimbing at roadside or landing;
Method D = hand felling and hand delimbing, skidding to roadside (R) or landing (L);
Method E = cut-to-length harvesting using multipurpose harvesters or feller–bunchers in tandem with processors, forwarding to roadside (R) or landing (L);
Method F = other harvest equipment combinations.

[c] Felling, delimbing and topping with harvesters; no cutting to length.

[d] Based on average volume per hectare for coniferous timber in predominantly softwood forests.

APPENDIX 5
Slope conditions under which the 29 firms conducted logging operations

Firm	No. of cutblocks	% of cutblocks considered generally flat	% of cutblocks considered moderately steep	% of cutblocks considered steeper than usual
1	75	45.33	0.00	54.67
2	39	89.74	0.00	10.26
3	21	61.90	38.10	0.00
4	60	75.00	25.00	0.00
5	44	9.09	68.18	22.73
6	43	34.88	32.56	32.56
7	64	45.31	45.31	9.38
8	15	86.67	13.33	0.00
9	10	80.00	20.00	0.00
10	40	0.00	75.00	25.00
11	12	83.33	0.00	16.67
12	40	70.00	0.00	30.00
13	41	51.22	48.78	0.00
14	23	100.00	0.00	0.00
15	21	0.00	100.00	0.00
16	171	29.82	53.22	16.96
17	16	100.00	0.00	0.00
18	13	100.00	0.00	0.00
19	55	100.00	0.00	0.00
20	125	88.00	12.00	0.00
21	48	81.25	14.58	4.17
22	34	76.47	11.76	11.77
23	25	92.00	4.00	4.00
24	33	93.94	6.06	0.00
25	34	70.59	5.88	23.53
26	39	100.00	0.00	0.00
27	42	14.29	47.61	38.10
28	10	100.00	0.00	0.00
29	13	90.00	10.00	0.00
Total or average[a]	1206	60.78	26.04	13.18

[a] Average cutblock values for each slope class (in percent) were calculated as the total number of cutblocks in each slope class relative to the total number of cutblocks reported by the 29 firms. The number of cutblocks in each slope class had to be determined by calculation (rounded to the nearest whole number) because most firms gave breakdowns of their cutblocks into each slope class as percentages rather than as numbers of cutblocks.

APPENDIX 6
Average timber sizes by timber size rating

	Timber size (trees / m^3)					
	Timber smaller than normal		Timber about normal in size		Timber larger than normal	
Firm	Coniferous	Deciduous	Coniferous	Deciduous	Coniferous	Deciduous
1	–[a]	–	3.50	–	2.50	–
2	–	2.71	2.70	–	–	–
3	–	–	2.50	2.00	–	–
4	–	–	2.38	1.96	–	–
5	–	–	2.81	3.30	–	–
6	–	–	3.24	1.90	–	–
7	–	–	–	–	2.20	2.50
8	–	5.46	–	–	–	–
9	–	–	6.00	3.50	–	–
10	–	–	2.00	2.37	–	–
11	–	–	6.50	–	–	–
12	7.50	–	5.50	–	2.50	–
13	–	–	2.60	–	–	–
14	–	–	2.23	–	–	1.89
15	–	–	3.50	–	–	–
16	4.50	–	–	2.75	–	–
17	–	–	–	2.18	–	–
18	–	–	–	–	2.50	2.00
19	–	–	3.50	3.50	–	–
20	–	–	3.75	1.80	–	–
21	–	–	2.50	4.00	–	–
22	–	–	2.50	1.70	–	–
23	–	–	3.00	2.00	–	–
24	–	6.0	4.00	–	–	–
25	–	–	2.91	3.24	–	–
26	–	–	–	–	–	2.80
27	4.02	–	–	2.50	–	–
28	–	–	6.00	–	–	–
29	4.30	–	–	2.00	–	–
Average	5.08	4.72	3.51	2.54	2.42	2.30

[a] Dashes indicate that the firm did not harvest timber of that species group and timber size rating.

APPENDIX 7
Timber sizes classified by timber size rating

	Timber size (m^3/tree)					
	Timber smaller than normal		Timber about normal in size		Timber larger than normal	
Firm	Coniferous	Deciduous	Coniferous	Deciduous	Coniferous	Deciduous
1	–[a]	–	0.29	–	0.40	–
2	–	0.37	0.37	–	–	–
3	–	–	0.40	0.50	–	–
4	–	–	0.42	0.51	–	–
5	–	–	0.36	0.30	–	–
6	–	–	0.31	0.53	–	–
7	–	–	–	–	0.45	0.40
8	–	0.18	–	–	–	–
9	–	–	0.17	0.29	–	–
10	–	–	0.50	0.42	–	–
11	–	–	0.15	–	–	–
12	0.13	–	0.18	–	0.40	–
13	–	–	0.38	–	–	–
14	–	–	0.45	–	–	0.53
15	–	–	0.29	–	–	–
16	0.22	–	–	0.36	–	–
17	–	–	–	0.46	–	–
18	–	–	–	–	0.40	0.50
19	–	–	0.29	0.29	–	–
20	–	–	0.27	0.56	–	–
21	–	–	0.40	0.25	–	–
22	–	–	0.40	0.59	–	–
23	–	–	0.33	0.50	–	–
24	–	0.17	0.25	–	–	–
25	–	–	0.34	0.31	–	–
26	–	–	–	–	–	0.36
27	0.25	–	–	0.40	–	–
28	–	–	0.17	–	–	–
29	0.23	–	–	0.50	–	–
Average	0.21	0.24	0.32	0.42	0.41	0.45

[a] Dashes indicate that the firm did not harvest timber of that species group and timber size rating.

APPENDIX 8

Harvest volumes and areas by forest type and species group

	Predominantly softwoods			Predominantly mixedwoods			Predominantly hardwoods				
Firm	Coniferous timber (m3)	Deciduous timber (m3)	Area harvested (ha)	Spruce harvest (m3)	Aspen harvest (m3)	Area harvested (ha)	Coniferous timber (m3)	Deciduous timber (m3)	Area harvested (ha)	Total harvest (m3)	Total area harvested (ha)
1	134 000	–[a]	750	–	–	–	–	–	–	134 000	750
2	108 912[b]	–	414	–	–	–	–	62 475	296	171 387	710
3	–	–	–	23 529[b]	36 496[b]	338[c]	–	–	–	60 025	338
4	–	–	–	80 000	228 000	1 465[d]	–	–	–	308 000	1 465
5	–	–	–	86 717[b]	94 346[b]	800[e]	–	–	–	181 063	800
6	89 375[b]	–	270	85 000[b]	7 273[b]	312	–	–	–	181 648	582
7	–	–	–	–	–	–	18 072[b]	178 976[b]	1 400	197 048	1 400
8	–	–	–	–	–	–	400	71 600	450	72 000	450
9	72 000	8 000	400	–	–	–	–	–	–	80 000	400
10	–	–	–	170 625[b]	9 474[b]	945[f]	–	–	–	180 099	945
11	100 000	–	452	–	–	–	–	–	–	100 000	452
12	260 000	–	1 500	–	–	–	–	–	–	260 000	1 500
13	275 000	–	736	–	–	–	–	–	–	275 000	736
14	–	–	–	52 087[b]	35 943[b]	147	–	–	–	88 030	147
15	–	–	–	165 000	–	450	–	–	–	165 000	450
16	–	–	–	69 849	6 629	251[g]	–	393 778	1 950	470 256	2 201
17	–	–	–	–	–	–	–	90 722[h]	388	90 722	388
18	55 000	10 000	260	–	–	–	–	–	–	65 000	260
19	–	–	–	–	–	–	80 000	220 000	1 500	300 000	1 500

	Predominantly softwoods			Predominantly mixedwoods			Predominantly hardwoods				
Firm	Coniferous timber (m^3)	Deciduous timber (m^3)	Area harvested (ha)	Spruce harvest (m^3)	Aspen harvest (m^3)	Area harvested (ha)	Coniferous timber (m^3)	Deciduous timber (m^3)	Area harvested (ha)	Total harvest (m^3)	Total area harvested (ha)
20	226 000	14 000	780	–	–	–	–	–	–	240 000	780
21	30 000	–	160	–	–	–	50 000	130 000	1 300	210 000	1 460
22	–	–	–	200 000	60 000	1 082	–	–	–	260 000	1 082
23	190 000	30 000	1 000	–	–	–	–	–	–	220 000	1 000
24	–	–	–	30 000	30 000	390	–	100 000	1 000	160 000	1 390
25	14 458	15 135	80	–	–	–	47 500	142 500	1 117	219 593	1 197
26	–	–	–	–	–	–	–	170 000	920	170 000	920
27	262 000	6 000	1 306	–	–	–	–	–	–	268 000	1 306
28	18 000	–	76[i]	–	–	–	–	–	–	18 000	76
29	80 000	2 000	304	–	–	–	–	–	–	82 000	304
Total	1 914 745	85 135	8 488	962 807	508 161	6 180	195 972	1 560 051	10 321	5 226 871	24 989

[a] Dashes indicate that the firm did not harvest timber of that species group from the particular forest type.

[b] Volumes determined by conversion from weight (in tonnes) using contractor-supplied conversion factors.

[c] Consisting of 133 ha for 20 854 m^3 of spruce and 205 ha for 41 176 m^3 of aspen.

[d] Consisting of 380 ha of spruce harvest and 1085 ha of aspen harvest.

[e] Consisting of 275 ha for 86 717 m^3 of spruce and 525 ha for 94 346 m^3 of aspen.

[f] Consisting of 910 ha for 170 625 m^3 of spruce and 35 ha for 9474 m^3 of aspen.

[g] Consisting of 192 ha for 69 848.75 m^3 of spruce and 59 ha for 6629 m^3 of aspen.

[h] Weight converted to volume using the survey average for deciduous timber of 0.96 t / m^3, because owner was unable to supply a conversion factor (all timber from private land).

[i] Area estimated from the survey average of 237.7 m^3 / ha for coniferous timber in predominantly softwood forests. Area not available from this firm because some cutblocks were only partially harvested.

