THE ECONOMICS OF INTEGRATED FULL-TREE HARVESTING AND CENTRAL PROCESSING IN JACK PINE

FINAL REPORT

by

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Special Report N⁰ SR-37

ENFOR Project P-322

June 1986

ISSN 0381-7733

DSS Contract N° 0SS84-00062
DSS File 55SS.KH405-4-0077

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ACKNOWLEDGEMENTS

Many people have made major contributions throughout the course of this study. In particular, there are several whose guidance and assistance have been particularly valuable. These are:

Dr. Denis Brière, Gordon Franklin and Ernest Heidersdorf of FERIC for their guidance and commentary.

Kim Hadley and Eugene Vajda of FERIC for their technical assistance.

André du Sault of FERIC for his help with the experimental design and field work.

Mr. John Johnson of the Canadian Forestry Service for his guidance and patience.

The assistance of Mr. D.D. Hamilton of Logging Development Corporation is gratefully acknowledged. Special thanks are due to Mr. Jean-Claude Houde of the Compagnie James Maclaren Inc. for help in gathering historical data. The help of Mr. Jean-Guy Routhier of Darveau, Grenier, Routhier & Associés in sorting out experimental methods and criticizing the draft report was greatly appreciated. Special thanks are due to Mr. C.R. Silversides for criticizing the draft report. Special thanks are also due to the following industry personnel for help with obtaining productivity data on jack pine operations and data on full-tree harvesting: Mr. Jim Waddell of E.B. Eddy Forest Products, Messrs. Malette and Corbeil of Malette Lumber, Mr. L.S. Meagher of the Ontario Paper Company, Mr. Bruce Hyde of Prince Albert Pulp, Mr. Roger de Champlain of Manac St.George Inc. and Mr.Jack Hughes (formerly with La Compagnie Price in Jonquière). The hospitality and assistance of Mr. Ben Morin and the staff of the Morard Pulpwood Company is gratefully acknowledged.

Very special thanks to Mrs. Karin Zundel and to Mrs. Odette Valade for help in proof-reading, graphics preparation and word processing.

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SUMMARY

This report presents the results of an analysis examining the economic worth associated with investing in forest harvesting systems designed to recover energy biomass* in conjunction with conventional products such as tree lengths or logs. This report also summarizes the findings of five field experiments designed to provide estimates of the energy biomass recovered by the feller-forwarder and cut-and-skid harvesting methods, to test experimental methods and to quantify the merchantable volume loading of standard highway-legal trailers loaded with full trees rather than tree lengths. The field experiments were undertaken in both frozen and unfrozen conditions to estimate the annual energy biomass yield.

The economic analysis compared 'proposed' integrated full-tree harvesting systems involving centralized processing with 'benchmark' systems based on conventional tree-length or roadside processing technology. The cut-and-skid and fully-mechanized harvesting methods were considered in both the tree-length and full-tree systems. Transportation of tree lengths and full trees was analyzed with five hauling system configurations. The first involves transportation of tree lengths using highway-legal trailers. The second involves using a hypothetical highway-legal full-tree hauling trailer. The third and fourth involve the use of oversized trailers for the transportation of tree lengths and full trees over private roads. The fifth involves two distinct phases, one off-highway and one on-highway with a reloading step between the two phases.

The results of the economic analysis indicate that the concept of harvesting and hauling full trees to a central plant for processing is attractive where large loads may be hauled over private roads. The comparison of the tree-length fully-mechanized system with the fully-mechanized full-tree system hauling over private roads yielded an after-tax rate of return of 14% (net of inflation) at hauling distances of 140 km. This rate of return was earned with energy biomass valued at $0 per oven-dry tonne. When the value was assumed to be $20 per oven-dry tonne, the rate of return jumped to 25%. The comparison of the tree-length cut-and-skid system and the tree-length fully-mechanized system indicated a rate of return of 22% without investment in central processing facilities. Sensitivity analyses identified truck merchantable load size, hauling distance and energy biomass value as critical variables.

Firms with some or all of the following characteristics were identified as being the most likely to benefit from integrated full-tree harvesting and central processing:

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* "Energy Biomass" refers to the tops and stem branches which are still attached to the tree harvested for conventional forest products when the tree reaches the roadside.

1) Off-highway hauls to:

   a) Mill
   b) Railhead
   c) Riverside jetty

2) Short hauling distances.

3) Terrain suited to large mechanized harvesting equipment.

4) High bush camp costs.

5) High energy prices (i.e. no natural gas service, no cheap electricity and no cheap energy biomass).

6) High slash disposal costs.

The average energy biomass recovery rate for the winter cut-and-skid phase was 67.7% and the recovery rate for the winter fully-mechanized (KFF) phase was 43.2%. Warm weather during the winter cut-and-skid phase led to a high energy biomass recovery rate. The average recovery rate for the summer cut-and-skid phase was 76.5% and that for the summer fully-mechanized (KFF) phase was 60.2%. The fact that the recovery rate for the cut-and-skid phases should exceed that of the fully-mechanized phases was unexpected. This result is attributed to the branching habit of jack pine trees.

Loading tests showed that a conventional highway logging trailer loaded with full trees could hold only 43.8% of the merchantable volume which would be contained in a load of tree lengths. It was estimated, however, that the merchantable volume loading could be increased to 87.2% of that for tree lengths by using an oversized trailer (which contains the same total payload weight as a load of tree lengths). The use of oversized trailers would greatly reduce the incremental cost associated with hauling full trees. The use of such trailers would be limited to private roads.

The results of this analysis are illustrative only. Both detailed and long-term biomass recovery tests should be performed in local conditions due to the sensitivity of the results to factors such as tree form, species, topography and road network characteristics.

The study recommends the following:

1) The concept of using integrated full-tree harvesting and centralized processing as a means of recovering energy biomass and of streamlining forest harvesting operations should be given serious consideration.

2) A prototype central processing plant should be constructed to provide 'hard' data regarding capital costs and operating parameters.

3) Truck load compaction equipment should be developed to increase merchantable wood loading in full-tree trailers.

4) The use of roadside biomass recovery systems such as the FERIC Logging Residue Processor should be tested as an alternative to integrated full-tree harvesting.

1.0 INTRODUCTION

This report summarizes the results of a four-phase project to study the economics of harvesting full trees to produce both conventional forest products and energy biomass*:

Phases one and two were undertaken to estimate the yield of energy biomass in frozen and unfrozen conditions respectively and to test an experimental method used to estimate yield. An estimate of the annual yield of energy biomass was prepared using the data in phases one and two.
Phase three quantified the merchantable volume which may be carried as full trees and tree lengths in conventional highway trailers. This information was used to assess the transportation cost penalty which is the main trade-off in hauling full trees to produce energy biomass and conventional forest products.

Phase four combined the energy biomass yield data and hauling data with historical and current economic data. These were used to evaluate the economic worth of integrated full- tree harvesting systems versus conventional tree-length systems.

It is assumed that tree lengths are transported directly from the roadside to the mill. Full trees are hauled from the roadside to a central processing plant located at the mill, where the trees are processed into conventional product forms.

This report is sub-divided into two distinct portions: an experimental report on energy biomass yield in jack pine and an economic analysis examining the feasibility of integrated full-tree harvesting and central processing as a means of producing both energy biomass and conventional forest products. The discussions of each portion are separate. The conclusions and recommendations of the two portions of the report have been integrated into sections 6.0 and 7.0.

The experimental portion of this study was performed to obtain supplementary data on the quantity of energy biomass which can be recovered by two full-tree harvesting methods in frozen and unfrozen conditions. Although several operations working in black spruce and balsam fir have been analysed, this has not been the case in jack pine. This study has remedied this situation by gathering data for an operation working predominantly in jack pine.

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* "Energy Biomass" refers to the tops and stem branches which are still attached to trees harvested for conventional forest products when they reach the roadside.

For the purpose of this analysis "biomass recovered" is defined as that portion of branch and top material which remains attached to the stem of the tree until the tree reaches the roadside. This definition is adopted because the author feels that the biomass physically attached to the stem will be most easy to recover. This is because the handling problems, and hence costs, associated with the collection of energy biomass on the ground do not apply to biomass attached to the stems of trees harvested for conventional forest products.

A company wishing to estimate the quantity of energy biomass recoverable at a central processing plant would need to perform two studies, only one of which was performed for this analysis. The first would involve a large-scale experiment in which full trees would be loaded on trailers similar to those to be used in the proposed harvesting system and hauled to a yard in which the trucks would be weighed. The trucks would then be unloaded, the trees delimbed and the tree lengths reloaded on the trucks. A final weighing of the reloaded trucks would yield the information required to determine the quantity of energy biomass deliverable to a central processing plant. The second study would involve a detailed analysis of the biomass available at the stump and of the loss of biomass in felling, forwarding, loading, hauling and unloading. The latter, would be useful in determining ways to modulate energy biomass recovery rates.

The first study would provide an accurate estimate of the amount of biomass recoverable from the logging operations whereas the second would yield a precise estimate of biomass losses in different processes. The difference between these two studies is similar to the difference between a FERIC shift-level availability and productivity (SLAP) study performed over several months and a detailed continuous time study carried out over one shift.

It appears, from Routhier (1981), that the major biomass losses occur in the felling and forwarding (or skidding) functions. Since budgetary restrictions did not permit the execution of a full set of field trials, this study is based on a detailed analysis of the energy biomass yield in the felling and forwarding processes and a small test of the amount of full trees which may be loaded on a conventional trailer.

The biomass recovery data used in this analysis are, therefore, mainly illustrative. The small number of stems which may be treated in this kind of detailed study make the results extremely sensitive to:

1) Micro-site and genetic differences within the stand.

2) Daily temperature variation (in winter).

3) Topographic and surficial terrain features.

These factors would become less significant in the large-scale study since their effects would represent the influence of the average conditions under which timber is harvested.

2.0 METHODS

2.1 METHODS - Description of Experiment

2.1.1 Objectives and Experimental Layout

Objectives

1) To provide estimates of the quantity of energy biomass recovered at roadside with the fully-mechanized full-tree harvesting method (Koehring feller-forwarder) and with the full-tree cut-and-skid harvesting method working in frozen and unfrozen conditions (see Sections 3.2 and 3.3).

2) To test the workability of a plan to use a scale mounted on a skidder to weigh trees and to determine the accuracy of this method.

3) To quantify the merchantable wood volume which may be carried in full-tree form and in tree-length form in conventional trailers and to estimate the weight of full-tree and tree-length loads (see Section 3.4).

The experiment was divided into five parts: winter and summer cut-and-skid phases, winter and summer fully-mechanized phases, and a truck hauling phase. In the cut-and-skid phases, trees were felled manually with a powersaw (see Figures 1, 2 and 3) and skidded to a landing. In the fully-mechanized phases trees were felled and forwarded to a landing by a Koehring feller-forwarder (see Figure 4). Full trees and tree-lengths were loaded on standard highway trailers with a Koehring K4-L knuckle-boom loader.

2.1.2 Stand Description

The stand in which this study was undertaken is located in the Gogama district of the Ontario Ministry of Natural Resources. In the 1971 Forest Resource Inventory, the stand is numbered 218. The working group is jack pine, with approximately 10% of basal area in white birch. The stand height is 20 m, and the age is 65 years, with stocking at 90% of site class 2 normal. Average stem merchantable volume for jack pine is 0.27 m^3. The stand is situated on a plateau with predominantly flat terrain cut with gullies. The area where the experiment was carried out was flat with a low hummock near the landing (see Figure 5). Stump height varied between 10 and 30 cm. With the exception of stumps and trees, surficial features which might affect the energy biomass yield by stripping biomass from trees (e.g., boulders) were not evident. The sandy, podzolic soil in the cutover remained covered by 10 to 50 cm of snow during the winter portion. The skidway was covered by similar quantities of snow until warm weather exposed the soil at the end of the winter study. The soil at the roadside was exposed for most of the winter portion. It was bare and dry during the summer phase.

Figure 1. Skidder operator felling tree using powersaw.

Figure 2. Once a full load of trees has been weighed at the stump, the load is skidded to the landing.

Figure 3. This load is ready to be unchoked at the landing.

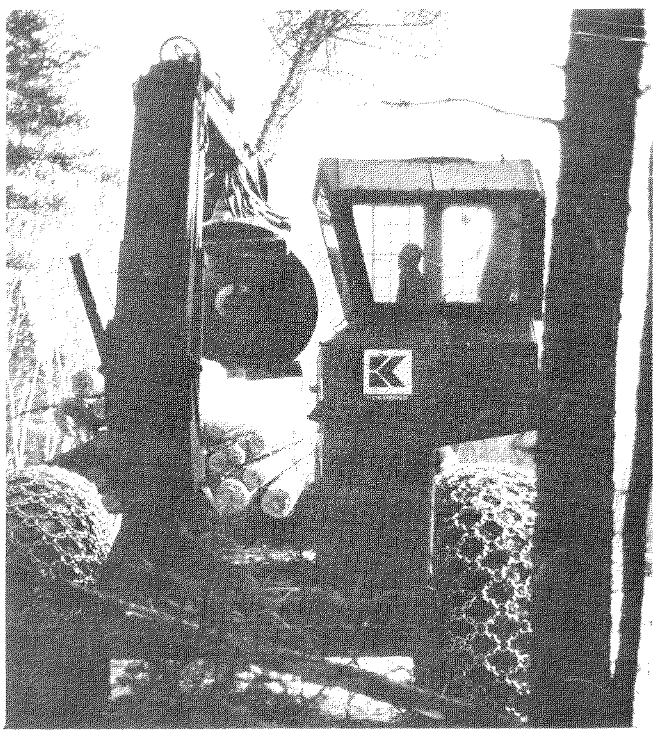

Figure 4. Koehring feller-forwarder dropping felled tree in bunk.

Figure 5. Photo shows skidway. Landing is located in background.

Figure 6. Tree is improperly balanced (note the butt in center of photo is leaning against tree).