APPENDIX 9
All logging and road-building machinery used by the 29 firms

Feller–bunchers

Vintage	Manufacturer and model
1986	693D (manufacturer not available)
1989	Koehring (model not available)
1990	Caterpillar 227
1991	Koehring 600
1991	Timbco T435
1992	Caterpillar FB300
1992	Timberjack 618
1993	Caterpillar 325
1993	Timberjack 618 (*n* = 2)
1994[a]	Koehring 628 (*n* = 2)
1994[a]	Koehring (model not available)
1994	Komatsu carrier with Denarco 3000 head
1994	Timbco (model not available)
1994	Timberjack 608
1994	Timberjack 618 (*n* = 4)

Vintage	Manufacturer and model
1994	Timberjack 628 (*n* = 2)
1994	Morbark Wolverine
1995	Timbco T445 (*n* = 2)
1995	Timberjack 618 (*n* = 8)
1996	Koehring 618 (*n* = 2)
1996	Prentice 630A (*n* = 2)
1996	Tigercat 845
1996	Timbco T455
1996	Timberjack 628
1996	Timberjack 923
1997	Koehring 618
1997	Tigercat 853
1997	Timbco T435C
1997	Timberjack 618
1997	Timberjack 850

Skidders

Vintage	Manufacturer and model
1985	Caterpillar 528
1987	Caterpillar 518
1989	Caterpillar 528
1990	John Deere 648D
1991	John Deere 648E
1991	John Deere 748E
1991	Timberjack 450
1992	John Deere 648E
1992	Timberjack 480B
1993	John Deere 648E
1993	John Deere 748E (*n* = 2)
1993	Timberjack 450C
1994	John Deere 548E
1994	John Deere 648E (*n* = 3)
1994	John Deere 748 (*n* = 4)
1994	John Deere 748E
1994[a]	Timberjack (model not available)
1994[a]	Timberjack SK206
1994	Timberjack 450
1994	Timberjack 450C
Vintage	Manufacturer and model

1994[a]	Timberjack 480C (*n* = 2)
1995	Caterpillar 525 (*n* = 2)
1995	John Deere 648E
1995	John Deere 648G (*n* = 2)
1995	John Deere 748
1995	John Deere 7486A
1995	John Deere 748E
1995	Timberjack 450
1995	Timberjack 450C
1996	Caterpillar D5H TSK
1996	John Deere 648
1996	John Deere 648E
1996	John Deere 748 (*n* = 2)
1996	Timberjack 460
1996	Timberjack 560
1996	Timberjack 660
1997	John Deere 648G
1997	John Deere 748 (*n* = 4)
1997	Timberjack 560 (*n* = 5)

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[a] Machine vintage not available. Vintage estimated based on average age of logging machines in the Logging Cost Survey.

Harvesters and processors

Vintage	Manufacturer, model, and machine type
1987	Rottne 860 2-grip processor
1988	Rottne 860 2-grip processor
1988	Rottne harvester–processor
1989	Linkbelt CS2800 with Lako 60 processor
1993	Hyundai 200 with Ultimate processor
1995	Caterpillar-Denarco 550 single-grip harvester
1995	Timberjack 1270 harvester–processor
1996	Caterpillar-Koehring 762 single-grip harvester
1996	Timberjack 608 with Keto harvester–processor
1996	Valmet 500T harvester
1997	Kochum 8535 single-grip harvester

Forwarders

Vintage	Manufacturer and model
1985	Kochum 8535
1986	Kochum 8535
1993	Trans-Gesco TG80
1995	Timberjack 1010
1996	Valmet 543F

Delimbers

Vintage	Manufacturer, model, and machine type
1986	Hitachi UH83 carrier with Denis delimber
1988	John Deere 790D carrier with Limmit 2200 delimber
1989	Komatsu-Denis delimber (model not available) (*n* = 2)
1989	Komatsu PC200 carrier with 1989 Denis delimber
1990	Caterpillar EL200 delimber
1990	John Deere 790 delimber[a]
1990	John Deere 790D carrier with Hurricana delimber
1991	Caterpillar 225 carrier with Limmit 2200
1991	Komatsu 200 carrier with Limmit delimber
1991	Caterpillar DL200B with Limmit delimber
1992	Caterpillar EL200 delimber
1992	Caterpillar EL300 / 7200 delimber
1992	John Deere 790D delimber
1992	Komatsu 220 delimber carrier with Denarco head
1992	Komatsu carrier with Limmit 2000 delimber
1993	Hyundai 200 carrier with Limmit 2100 delimber
1993	John Deere 892D carrier with Target processing head
1993	Komatsu 200 delimber
1993	Komatsu 200 carrier with Limmit delimber
1993	Komatsu DC200-5 delimber
1994	Caterpillar 320 delimber
1994	Caterpillar B30 / 2300 delimber
1994	Hyundai 200 carrier with Limmit delimber
1994	John Deere 690E carrier with Limmit 2100 delimber
1994	John Deere 892 delimber
1994	John Deere 892E carrier with Limmit 2200 delimber
1994	Komatsu 200 carrier with Limmit delimber
1994	Komatsu 220 delimber
1994	Komatsu PC200 carrier with Limmit delimber
1994	Komatsu PC220 carrier with Limmit 2100 delimber
1994[b]	Komatsu delimber (model not available) (*n* = 2)
1995	Caterpillar 320 delimber
1995	Caterpillar 320 carrier with Limmit 2000

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[a] Machine was idle for logging season and therefore was not included in any analyses.

[b] Vintage not available. Vintage estimated based on average age of logging machines in the Logging Cost Survey.

Delimbers continued

Vintage	Manufacturer, model, and machine type
1995	Caterpillar 392 carrier with Limmit 2000
1995	Hitache carrier with Limmit delimber (model not available)
1995	Hyundai 200 carrier with Limmit 2000 delimber
1995	John Deere 792A delimber
1995	John Deere 892 delimber
1995	Komatsu 200 delimber
1995	Komatsu 220 carrier with Target processing head
1995	Komatsu carrier with Denarco 3500 delimber
1995	Komatsu PC200 carrier with Denarco 2000 delimber
1995	Komatsu PC200 carrier with Limmit delimber
1995	Komatsu PC220 carrier with Limmit 2100 delimber (n = 2)
1995	Timberjack 618 carrier with Limmit 2100 delimber

Vintage	Manufacturer, model, and machine type
1996	Caterpillar 322 carrier with Limmit delimber
1996	Hyundai 290 carrier with Limmit 2300 delimber
1996	Komatsu 220 delimber
1996	Komatsu PC200 carrier with Denarco 2000 delimber
1996	Komatsu PC200 carrier with Limmit delimber
1996	Komatsu PC220 carrier with Limmit 2100 delimber
1997	John Deere delimber (model not available)
1997	Komatsu 200 delimber
1997	Komatsu 220 carrier with Limmit 2200 delimber
1997	Komatsu carrier with Limmit 2000 delimber

Loaders

Vintage	Manufacturer and mode
1986	Caterpillar 235B log loader
1991	Caterpillar 300 log loader
1993	Caterpillar 325 loader
1993	John Deere 892D loader

Vintage	Manufacturer and mode
1993	Komatsu loader (model not available)
1994	Komatsu PC300HD Button Top
1995	Caterpillar 330 log loader
1996	Caterpillar 330 log loader

Road-building machinery

Vintage	Manufacturer, model, and machine type
1965	Caterpillar D7E bulldozer
1972	Caterpillar D8H bulldozer
1975	Caterpillar D8K crawler
1978	Caterpillar 976 crawler
1978	Caterpillar D8K bulldozer
1978	Caterpillar 140 grader
1979	Caterpillar D6D bulldozer
1979	Caterpillar D8K bulldozer
1979	Caterpillar 140 grader
1979	Komatsu D85E-18 crawler–bulldozer
1980	Caterpillar D7G crawler
1980	Caterpillar D8K bulldozer (n = 2)
1980	Caterpillar D8K crawler–bulldozer
1980	Komatsu D85E-18 crawler–bulldozer

Vintage	Manufacturer, model, and machine type
1981	Caterpillar D7G bulldozer (n = 2)
1981	Caterpillar D8K bulldozer (n = 2)
1981	Champion 740 grader
1982	Caterpillar D7G crawler
1984	Komatsu D85E crawler–bulldozer
1985	Caterpillar D7G crawler
1985[a]	Caterpillar D7E bulldozer
1985	Champion 740 grader
1985[a]	Gilbert tractor 5220-1031
1985	John Deere 850 bulldozer
1985[a]	Komatsu D65E-18 bulldozer
1985[a]	Komatsu D65P-6 bulldozer
1985[a]	Komatsu 585E TRAK 35365
1986	Caterpillar D65E bulldozer

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[a] Vintage not available. Vintage estimated based on average age of road-building machines in the Logging Cost Survey.

Road-building machinery continued

Vintage	Manufacturer, model, and machine type
1986	John Deere 850 crawler
1986	Komatsu D65E-8 crawler–bulldozer
1987	Caterpillar D4 bulldozer
1987	Caterpillar D7H bulldozer
1989	Caterpillar EL200 backhoe
1989	John Deere 790 excavator
1989	John Deere 790D backhoe
1989	John Deere 850B crawler
1989	John Deere 850D bulldozer
1989	Komatsu D83-1 crawler–bulldozer
1990	Caterpillar D65 crawler
1990	Champion grader 20749
1990	Komatsu D65 bulldozer
1991	Hyundai 280 excavator
1994	Caterpillar EL322 backhoe
1994	Komatsu D85 bulldozer
1994	Excavator (manufacturer and model not available)
1995	Champion grader
1995	Komatsu D85 bulldozer
1996	Caterpillar 322L excavator
1996	Champion 780 grader
1996	Excavator (manufacturer and model not available)
1996	John Deere 690E excavator
1997	Komatsu crawler (model not available)

APPENDIX 10

Paired-difference tests between actual and estimated loan payments

0.05 level of significance, univariate procedure

Moments

n	138	Sum weights	138
Mean	479.242 7	Sum	66 135.49
SD	33 038.94	Variance	1.091 6E9
Skewness	–0.846 8	Kurtosis	3.782 117
USS	1.496 E11	CSS	1.495 E11
CV	6 893.989	Std mean	2 812.461
T:mean = 0	0.170 4	Pr > | *T* |	0.864 9
Num ^ = 0	96	Num > 0	55
M (sign)	7	Pr ≥ | *M* |	0.184 3
Sgn rank	275	Pr ≥ | *S* |	0.317 5

Quantiles (DF = 5)

100% (maximum)	105 000	99%	80 468.8
75% (Q3)	10 573.4	95%	54 600
50% (medium)	0	90%	36 837.47
25% (Q1)	–3 916.97	10%	–35 169.9
0% (minimum)	–134 009	5%	–80 468.8
		1%	–103 805
Range	239 008.7		
Q3–Q1	14 490.37		
Mode	0		

Extremes

Lowest	(no. of observations)	Highest	(no. of observations)
–134 009	(1)	63 679	(50)
–103 805	(5)	66 000	(137)
–96 177.8	(134)	73 673.1	(120)
–94 626.7	(90)	80 468.8	(103)
–87 503.4	(110)	105 000	(56)

Note: SD = standard deviation, USS = uncorrected sum of squares, CSS = corrected sum of squares, CV = coefficient of variation, Std mean = standard error of the mean, *T*:mean = the Student's *t* value for testing the hypothesis that the population mean is zero, Pr > | *T* | = the probability of a greater absolute value for this *t*-value, Num ^ = the number of nonzero observations, Num = the number of positive observations, *M* (sign) = the sign statistic for testing the hypothesis that the population mean is zero, Pr ≥ | *M* | = the probability of a greater absolute value for the mean under the hypothesis that the population mean is zero, Sgn rank = the centered (the expected value is subtracted) Wilcoxon signed rank statistic for testing the hypothesis that the population mean is zero, Pr ≥ | *S* | = the probability of a greater absolute value for this statistic under the hypothesis that the population mean is zero, DF = degrees of freedom, Q3 = quantile 3, Q1 = quantile 1.

APPENDIX 11

Paired-difference tests between actual and estimated insurance payments

0.05 level of significance, univariate procedure

Moments

n	104	Sum weights	104
Mean	0	Sum	0
SD	1 490.857	Variance	2 222 654
Skewness	0.263 146	Kurtosis	2.987 841
USS	2.289 3E8	CSS	2.289 3E8
CV	.	Std mean	146.190 6
T:mean = 0	0	Pr > | *T* |	1.000 0
Num ^ = 0	102	Num > 0	52
M (sign)	1	Pr ≥ | *M* |	0.921 2
Sgn rank	91	Pr ≥ | *S* |	0.763 0

Quantiles (DF = 5)

100% (maximum)	5 396.55	99%	4 780.66
75% (Q3)	503.63	95%	2 073.8
50% (medium)	1.9	90%	1 408.1
25% (Q1)	–385.565	10%	–1 585.45
0% (minimum)	–4 062.13	5%	–2 806.32
		1%	–3 827.81
Range	9 458.68		
Q3–Q1	889.195		
Mode	–379.23		

Extremes

Lowest (no. of observations)	Highest (no. of observations)
–4 062.13 (30)	2 839.08 (35)
–3 827.81 (5)	3 571.63 (98)
–3 676.93 (31)	3 571.63 (99)
–3 263.74 (92)	4 780.66 (89)
–2 826.72 (101)	5 396.55 (100)

Note: SD = standard deviation, USS = uncorrected sum of squares, CSS = corrected sum of squares, CV = coefficient of variation, Std mean = standard error of the mean, *T*:mean = the Student's *t* value for testing the hypothesis that the population mean is zero, Pr > | *T* | = the probability of a greater absolute value for this *t*-value, Num ^ = the number of nonzero observations, Num = the number of positive observations, *M* (sign) = the sign statistic for testing the hypothesis that the population mean is zero, Pr ≥ | *M* | = the probability of a greater absolute value for the mean under the hypothesis that the population mean is zero, Sgn rank = the centered (the expected value is subtracted) Wilcoxon signed rank statistic for testing the hypothesis that the population mean is zero, Pr ≥ | *S* | = the probability of a greater absolute value for this statistic under the hypothesis that the population mean is zero, DF = degrees of freedom, Q3 = quantile 3, Q1 = quantile 1.

APPENDIX 12

Paired-difference tests between actual and estimated operator wages and benefits

0.05 level of significance, univariate procedure

Moments

n	113	Sum weights	113
Mean	–0.004 07	Sum	–0.46
SD	10 255.57	Variance	1.051 8E8
Skewness	0.372 922	Kurtosis	4.496 942
USS	1.178 E10	CSS	1.178 E10
CV	–2.519 E8	Std mean	964.762 4
T:mean = 0	–4.22E-6	Pr > |*T*|	1.000 0
Num ^ = 0	111	Num > 0	53
M (sign)	–2.5	Pr ≥ |*M*|	0.704 4
Sgn rank	–41.5	Pr ≥ |*S*|	0.903 5

Quantiles (DF = 5)

100% (maximum)	35 848.38	99%	33 136.71
75% (Q3)	2 905.83	95%	12 168.75
50% (medium)	–116.67	90%	7 797.83
25% (Q1)	–3 387.5	10%	–8 997.29
0% (minimum)	–33 446.6	5%	–19 151.6
		1%	–33 404.3
Range	69 295		
Q3–Q1	6 293.33		
Mode	–19 151.6		

Extremes

Lowest (no. of observations)	Highest (no. of observations)
–33 446.6 (105)	16 884.62 (10)
–33 404.3 (104)	33 135.71 (107)
–21 423.3 (110)	33 135.71 (108)
–19 736.3 (56)	33 136.71 (109)
–19 151.6 (97)	35 848.38 (101)

Note: SD = standard deviation, USS = uncorrected sum of squares, CSS = corrected sum of squares, CV = coefficient of variation, Std mean = standard error of the mean, *T*:mean = the Student's *t* value for testing the hypothesis that the population mean is zero, Pr > | *T* | = the probability of a greater absolute value for this *t*-value, Num ^ = the number of nonzero observations, Num = the number of positive observations, *M* (sign) = the sign statistic for testing the hypothesis that the population mean is zero, Pr ≥ | *M* | = the probability of a greater absolute value for the mean under the hypothesis that the population mean is zero, Sgn rank = the centered (the expected value is subtracted) Wilcoxon signed rank statistic for testing the hypothesis that the population mean is zero, Pr ≥ | *S* | = the probability of a greater absolute value for this statistic under the hypothesis that the population mean is zero, DF = degrees of freedom, Q3 = quantile 3, Q1 = quantile 1.

APPENDIX 13

Paired-difference tests between actual and estimated fuel and oil expenditures

0.05 level of significance, univariate procedure

Moments

n	86	Sum weights	86
Mean	–0.001 86	Sum	–0.16
SD	4 048.567	Variance	16 390 897
Skewness	–0.207 7	Kurtosis	3.535 129
USS	1.393 2E9	CSS	1.393 2E9
CV	–2.176 E8	Std mean	436.568 2
T:mean = 0	–4.26E-6	Pr > |*T*|	1.000 0
Num ^ = 0	84	Num > 0	33
M (sign)	–9	Pr ≥ |*M*|	0.063 0
Sgn rank	–83.5	Pr ≥ |*S*|	0.712 0

Quantiles (DF = 5)

100% (maximum)	12 363.87	99%	12 363.87
75% (Q3)	836.11	95%	8 499.82
50% (medium)	–4.75	90%	4 891.89
25% (Q1)	–1 195.81	10%	–3 386.11
0% (minimum)	–13 460	5%	–7 009.57
		1%	–13 460
Range	25 823.88		
Q3–Q1	2 031.92		
Mode	–2 557.04		

Extremes

Lowest	(no. of observations)	Highest	(no. of observations)
–13 460	(79)	8 499.82	(44)
–13 448.2	(78)	9 684.69	(81)
–9 783.78	(33)	9 684.69	(82)
–7 636.13	(37)	9 685.69	(83)
–7 009.57	(6)	12 363.87	(34)

Note: SD = standard deviation, USS = uncorrected sum of squares, CSS = corrected sum of squares, CV = coefficient of variation, Std mean = standard error of the mean, *T*:mean = the Student's *t* value for testing the hypothesis that the population mean is zero, Pr > |*T*| = the probability of a greater absolute value for this *t*-value, Num ^ = the number of nonzero observations, Num = the number of positive observations, *M* (sign) = the sign statistic for testing the hypothesis that the population mean is zero, Pr ≥ |*M*| = the probability of a greater absolute value for the mean under the hypothesis that the population mean is zero, Sgn rank = the centered (the expected value is subtracted) Wilcoxon signed rank statistic for testing the hypothesis that the population mean is zero, Pr ≥ |*S*| = the probability of a greater absolute value for this statistic under the hypothesis that the population mean is zero, DF = degrees of freedom, Q3 = quantile 3, Q1 = quantile 1.

APPENDIX 14
Regression analysis of felling productivity in relation to forest, logging, and machine characteristics

(forward selection procedure for dependent variable FRATE)

Step 1 Variable FTYPE entered, $R^2 = 0.20$, $C(p) = 30.077$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	1	614.356 62	614.356 62	6.20	0.020 1
Error	24	2 379.979 89	99.165 83		
Total	25	2 994.336 51			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	23.170 91	5.954 77	1 501.474 91	15.14	0.000 7
FTYPE	9.839 09	3.952 99	614.356 62	6.20	0.020 1

Bounds on condition number: 1, 1.

Step 2 Variable Q2 entered, $R^2 = 0.32$, $C(p) = 31.385$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	2	958.711 24	479.355 62	5.42	0.011 8
Error	23	2 035.625 28	88.505 45		
Total	25	2 994.336 51			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	29.384 18	6.447 44	1 838.324 08	20.77	0.000 1
FTYPE	8.805 79	3.771 04	482.597 37	5.45	0.028 6
Q2	–0.033 24	0.016 85	344.354 61	3.89	0.060 7

Bounds on condition number: 1.019 7, 4.078 7.

Step 3 Variable SDI entered, $R^2 = 0.52$, $C(p) = 18.476$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	3	1 549.344 26	516.448 09	7.86	0.001 0
Error	22	1 444.992 25	65.681 47		
Total	25	2 994.336 51			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–3.415 76	12.267 33	5.092 08	0.08	0.783 3
FTYPE	11.970 78	3.415 76	806.701 62	12.28	0.002 0
SDI	0.358 34	0.119 50	590.633 03	8.99	0.006 6
Q2	–0.051 43	0.015 73	701.746 52	10.68	0.003 5

Bounds on condition number: 1.324, 10.947.

Step 4 Variable SDI2 entered, $R^2 = 0.57$, $C(p) = 16.500$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	4	1 707.642 20	426.910 55	6.97	0.001 0
Error	21	1 286.694 31	61.271 16		
Total	25	2 994.336 51			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–86.596 27	53.089 27	163.020 00	2.66	0.117 8
FTYPE	11.453 34	3.314 76	731.503 69	11.94	0.002 4
SDI	2.540 91	1.362 77	213.006 12	3.48	0.076 3
Q2	–0.046 45	0.015 51	549.735 22	8.97	0.006 9
SDI2	–13.690 06	8.517 18	158.297 93	2.58	0.122 9

Bounds on condition number: 187.72, 1 498.8.

Step 5 Variable AVAGE entered, $R^2 = 0.60$, $C(p) = 16.527$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	5	1 784.976 86	356.995 37	5.90	0.001 7
Error	20	1 209.359 65	60.467 98		
Total	25	2 994.336 51			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–76.060 49	53.541 18	122.355 26	2.02	0.170 3
AVAGE	–0.838 50	0.741 45	77.334 66	1.38	0.271 5
FTYPE	12.199 91	3.358 48	797.908 27	13.20	0.001 7
SDI	2.267 39	1.375 24	164.369 34	2.72	0.114 8
Q2	–0.049 76	0.015 68	608.851 75	10.07	0.004 8
SDI2	–11.688 33	8.644 33	108.552 26	1.83	0.191 4

Bounds on condition number: 195.94, 1 950.3.

Step 6 Variable AV2 entered, $R^2 = 0.67$, $C(p) = 12.551$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	6	2 021.720 05	336.953 34	6.58	0.000 7
Error	19	972.616 46	51.190 34		
Total	25	2 994.336 51			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–62.919 61	49.646 16	82.222 14	1.61	0.220 3
AVAGE	–6.026 65	2.507 10	295.798 61	5.78	0.026 6
FTYPE	11.607 97	3.102 35	716.671 13	14.00	0.001 4
SDI	2.227 53	1.265 48	158.606 12	3.10	0.094 5
AV2	0.458 89	0.213 39	236.743 19	4.62	0.044 6
Q2	–0.052 50	0.014 48	672.664 40	13.14	0.001 8
SDI2	–11.514 37	7.953 99	107.279 94	2.10	0.164 0

Bounds on condition number: 195.96, 2 524.

Step 7 Variable STUMP entered, R^2 = 0.72, C(p) = 11.362

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	7	2 148.075 19	306.867 88	6.53	0.000 6
Error	18	846.261 32	47.014 52		
Total	25	2 994.336 51			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–70.697 26	47.814 11	102.783 87	2.19	0.156 5
AVAGE	–6.888 65	2.447 22	361.788 82	7.70	0.012 5
FTYPE	12.504 73	3.023 02	804.448 24	17.11	0.000 6
SDI	2.427 11	1.218 87	186.422 45	3.97	0.061 8
STUMP	1.135 64	0.692 72	126.355 14	2.69	0.118 5
AV2	0.530 06	0.209 05	302.242 62	6.43	0.020 7
Q2	–0.052 69	0.013 92	602.883 43	13.25	0.001 9
SDI2	–13.031 88	7.678 67	125.417 40	2.88	0.106 9

Bounds on condition number: 198.85, 2 996.4.