2.2 METHODS - Cut-and-Skid

This section describes the weighing procedure and the sampling method.

A Checkmate model crane scale was used to weigh full trees and tree lengths. The scale had a capacity of 4 545 kg (10 000 lbs). The readings were taken through an LED display. The readings were given in 5 lb units with an accuracy of 0.5%.

In order to weigh trees, chains were attached to them as close to the centre of gravity as possible and then to the hook on the bottom of the scale. The scale was hung from its mount on the skidder blade by using a clevis (see Figure 6). The entire tree was then lifted by the skidder hydraulic system. If the scale was not located directly over the centre of gravity, the tree rested on the ground on its heavier side (see Figure 6). The tree was then lowered and the position of the scale adjusted toward the heavier side by moving the skidder blade. Following this adjustment, the tree was lifted again. If the scale was located directly over the centre of gravity, neither the top, the butt nor any of the branches could touch the ground. At this time, a reading was taken from the scale (see Figure 7). The centre of gravity was marked with a lumber crayon and the tree was lowered to the ground. Weight readings of trees suspended by the chain incorporated the weight of the chain (summer - 15 lbs, winter - 10 lbs). When data were prepared for analysis, the appropriate weight was subtracted from each reading in order to compensate for the weight of the chain.

The weighing technique described above was incorporated into the sampling technique. The steps involved (see Figures 1 to 8) in the sampling technique are listed below:

1) Fell tree with powersaw.
2) Number stem.
3) Attach chains over centre of gravity.
4) Weigh tree.
5) Mark centre of gravity.
6) Repeat steps 1 to 5 until a full load (8 to 12 trees) is ready for skidding.
7) Skid load to landing.
8) Attach chains over mark indicating centre of gravity.
9) Weigh tree.
10) Delimb tree.
11) Top tree.
12) Weigh top.*
13) Select and remove branch for moisture content analysis.*
14) Measure stem length.
15) Measure stem diameter at butt, centre and top.
16) Attach chain.
17) Weigh stem.
18) Cut 'cookie' from butt, top end of stem and from centre of unmerchantable top for use in moisture content analysis.*
19) Repeat steps 8 to 18 until load has been completely weighed.

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* These steps were carried out on one tree per load (selected randomly).

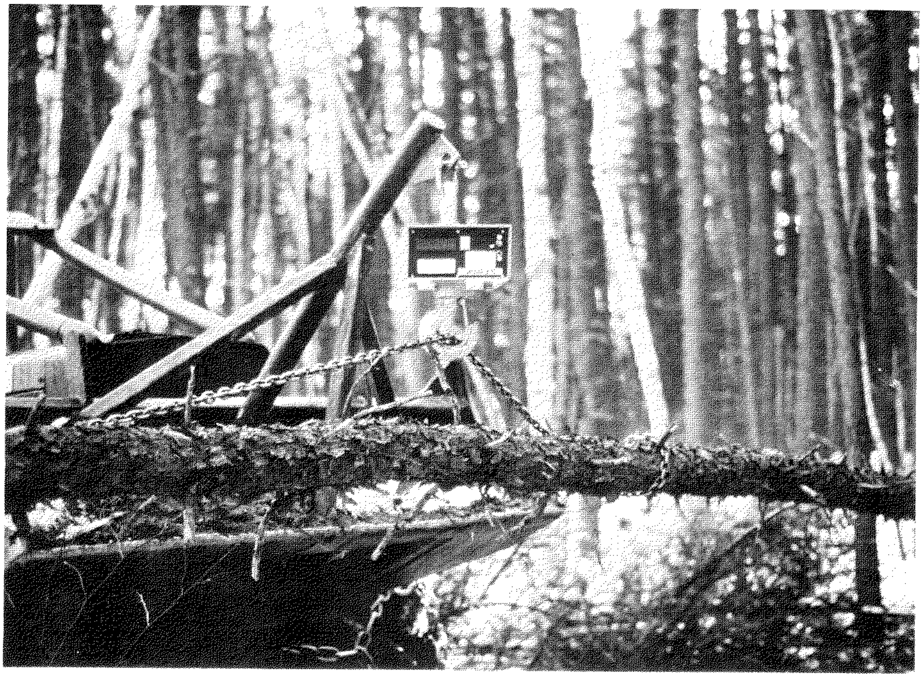

Figure 7. Once tree is properly balanced, a reading is taken (note the reading on the scale is 345 lbs).

Figure 8. These trees are piled at the landing ready for weighing (note stem numbers on butts).

The samples taken from each load for the moisture content analysis (three 'cookies' and one branch) were placed in plastic bags and weighed on the same day they were collected. The samples were then oven-dried using standard temperatures and time periods and weighed. The two weights were used to calculate the moisture content.

Two problems were encountered while following the steps of the method outlined above. The first of these problems occurred while large trees (e.g., butt diameter > 30 cm) were being weighed. These trees showed a tendency to sag at the top and butt ends. This made it impossible to lift all branches clear of the ground. When this occurred, it was noted on the data sheets. Trees which had this notation were not included in calculations. Although this practice would tend to bias the sample toward the smaller stems, it should be noted that the problem occurred rarely since the conjunction of both unfavourable terrain and large tree size was required to cause the problem. This difficulty could be overcome by using an attachment capable of lifting the trees farther from the ground. The second problem occurred because trees had to be felled parallel to one another in order that they could be weighed with the long axis of the stem perpendicular to the direction of skidding. In some cases, when trees were choked and skidded a few stems broke. Such stems were removed from the sample since the excessive breakage was an artifact introduced by the sampling method. In normal skidding, trees are felled as close to parallel to the direction of the skidding as possible, resulting in less breakage.

2.3 METHODS - Fully Mechanized

Koehring feller-forwarders felled loads of trees (approximately 90 trees per load) and forwarded them to a landing where they were unloaded. Once trees were piled at the landing, the following steps were undertaken (see Figures 9 to 12):

1) Randomly select one tree in eight.
2) Spray selected trees with marker paint.
3) Remove trees surrounding selected trees using Denis delimber.
4) Pile selected trees parallel on ground using Denis delimber.
5) Attach chains to tree near centre of gravity.
6) Weigh tree.
7) Delimb tree.*
8) Top tree.*
9) Measure butt diameter.
10) Weigh stem.*
11) Repeat steps 5 to 10 for all selected trees in each load.

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* These steps were followed for one tree in two for the winter study and for each tree in the summer study.

Figure 9. Trees showing paint from random selection in piles left by Koehring feller-forwarder.

Figure 10. Boom of the Denis delimber removing selected stems from KFF pile (note other selected stems parallel on ground in right side of photo).

Figure 11. Stems selected from the KFF pile lying on ground before weighing.

Figure 12. Pile of delimbed trees harvested by KFF (note large pile of slash in the background).

2.4 METHODS - Truck Loading

In order to quantify the differences in merchantable payload associated with hauling full trees rather than tree lengths in identical trailers, five truckloads of full trees (loaded uni-directionally) and five truckloads of tree lengths (loaded in the butt-and-top configuration) were loaded and scaled (see Figures 13-16).

A Koehring K-4L knuckle-boom loader was used to load the standard (highway legal) 4-stake trailer. Trees were loaded to the level which is legal for highway transport (see Figure 13) and then unloaded and marked for subsequent scaling. When all the loads had been marked and the loading process finished, the piles were scaled using a scaling stick and local volume tables prepared during the study.

3.0 RESULTS

3.1 RESULTS - Cut-and-Skid

3.1.1 Energy Biomass Recovery

The most important information generated in this phase of the experiment was the data on the proportion of energy biomass available in full trees on the stump which was brought to roadside. Tables 1 and 2 list the percentage of energy biomass recovered at roadside for each skidder load examined in winter and summer respectively.

This figure was obtained using the following formula:

$$\%\ \text{Energy Biomass Recovery} = \frac{TRWTi - TSWT_i}{TBWTi - TSWT_i} \times 100$$

$TBWT_i$ = The sum of full-tree weights at the stump for load i.

$TRWT_i$ = The sum of full-tree weights at roadside for load i.

$TSWT_i$ = The sum of stem weights at roadside for load i.

The weighted average energy biomass recovery percentage was calculated by summing $TBWT_i$, $TRWT_i$, and $TSWT_i$ for all of the i=1 to n loads (n=11 for winter and n=10 for summer) and using the formula above. The weighted average energy biomass recovery factor for the 11 loads harvested in winter is 67.7%. The weighted average energy biomass recovery factor for the 10 loads harvested in summer is 76.5%.

Figure 13. Load of full trees at highway-legal height.

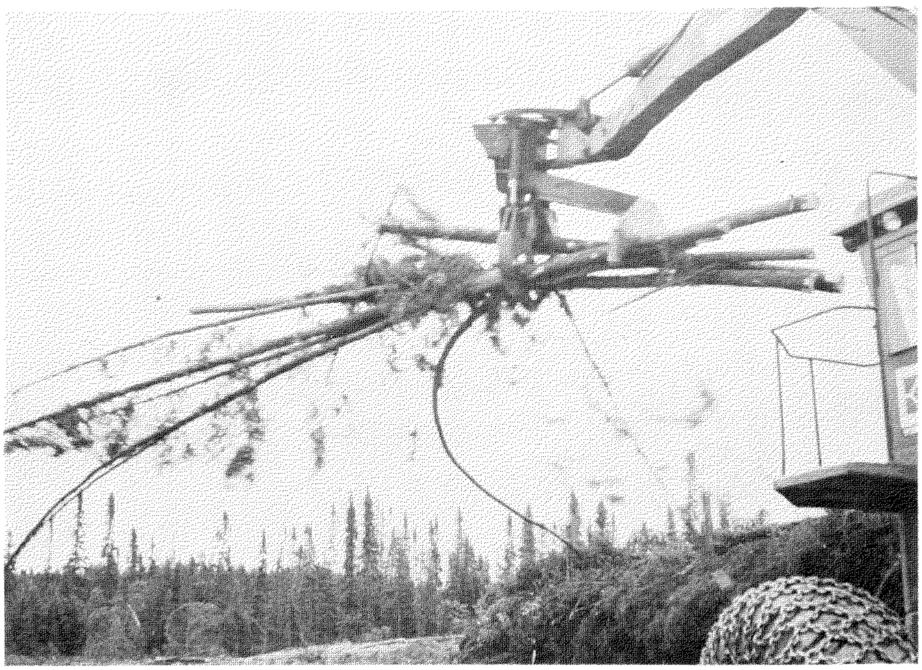


Figure 14. Tree caught in load during unloading with heel-boom loader.

Figure 15. Trees broken and fanning out during unloading with heel-boom loader.

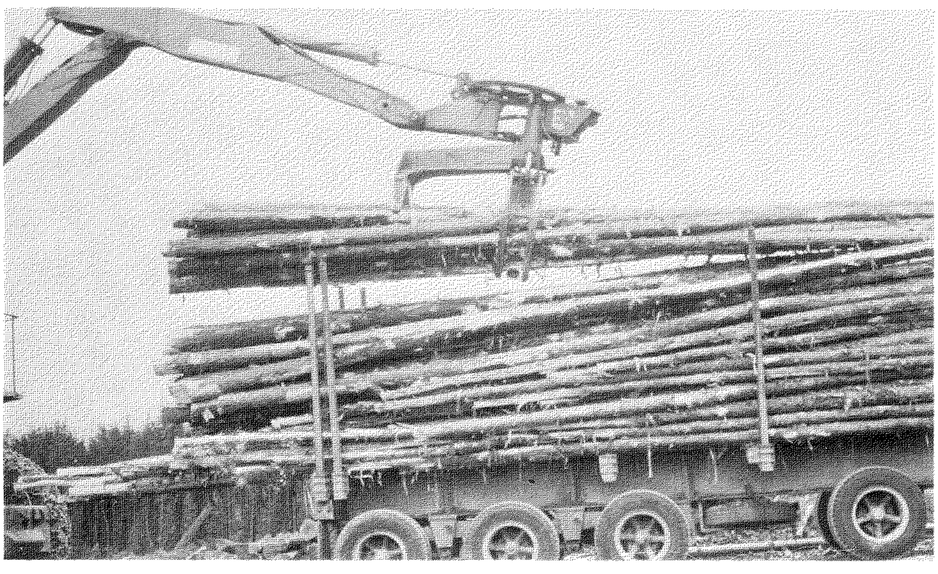


Figure 16. Heel-boom loader with tree-lengths (note that stems are not fanning out or breaking).

Table 1. Energy biomass recovery factors and average temperature during winter skidding

Load Number	% Energy Biomass Recovery	Average Temperature (deg Celsius)
2	73.2	11.6
3	86.0	11.6
4	63.4	- 4.4
5	79.3	- 4.4
6	56.1	- 6.9
7	66.2	- 3.3
8	66.2	- 3.3
9	63.4	- 3.3
10	54.8	-10.0
11	74.4	-10.0
12	80.9	-10.0

Weighted Mean = 67.7
Arithmetic Mean = 69.4
Standard Deviation = 10.1

Table 2. Energy biomass recovery factors during summer skidding

Load Number	% Energy Biomass Recovery
1	85.0
2	78.2
3	78.0
4	58.8
5	69.9
6	66.9
7	72.4
8	97.3
9	81.0
10	77.8

Weighted Mean = 76.5
Arithmetic Mean = 76.5
Standard Deviation = 10.5

3.1.2 Energy Biomass Recovery vs. Temperature

The fluctuation in ambient temperatures during the winter phase (varying between 12 and -12°C) presented the opportunity to test whether a direct relationship existed between temperature and energy biomass recovery in winter skidding. Table 1 shows average daily temperature and energy biomass recovery. Average daily temperature was the average of the daily minimum and maximum temperatures as recorded on a maximum-minimum thermometer hung in the shade near the work site. Biomass recovery (expressed as a percentage) was regressed on average daily temperature. The following equation was the result of this regression:

% Energy Biomass = 71.0786 + 0.545 x TEMPERATURE (°C) r^2 = 0.178 Recovery

The significance of the low correlation coefficient is discussed in section 4.0.