Step 8 Variable QUANT entered, R^2 = 0.74, C(p) = 11.773

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	8	2 211.031 27	276.378 90	6.00	0.001 0
Error	17	783.305 34	46.076 78		
Total	25	2 994.336 51			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–90.893 50	50.389 67	149.921 82	3.25	0.089 0
QUANT	0.101 71	0.087 02	62.955 98	1.37	0.258 6
AVAGE	–7.302 41	2.462 23	405.280 96	8.80	0.008 7
FTYPE	11.449 95	3.125 80	618.252 76	13.42	0.001 9
SDI	2.551 83	1.211 36	204.475 28	4.44	0.050 3
STUMP	0.923 58	0.709 37	78.105 97	1.70	0.210 3
AV2	0.594 65	0.214 21	355.078 81	7.71	0.012 9
Q2	–0.170 84	0.103 71	125.023 36	2.71	0.117 9
SDI2	–13.923 44	7.639 87	153.039 23	3.32	0.086 0

Bounds on condition number: 200.85, 4 650.1.

Step 9 Variable VQ entered, $R^2 = 0.77$, $C(p) = 11.462$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	9	2 302.565 64	255.840 63	5.92	0.001 1
Error	16	691.770 88	43.253 68		
Total	25	2 994.336 51			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–123.365 93	53.671 43	228.426 47	5.28	0.035 3
QUANT	0.138 50	0.088 00	107.089 75	2.48	0.135 1
AVAGE	–7.472 94	2.387 99	423.408 92	9.79	0.006 5
FTYPE	14.292 31	3.603 37	680.190 27	15.73	0.001 1
SDI	3.229 70	1.262 52	282.937 78	6.54	0.021 1
STUMP	0.601 56	0.721 91	30.021 17	0.69	0.417 0
AV2	0.586 94	0.207 57	345.705 65	8.00	0.012 1
VQ	–5.131 47	3.526 72	91.534 47	2.12	0.165 0
Q2	–0.174 25	0.100 49	129.988 26	3.01	0.102 2
SDI2	–18.107 33	7.939 59	224.882 25	5.20	0.036 6

Bounds on condition number: 231.17, 5 911.

Step 10 Variable STUCK entered, $R^2 = 0.81$, $C(p) = 10.085$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	10	2 436.367 04	243.634 70	6.55	0.000 7
Error	15	557.989 47	37.199 30		
Total	25	2 994.336 51			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–141.863 78	50.730 52	290.896 91	7.82	0.013 6
QUANT	0.188 48	0.085 78	179.608 06	4.83	0.044 1
AVAGE	–7.806 45	2.222 00	459.150 90	12.34	0.003 1
FTYPE	14.630 75	3.347 13	710.758 89	19.11	0.000 5
SDI	3.655 49	1.192 40	349.606 61	9.40	0.007 8
STUMP	3.023 17	1.441 87	163.533 05	4.40	0.053 4
AV2	0.606 49	0.192 81	368.064 12	9.89	0.006 7
VQ	–7.850 29	3.571 65	179.708 90	4.83	0.044 1
Q2	–0.215 04	0.095 66	187.959 69	5.05	0.040 1
SDI2	–20.952 21	7.515 75	289.101 10	7.77	0.013 8
STUCK	–2.423 71	1.278 06	133.781 40	3.60	0.077 3

Bounds on condition number: 240.76, 7 013.7.

Step 11 Variable SLOPE2 entered, R^2 = 0.83, C(p) = 10.469

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	11	2 500.386 45	227.307 86	6.44	0.000 9
Error	14	493.950 06	35.282 05		
Total	25	2 994.336 51			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–119.482 77	52.124 12	185.390 78	5.25	0.037 9
QUANT	0.198 93	0.083 90	198.371 86	5.62	0.032 6
AVAGE	–7.985 06	2.168 04	478.605 08	13.57	0.002 5
FTYPE	14.215 21	3.274 30	665.004 98	18.85	0.000 7
SDI	3.120 69	1.227 24	228.136 52	6.47	0.023 4
STUMP	3.376 68	1.428 53	197.131 24	5.59	0.033 1
AV2	0.595 09	0.187 97	353.639 98	10.02	0.006 9
SLOPE2	–0.035 95	0.026 68	64.039 41	1.82	0.199 3
VQ	–7.540 69	3.485 97	165.092 91	4.68	0.048 3
Q2	–0.237 76	0.094 68	222.490 59	6.31	0.024 9
SDI2	–17.386 67	7.783 29	176.060 32	4.99	0.042 3
STUCK	–2.630 85	1.254 15	155.255 88	4.40	0.054 6

Bounds on condition number: 272.34, 8 420.1.

Step 12 Variable SUMWIN entered, R^2 = 0.86, C(p) = 10.293

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	12	2 586.562 53	205.546 88	6.87	0.000 8
Error	13	407.773 98	31.367 23		
Total	25	2 994.336 51			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–122.372 99	49.178 18	194.223 75	6.19	0.027 2
QUANT	0.206 07	0.079 22	212.238 08	6.77	0.022 0
AVAGE	–7.139 61	2.106 90	360.195 30	11.48	0.004 8
FTYPE	12.939 10	3.181 85	518.711 11	16.54	0.001 3
SDI	3.146 05	1.157 25	231.819 66	7.39	0.017 6
SUMWIN	4.137 12	2.495 99	86.176 09	2.75	0.121 3
STUMP	4.105 64	1.416 93	263.356 04	8.40	0.012 5
AV2	0.516 77	0.183 42	248.983 03	7.94	0.014 5
SLOPE2	–0.050 94	0.026 73	113.876 13	3.63	0.079 1
VQ	–8.656 99	3.355 18	208.823 58	6.66	0.022 8
Q2	–0.243 89	0.089 35	233.705 24	7.45	0.017 2
SDI2	–17.787 59	7.342 26	184.073 51	5.87	0.030 8
STUCK	–3.159 47	1.224 78	208.733 16	6.65	0.022 9

Bounds on condition number: 272.54, 9 266.5.

Step 13 Variable SOBUCK entered, $R^2 = 0.88$, $C(p) = 11.391$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	13	2 622.290 13	201.704 63	6.51	0.001 3
Error	12	372.046 38	31.003 87		
Total	25	2 994.336 51			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–102.663 09	52.226 38	119.802 16	3.86	0.072 9
QUANT	0.199 19	0.079 02	197.002 94	6.35	0.026 9
AVAGE	–6.748 37	2.126 13	312.344 63	10.07	0.008 0
FTYPE	13.427 76	3.195 95	547.297 21	17.65	0.001 2
SDI	2.558 95	1.273 91	125.102 65	4.04	0.067 6
SUMWIN	4.839 46	2.566 29	110.254 60	3.56	0.083 8
STUMP	7.531 30	3.488 26	144.523 11	4.66	0.051 8
AV2	0.483 37	0.184 99	211.673 05	6.83	0.022 7
SLOPE2	–0.054 88	0.026 83	129.707 87	4.18	0.063 4
VQ	–7.924 84	3.404 70	167.972 81	5.42	0.038 2
Q2	–0.246 20	0.088 86	238.019 03	7.68	0.016 9
SOBUCK	2.529 03	2.355 91	35.727 59	1.15	0.304 2
SDI2	–14.082 00	8.075 11	94.286 11	3.04	0.106 7
STUCK	–6.447 08	3.295 77	118.639 61	3.83	0.074 1

Bounds on condition number: 333.48, 1 295 5.

Summary of forward-selection procedure for dependent variable FRATE

Step	Variable entered	Number in	Partial R^2	Model R^2	C(p)	F	$p > F$
1	FTYPE	1	0.2052	0.2052	38.0771	6.20	0.0201
2	Q2	2	0.1150	0.3202	31.3847	3.89	0.0607
3	SDI	3	0.1973	0.5174	18.4755	8.99	0.0066
4	SDI2	4	0.0529	0.5703	16.4797	2.58	0.1229
5	AVAGE	5	0.0258	0.5961	16.5275	1.28	0.2715
6	AV2	6	0.0791	0.6752	12.5515	4.62	0.0446
7	STUMP	7	0.0422	0.7174	11.3619	2.69	0.1185
8	QUANT	8	0.0210	0.7384	11.7728	1.37	0.2586
9	VQ	9	0.0306	0.7690	11.4622	2.12	0.1650
10	STUCK	10	0.0447	0.8137	10.0852	3.60	0.0773
11	SLOPE2	11	0.0214	0.8350	10.4686	1.82	0.1993
12	SUMWIN	12	0.0288	0.8638	10.2933	2.75	0.1213
13	SOBUCK	13	0.0119	0.8757	11.3915	1.15	0.3042

Obs	Dep var FRATE	Predict value	SE predict	Lower 95% mean	Upper 95% mean	Lower 95% predict	Upper 95% predict	Residual	SE residual	Student residual	–2–1–0 1 2	Cook's D
1	26.0500	31.9736	3.6837	23.9475	39.9996	17.4271	46.5200	–5.9236	4.175	–1.419	| **| |	0.112
2	32.2900	26.9850	3.1756	20.0661	33.9040	13.0188	40.9512	5.3050	4.574	1.160	| |** |	0.046
3	41.3500	39.6292	3.3399	32.3521	46.9063	25.4822	53.7762	1.7208	4.455	0.386	| | |	0.000
4	22.5400	22.5848	4.8805	11.9510	33.2185	6.4522	38.7173	–0.0448	2.680	–0.0167	| | |	0.112
5	39.6400	31.9348	3.2871	24.7729	39.0967	17.8466	46.0229	7.7052	4.494	1.714	| |*** |	0.015
6	49.2600	51.7031	3.4945	44.0892	59.3171	37.3799	66.0264	–2.4431	4.335	–0.560	| *| |	0.042
7	30.0000	33.3967	3.7838	25.1525	41.6409	18.7287	48.0647	–3.3967	4.085	–0.832	| *| |	0.049
8	42.9000	38.3729	3.4767	30.7978	45.9480	24.0703	52.6755	4.5271	4.349	1.041	| |** |	0.105
9	40.0200	37.8199	4.7325	27.5087	48.1311	21.8981	53.7417	2.2001	2.934	0.750	| |* |	0.008
10	18.5000	19.0874	4.7513	8.7353	29.4395	3.1391	35.0357	–0.5874	2.903	–0.202	| | |	0.000
11	29.9800	30.3984	3.2361	23.3475	37.4492	16.3664	44.4303	–0.4184	4.531	–0.0923	| | |	0.000
12	24.2500	26.4660	4.1000	17.5329	35.3991	11.4000	41.5319	–2.2160	3.767	–0.588	| *| |	0.029
13	44.0000	44.1689	5.5328	32.1140	56.2239	27.0662	61.2717	–0.1689	0.626	–0.270	| | |	0.406
14	44.4800	48.6806	3.5004	41.0539	56.3074	34.3506	63.0106	–4.2006	4.330	–0.970	| *| |	0.044
15	53.9200	52.5844	5.2902	41.0580	64.1107	35.8500	69.3187	1.3356	1.737	0.769	| |* |	0.382
16	21.9200	25.0971	4.2136	15.9165	34.2777	9.8831	40.3111	–3.1771	3.640	–0.873	| *| |	0.073
17	53.8400	57.4140	4.1700	48.3284	66.4996	42.2572	72.5709	–3.5740	3.690	–0.969	| *| |	0.086
18	32.1000	33.7531	3.8035	25.4660	42.0403	19.0610	48.4453	–1.6531	4.067	–0.407	| | |	0.010
19	35.0000	39.2613	3.5711	31.4806	47.0420	24.8487	53.6738	–4.2613	4.272	–0.997	| *| |	0.050
20	37.1400	42.4378	3.2737	35.3050	49.5706	28.3645	56.5111	–5.2978	4.504	–1.176	| **| |	0.052
21	44.0000	41.3624	3.9450	32.7669	49.9578	26.4902	56.2306	2.6376	3.929	0.671	| |* |	0.032
22	32.0000	29.9071	4.8490	19.3421	40.4722	13.8198	45.9945	2.0929	2.737	0.765	| |* |	0.131
23	52.2800	43.6926	3.6525	35.7344	51.6507	29.1834	58.2017	8.5874	4.203	2.043	| |****|	0.225
24	56.6700	52.4863	4.1355	43.4757	61.4968	37.3743	67.5983	4.1837	3.728	1.122	| |** |	1.111
25	39.1900	40.5141	4.1405	31.4927	49.5355	25.3956	55.6325	–1.3241	3.723	–0.356	| | |	0.011
26	23.1700	24.7787	4.8122	14.2938	35.2637	8.7439	40.8136	–1.6087	2.801	–0.574	| *| |	0.070

Sum of residuals = 0.
Sum of squared residuals = 372.046 38.
Sum of squares of predicted residual errors (press) = 1 653.139 07.