It should be noted that temperatures fluctuated considerably in any given day (e.g., fluctuations of 7-8°C were not uncommon). The temperature variation within a stand or even within a tree can also vary significantly at any given time (Geiger 1975). This implies that ambient temperature can only be used as a general guide in the prediction of biomass recovery rates.

3.1.3 Regressions of Volume and Full-Tree Weight at the Stump

Using data gathered in winter for 92 trees (in 11 loads), regression equations were formed to calculate expected values of merchantable bole volume and full-tree weight at the stump given butt diameter and stem weight data (see Appendix 1 for more data on regressions). These equations are used in section 3.2. The equations for the winter phase are as follows:

Merchantable (m^3) = -0.002633 + 6.1021x10^{-4} (BUTT DIAMETER [cm])^2,
Stem Volume

r^2 = .943 SE = .0305

Full-Tree (kg) = 1.108409 + 1.206027 (STEM WEIGHT)
Weight in bush

r^2 = .985 SE = 15.54

Using the data gathered in unfrozen conditions for 96 trees (in 10 loads), regression equations were formed to calculate expected values of merchantable bole volume and full-tree weight at the stump given butt diameter and stem weight data. Because of its lower standard error and higher coefficient of correlation, the equation using stem weight as the independent variable was used in all calculations except for those for the hauling trials. (see Appendix 2 for more information on the regressions). The equations for the summer phase are as follows:

Merchantable Stem Volume (m^3) $= 0.027272 + 6.453 \times 10^{-4}$ (BUTT DIAMETER [cm]$)^2$

$r^2 = 0.913$ SE $= 0.039$

Merchantable Stem Volume (m^3) $= -0.006864 + 0.001256$ (STEM WEIGHT [kg])

$r^2 = 0.969$ SE $= 0.023$

Full Tree Weight in bush (kg) $= 4.994609 + 1.222222$ (STEM WEIGHT [kg])

$r^2 = 0.986$ SE $= 15.166$

3.1.4 Summary of Important Data

In each of the cut-and-skid phases (frozen and unfrozen), the following information was gathered:

1) Average stem merchantable volume (m^3).

2) Density of merchantable wood (kg/m^3), green and oven-dry.

3) Energy biomass available at the stump (kg/m^3 merch.), green and oven-dry.

4) Energy biomass recovered at roadside (kg/m^3 merch.), green and oven-dry.

5) Energy biomass recovered as a percentage of stem weight (with stem bark weight included in stem weight).

6) Percentage of energy biomass available at the stump which is recovered at roadside.

7) Moisture content of the full trees, expressed as a percentage.

The values of these parameters are presented in Tables 3 and 4.

Table 3. Summary of important data, cut-and-skid winter phase

Average Merchantable Volume per Tree = 0.27 m^3, Standard Deviation = 0.14 m^3

	Green (kg/m^3)	Oven-Dry (kg/m^3)
$\frac{\text{Weight of Merchantable Stem Wood (kg)*}}{\text{Merchantable Volume (m}^3\text{)}}$ =	735.4	367.7
$\frac{\text{Weight of Energy Biomass at Stump (kg)}}{\text{Merchantable Volume (m}^3\text{)}}$ =	169.0	84.5
$\frac{\text{Weight of Energy Biomass Recovered (kg)}}{\text{Merchantable Volume (m}^3\text{)}}$ =	114.4	57.2

$$\frac{\text{Weight of Energy Biomass Recovered (kg)}}{\text{Weight of Stems (kg) (includes bark)}} \times 100 = 14.3\%$$

$$\frac{\text{Weight of Energy Biomass Recovered (kg)}}{\text{Weight of Energy Biomass at Stump (kg)}} \times 100 = 67.7\%$$

Average moisture content = 50.0% (wet basis)

* Alemdag (1983) reported that the proportion of bark on a merchantable stem (as a percentage of the weight of the solid wood) in jack pine was approximately 7.9%. This estimate is used in the calculation of the data presented above.

Table 4. Summary of important data, cut-and-skid summer phase

Average Merchantable Volume per Tree = 0.26 m^3, Standard Deviation = 0.13 m^3

		Green (kg/m^3)	Oven-Dry (kg/m^3)
Weight of Merchantable Stem Wood (kg)* / Merchantable Volume (m^3)	=	757.1	402.0
Weight of Energy Biomass at Stump (kg) / Merchantable Volume (m^3)	=	200.6	106.5
Weight of Energy Biomass Recovered (kg) / Merchantable Volume (m^3)	=	153.5	81.5

$$\frac{\text{Weight of Energy Biomass Recovered (kg)}}{\text{Weight of Stems (kg) (includes bark)}} \times 100 = 18.8\%$$

$$\frac{\text{Weight of Energy Biomass Recovered (kg)}}{\text{Weight of Energy Biomass at Stump (kg)}} \times 100 = 76.5\%$$

Average moisture content = 46.9% (wet basis)

* Alemdag (1983) reported that the proportion of bark on a merchantable stem (as a percentage of the weight of the solid wood) in jack pine was approximately 7.9%. This estimate is used in the calculation of the data presented above.

3.2 RESULTS - Fully-Mechanized

3.2.1 Energy Biomass Recovery

The percentage of biomass available at the stump which is brought to roadside is listed in Tables 5 and 6 for each KFF load in winter and summer respectively. The means given in these tables are weighted according to load size and do not, therefore, correspond to the arithmetic means of the percent recovery for each load. The weighted means are used in calculations. The temperature remained relatively constant at -20°C for the four hours during which the winter harvesting was underway. The formula used in calculating percent recovery is given in section 3.1.1. The full-tree weights used in this calculation were generated using regressions on stem weight rather than on butt diameter since this independent variable gave a better fit and a lower standard error.

3.2.2 Summary of Important Data

In each of the fully-mechanized phases (frozen and unfrozen), the following information was gathered:

1) Average stem merchantable volume (m^3).

2) Density of merchantable wood (kg/m^3), green and oven-dry.

3) Energy biomass available at the stump (kg/m^3 merch.), green and oven-dry (estimated).

4) Energy biomass recovered at roadside (kg/m^3 merch.), green and oven-dry.

5) Energy biomass recovered as a percentage of stem weight (with stem bark weight included in stem weight).

6) Percentage of energy biomass available at the stump which is recovered at roadside.

7) Moisture content of the full trees, expressed as a percentage.

The values of these parameters are presented in Tables 7 and 8.

It is important to note that the weight of full trees could not be physically measured since trees felled by the Koehring feller-forwarder are not deposited on the ground before primary transportation. These values were, therefore, estimated using regression equations developed in the cut-and-skid phases (see Section 3.1.3).

Table 5. Energy biomass recovery factors for fully-mechanized system in winter

Load Number	% Energy Biomass Recovery
1	49.9
2	40.8
3	53.6
4	42.3
5	49.8
6	32.6
7	31.9
8	46.2
9	30.4

Weighted Mean = 43.2
Arithmetic Mean = 41.9
Standard Deviation = 8.7

Table 6. Energy biomass recovery in fully-mechanized harvesting in summer

Load Number	% Energy Biomass Recovery
1	77.5
2	54.2
3	52.3
4	63.4
5	60.2
6	59.8
7	74.9
8	37.2
9	70.6
10	54.9

Weighted Mean = 60.2
Arithmetic Mean = 60.5
Standard Deviation = 12.0

Table 7. Summary of important data, winter fully-mechanized (KFF) Phase

Average Merchantable Volume per Tree = 0.23 m^3, Standard Deviation = 0.11 m^3

		Green (kg/m^3)	Oven-Dry (kg/m^3)
$\frac{\text{Weight of Merchantable Stem Wood (kg)*}}{\text{Merchantable Volume (m}^3\text{)}}$	=	862.4	431.2
$\frac{\text{Weight of Energy Biomass at Stump (kg)}}{\text{Merchantable Volume (m}^3\text{)}}$	=	198.0	99.0
$\frac{\text{Weight of Energy Biomass Recovered (kg)}}{\text{Merchantable Volume (m}^3\text{)}}$	=	85.5	42.8

$$\frac{\text{Weight of Energy Biomass Recovered (kg)}}{\text{Weight of Stems (kg) (includes bark)}} \times 100 = 9.1\%$$

$$\frac{\text{Weight of Energy Biomass Recovered (kg)}}{\text{Weight of Energy Biomass at Stump (kg)}} \times 100 = 43.2\%$$

Average moisture content = 50.0% (wet basis)

* Alemdag (1983) reported that the proportion of bark on a merchantable stem (as a percentage of the weight of the solid wood) in jack pine was approximately 7.9%. This estimate is used in the calculation of the data presented above.

Table 8. Summary of important data, summer fully-mechanized (KFF) phase

Average Merchantable Volume per Tree = 0.29 m^3, Standard Deviation = 0.12 m^3

		Green (kg/m^3)	Oven-Dry (kg/m^3)
$\frac{\text{Weight of Merchantable Stem Wood (kg)*}}{\text{Merchantable Volume (m}^3\text{)}}$	=	716.6	380.5
$\frac{\text{Weight of Energy Biomass at Stump (kg)}}{\text{Merchantable Volume (m}^3\text{)}}$	=	188.6	100.2
$\frac{\text{Weight of Energy Biomass Recovered (kg)}}{\text{Merchantable Volume (m}^3\text{)}}$	=	113.6	60.3

$$\frac{\text{Weight of Energy Biomass Recovered (kg)}}{\text{Weight of Stems (kg) (includes bark)}} \times 100 = 14.7\%$$

$$\frac{\text{Weight of Energy Biomass Recovered (kg)}}{\text{Weight of Energy Biomass at Stump (kg)}} \times 100 = 60.2\%$$

Average moisture content = 46.9% (wet basis)

* Alemdag (1983) reported that the proportion of bark on a merchantable stem (as a percentage of the weight of the solid wood) in jack pine was approximately 7.9%. This estimate is used in the calculation of the data presented above.

3.3 TRUCK LOADING

The merchantable volumes and weights of five loads of full trees and five loads of tree lengths are summarized in Tables 9 and 10 respectively. The weights used in Table 9 were calculated from known densities of tree lengths (including bark) and from the weight of energy biomass recovered per unit of stem weight (calculated during this study) for the fully-mechanized system. The weights given in Table 10 were calculated using the known density of tree lengths (including bark).

The estimates of volume were obtained by a standard butt-scale. The scaling data were converted to volume using regression equations generated in this study and volume tables in Keen (1963).

It is interesting to note that the difficulties in loading full trees reported by Routhier (1981) were also experienced in this study. Figures 14 and 15 show how tops may become caught in a pile or on the truck (during unloading). This leads to breakage owing to the leverage exerted by the knuckle-boom loader. This kind of difficulty was not exhibited when a jib-crane was used to unload trees (Hamilton 1985) and is probably because the grapple on the jib-crane picks up trees in the centre rather than at one end. There is, in this case, a shorter distance between the point at which the force is applied to the tree and the point where the top is intertwined. This, reduces the stress applied to the top section and thereby reduces breakage. Figure 16 shows the K-4L loader with a load of tree lengths. The reader will note that the stems have come away from the load cleanly.

4.0 DISCUSSION OF FIELD WORK

Although the regression of energy biomass recovery on temperature in subsection 3.1.2 clearly showed that no strong linear relationship could be found between these two variables, a comparison of summer and winter energy biomass recovery rates does show that temperature is a very significant factor (see Figure 17). In frozen conditions, the cut-and-skid weighted mean energy biomass recovery rate was 67.7%, whereas in summer the value was 76.5%.

The energy biomass recovery rate for the fully-mechanized system in frozen conditions was 43.2% whereas it was 60.2% in unfrozen conditions. This difference of 17% very closely matches that for black spruce harvested by the fully-mechanized system (Routhier 1981) although the jack pine recovery rates are much lower in absolute terms. Routhier (1981) did not compare winter and summer yields for trees felled manually and skidded with choker skidders.

The very small difference between frozen and unfrozen yields in this experiment is most likely influenced by the higher than normal temperatures experienced during the winter phase and perhaps to the other factors discussed in section 1.0.