Note: FRATE = felling rate, C (p) = total squared error, DF = degrees of freedom, FTYPE = forest type, Q2 = square of quantitative timber size index divided by 1000, SDI = species diversification index, SDI2 = square of species diversification index divided by 1000, AVAGE = average age of all felling machines owned by the firm, AV2 = square of average age of felling machines owned by the firm, AV2 =square of average age of felling machines owned by the firm, STUMP = logging methods index, QUANT = quantitative timber size index, VQ = quantitative timber size index divided by average volume (in cubic metres per hectare), STUCK = logging methods index + bucking index, SLOPE2 = square of slope index divded by 1000, SUMWIN = seasonal index, SOBUCK = sorting index + bucking index, SE = standard error, Cook's D = Cook's D influence statistic.

APPENDIX 15

Regression analysis of skidding productivity in relation to forest, logging, and machine characteristics

(forward selection procedure for dependent variable FRATE)

Step 1 Variable AVCUT entered, $R^2 = 0.15$, $C(p) = 9.365$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	1	499.560 84	499.560 84	3.21	0.089 9
Error	18	2 799.286 33	155.515 91		
Total	19	3 298.847 17			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	22.756 38	6.894 51	1 694.238 50	10.89	0.004 0
TOTGEN	0.495 89	0.276 68	499.560 84	3.21	0.089 9

Bounds on condition number: 1, 1.

Step 2 Variable VQ entered, $R^2 = 0.33$, $C(p) = 5.951$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	2	1 097.099 15	548.549 58	4.24	0.032 2
Error	17	2 201.748 02	129.514 59		
Total	19	3 298.847 17			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	25.511 19	6.42119	2 044.319 76	15.78	0.001 0
AVCUT	0.866 70	0.30587	1 039.883 39	8.03	0.011 5
VQ	–7.463 58	3.47475	597.538 31	4.61	0.046 4

Bounds on condition number: 1.467 5, 5.869 8.

Step 3 Variable AV2 entered, $R^2 = 0.41$, $C(p) = 5.550$

	DF	Sum of squares	Mean square	F	$p > F$
Regression	3	1 362.078 72	454.026 24	3.75	0.032 5
Error	16	1 936.768 45	121.048 03		
Total	19	3 298.847 17			

Variable	Parameter estimate	Standard error	Type II sum of squares	F	$p > F$
INTERCEP	29.369 43	6.733 24	2 303.032 91	19.03	0.000 5
AVCUT	0.801 24	0.298 99	869.272 29	7.18	0.016 4
AV2	–0.105 51	0.071 31	264.979 57	2.19	0.158 4
VQ	–7.596 07	3.360 45	618.500 70	5.11	0.038 1

Bounds on condition number: 1.500 3, 12.028.

Step 4 Variable AVAGE entered, $R^2 = 0.52$, $C(p) = 4.502$

	DF	Sum of squares	Mean square	F	$p > F$
Regression	4	1 698.434 88	424.608 72	3.98	0.0214
Error	15	1 600.412 29	106.694 15		
Total	19	3 298.847 17			

Variable	Parameter estimate	Standard error	Type II sum of squares	F	$p > F$
INTERCEP	15.312 29	10.131 21	243.723 68	2.28	0.151 5
AVAGE	5.971 83	3.363 39	336.356 16	3.15	0.096 1
AVCUT	0.983 40	0.298 87	1 155.156 83	10.83	0.005 0
AV2	–0.547 67	0.257 87	481.254 52	4.51	0.050 7
VQ	–9.331 44	3.302 85	851.647 37	7.98	0.012 8

Bounds on condition number: 15.834, 138.32.

Step 5 Variable SDI entered, $R^2 = 0.58$, $C(p) = 4.494$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	5	1 920.021 23	384.004 25	3.90	0.020 1
Error	14	1 378.825 94	98.487 57		
Total	19	3 298.847 17			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–2.429 99	15.318 60	2.478 30	0.03	0.876 2
AVAGE	5.927 48	3.231 59	331.350 91	3.36	0.088 0
SDI	0.220 78	0.147 19	221.586 35	2.25	0.155 8
AVCUT	0.987 49	0.287 16	1 164.681 35	11.83	0.004 0
AV2	–0.555 70	0.247 81	495.232 00	5.03	0.041 6
VQ	–9.436 74	3.174 06	870.551 95	8.84	0.010 1

Bounds on condition number: 15.836, 178.02.

Step 6 Variable SLOPE entered, $R^2 = 0.63$, $C(p) = 5.217$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	6	2 060.925 28	343.487 55	3.61	0.024 9
Error	13	1 237.921 89	95.224 76		
Total	19	3 298.847 17			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	4.702 47	16.163 70	8.059 71	0.08	0.775 7
SLOPE	–0.031 28	0.025 71	140.904 05	1.48	0.245 4
AVAGE	6.299 42	3.192 29	370.805 79	3.89	0.070 1
SDI	0.252 88	0.147 12	281.354 54	2.95	0.109 3
AVCUT	0.942 83	0.284 74	1 044.067 40	10.96	0.005 6
AV2	–0.599 62	0.246 33	564.232 60	5.93	0.030 1
VQ	–9.423 53	3.121 06	868.105 09	9.12	0.009 9

Bounds on condition number: 15.982, 223.54.

Step 7 Variable QUANT entered, $R^2 = 0.65$, $C(p) = 6.479$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	7	2 142.384 21	306.054 89	3.18	0.038 1
Error	12	1 156.462 97	96.371 91		
Total	19	3 298.847 17			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–7.491 69	20.984 11	12.283 70	0.13	0.727 3
QUANT	0.061 44	0.066 83	81.458 92	0.85	0.376 0
SLOPE	–0.033 83	0.026 02	162.952 79	1.69	0.217 9
AVAGE	7.890 31	3.647 98	450.851 78	4.68	0.051 4
SDI	0.217 44	0.152 94	194.787 69	2.02	0.180 6
AVCUT	1.0869 8	0.326 55	1 067.817 55	11.08	0.006 0
AV2	–0.702 44	0.271 88	643.307 06	6.68	0.023 9
VQ	–15.370 83	7.190 56	440.371 90	4.57	0.053 8

Bounds on condition number: 20.623, 411.9.

Step 8 Variable STUMP entered, $R^2 = 0.69$, $C(p) = 7.138$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	8	2 290.419 70	286.302 46	3.12	0.041 9
Error	11	1 008.427 47	91.675 22		
Total	19	3 298.847 17			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–11.061 26	20.658 26	26.282 92	0.29	0.603 0
QUANT	0.138 95	0.089 27	222.112 00	2.42	0.147 9
SLOPE	–0.029 92	0.025 56	125.649 50	1.37	0.266 4
AVAGE	6.043 77	3.843 27	226.707 10	2.47	0.144 1
SDI	0.300 81	0.162 96	312.371 61	3.41	0.092 0
AVCUT	1.139 32	0.321 14	1 153.833 60	12.59	0.004 6
STUMP	–11.230 87	8.838 05	148.035 50	1.61	0.230 0
AV2	–0.524 51	0.299 87	280.465 11	3.06	0.108 1
VQ	–22.384 54	8.924 57	576.731 32	6.29	0.029 1

Bounds on condition number: 24.292, 657.39.

Step 9 Variable VOLUME entered, $R^2 = 0.73$, $C(p) = 7.926$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	9	2 424.104 54	269.344 95	3.08	0.047 2
Error	10	874.742 64	87.474 26		
Total	19	3 298.847 17			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–18.137 66	20.975 55	65.405 77	0.75	0.407 5
QUANT	0.177 40	0.092 58	321.196 17	3.67	0.084 3
SLOPE	–0.038 68	0.025 95	194.280 17	2.22	0.167 0
AVAGE	6.349 56	3.762 32	249.146 51	2.85	0.122 4
SDI	0.317 34	0.159 74	345.212 80	3.95	0.075 0
AVCUT	1.169 60	0.314 65	1 208.608 70	13.82	0.004 0
STUMP	–17.474 85	10.002 12	267.007 43	3.05	0.111 2
AV2	–0.476 43	0.295 49	227.397 66	2.60	0.138 0
VQ	–26.086 94	9.217 79	700.605 01	8.01	0.017 8
VOLUME	0.000 041 70	0.000 033 73	133.684 84	1.53	0.244 6

Bounds on condition number: 24.72, 804.11

Step 10 Variable TOTB entered, $R^2 = 0.79$, $C(p) = 8.170$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	10	2 618.049 50	261.804 95	3.46	0.037 7
Error	9	680.797 68	75.644 19		
Total	19	3 298.847 17			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–13.243 40	19.743 70	34.034 32	0.45	0.519 2
QUANT	0.150 48	0.087 72	222.617 90	2.94	0.120 4
SLOPE	–0.051 58	0.025 44	310.894 08	4.11	0.073 3
AVAGE	6.748 88	3.507 55	280.046 46	3.70	0.086 5
SDI	0.409 70	0.159 35	500.005 93	6.61	0.030 1
AVCUT	0.276 86	0.629 65	14.624 56	0.19	0.670 5
TOTB	–0.330 22	0.206 23	193.944 96	2.56	0.143 8
STUMP	–15.841 55	9.356 98	216.820 28	2.87	0.124 7
AV2	–0.497 04	0.275 09	246.955 18	3.26	0.104 3
VQ	–18.820 87	9.698 89	284.846 57	3.77	0.084 2
VOLUME	0.000 154 01	0.000 076 83	303.923 43	4.02	0.076 0

Bounds on condition number: 24.774, 1 291.5.
Note: No other variable met the 0.5 significance level for entry into the model.