Table 9. Volume and estimated total weight of full trees loaded uni-directionally on a highway logging trailer

Load Number	Merchantable Volume (m^3)	Estimated Weight (kg)
1	25.6	22,779
2	26.9	23,936
3	20.2	17,974
4	22.5	20,020
5	19.4	17,262

Mean = 22.9 = 20,396
Standard Deviation = 3.3 = 2,919

Table 10. Volume and estimated weight of tree lengths loaded bi-directionally on a highway logging trailer

Load Number	Merchantable Volume (m^3)	Estimated Weight (kg)
6	52.8	40,825
7	48.7	37,655
8	54.4	42,062
9	54.5	42,139
10	51.0	39,433

Mean = 52.3 = 40,423
Standard Deviation = 2.5 = 1,900

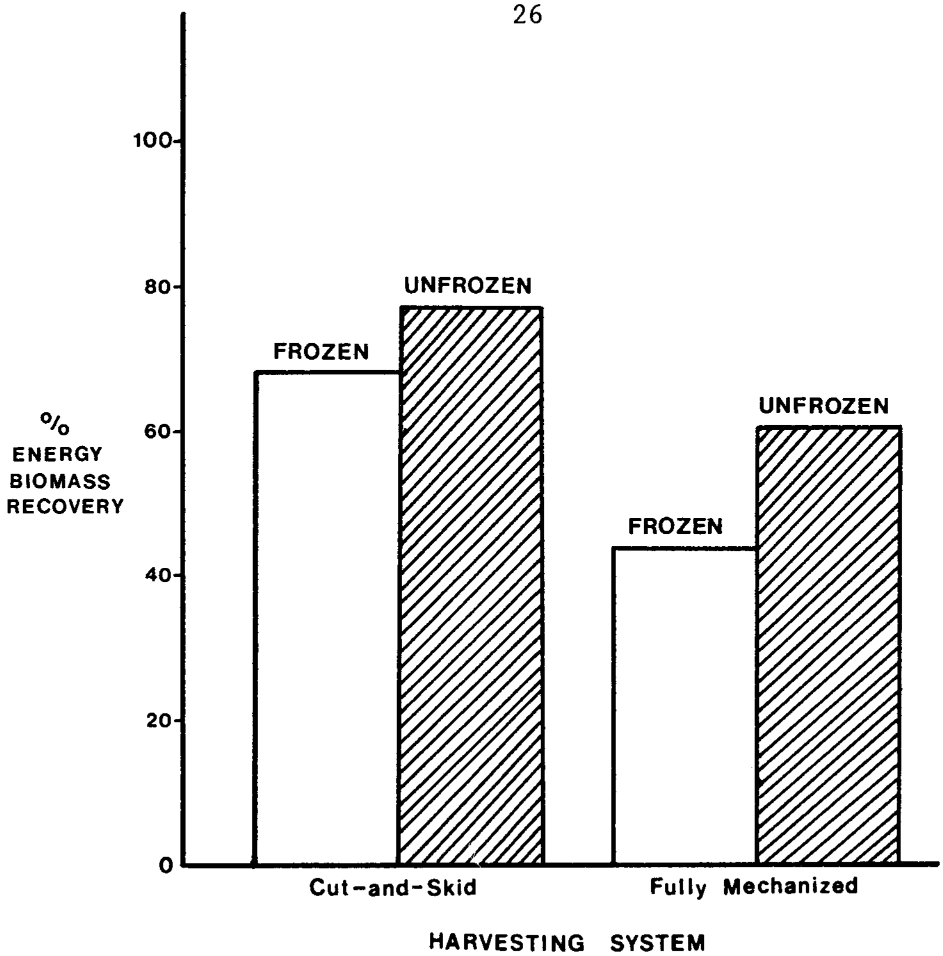


Figure 17. Energy biomass recovery rates for two harvesting methods working in jack pine.

Based on the findings of Routhier (1981), one might expect a higher energy biomass recovery rate for trees harvested by the fully-mechanized method than for trees harvested by the cut-and-skid method, but this is not borne out by the study results. It is unlikely that these values are the result of experimental error since the method used was consistent with Routhier (1981). The low standard errors and excellent curve fits apparent in Appendices 1 and 2 further reduce the probability that experimental error was to blame for the unexpected results.

It is important to note, however, that the branching habit of black spruce, the species studied by Routhier (1981), differs considerably from that of jack pine. The latter has branches of greater diameter and length than black spruce. Jack pine also has a higher proportion of its energy biomass in branches below the merchantable top than does black spruce (see Figures 18 and 19). It may be that the greater diameter of jack pine branches, and thus the greater proportion of branch mass in wood material, would allow greater recovery of biomass in the low compressive stresses experienced in skidding when compared with forwarding in a Koehring feller-forwarder bunk. Black spruce, with its more slender, flexible branches might survive the compressive stresses of the Koehring feller-forwarder but not the shear stresses imposed by skidding against stumps and boulders.

The context in which this detailed biomass yield study would normally take place is discussed in section 1.0. The sensitivity of the conclusions of this report to the validity of the data collected in the yield study is discussed in section 5.5.8.

A common practice in skidding full trees is to purposely rub skidder loads against stumps and standing trees in order to reduce the branchiness of the trees prior to delimbing. The operators in this study were asked to avoid this practice. Most wood skidded is piled on arrival at the landing. The trees in this study were not piled. The trees were, however, felled perpendicular to the direction of skidding. This caused some extra branch (and occasionally top) breakage as the trees were brought through an angle of 45 - 90 to bring them into position for skidding. It is also important to note that branches lost in piling of skidded trees would be recoverable at the roadside, as would be a large portion of biomass broken during forwarding with a Koehring feller-forwarder. A significant portion of the energy biomass loss in forwarding is lost when trees rub against the stakes which form the walls of the Koehring feller-forwarder bunk during the unloading process. It also should be noted that the material produced by the cut-and-skid method is more likely to be contaminated by soil (see Figure 20) than that produced by the fully-mechanized system since the latter does not involve bringing the trees in direct contact with the soil during the transportation phase.

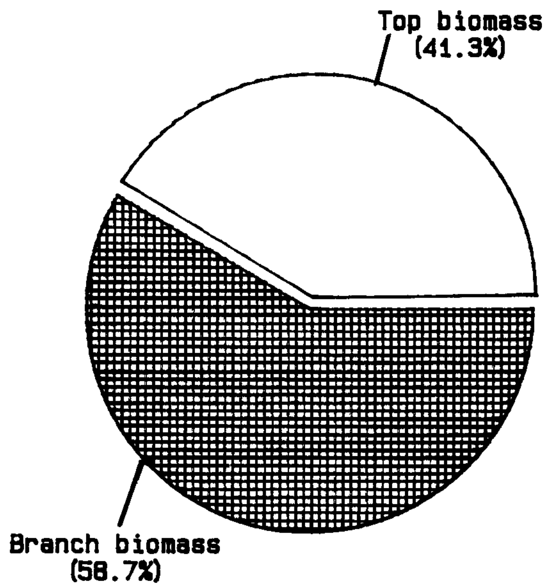
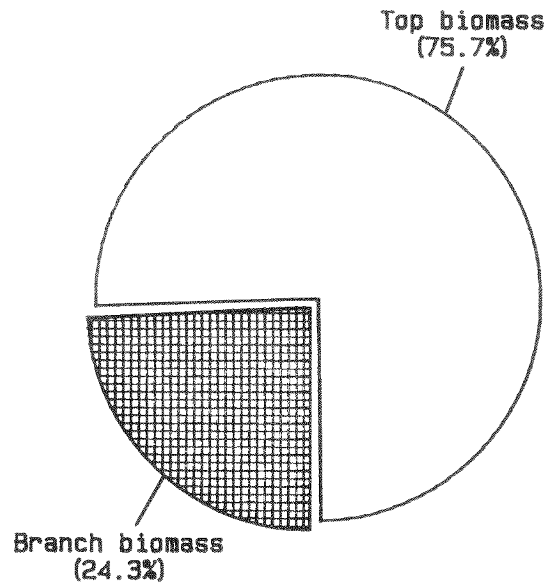


Figure 18. Distribution of roadside biomass in jack pine (cut-and-skid unfrozen conditions).



(After Routhier, 1981)

Figure 19. Distribution of biomass recovered at roadside in black spruce (fully-mechanized harvesting in frozen conditions).

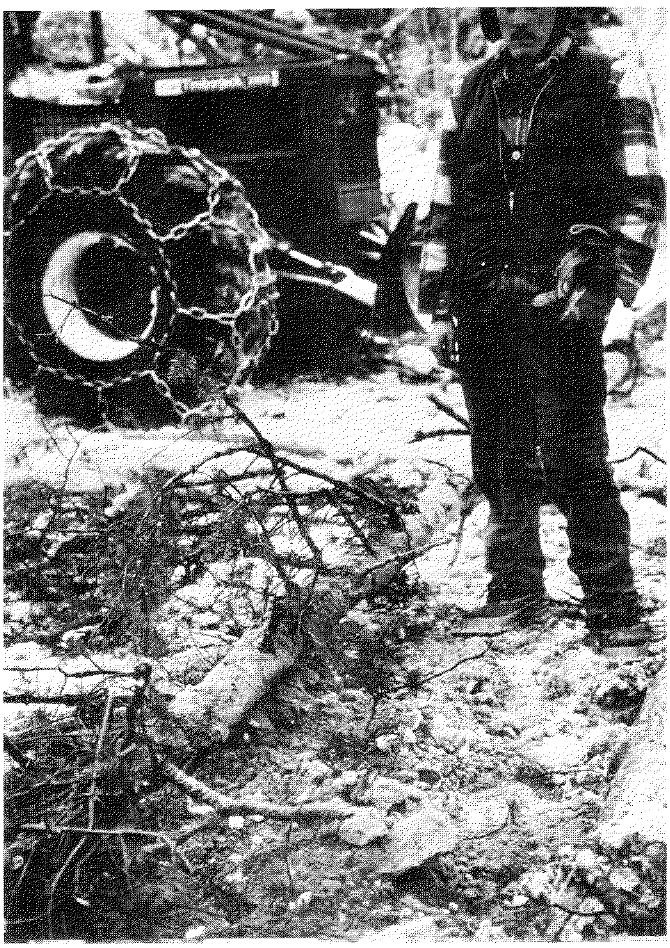


Figure 20. Note large quantity of soil on stem of tree.

Tables 9 and 10 summarize data on the merchantable volume of full trees and tree lengths carried on a trailer designed for highway use and loaded to meet the height regulations. For full trees, the average merchantable volume was 22.9 m^3 or 43.8% of that for tree-lengths so a tractor designed for tree-length hauling would be considerably under-loaded in a full tree hauling operation required to meet the highway haulage regulations. However, on private roads and with trailers designed for full tree loads of equal weight to a highway acceptable load of tree lengths; the same tractor would be suitable. The merchantable volume per truck-load of full trees would then be increased to 86.8% that of a load of tree lengths. This would reduce the hauling cost penalty for full trees provided the larger trailers could be kept to private roads where highway size restrictions do not apply.

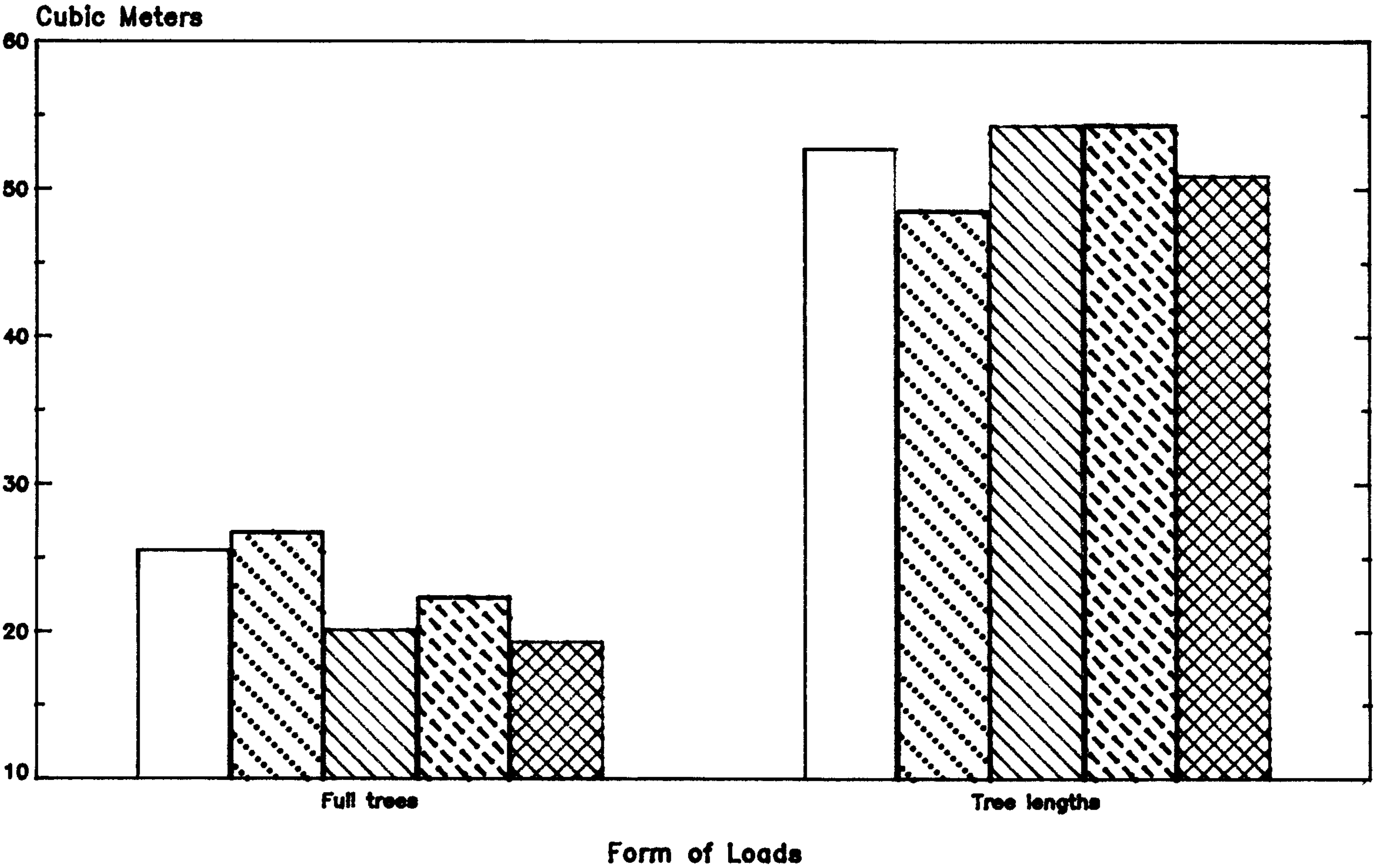


Figure 21. Merchantable volume per truckload in a conventional highway logging trailer (loads were composed of 92.9% jack pine, 4.8% black spruce and 2.3% poplar. The cross-hatching is used solely to help distinguish between columns representing different truck loads).

5.0 ECONOMIC ANALYSIS

5.1 Objectives

1) A comparison of the economic worth of a conventional tree-length harvesting operation and of an integrated full-tree operation in which full trees are shipped to a mill for conversion into conventional products (logs) and energy biomass.

2) The identification of factors to which the economic worth of the proposed integrated full-tree harvesting system is sensitive.

5.2 Overview of Analytical Methods

This project was initiated to fill a gap in knowledge regarding integrated full-tree harvesting of species other than black spruce and balsam fir. These latter species were studied in excellent reports by Lavoie (1980) and Routhier (1981).

This study has attempted to emulate the approach taken by Routhier (1981) for two reasons. The first is that the approach provided a very comprehensive look at integrated full-tree harvesting and processing. The second is the desire to make this report roughly comparable with Routhier (1981).

There are, however, some differences in approach between this study and Routhier (1981). The latter project had a significantly higher budget which permitted expensive harvesting and transportation productivity studies, whereas data used in this analysis must be inferred from less rigorous field work. This study also differs in that the analysis compares an existing harvesting system with no central processing to a proposed system with all processing functions centralized. Routhier (1981) included central processing steps in both the tree-length system and the full tree system. In this manner, his analysis identified only the economic differences attributable to the collection of residues at the central plant.

This analysis will compare the use of existing stump area or roadside processing technology with central processing. This basic difference, in part, explains the difference in rates of return on investment found in this report compared to those found in Routhier (1981). The analysis is based on a 'green fields' principle in which all of the equipment required for the two systems being compared must be purchased at the beginning of the analysis period. All costs are given in 1985 Canadian dollars unless otherwise stated in the text.

In Routhier (1981), the only process step centralized in the full-tree system which is not centralized in the tree-length system is the delimbing function. In this analysis, the return on extra investment is earned not only by the centralization of delimbing and the sale of energy biomass, but also with the centralization of the unloading, slashing and topping functions. In operations where these functions are already centralized, operating cost savings would be lower than those calculated in this analysis. Whereas Routhier (1981) tested the hauling characteristics of full-tree loads in off-road, oversized trailers, the field tests performed in this study quantified only the merchantable load size reduction in conventional trailers. The information gathered in the hauling tests is combined with data gathered from industry sources and equipment manufacturers to provide the values used in the analyses of both on-highway and off-highway hauling configurations.

5.2.1 Investment Analysis

Changing harvesting systems toward centralized processing is a traditional replacement of labour with capital. The extra capital investment required for central processing plants is expected to yield a reduction in annual costs which may come both from savings in operating expenses and from extra revenues from the sale of energy biomass produced at the plant. The analysis must, therefore, for comparative purposes, identify the net investment associated with different systems and the net annual benefits (the sum of operating cost savings and extra revenues) attributable to each harvesting system.

5.2.1.1 Capital Costs

The identification of the net investment requires that investment schedules (see Appendix 3) be prepared for each system. This table details the amount and time of investments and accrual of residual values. The data in these tables are then converted to after-tax investments using a capital cost factor (Edge 1964) determined as follows:

$$\text{Capital Cost Factor} = \frac{1 - (T \times D)}{i + D}$$

T = Taxation rate (e.g., 0.45)
D = Depreciation factor (e.g., 0.3)
i = Discount rate or rate of return (e.g., 0.15)

After-tax investments are discounted to their present values using the following method:

$$\text{Present Value of Investment} = \text{Future Value} \times \frac{1}{(i + 1)^n}$$

i = Discount rate (e.g., 0.15)
n = Period over which cost is to be discounted (in years)

5.2.1.2 Residual Value

The economic life of different kinds of capital equipment varies. The economic life of the central plant is taken to be 15 years (Hamilton 1982). This becomes the period considered in this analysis. Other equipment types have economic lives ranging from five to eight years. Since these economic lifespans do not necessarily divide into 15 years evenly, there must be some means to take into account the residual value of these capital investments at the end of the period considered. In the analysis, equipment which is not fully depreciated at the end of the analysis period is considered to have a residual value equal to its undepreciated capital (book) value. A piece of equipment purchased before the end of the period considered in the investment analysis will have a residual value calculated as follows:

Residual Value = $(1 - D)^z$ x Capital Cost.

D = Depreciation factor (for mobile machinery this is 0.30, on a declining balance basis).

z = Number of years depreciation before the end of the analysis period.

This appears as a cash inflow and is deducted from capital outlay in the final year. The residual value of equipment which has been fully depreciated is assumed to be 10% of the purchase price.

5.2.1.3. Detailed Cost Analysis

The number of machines required and the system annual operating costs were calculated with the help of a specially developed computerized cost/investment analysis package. A sample of the input data and calculated values for one piece of equipment are given in Figure 22. The input data were collected from various interviews with industry personnel, published literature, FERIC equipment evaluations and productivity studies. These data are felt to be representative of operations harvesting jack pine.

The cost analysis program generated the following data:

1) Annual Operating Costs

   a) Variable costs (volume-related)
   b) Fixed costs (not volume-related)

2) Investment Schedules

3) System Energy Biomass Production

4) System Employment by Location

Numbers one to three above are used in the investment analysis program. Number four is used in the cost analysis program to calculate some of the indirect cost components (e.g., meal costs).

5.2.1.4. Energy Biomass Selling Price Required

The annual operating costs are converted to after-tax costs and then discounted to their present value with the following formula:

Present Value of Annual Operating Costs =

$$\frac{(1 + i)^n - 1}{i\,(1 + i)^n} \times \text{Annual Operating Costs (after tax)}$$

i = Discount rate (annual)
n = Number of years

# mach & cap. $	KFF	
total volume m^3	502 330	Input
days/year	200	
shifts/day	2	
SMH/shift	8	
machine utilization	.7	
m^3/PMH	24	
capital cost/machine	600 000	
m^3/machine-year	53 760	Output
# machines required	10	
capital cost	6 000 000	
labour cost and employment		
mechanic hours/PMH	1	Input
mechanic cost/hour	40	
operator $/SMH- straight time	16	
overtime factor	8	
overtime hours/shift	0	
men/machine-shift	1	
mechanic cost/m^3	1.67	Output
mechanic employment	14	
operator $/$m^3$- straight time	.95	
operator $/$m^3$- overtime	0	
operator employment	20	
total labour $/$m^3$	2.62	
machine cost		
ownership $/machine-year	10 000	Input
parts $/PMH	26.5	
fuel & lube $/PMH	17.5	
ownership $/$m^3$	.20	Output
parts $/$m^3$	1.10	
fuel & lube $/$m^3$	.73	
total mach. $/$m^3$	2.03	
total $/$m^3$	4.65	Output Summary
operating $/year	2 335 835.52	
total employment	34	

Figure 22. Sample output of cost analysis program for Koehring feller-forwarder.

When the present values of both capital and operating costs have been calculated for the two systems being compared, they are summed for each system. The summed present values for the benchmark system are subtracted from the summed present values for the proposed system. The difference represents the net present value of the extra costs of establishing and operating the proposed system. These extra costs must be defrayed by the sale of energy biomass. The present value of the extra costs are converted into fifteen equal annual payments using the formula:

$$\text{Annual payment} = \frac{i\ (1 + i)^n}{(1 + i)^n - 1} \times \text{Present Value of extra costs}$$

i = Discount rate
n = Number of years

The equal annual payments (equivalent to the annualized present value of the incremental cost of the proposed system) are divided by the annual production of energy biomass (in oven-dry tonnes) to obtain the required after-tax break-even value of energy biomass. This after-tax value is converted to a before-tax value by dividing it by (1-Tax Rate). This is the value which must be obtained by the company selling the energy biomass in order to achieve a return on investment equal to the discount rate ("i" used in the formulas). It should be obvious that the value of energy biomass will be different for different discount rates. It is, therefore, possible to construct tables listing the required value of the energy biomass (referred to in the tables as 'required selling price') for different discount rates (rates of return on investment) and for different comparisons of benchmark and proposed systems. It is important to note that the rates of return listed in these tables are calculated after-tax and net of inflation. A rough estimate of the gross rate of return (e,g., for use in simple payback period analysis) can be obtained by adding the estimated rate of inflation over the analysis period to the after-tax rate of return and then doubling the sum to take into account the effect of taxes. These rates of return are calculated in real 1985 dollars and are retained as net income.

5.2.2. Sensitivity Analysis

The second objective of the investment analysis is to determine the factors which significantly affect the rate of return on investment in the proposed integrated full-tree harvesting system. In this analysis, the following factors were tested for their effect on economic worth of the harvesting systems compared:

1) Hauling Distance.
2) Truck Merchantable Load Size.
3) Energy Biomass Selling Price.
4) Central Processing Plant Capital Cost.
5) Central Processing Plant Machine Utilization Rate.
6) Two-Stage Hauling System Configuration.

These factors were chosen for sensitivity analysis because they were believed to be critical variables across the different operations. Hauling distance varies significantly both within an operation (with time) and for different operations. Truck merchantable load size (the quantity of solid wood which can be used for conventional products like pulpwood and sawlogs) will vary according to the kind of trailer used, the kind of road over which the load is driven (private vs. public) and the physical properties of the full trees transported. Since jack pine is not hauled commercially as full trees at the time of writing, the merchantable load size is to some degree still in question. The value of the energy biomass produced at the central plant is affected by many factors including:

a) The investment required to use energy biomass as a substitute fuel (e.g., boiler, storage facilities, handling equipment, pollution abatement equipment, etc.).

b) The local cost of alternative fuel sources (oil, gas, electricity, unutilized sawmill waste, etc.).

c) The cost of moving the energy biomass to a location where it can be used (assuming the material is to be used at some location other than the mill or that the central plant is not located at the mill).

Since central processing plants of the type assumed in this analysis have not yet been built or operated, the capital cost and machine utilization rate can only be estimated. These two parameters have, therefore, been tested for their effect on the economic worth of proposed harvesting systems.

The analysis was carried out for hauling distances varying between 40 and 140 km. Three hauling system configurations were tested. These configurations are described below:

a) On-Highway Haul - Tree lengths and full trees are hauled in conventional highway trailers. The merchantable load size for the tree-length trailers is 52.3 m^3 and for the full-tree trailers is 33.8 m^3.

b) Off-Highway Haul - Tree lengths and full trees are hauled in oversized trailers of different sizes. These trailers are limited to private roads. The merchantable load size for the tree-length trailers is 72.9 m^3 and for the full-tree trailers is 59.8 m^3 (the source of these data is found in Section 5.3.4.1).

c) Two-Stage Haul - Full trees are hauled in oversized trailers from the roadside over private roads to the central processing plant which is located at the highway's edge. The full trees are converted into shortwood at the central processing plant. This shortwood is then loaded on conventional highway-legal trailers having a merchantable load size of 52.3 m^3 and hauled over public roads to the mill. In the analysis using this hauling configuration an on-highway tree-length haul is compared with a two-stage haul using identical total hauling distances.

5.3 Overview of Systems Compared

The harvesting system most widely used in the forest industry is the tree-length system (CPPA 1984). The use of the full-tree harvesting system has been increasing in the last decade (CPPA 1971, 1984). One of the reasons for this increase in popularity has been the economic benefits of concentrating the processing at the roadside. The centralized processing concept is a logical extension of this trend. This concept was proposed as long ago as 15 years (Currie et.al. 1970) and has gained momentum in the last seven years (Kwasnitchka 1978; Lavoie 1980; Hedin 1980; Routhier 1981; Hamilton 1982; Bjerkelund 1983 and Hamilton 1985). In this analysis the tree-length harvesting system is compared with the integrated full-tree harvesting system (which includes central processing). It should be noted that the 'fully-mechanized tree-length system' is in fact a harvesting system which delivers full trees to roadside. It is termed a 'tree-length' system since the wood is hauled in tree-length form from the roadside. Two levels of mechanization of each system are considered:

a) Motor Manual (Cut-and-Skid)

b) Fully Mechanized (Koehring Feller-Forwarder)

5.3.1. System Descriptions

Each system considered is broken down into component processes using the arc and node method (see Figure 23). Each arc denotes a process step performed by a combination of machine and manpower (e.g., mechanized delimbing). Each node corresponds to a product form (e.g., tree-length), the product location (e.g., roadside) and its "status" (e.g., "Free-on-Board" or unloaded).

The first system considered is the tree-length, cut-and-skid system. Trees are felled by workers using chain saws. The trees are then manually delimbed and topped and skidded to roadside using a choker skidder. The tree lengths are loaded on standard highway logging trailers or oversized off-highway trailers at roadside using a Koehring K4-L loader. The trees are hauled to the millyard where they are unloaded by a K4-L loader. The tree lengths are slashed into eight-foot bolts using a Nesco three-man slasher.

The second system considered is the tree-length, fully-mechanized system. Trees are felled and forwarded to roadside (by a Koehring feller-forwarder) and then delimbed by a Roger delimber. The tree lengths are loaded on standard highway logging trailers or oversized off-highway trailers at roadside using a Koehring K4-L loader. The trees are hauled to the millyard where they are unloaded by a K4-L loader. The tree lengths are slashed into eight-foot bolts using a Nesco three-man slasher.

The third system considered is the full-tree cut-and-skid system. Trees are felled by workers using chain saws and skidded to roadside using a choker skidder (equipped with a larger engine than the skidder used in the tree-length operation). The full trees are then loaded either on a highway legal trailer equipped with load compaction equipment or on an oversized trailer suitable for hauling over private roads. The trees are hauled to the central processing plant where they are unloaded using a high capacity crane loader. The trees are then delimbed, topped and bucked. The residues (branches and tops) are comminuted into hogged fuel.

The fourth system considered is the full-tree fully-mechanized system. Trees are felled and forwarded to roadside using a Koehring feller-forwarder. The full trees are then loaded either on a highway legal trailer equipped with load compaction equipment or on an oversize trailer suitable for hauling over private roads . The trees are hauled to the central processing plant where they are unloaded using a high capacity crane loader. The trees are then delimbed, topped and bucked. The residues (branches and tops) are hogged.

5.3.2 Assumptions of System Parameters

The detailed cost analyses which were performed for each process arc (see Figure 23) were based on the values in Table 11. These data were used to calculate the investment schedules and operating cost estimates used in the analysis. Specific assumptions not dealt with in Table 11 are detailed below. The equipment life in years was used in the calculation of investment tables. It is felt that the economic lifespans used provide a good estimate of average industry lifespans for equipment.