Summary of forward-selection procedure for dependent variable FRATE

Step	Variable entered	Number in	Partial R^2	Model R^2	C(p)	F	$p > F$
1	AVCUT	1	0.1514	0.1514	9.3652	3.21	0.0899
2	VQ	2	0.1811	0.3326	5.9507	4.61	0.0464
3	AV2	3	0.0803	0.4129	5.5496	2.19	0.1584
4	AVAGE	4	0.1020	0.5149	4.5018	3.15	0.0961
5	SDI	5	0.0672	0.5820	4.4940	2.25	0.1558
6	SLOPE	6	0.0427	0.6247	5.2172	1.48	0.2454
7	QUANT	7	0.0247	0.6494	6.4791	0.85	0.3760
8	STUMP	8	0.0449	0.6943	7.1377	1.61	0.2300
9	VOLUME	9	0.0405	0.7348	7.9263	1.53	0.2446
10	TOTB	10	0.0588	0.7936	8.1689	2.56	0.1438

Obs	Dep var FRATE	Predict value	SE predict	Lower 95% mean	Upper 95% mean	Lower 95% predict	Upper 95% predict	Residual	SE residual	Student residual	–2–1–0 1 2	Cook's D
1	21.8000	24.4161	6.4611	9.8001	39.0322	–0.0936	48.9259	–2.6161	5.822	–0.449	| | |	0.023
2	27.8100	25.2219	3.9624	16.2584	34.1855	3.6015	46.8424	2.5881	7.742	0.334	| | |	0.003
3	18.2500	23.3204	6.0167	9.7097	36.9311	–0.6034	47.2442	–5.0704	6.280	–0.807	| *| |	0.054
4	44.8300	51.1178	6.2393	37.0035	65.2321	26.9040	75.3317	–6.2878	6.059	–1.038	| **| |	0.104
5	15.0400	22.2762	6.4119	7.7716	36.7809	–2.1672	46.7197	–7.2362	5.876	–1.231	| **| |	0.164
6	38.5300	39.9718	7.2777	23.5085	56.4350	14.3176	65.6259	–1.4418	4.762	–0.303	| | |	0.019
7	32.8400	27.4843	5.7340	14.5131	40.4555	3.9184	51.0501	5.3557	6.540	0.819	| |* |	0.047
8	32.1600	33.8062	5.8079	20.6678	46.9445	10.1479	57.4644	–1.6462	6.474	–0.254	| | |	0.005
9	33.6000	28.9774	6.6265	13.9873	43.9674	4.2428	53.7120	4.6226	5.633	0.821	| |* |	0.085
10	25.5100	23.0170	7.6364	5.7422	40.2917	–3.1654	49.1993	2.4930	4.163	0.599	| |* |	0.110
11	65.4800	55.1546	6.2376	41.0443	69.2650	30.9431	79.3662	10.3254	6.061	1.704	| |*** |	0.279
12	16.2500	15.6002	8.4948	–3.6163	34.8167	–11.9020	43.1024	0.6498	1.866	0.348	| | |	0.228
13	24.0000	25.8871	7.5290	8.8553	42.9190	–0.1356	51.9099	–1.8871	4.354	–0.433	| | |	0.051
14	42.0000	29.7168	4.0337	20.5921	38.8416	8.0291	51.4046	12.2832	7.705	1.594	| |*** |	0.063
15	52.0000	52.6873	5.1084	41.1312	64.2433	29.8697	75.5048	–0.6873	7.039	–0.098	| | |	0.000
16	32.3500	40.4464	7.1173	24.3461	56.5468	15.0236	65.8692	–8.0964	4.999	–1.620	| ***| |	0.483
17	25.0000	28.8747	8.0070	10.7615	46.9879	2.1317	55.6177	–3.8747	3.396	–1.141	| **| |	0.658
18	49.9100	48.9199	6.0831	35.1590	62.6808	24.9103	72.9295	0.9901	6.216	0.159	| | |	0.002
19	37.7800	46.5264	5.5951	33.8693	59.1835	23.1320	69.9208	–8.7464	6.659	–1.314	| **| |	0.111
20	46.0100	37.7275	6.5879	22.8246	52.6304	13.0456	62.4093	8.2825	5.678	1.459	| |****|	0.260

Sum of residuals = 0.
Sum of squared residuals = 680.797 68.
Sum of squares of predicted residual errors (press) = 3 724.482 08.

Note: FRATE = felling rate, C(p) = total squared error, DF = degrees of freedom, AVCUT = average cutblock size in hectares, VQ = quantitative timber size index divided by average volume per hectare, AV2 = square of average age of logging machines, AVAGE = average age of all logging machines, SDI = species diversification index, SLOPE = slope index, QUANT = quantitative timber size index, STUMP = logging methods index, VOLUME = total volume harvested in cubic metres, TOTB = total number of cutblocks accessed during the logging season, SE = standard error, Cook's D = Cook's D influence statistic.

APPENDIX 16
Regression analysis of processing productivity in relation to forest, logging, and machine characteristics

(forward selection procedure for dependent variable FRATE)

Step 1 Variable STUMP entered, $R^2 = 0.13$, $C(p) = 26.441$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	1	278.108 58	278.108 58	3.92	0.058 9
Error	25	1 774.551 54	70.982 06		
Total	26	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	34.496 53	3.857 89	5 675.435 83	79.96	0.000 1
STUMP	–5.502 54	2.779 91	278.108 58	3.92	0.058 9

Bounds on condition number: 1, 1.

Step 2 Variable AVAGE entered, $R^2 = 0.19$, $C(p) = 25.119$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	2	397.335 20	198.667 60	2.88	0.075 6
Error	24	1 655.324 91	68.971 87		
Total	26	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	37.085 70	4.282 52	5 172.337 73	74.99	0.000 1
AVAGE	–1.207 84	0.918 67	119.226 63	1.73	0.201 0
STUMP	–3.958 20	2.981 40	121.570 73	1.76	0.196 8

Bounds on condition number: 1.183 738, 4.734 95.

Step 3 Variable Q2 entered, $R^2 = 0.26$, $C(p) = 23.381$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	3	531.499 76	177.166 59	2.68	0.070 8
Error	23	1 521.160 36	66.137 41		
Total	26	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	38.466 71	4.304 23	5 282.334 80	79.87	0.000 1
AVAGE	–1.330 05	0.903 68	143.270 55	2.17	0.154 6
STUMP	–2.147 68	3.184 23	30.086 92	0.45	0.506 7
Q2	–0.000 02	0.000 01	134.164 55	2.03	0.167 8

Bounds on condition number: 1.408 155, 11.397 34.

Step 4 Variable SDI entered, $R^2 = 0.32$, $C(p) = 21.967$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	4	654.022 09	163.505 52	2.57	0.066 2
Error	22	1 398.638 03	63.574 45		
Total	26	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	26.519 54	9.584 92	486.673 01	7.66	0.011 3
AVAGE	–1.167 32	0.893 72	108.457 41	1.71	0.205 0
SDI	0.162 80	0.117 27	122.522 33	1.93	0.179 0
STUMP	–3.720 53	3.321 15	79.783 82	1.25	0.274 7
Q2	–0.000 03	0.000 02	191.092 67	3.01	0.097 0

Bounds on condition number: 1.593 614, 21.519 65.

Step 5 Variable SDI2 entered, $R^2 = 0.44$, $C(p) = 16.792$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	5	911.560 06	182.312 01	3.36	0.022 1
Error	21	1 141.100 05	54.338 10		
Total	26	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–81.098 89	50.221 10	141.697 36	2.61	0.121 3
AVAGE	–0.882 32	0.836 56	60.445 75	1.11	0.303 5
SDI	2.942 20	1.281 28	286.525 38	5.27	0.032 0
STUMP	–4.836 74	3.112 95	131.179 44	2.41	0.135 2
Q2	–0.000 02	0.000 01	134.943 94	2.48	0.130 0
SDI2	–0.017 27	0.007 93	257.537 98	4.74	0.041 0

Bounds on condition number: 182.569 2, 1 841.614.

Step 6 Variable QUANT entered, $R^2 = 0.48$, $C(p) = 17.031$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	6	974.775 35	162.462 56	3.01	0.028 9
Error	20	1 077.884 77	53.894 24		
Total	26	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–110.080 91	56.724 45	202.967 14	3.77	0.066 5
QUANT	0.102 20	0.094 36	63.215 28	1.17	0.291 7
AVAGE	–0.473 26	0.914 75	14.425 61	0.27	0.610 6
SDI	3.199 35	1.297 93	327.460 50	6.08	0.022 9
STUMP	–6.858 10	3.618 66	193.576 83	3.59	0.072 6
Q2	–0.000 14	0.000 11	88.756 76	1.65	0.214 1
SDI2	–0.018 77	0.008 02	295.021 24	5.47	0.029 8

Bounds on condition number: 188.89, 3 179.039.

Step 7 Variable VQ entered, $R^2 = 0.52$, $C(p) = 16.667$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	7	1 059.603 88	151.371 98	2.90	0.030 8
Error	12	993.056 24	52.266 12		
Total	19	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–146.736 33	62.835 62	285.025 52	5.45	0.030 7
QUANT	0.153 45	0.101 26	120.020 84	2.30	0.146 1
AVAGE	–0.313 36	0.909 53	6.203 94	0.12	0.734 2
SDI	4.037 16	1.437 44	412.281 08	7.89	0.011 2
STUMP	–8.663 56	3.835 04	266.730 40	5.10	0.035 8
VQ	–4.018 43	3.154 25	84.828 53	1.62	0.218 0
Q2	–0.000 17	0.000 11	119.544 07	2.29	0.146 9
SDI2	–0.024 18	0.008 97	379.849 44	7.27	0.014 3

Bounds on condition number: 241.162 9, 4 592.732.

Step 8 Variable VOLHA entered, $R^2 = 0.59$, $C(p) = 14.472$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	8	1 210.185 56	151.273 19	3.23	0.018 4
Error	18	842.474 56	46.804 14		
Total	26	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–124.007 04	60.797 04	194.720 64	4.16	0.056 3
QUANT	0.171 20	0.096 33	147.824 06	3.16	0.092 4
AVAGE	–0.519 95	0.868 37	16.780 59	0.36	0.556 8
VOLHA	–0.039 81	0.022 19	150.581 68	3.22	0.089 7
SDI	3.813 81	1.365 94	364.867 80	7.80	0.012 0

Step 9 Variable SUMWIN entered, $R^2 = 0.63$, $C(p) = 13.969$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	9	1 300.030 27	144.447 81	3.26	0.017 2
Error	17	752.629 84	44.272 34		
Total	26	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–128.088 63	59.199 20	207.263 11	4.68	0.045 0
QUANT	0.185 27	0.094 21	171.209 10	3.87	0.065 8
AVAGE	–0.869 49	0.879 47	43.272 70	0.98	0.336 7
VOLHA	–0.045 72	0.021 98	191.578 26	4.33	0.052 9
SDI	4.075 52	1.341 13	408.844 02	9.23	0.007 4
SUMWIN	–4.432 87	3.111 75	89.844 71	2.03	0.172 4
STUMP	–11.318 75	3.709 01	412.300 02	9.31	0.007 2
VQ	–9.267 20	3.998 68	237.791 27	5.37	0.033 2
Q2	–0.000 17	0.000 10	119.950 71	2.71	0.118 1
SDI2	–0.024 29	0.008 34	375.805 05	8.49	0.009 7

Bounds on condition number: 245.997 7, 6 114.541.