5.3.3 Hours of Work

The hours of work for equipment, other than that used in the transportation phase, are normally eight-hour shifts. The cut-and-skid operations are limited to one shift per day. Other operations (e.g., delimbing, slashing, etc.) are operated for two shifts per day. The scheduling of transportation phases is examined in Section 5.3.4.4.

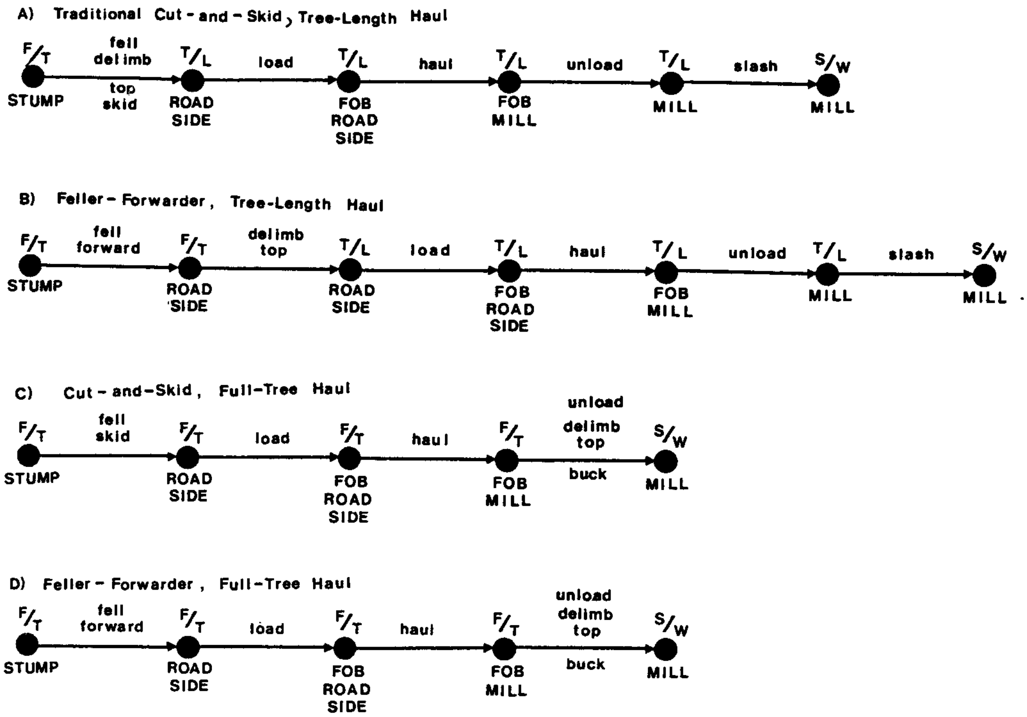


Figure 23. Graphic representations of the four harvesting systems compared in the basic economic analysis.

Table 11. Machine parameters used in detailed cost analysis

	SKIDDERS		FELLER-FORWARDER	DELIMBER	LOADER	TRUCKS ON-HIGHWAY		LOADER	SLASHER	TRUCKS OFF-HIGHWAY		LOADER
	TREE-LENGTH	FULL-TREE			TREE-LENGTH	TREE-LENGTH	FULL-TREE	FULL-TREE		TREE-LENGTH	FULL-TREE	SHORTWOOD
Capital cost ($)	70 000	78 000	600 000	220 000	500 000	154 000	182 000	500 000	330 000	195 000	215 000	500 000
Prod. life (yrs.)	6	6	7	7	8	5	5	8	7	5	5	8
SMH/year	1 600	1 600	3 200	3 200	3 200	3 550	3 660	3 200	3 200	3 550	3 660	3 200
Mach. util. (%)	80	80	70	70	55	75	75	55	65	75	75	55
Productivity (m^3/PMH)	8	8	23	26.6	120	11.2*	7.09*	90	62.4	14.8 *	11.9*	120
Mechanic hours per PMH	0.25	0.25	1.00	0.50	1.00	0.33	0.36	1.00	0.50	0.33	0.36	1.00
Repair shop rate ($/hour)	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
Parts cost ($/PMH)	8.00	8.00	26.50	14.00	22.00	10.00	11.00	22.00	22.00	10.00	11.00	22.00
fuel-lube cost ($/PMH)	3.45	3.45	17.50	6.20	17.50	15.00	15.00	17.50	10.00	22.00	22.00	17.50
Operator $/SMH (incl. 30% fringe benefits)	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00

* Based on a hauling distance of 140 km.

5.3.4 Hauling

5.3.4.1 Load Size

Section 3.3 details the results of the test of merchantable loading of tree lengths and full trees in conventional trailers. These results agree with results reported by Hamilton (1985) with similar species. The net merchantable volume in full trees actually loaded on a conventional highway trailer in this study was 22.9 m^3. This loading was achieved in a trailer loaded uni-directionally, without load compaction equipment. Loading a trailer bi-directionally and using compaction equipment, one might hope to increase the merchantable loading from 43.8% of that for tree lengths to approximately 65%, corresponding to a load size of 33.8 m^3. This load size was one of the four used in the analysis. The load size used for the tree-length on-highway hauling configuration was, as measured in this experiment, 52.3 m^3 (see Section 3.3).

The load size used for the tree-length off-highway hauling configuration was calculated using information from the forest industry, equipment suppliers and from this study. A trailer with dimensions of 3.66 m x 3.05 m x 14.33 m (12' x 10' x 47') holds approximately 71 m^3 of merchantable black spruce (25 cunits). The size of the load of tree lengths is limited by the tire specifications. Using wood density and bark percentages from Alemdag (1983), we can calculate the density of black spruce tree lengths to be approximately 794 kg per merchantable cubic meter. A 71 m^3 load, therefore, weighs approximately 56 374 kg. Assuming a density of 773.2 kg per merchantable cubic meter for jack pine tree lengths (from this study), we can calculate the merchantable volume of jack pine to be 72.9 m^3 per truck load.

The off-highway load size for the full-tree system was calculated using information from the forest industry, from equipment suppliers and from this study. A trailer with dimensions of 4.26 m x 3.66 m x 14.33 m (14' x 12' x 47') has an available gross volume of 223 m^3. Using a bulk density for full trees of 0.268 m^3 of merchantable wood per m^3 of gross volume (calculated from the volume of full trees loaded on the conventional highway-legal trailer used in this experiment), we can calculate the merchantable volume per truck load to be 59.8 m^3. It should be noted that the bulk density developed for the highway-legal trailer is likely to underestimate slightly the bulk density of the oversized trailers since greater compaction is likely to occur in the taller trailer. This merchantable load size is well within the weight specifications of the tires used on the trailers. The bulk density used above assumes no mechanical load compaction.

5.3.4.2 Cost of Special Trailer

A logging trailer equipped with load compaction equipment has been designed and costed by Hamilton (1985). This kind of trailer is used in the first phase of the analysis. Based on information given in Hamilton (1985) and on discussion with Mr. D.D. Hamilton of Logging Development Corporation, the cost of this trailer plus an appropriate tractor unit, in current dollars, would not be expected to exceed \$182 000. Conventional tree-length hauling equipment was costed at approximately \$154 000 by hauling equipment dealers. The load compaction equipment installed on the trailer described above could expect to have slightly higher operating costs owing to the addition of hydraulic equipment. This is reflected in the higher number of mechanic hours and parts cost per productive machine hour shown in Table 11. The off-highway tree-length hauling rig was costed at $195 000 and the the full-tree off-highway rig was costed at $215 000 by trucking equipment suppliers specializing in off-highway hauling equipment. According to industry sources, the large off-highway trailers can be used on roads designed for conventional highway rigs with no requirement for additional investment in road construction.

5.3.4.3 Travel Speeds

In this study the average travel speed while hauling was varied according to the distance travelled. The speeds and distances were assumed as follows:

Distance	Travel Speed
40-60 km	50 km/hour
80-100 km	60 km/hour
120-140 km	70 km/hour

The average travel speed is controlled by the weighted average speed over the various classes of road to be travelled. It is likely that as hauling distance increases, the proportion of the trip travelled over the lower quality roads will decrease. This will lead to higher average travel speeds on the longer hauls. The values given above were created to reflect this effect. It should also be noted that these speeds are representative of the flat terrain in which jack pine is normally found. Where topography is unfavourable (e.g., steep adverse slopes), these speeds could not be sustained.

5.3.4.4 Scheduling of Hauling

Each hauling distance considered required a recalculation of hauling costs, indirect costs and investment. Each hauling distance was associated with its own combinational shift length and number of loads per shift. These data are summarized in Table 12.

Table 12: Scheduling intensity of full-tree and tree-length hauling operations

HAULING DISTANCE (km)	LOADS PER SHIFT	SHIFTS PER DAY	SHIFT LENGTH (hours)			
			OFF-HIGHWAY		ON-HIGHWAY	
			TREE-LENGTH	FULL-TREE	TREE-LENGTH	FULL-TREE
40	3	2	10.12	10.52	9.04	9.48
60	2	2	8.88	8.45	8.16	8.45
80	2	2	9.59	9.86	8.87	9.16
100	2	2	11.37	11.64	10.65	10.94
120	2	2	11.62	11.89	10.90	11.20
140	1.5	2	9.86	10.06	9.32	9.54

5.3.5 Central Processing Plant

The central processing plant design used in this analysis was developed by Mr. D.D. Hamilton of Logging Development Corporation. The designs for a variety of similar central processing plants were introduced in Routhier (1981) and presented in greater detail in Hamilton (1982). This analysis uses the delimbing/slashing central processing plant design presented in Routhier (1981). The capital and operating costs used in this study are identical to those used in Routhier (1981) but have been inflated to represent current (1985) dollars. Capital costs of plant equipment were inflated with the wood products sub-group of the Machinery and Equipment Price Index group and the wood handling equipment used in the plant was inflated using the forestry sub-group (Statistics Canada 1985a). The operating costs have been inflated using the Consumer Price Index (Statistics Canada 1985b). Capital and operating costs are listed in Table 13 along with other operating data required to perform this study. Figure 24 shows the basic layout of the plant used in this analysis. It is assumed, for the purpose of this analysis, that the central processing plant is located at the mill. The only exception to this is the analysis of the two-stage haul (see Section 5.5.6) in which the central processing plant is located at the highway's edge.

Table 13: Operating data for central processing plant at mill site. (Adapted from Routhier 1981)

Annual production of merchantable wood = 502 330 m^3 for conventional products (logs).

Days of operation per year = 240

Shifts per day = 2 @ 8 hours/shift

Machine utilization rate = 85%

Productivity = 153.9 m^3/PMH

Employment:

plant operation = 9 workers/shift x 2 shifts/day = 18.
plant maintenance = 3 workers per two shifts.

Capital costs:

wood handling = $319 500 (equipment life = 8 years)
processing plant = $5 949 000 (equipment life = 15 years)

Operating costs:

wood handling = $134 160/year
plant operation = $1 385 770/year

Annual residue production:

wood harvested by cut-and-skid method = 28 446 o.d.t/year
wood harvested by fully mechanized method = 26 567 o.d.t/year

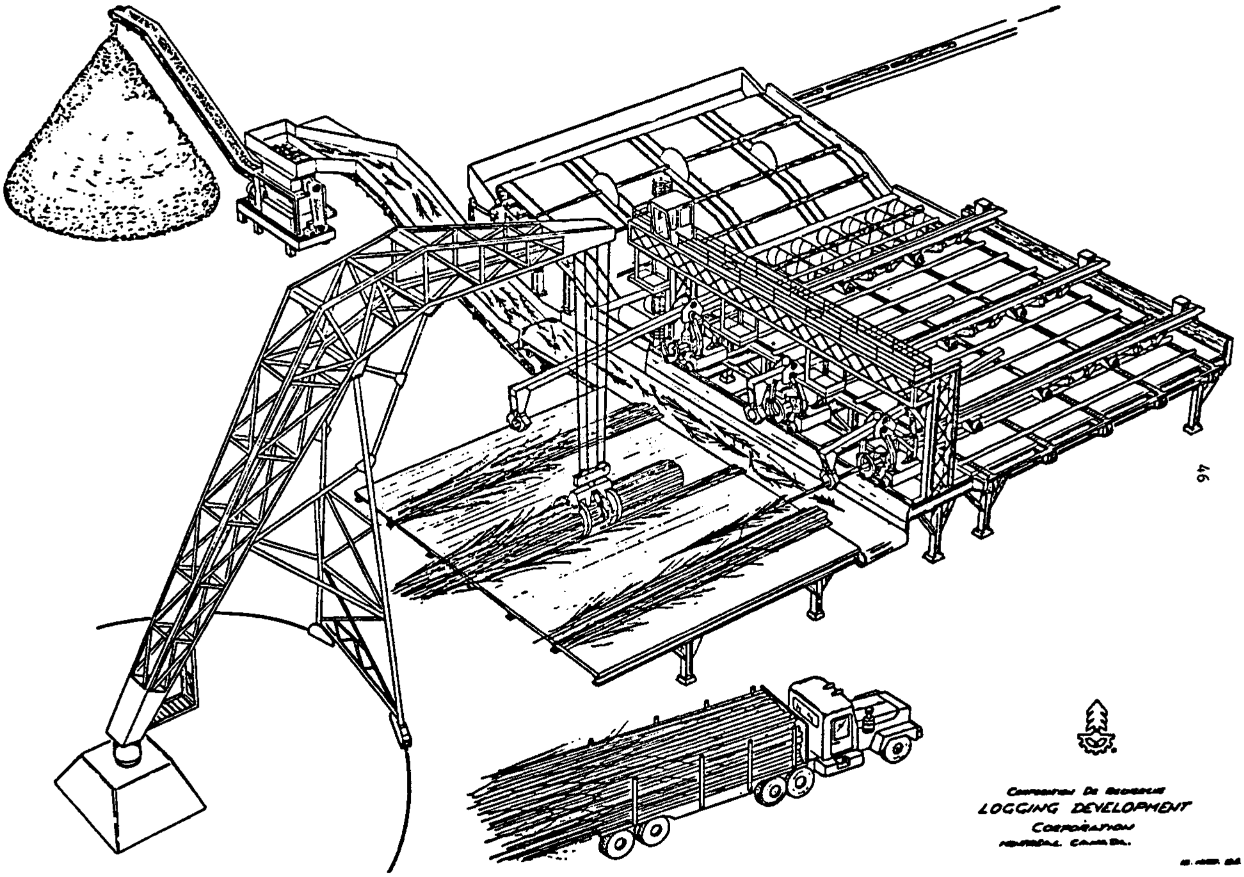


Figure 24. General layout of the central processing plant (Hamilton 1982).

5.3.5.1 Calculation of Annual Residue Production

The calculation of annual residue production assumes that 58.3% (7 of 12 months) of the wood is cut in unfrozen conditions and 41.7% (5 of 12 months) is cut in frozen conditions. The quantity (kg/m^3 mechantable wood) of energy biomass available at the stump is known for both frozen and unfrozen conditions. The weighted average biomass available at the stump may be calculated as follows for the cut-and-skid system:

$(0.583 \times 106.5) + (0.417 \times 84.5) = 97.3$ o.d.kg/m^3

(see Table 3 and 4 for the data used above) A similar calculation for the fully-mechanized system yields a result of 99.6 o.d.kg/m^3. Tables 7 and 8 list the data used in this calculation.

The annual production of energy biomass can be calculated by multiplying the weighted average annual biomass available at the stump (calculated above) by the annual production of merchantable wood and then by the weighted average annual recovery factor. The weighted average annual recovery factors for the two full-tree harvesting systems are as follows (from Tables 3, 4, 7 and 8):

Cut-and-Skid = 72.8%
Fully-Mechanized = 53.1%

The cut-and-skid energy biomass recovery factor for the winter phase is believed to be an overestimate since the the cut-and-skid phase of the winter field tests was performed in unseasonably high temperatures. The cut-and-skid estimates in both seasons may be overestimated because the wood was not subjected to piling with a skidder blade at the roadside nor were the piles run over while piles were being built, procedures which may cause considerable breakage. The cut-and-skid energy biomass recovery factor was, therefore, adjusted downward from 72.8% to 58.2% (20% reduction) to reflect these considerations.

The average annual energy biomass yield was, therefore, calculated as follows:

Cut-and-Skid:

$$\frac{502\ 330\ \text{m}^3/\text{year} \times 97.3\ \text{o.d.kg/m}^3\ \text{merch.} \times 0.582}{1\ 000\ \text{o.d.kg/odt}} = 28\ 446\ \text{o.d.t/year}$$

Fully-Mechanized:

$$\frac{502\ 330\ \text{m}^3/\text{year} \times 99.6\ \text{o.d.kg/m}^3\ \text{merch.} \times 0.531}{1\ 000\ \text{o.d.kg/odt}} = 26\ 657\ \text{o.d.t/year}$$

5.3.5.2 Annual Production of Wood Merchantable for Conventional Products

The central processing plant design introduced in Routhier (1981) varied in estimated annual production between 241,800 m^3 and 316,200 m^3 depending entirely on average tree volume. The plant has a fixed production in terms of numbers of stems which is estimated at 1,860,000 per year with production parameters as listed in Table 13 . It was felt, in discussions with Mr. D.D. Hamilton, that this number of stems could be sustained in larger timber. The average tree size in this study was approximately 0.27 m^3. The annual production of 502,330 m^3 used in this study was arrived at by multiplying the number of stems (1,860,000/year) by the average volume per tree (0.27 m^3).

5.3.6 Indirect Costs

The indirect costs used in this analysis are consistent with Routhier (1981). The costs have been converted into current costs using the Consumer Price Index. Table 14 lists the categories of indirect costs considered. Scaling costs, camp heat and electricity costs and camp maintenance costs vary only with the degree of mechanization of the woodlands operations. There are eight levels of meal costs. Each combination of harvesting system and hauling configuration has a separate meal cost component. The indirect cost data for the two-phase haul is not shown since this hauling configuration is not part of the basic analysis. Truck operators hauling from the roadside eat their lunch meal in the camp. Truck operators hauling the shortwood in the second phase of the two-stage haul do not eat their lunch in the camp.

Table 14. Indirect costs for the eight systems tested* (1985$). Hauling distance = 140 km

INDIRECT COSTS ($/year)	ON-HIGHWAY HAUL				OFF-HIGHWAY HAUL			
	TREE LENGTH		FULL TREE		TREE LENGTH		FULL TREE	
	CUT-AND-SKID	FULLY MECHANIZED	CUT-AND-SKID	FULLY MECHANIZED	CUT-AND-SKID	FULLY MECHANIZED	CUT-AND-SKID	FULLY MECHANIZED
SCALING	201,888	151,416	201,888	151,416	201,888	151,416	201,888	151,416
CAMP MAINTENANCE	117,768	84,120	117,768	84,120	117,768	84,120	117,767	84,120
CAMP HEAT AND POWER	134,592	105,150	134,592	105,150	134,592	105,150	134,592	105,150
MEALS	376,614	166,698	294,980	138,572	368,382	158,466	277,144	120,736
TOTAL	830,862	507,384	749,228	479,258	822,630	499,152	731,392	461,422
INDIRECT COST/M^3	1.65	1.01	1.49	0.95	1.64	0.99	1.46	0.92

5.4 ECONOMIC ANALYSIS - Results

The method of presentation of results in this analysis is consistent with that of Routhier (1981). Tables 15 to 20 summarize the results of the economic analyses. Each table is a list of the energy biomass price which must be obtained in order to have the extra investments made in changing from a tree-length system to a full-tree system earn the rates of return on investment indicated on the vertical axis. The prices which must be obtained to justify a change from the tree-length cut-and-skid system to either the full-tree cut-and-skid system or the fully-mechanized system are listed. The prices which must be obtained to justify a change from the tree-length fully-mechanized system to the full-tree fully-mechanized system are also summarized. In both cases, the selling prices required are listed for both on-highway and off-highway hauling configurations. Each individual table is calculated for a different hauling distance. The required selling prices for the change from a fully-mechanized tree-length system to a full tree cut-and-skid system were not calculated since it is highly unlikely that a company would choose to move in this direction.

Negative values in the tables indicate that the proposed system change can be justified without receiving any value from the sale of energy biomass at the rate of return indicated. In Table 15, for a hauling distance of 40 km, if an after-tax return on incremental investment of 12% is required, the change from the tree-length cut-and-skid system to the full-tree cut-and-skid system would require revenues of $30.23 per oven-dry tonne of energy biomass in the on-highway hauling configuration. Only $5.75 per oven-dry tonne is required in the off-highway configuration to earn the same 12% return on investment. The difference between these two prices, $24.48 per oven-dry tonne of energy biomass, is the additional value per tonne of energy biomass which must be earned to offset the higher capital costs (a smaller load per truck implies the need for more trucks to move equal volumes) and higher operating costs (labour costs are divided by a smaller volume production) of the system hauling smaller loads on highways.

From Table 15, it can also be noted that, in the case of the change from the fully-mechanized tree-length system to the full-tree fully-mechanized system (on-highway hauling configuration), the energy biomass selling price required is negative for rates of return of 4%, 6% and 8% and positive for the higher rates of return on investment. This implies that the operating cost savings generated by investment in the full-tree system will yield up to 8% (or slightly more) return on investment even if the energy biomass has no value. In the case of this same system change, but for the off-highway hauling configuration, all of the values of selling price required are negative. This implies that the return on investment earned by operating cost savings is in excess of 12%. In the row labeled "IRR at $0/o.d.t" in this table the rate of return earned from operating cost savings alone is listed. Where the IRR value would be negative (i.e., where a positive selling price is required) no number is listed in this category.

Table 15. Required selling prices of energy biomass ($/o.d.t) at various rates of return on extra investment. Hauling distance = 40 km

BENCHMARK HARVESTING SYSTEM - TREE-LENGTH	IRR	PROPOSED HARVESTING SYSTEM - FULL TREE			
		OFF-HIGHWAY HAUL		ON-HIGHWAY HAUL	
		cut-and-skid method	fully-mechanized method	cut-and-skid method	fully-mechanized method
CUT-AND-SKID	.04	-11.20	-56.76	11.82	-32.11
CUT-AND-SKID	.06	-7.35	-52.06	16.02	-27.03
CUT-AND-SKID	.08	-3.23	-46.95	20.51	-21.53
CUT-AND-SKID	.10	1.15	-41.43	25.25	-15.63
CUT-AND-SKID	.12	5.75	-35.54	30.23	-9.33
CUT-AND-SKID	IRR at $0/o.d.t	0.09	0.22	-----	0.15
FULLY-MECHANIZED	.04		-31.06		-6.42
FULLY-MECHANIZED	.06		-28.48		-3.45
FULLY-MECHANIZED	.08		-25.68		-0.26
FULLY-MECHANIZED	.10		-22.69		3.12
FULLY-MECHANIZED	.12		-19.54		6.67
FULLY-MECHANIZED	IRR at $0/o.d.t		0.23		0.08

Table 16. Required selling prices of energy biomass ($/o.d.t) at various rates of return on extra investment. Hauling distance = 60 km

BENCHMARK HARVESTING SYSTEM - TREE-LENGTH	IRR	PROPOSED HARVESTING SYSTEM - FULL TREE			
		OFF-HIGHWAY HAUL		ON-HIGHWAY HAUL	
		cut-and-skid method	fully-mechanized method	cut-and-skid method	fully-mechanized method
CUT-AND-SKID	.04	-7.44	-52.73	25.63	-17.32
CUT-AND-SKID	.06	-3.54	-47.98	30.23	-11.82
CUT-AND-SKID	.08	0.63	-42.81	35.12	-5.89
CUT-AND-SKID	.10	5.06	-37.25	40.27	0.45
CUT-AND-SKID	.12	9.71	-31.29	45.66	7.19
CUT-AND-SKID	IRR at $0/o.d.t	0.08	0.21	-----	0.10
FULLY-MECHANIZED	.04		-27.04		8.37
FULLY-MECHANIZED	.06		-24.40		11.76
FULLY-MECHANIZED	.08		-21.54		15.38
FULLY-MECHANIZED	.10		-18.50		19.20
FULLY-MECHANIZED	.12		-15.29		23.19
FULLY-MECHANIZED	IRR at $0/o.d.t		0.21		-----

Table 17. Required selling prices of energy biomass ($/o.d.t) at various rates of return on extra investment. Hauling distance = 80 km

		PROPOSED HARVESTING SYSTEM - FULL TREE			
		OFF-HIGHWAY HAUL		ON-HIGHWAY HAUL	
BENCHMARK HARVESTING SYSTEM - TREE-LENGTH	IRR	cut-and-skid method	fully-mechanized method	cut-and-skid method	fully-mechanized method
CUT-AND-SKID	.04	-6.17	-51.37	29.40	-13.29
	.06	-2.27	-46.62	34.00	-7.79
	.08	1.90	-41.46	38.88	-1.86
	.10	6.32	-35.89	44.03	4.48
	.12	10.98	-29.94	49.42	11.23
	IRR at $0/o.d.t	0.07	0.21	-----	0.09
FULLY-MECHANIZED	.04		-25.68		12.41
	.06		-23.04		15.79
	.08		-20.19		19.41
	.10		-17.14		23.23
	.12		-13.94		27.23
	IRR at $0/o.d.t		0.20		-----

Table 18. Required selling prices of energy biomass ($/o.d.t) at various rates of return on extra investment. Hauling distance = 100 km

		PROPOSED HARVESTING SYSTEM - FULL TREE			
		OFF-HIGHWAY HAUL		ON-HIGHWAY HAUL	
BENCHMARK HARVESTING SYSTEM - TREE-LENGTH	IRR	cut-and-skid method	fully-mechanized method	cut-and-skid method	fully-mechanized method
CUT-AND-SKID	.04	-3.01	-47.99	38.82	-3.21
	.06	0.89	-43.24	43.41	2.29
	.08	5.06	-38.07	48.30	8.22
	.10	9.49	-32.50	53.45	14.56
	.12	14.14	-26.55	58.84	21.31
	IRR at $0/o.d.t	0.06	0.20	-----	0.05
FULLY-MECHANIZED	.04		-22.29		22.49
	.06		-19.66		25.87
	.08		-16.80		29.49
	.10		-13.75		33.31
	.12		-10.55		37.31
	IRR at $0/o.d.t		0.19		-----

Table 19. Required selling prices of energy biomass ($/o.d.t) at various rates of return on extra investment. Hauling distance = 120 km

			PROPOSED HARVESTING SYSTEM - FULL TREE			
			OFF-HIGHWAY HAUL		ON-HIGHWAY HAUL	
			cut-and-skid method	fully-mechanized method	cut-and-skid method	fully-mechanized method
BENCHMARK HARVESTING SYSTEM - TREE-LENGTH	CUT-AND-SKID	IRR				
		.04	-2.55	-47.50	40.16	-1.77
		.06	1.34	-42.75	44.76	3.73
		.08	5.52	-37.59	49.64	9.66
		.10	9.94	-32.02	54.79	16.00
		.12	14.59	-26.07	60.18	22.75
		IRR at $0/o.d.t	0.05	0.20	-----	0.05
	FULLY-MECHANIZED	IRR				
		.04		-21.81		23.93
		.06		-19.17		27.31
		.08		-16.32		30.93
		.10		-13.27		34.75
		.12		-10.07		38.75
		IRR at $0/o.d.t		0.18		-----

Table 20. Required selling prices of energy biomass ($/o.d.t) at various rates of return on extra investment. Hauling distance = 140 km

			PROPOSED HARVESTING SYSTEM - FULL TREE			
			OFF-HIGHWAY HAUL		ON-HIGHWAY HAUL	
			cut-and-skid method	fully-mechanized method	cut-and-skid method	fully-mechanized method
BENCHMARK HARVESTING SYSTEM - TREE-LENGTH	CUT-AND-SKID	IRR				
		.04	2.15	-42.47	50.72	9.54
		.06	6.27	-37.48	55.71	15.46
		.08	10.67	-32.06	61.00	21.82
		.10	15.34	-26.24	66.56	28.60
		.12	20.23	-20.03	72.36	35.79
		IRR at $0/o.d.t	0.03	0.18	-----	0.00
	FULLY-MECHANIZED	IRR				
		.04		-16.78		35.23
		.06		-13.90		39.04
		.08		-10.79		43.09
		.10		-7.49		47.35
		.12		-4.03		51.79
		IRR at $0/o.d.t		0.14		-----

Observing the change in the values recorded in the IRR rows in each table as hauling distances vary can indicate the effect of distance on rates of return. The effect of hauling distance on after-tax rates of return is demonstrated in Figure 25. The upper curve represents the change in IRR value with changes in hauling distance for the conversion from the tree-length cut-and-skid system to the fully-mechanized full-tree system in the off-highway hauling configuration. The lower curve represents the same relationship for the on-highway hauling configuration. Figure 26 shows the rates of return earned by changes from both tree-length systems to the fully-mechanized full-tree system for the off-highway hauling configuration with hauling distances varying from 40 to 140 km. The comparison of the labour-intensive cut-and-skid system with the capital-intensive fully-mechanized full-tree system yields a higher rate of return than the comparison with the fully-mechanized tree-length system at most hauling distances. This figure assumes a zero value for residues.