Step 10 Variable SORT entered, $R^2 = 0.69$, $C(p) = 12.891$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	10	1 410.500 79	141.050 08	3.51	0.012 5
Error	16	642.159 32	40.134 96		
Total	26	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–177.043 34	63.621 76	310.792 58	7.74	0.013 3
QUANT	0.197 79	0.090 02	193.763 04	4.83	0.043 1
AVAGE	–1.316 24	0.879 60	89.870 73	2.24	0.154 0
SORT	–4.110 21	2.477 43	110.470 52	2.75	0.116 6
VOLHA	–0.036 41	0.021 67	113.341 34	2.82	0.112 3
SDI	5.450 72	1.522 37	514.503 62	12.82	0.002 5
SUMWIN	–6.187 24	3.145 84	155.254 38	3.87	0.066 8
STUMP	–9.766 06	3.653 36	286.799 05	7.15	0.016 7
VQ	–10.064 94	3.837 50	276.088 67	6.88	0.018 5
Q2	–0.000 17	0.000 10	127.482 13	3.18	0.093 7
SDI2	–0.033 02	0.009 52	482.428 63	12.02	0.003 2

Bounds on condition number: 354.328, 8 948.654.

Step 11 Variable SLOPE entered, $R^2 = 0.70$, $C(p) = 14.131$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	11	1 437.795 84	130.708 71	3.19	0.019 7
Error	15	614.864 28	40.990 95		
Total	26	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–204.715 13	72.691 17	325.105 63	7.93	0.013 0
QUANT	0.210 50	0.092 30	213.217 89	5.20	0.037 6
SLOPE	0.015 38	0.018 85	27.295 04	0.67	0.427 3
AVAGE	–1.217 27	0.897 17	75.459 42	1.84	0.194 9
SORT	–4.464 69	2.541 12	126.537 70	3.09	0.099 3
VOLHA	–0.034 21	0.022 06	98.567 80	2.40	0.141 8
SDI	6.037 30	1.698 17	518.098 64	12.64	0.002 9
SUMWIN	–7.073 27	3.359 51	181.708 61	4.43	0.052 5
STUMP	–11.039 27	4.008 26	310.926 14	7.59	0.014 8
VQ	–10.329 79	3.891 76	288.787 31	7.05	0.018 0
Q2	–0.000 18	0.000 10	136.732 72	3.34	0.087 8
SDI2	–0.036 65	0.010 60	489.741 48	11.95	0.003 5

Bounds on condition number: 429.975 6, 11 577.61.

Step 12 Variable SLOPE2 entered, $R^2 = 0.79$, $C(p) = 10.869$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	12	1 626.665 82	135.555 48	4.45	0.004 9
Error	14	425.994 30	30.428 16		
Total	26	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–169.358 65	64.216 73	211.638 20	6.96	0.019 5
QUANT	0.177 70	0.080 60	147.893 73	4.86	0.044 7
SLOPE	0.426 70	0.165 89	201.314 47	6.62	0.022 1
AVAGE	–0.909 28	0.782 80	41.055 25	1.35	0.264 8
SORT	0.189 36	2.878 01	0.131 73	0.00	0.948 5
VOLHA	–0.040 67	0.019 18	136.725 70	4.49	0.052 4
SDI	3.486 24	1.785 81	115.962 96	3.81	0.071 2
SUMWIN	–4.438 76	3.081 59	63.132 05	2.07	0.171 7
STUMP	–11.768 43	3.465 80	350.836 96	11.53	0.004 4
SLOPE2	–0.000 67	0.000 27	188.869 98	6.21	0.025 9
VQ	–8.354 19	3.445 54	178.883 01	5.88	0.029 4
Q2	–0.000 17	0.000 08	117.874 41	3.87	0.069 2
SDI2	–0.020 40	0.011 23	100.468 83	3.30	0.090 7

Bounds on condition number: 649.221 1, 21 819.57.

Step 13 Variable SB2 entered, $R^2 = 0.81$, $C(p) = 11.790$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	13	1 665.382 27	128.106 33	4.30	0.006 6
Error	13	387.277 85	29.790 60		
Total	26	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–182.210 65	64.532 76	237.501 45	7.97	0.014 4
QUANT	0.181 53	0.079 82	154.061 54	5.17	0.040 6
SLOPE	0.468 52	0.168 19	231.164 47	7.76	0.015 4
AVAGE	–0.959 39	0.775 80	45.558 07	1.53	0.238 1
SORT	–2.114 92	3.492 13	10.926 65	0.37	0.555 2
VOLHA	–0.048 41	0.020 16	171.770 23	5.77	0.032 0
SDI	3.722 99	1.779 17	130.445 82	4.38	0.056 6
SUMWIN	–5.106 04	3.104 81	80.571 02	2.70	0.124 0
STUMP	–12.988 91	3.592 53	389.425 45	13.07	0.003 1
SLOPE2	–0.000 73	0.000 27	214.996 60	7.22	0.018 7
VQ	–8.582 84	3.415 15	188.157 78	6.32	0.025 9
Q2	–0.000 17	0.000 08	119.778 32	4.02	0.066 2
SB2	0.267 89	0.234 99	38.716 45	1.30	0.274 9
SDI2	–0.021 74	0.011 17	112.813 40	3.79	0.073 6

Bounds on condition number: 656.459 2, 24 120.81.

Step 14 Variable AV2 entered, $R^2 = 0.82$, $C(p) = 13.041$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	14	1 692.250 00	120.875 00	4.02	0.010 3
Error	12	360.410 11	30.034 18		
Total	26	2 052.660 12			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–156.049 32	70.452 84	147.347 41	4.91	0.046 9
QUANT	0.173 19	0.080 63	138.558 85	4.61	0.052 8
SLOPE	0.527 25	0.179 93	257.886 45	8.59	0.012 6
AVAGE	–4.732 15	4.064 24	40.716 95	1.36	0.266 9
SORT	–2.027 20	3.507 61	10.032 03	0.33	0.574 0
VOLHA	–0.050 14	0.020 33	182.753 12	6.08	0.029 7
SDI	3.027 46	1.931 86	73.759 84	2.46	0.143 1
SUMWIN	–4.626 00	3.158 52	64.425 97	2.15	0.168 7
STUMP	–12.104 87	3.726 31	316.940 37	10.55	0.007 0
AV2	0.364 55	0.385 44	26.867 74	0.89	0.362 9
SLOPE2	–0.000 82	0.000 29	241.828 98	8.05	0.015 0
VQ	–7.837 21	3.518 53	149.009 85	4.96	0.045 8
Q2	–0.000 17	0.000 08	124.631 68	4.15	0.064 3
SB2	0.261 40	0.236 05	36.831 62	1.23	0.289 8
SDI2	–0.017 33	0.012 15	61.132 45	2.04	0.179 2

Bounds on condition number: 769.849, 31 210.24.

Note: No other variable met the 0.5 significance level for entry into the model.

Summary of forward-selection procedure for dependent variable FRATE

Step	Variable entered	Number in	Partial R^2	Model R^2	C(p)	F	$p > F$
1	STUMP	1	0.1355	0.1355	26.4408	3.9180	0.0589
2	AVAGE	2	0.0581	0.1936	25.1190	1.7286	0.2010
3	Q2	3	0.0654	0.2589	23.3810	2.0286	0.1678
4	SDI	4	0.0597	0.3186	21.9675	1.9272	0.1790
5	SDI2	5	0.1255	0.4441	16.7922	4.7395	0.0410
6	QUANT	6	0.0308	0.4749	17.0309	1.1730	0.2917
7	VQ	7	0.0413	0.5162	16.6675	1.6230	0.2180
8	VOLHA	8	0.0734	0.5896	14.4722	3.2173	0.0897
9	SUMWIN	9	0.0438	0.6333	13.9690	2.0294	0.1724
10	SORT	10	0.0538	0.6872	12.8912	2.7525	0.1166
11	SLOPE	11	0.0133	0.7005	14.1307	0.6659	0.4273
12	SLOPE2	12	0.0920	0.7925	10.8686	6.2071	0.0259
13	SB2	13	0.0189	0.8113	11.7899	1.2996	0.2749
14	AV2	14	0.0131	0.8244	13.0414	0.8946	0.3629

Obs	Dep var FRATE	Predict value	SE predict	Lower 95% mean	Upper 95% mean	Lower 95% predict	Upper 95% predict	Residual	SE residual	Student residual	–2–1–0 1 2	Cook's D
1	35.4100	31.9477	2.779	25.8925	38.0030	18.5595	45.3360	3.4623	4.723	0.733	| |* |	0.012
2	24.8100	29.5002	4.269	20.1993	38.8010	14.3646	44.6357	–4.6902	3.437	–1.365	| **| |	0.192
3	14.0900	15.4529	4.962	4.6414	26.2643	–0.6551	31.5608	–1.3629	2.326	–0.586	| *| |	0.104
4	28.6100	27.3629	4.091	18.4501	36.2757	12.4627	42.2631	1.2471	3.647	0.342	| | |	0.010
5	49.2600	44.0085	4.095	35.0861	52.9308	29.1025	58.9144	5.2515	3.642	1.442	| |** |	0.175
6	26.6700	28.2146	4.311	18.8226	37.6066	13.0229	43.4063	–1.5446	3.384	–0.456	| | |	0.023
7	35.4200	37.5516	3.919	29.0138	46.0895	22.8726	52.2307	–2.1316	3.831	–0.556	| *| |	0.022
8	25.7300	21.2792	4.747	10.9358	31.6225	5.4816	37.0768	4.4508	2.738	1.625	| |*** |	0.529
9	15.2900	16.3437	4.974	5.5070	27.1804	0.2188	32.4686	–1.0537	2.301	–0.458	| | |	0.065
10	20.6300	20.3309	3.503	12.6987	27.9631	6.1595	34.5023	0.2991	4.215	0.071	| | |	0.000
11	38.7300	34.5181	3.668	26.5261	42.5101	20.1497	48.8865	4.2119	4.072	1.034	| |** |	0.058
12	20.9600	20.7766	5.081	9.7054	31.8478	4.4931	37.0600	0.1834	2.053	0.089	| | |	0.003
13	33.0000	33.3236	3.761	25.1298	41.5174	18.8420	47.8052	–0.3236	3.986	–0.081	| | |	0.000
14	30.4400	27.7476	3.400	20.3391	35.1561	13.6954	41.7998	2.6924	4.298	0.626	| |* |	0.016
15	32.7400	36.5810	3.982	27.9053	45.2566	21.8214	51.3406	–3.8410	3.766	–1.020	| **| |	0.078
16	14.8500	18.8911	3.970	10.2404	27.5417	4.1462	33.6360	–4.0411	3.778	–1.070	| **| |	0.084
17	42.3100	34.1661	3.808	25.8687	42.4635	19.6256	48.7066	8.1439	3.941	2.066	| |****|	0.266
18	24.4400	29.3283	3.952	20.7178	37.9388	14.6069	44.0497	–4.8883	3.797	–1.287	| **| |	0.120
19	24.7100	22.1115	4.219	12.9188	31.3042	7.0421	37.1808	2.5985	3.498	0.743	| |* |	0.054
20	37.1400	38.6975	3.622	30.8068	46.5882	24.3852	53.0098	–1.5575	4.113	–0.379	| | |	0.007
21	29.3300	33.2178	3.070	26.5281	39.9075	19.5309	46.9047	–3.8878	4.540	–0.856	| *| |	0.022
22	17.7800	18.6208	4.900	7.9443	29.2973	2.6031	34.6385	–0.8408	2.454	–0.343	| | |	0.031
23	32.6800	37.9479	2.767	31.9199	43.9760	24.5720	51.3239	–5.2679	4.731	–1.114	| **| |	0.028
24	27.4200	26.6169	3.449	19.1031	34.1307	12.5089	40.7249	0.8031	4.259	0.189	| | |	0.002
25	15.4100	21.2633	4.238	12.0292	30.4974	6.1687	36.3579	–5.8533	3.475	–1.685	| ***| |	0.281
26	19.1300	14.1892	4.762	3.8127	24.5656	–1.6301	30.0085	4.9408	2.712	1.822	| |*** |	0.683
27	27.3300	24.3306	4.658	14.1815	34.4798	8.6595	40.0018	2.9994	2.887	1.039	| |** |	0.187

Sum of residuals = 0.
Sum of squared residuals = 360.410 1.
Sum of squares of predicted residual errors (press) = 2 215.286 6.

Note: FRATE = processing rate, C (p) = total squared error, DF = degrees of freedom, STUMP = logging methods index, AVAGE = average age of logging machines, Q2 = square of quantitative timber size index, SDI = species diversification index, SDI2 = square of species diversification index, QUANT = quantitative timber size index, VQ = quantitative timber size index divided by average volume per hectare, VOLHA = average volume (m^3/ ha), SUMWIN = seasonal index, SORT = sorting index, SLOPE = slope index, SLOPE 2 = square of slope index, SB2 = square of sorting index + bucking index, AV2 = square of average age of logging machines, SE = standard error, Cook's D = Cook's D influence statistic.

APPENDIX 17
Regression analysis of road-building productivity in relation to forest, cutblock, and machine characteristics
(forward selection procedure for dependent variable PMH)

Step 1 Variable SLOPE entered, $R^2 = 0.28$, $C(\mathrm{p}) = 3.617$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	1	49 485 727.965 52	49 485 727.965 52	7.15	0.015 5
Error	18	124 656 654.734 48	6 925 369.707 47		
Total	19	174 142 382.700 00			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–2 598.986 99	2 195.203 87	9 707 367.089 28	1.40	0.251 8
SLOPE	18.951 43	7.089 63	49 485 727.965 52	7.15	0.015 5

Bounds on condition number: 1, 1.

Step 2 Variable SLOPE2 entered, $R^2 = 0.39$, $C(\mathrm{p}) = 2.846$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	2	67 094 663.156 68	33 547 331.578 34	5.33	0.016 0
Error	17	107 047 719.543 32	6 296 924.679 02		
Total	19	174 142 382.700 00			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–19 619.760 01	10 391.354 29	22 447 685.831 80	3.56	0.076 2
SLOPE	134.775 93	69.591 63	23 617 783.833 02	3.75	0.069 6
SLOPE2	–0.182 84	0.109 34	17 608 935.191 16	2.80	0.112 8

Bounds on condition number: 105.969 7, 23.878 7.

Step 3 Variable SORT entered, $R^2 = 0.51$, $C(\mathrm{p}) = 1.371$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	3	89 177 157.378 74	29 725 719.126 25	5.60	0.008 1
Error	16	84 965 225.321 26	5 310 326.582 58		
Total	19	174 142 382.700 00			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–20 310.903 05	9 548.656 43	24 026 757.356 98	4.52	0.049 3
SLOPE	149.166 67	64.296 20	28 582 221.705 03	5.38	0.033 9
SORT	–1 407.262 11	690.099 24	22 082 494.222 06	4.16	0.058 3
SLOPE2	–0.209 40	0.101 25	22 713 833.560 64	4.28	0.055 2

Bounds on condition number: 107.752 5, 48.204 5.

Step 4 Variable FTYPE entered, $R^2 = 0.58$, $C(\mathrm{p}) = 1.527$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	4	100 893 452.180 91	25 223 363.045 23	5.17	0.008 1
Error	15	73 248 930.519 09	4 883 262.034 61		
Total	19	174 142 382.700 00			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–16 335.819 68	9 509.475 03	14 410 491.916 62	2.95	0.106 4
SLOPE	145.726 50	61.696 61	27 243 599.344 32	5.58	0.032 1
FTYPE	–1 719.123 58	1 109.856 85	11 716 294.802 17	2.40	0.142 2
SORT	–1 495.819 69	664.233 34	24 764 364.103 53	5.07	0.039 7
SLOPE2	–0.210 78	0.097 10	23 011 033.289 95	4.71	0.046 4

Bounds on condition number: 107.761 5, 869.74.

Step 5 Variable HA entered, $R^2 = 0.67$, $C(p) = 1.081$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	5	116 437 287.624 15	23 287 457.524 83	5.65	0.004 7
Error	14	57 705 095.075 85	4 121 792.505 42		
Total	19	174 142 382.700 00			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–12 110.976 55	9 003.447 59	7 458 075.400 18	1.81	0.200 0
SLOPE	111.776 70	59.317 33	14 636 104.660 42	3.55	0.080 4
FTYPE	–2 377.861 52	1 074.603 37	20 181 936.856 38	4.90	0.044 0
HA	2.031 71	1.046 22	15 543 835.443 24	3.77	0.072 5
SORT	–1 550.142 54	610.892 11	26 539 965.825 97	6.44	0.023 7
SLOPE2	0.159 33	0.093 06	12 082 926.859 26	2.93	0.108 9

Bounds on condition number: 117.617 8, 1 192.486.

Step 6 Variable SUMWIN entered, $R^2 = 0.69$, $C(p) = 2.401$

	DF	Sum of squares	Mean square	*F*	*p* > *F*
Regression	6	120 761 396.809 79	20 126 899.468 30	4.90	0.007 9
Error	13	53 380 985.890 21	4 106 229.683 86		
Total	19	174 142 382.700 00			

Variable	Parameter estimate	Standard error	Type II sum of squares	*F*	*p* > *F*
INTERCEP	–17 618.389 22	10 467.056 47	11 633 931.541 85	2.83	0.116 2
SLOPE	140.418 97	65.454 59	18 897 944.573 19	4.60	0.051 4
FTYPE	–2 335.342 57	1 073.372 75	19 437 629.414 99	4.73	0.048 6
HA	1.499 53	1.165 93	6 792 214.117 39	1.65	0.220 8
SORT	–1 455.400 55	616.687 83	22 870 599.961 21	5.57	0.034 6
SUMWIN	1 115.081 02	1 086.625 06	4 324 109.185 64	1.05	0.323 5
SLOPE2	–0.204 84	0.102 93	16 263 592.365 51	3.96	0.068 0

Bounds on condition number: 144.001 3, 1 758.72.

Note: No other variable met the 0.5 significance level for entry into the model.

Summary of forward-selection procedure for dependent variable PMH

Step	Variable entered	Number in	Partial R^2	Model R^2	C(p)	F	$p > F$
1	SLOPE	1	0.284 2	0.284 2	3.617 2	7.145 6	0.015 5
2	SLOPE2	2	0.101 1	0.385 3	2.846 1	2.796 4	0.112 8
3	SORT	3	0.126 8	0.512 1	1.371 0	4.158 4	0.058 3
4	FTYPE	4	0.067 3	0.579 4	1.527 2	2.399 3	0.142 2
5	HA	5	0.089 3	0.668 6	1.081 1	3.771 1	0.072 5
6	SUMWIN	6	0.024 8	0.693 5	2.400 6	1.053 1	0.323 5

Obs	Dep var FRATE	Predict value	SE predict	Lower 95% mean	Upper 95% mean	Lower 95% predict	Upper 95% predict	Residual	SE residual	Student residual	–2–1–0 1 2	Cook's D
1	9 500.0	6 284.5	1 028.058	4 063.5	8 505.5	1 375.6	11 193.4	3 215.5	1 746.232	1.841	| |*** |	0.168
2	3 173.5	4 171.1	1 206.945	1 563.7	6 778.6	–924.3	9 266.6	–997.6	1 627.732	–0.613	| *| |	0.030
3	500.0	2 515.5	1 316.391	–328.4	5 359.4	–2 704.9	7 735.8	–2 015.5	1 540.566	–1.308	| **| |	0.179
4	2 292.0	3 325.0	1 160.043	818.9	5 831.1	–1 719.3	8 369.3	–1 033.0	1 661.484	–0.622	| *| |	0.027
5	2 000.0	1 171.0	1 471.467	–2 007.9	4 349.9	–4 239.2	6 581.2	829.0	1 393.203	0.595	| |* |	0.056
6	5 400.0	4 076.1	959.029	2 004.3	6 148.0	–767.1	8 919.4	1 323.9	1 785.075	0.742	| |* |	0.023
7	6 000.0	3 490.6	1 038.521	1 247.0	5 734.2	–1 428.6	8 409.8	2 509.4	1 740.030	1.442	| |** |	0.106
8	300.0	–650.9	974.109	–2 755.3	1 453.5	–5 508.2	4 206.4	950.9	1 776.891	0.535	| |* |	0.012
9	2 000.0	5 401.7	1 399.684	2 377.9	8 425.6	81.2	10 722.3	–3 401.7	1 465.303	–2.322	|****| |	0.703
10	10 800.0	8 484.1	1 317.889	5 637.0	11 331.2	3 262.0	13 706.2	2 315.9	1 539.285	1.505	| |*** |	0.237
11	4 000.0	4 888.9	1 232.683	2 225.8	7 551.9	–235.2	10 013.0	–888.9	1 608.329	–0.553	| *| |	0.026
12	6 114.5	7 102.0	1 385.145	4 109.6	10 094.5	1 799.3	12 404.8	–987.5	1 479.054	–0.668	| *| |	0.056
13	1 080.0	413.1	1 261.958	–2 313.2	3 139.4	–4 744.2	5 570.3	666.9	1 585.463	0.421	| | |	0.016
14	500.0	–830.3	1 316.690	–3 674.8	2 014.3	–6 051.0	4 390.5	1 330.3	1 540.311	0.864	| |* |	0.078
15	700.0	595.9	1 262.560	–2 131.7	3 323.5	–4 562.0	5 753.9	104.1	1 584.983	0.066	| | |	0.000
16	1 926.0	2 815.6	815.803	1 053.1	4 578.0	–1 903.6	7 534.8	–889.6	1 854.911	–0.480	| | |	0.006
17	1 200.0	2 871.1	1 173.244	336.4	5 405.7	–2 187.5	7 929.6	–1 671.1	1 652.189	–1.011	| **| |	0.074
18	1 000.0	1 138.9	886.543	–776.3	3 054.2	–3 639.5	5 917.3	–138.9	1 822.161	–0.076	| | |	0.000
19	1 000.0	2 611.1	1 430.075	–478.3	5 700.6	–2 747.0	7 969.3	–1 611.1	1 435.659	–1.122	| **| |	0.179
20	1 600.0	1 210.8	1 054.315	–1 066.9	3 488.5	–3 724.0	6 145.6	389.2	1 730.506	0.225	| | |	0.003

Sum of residuals = 0.
Sum of squared residuals = 53 380 985.890.
Sum of squares of predicted residual errors (press) = 143 195 263.14.

Note: PMH = productive machine hours, C (p) = total squared error, DF = degrees of freedom, SLOPE = slope index, SLOPE2 = square of slope index, SORT = sorting index, FTYPE = forest type, HA = total area harvested, SUMWIN = seasonal index, SE = standard error, Cook's D = Cook's D influence statistic.