Figure 27 shows the relationship between unit hauling costs and hauling distance for the five hauling scenarios considered. The "lumpy" appearance of the curves is caused by the changes in hauling speed, which were not continuous, and by the variation in the scheduling of operations, which is not continuous because of the nature of union pay schedules, etc.

Figure 28 shows the harvesting and processing costs for the tree-length and full-tree systems. These costs do not include hauling costs. It should be noted that these costs do include indirect costs such as scaling and camp maintenance.

5.5 ECONOMIC ANALYSIS - Discussion

This discussion of the results of the economic analysis is presented as follows: the sensitivity of the economic benefits to variations in hauling distance, truck load size, energy biomass selling price, central processing plant capital costs, central processing plant machine utilization and to the substitution of a two-stage hauling configuration. The overall results of the economic analysis and the limitations imposed by the assumptions made in this study on the value of the results are discussed.

5.5.1 Sensitivity to Hauling Distance

The degree to which the economic worth of proposed harvesting systems is sensitive to changes in hauling distances varies with the assumptions used in each scenario. From Figure 25 it can be seen that, as hauling distance increases from 40 to 140 km, the rates of return earned on new capital investment decrease in both of the scenarios considered.

It is also evident from Figure 25 that load size affects the degree to which returns are affected by hauling distance. The curve for the off-highway hauling configuration shows a decrease in the rate of return from 0.22 at 40 km to 0.18 at 140 km. The curve for the on-highway hauling configuration shows a decrease from 0.15 at 40 km to 0.00 at 140 km. These represent decreases in the rate of return of 18 and 100% respectively. This marked difference is caused by the rapid increase in hauling costs with distance for the on-highway hauling configuration (see Figure 27) and by the extra investment required to move the wood in smaller trailers.

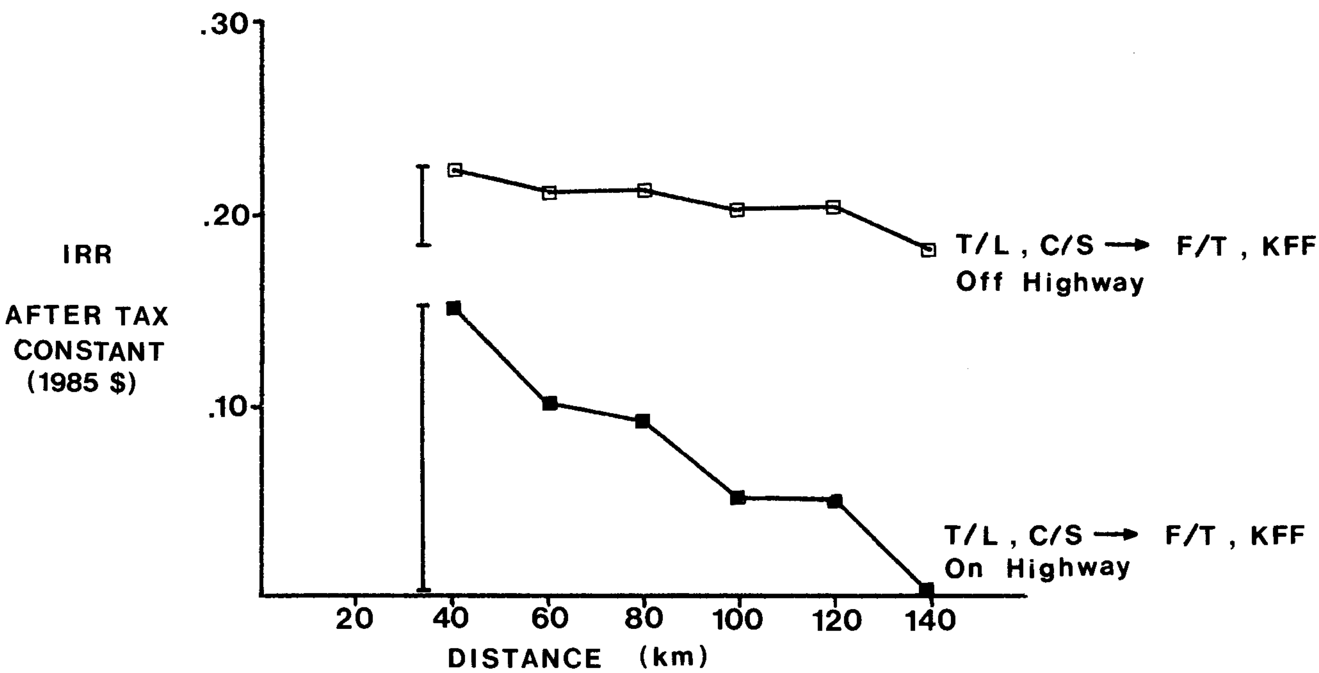


Figure 25. Rates of return for two hauling configurations at various hauling distances.

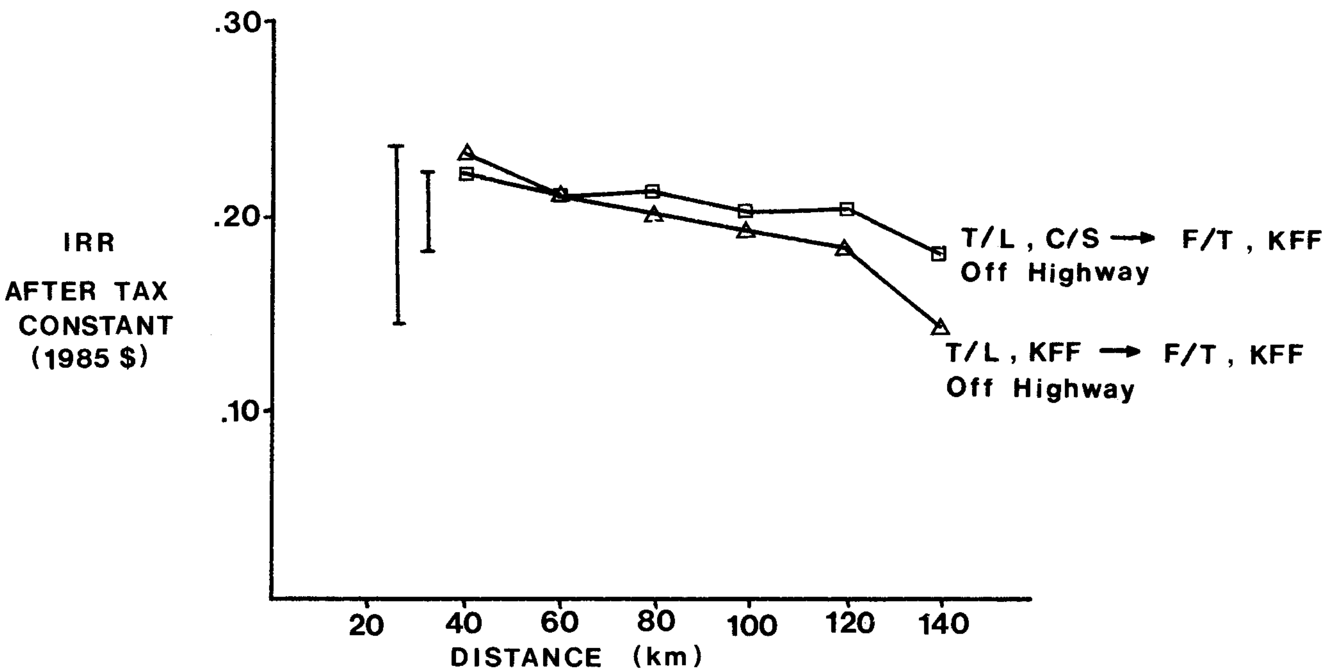


Figure 26. Rates of return for two harvesting system comparisons (same hauling configuration) at various hauling distances.

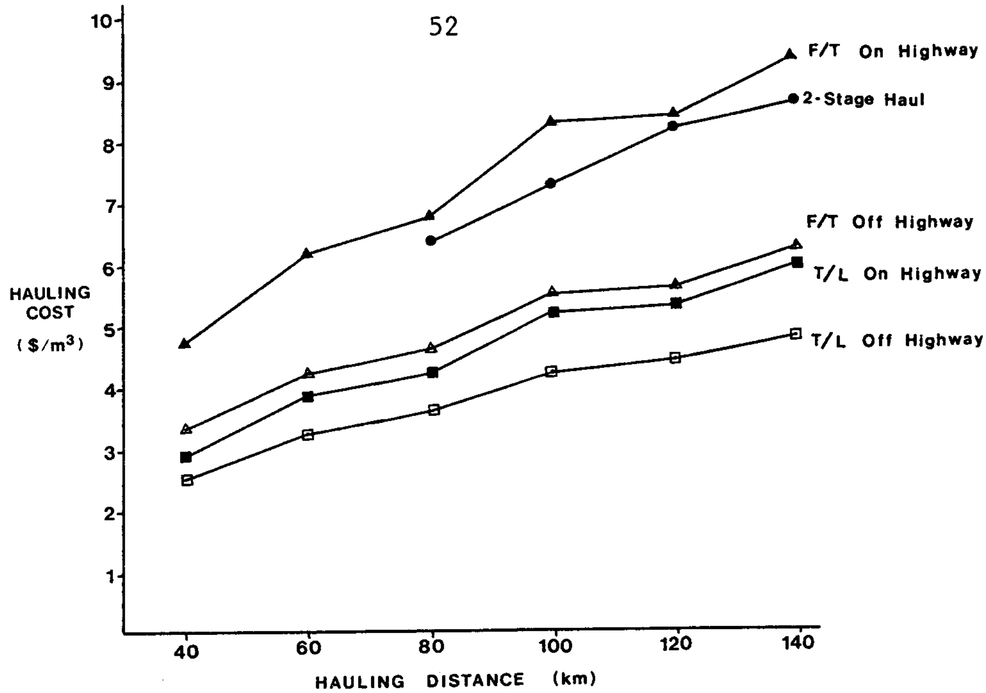


Figure 27. Hauling costs versus hauling distance (costs not including depreciation).

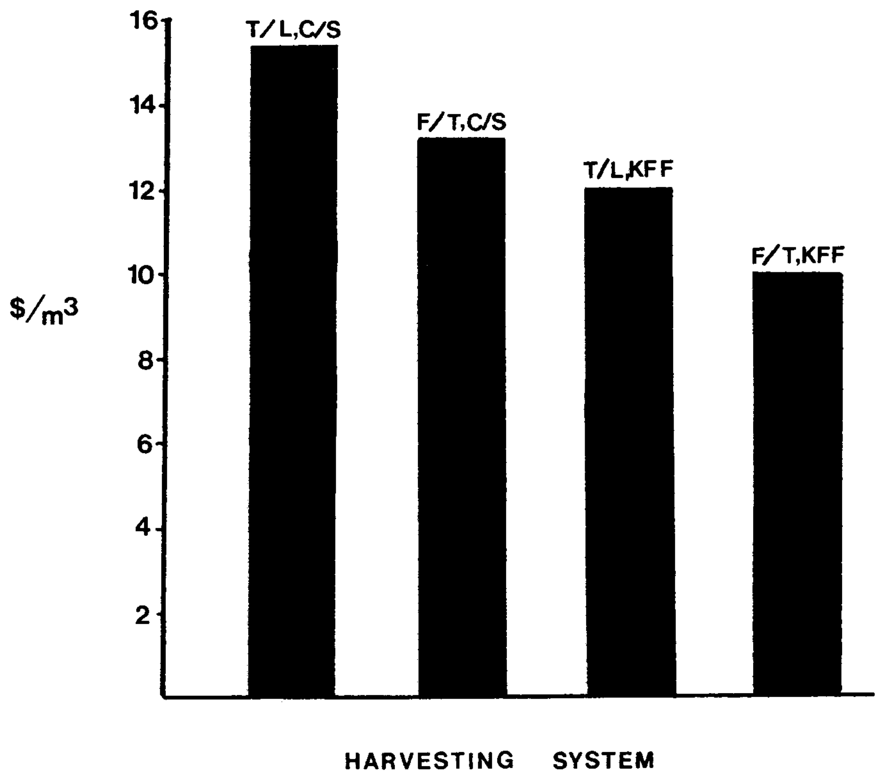


Figure 28. Harvesting and processing costs for the four systems considered in the basic economic analysis (costs not including depreciation). These harvesting costs must be added to the appropriate hauling cost (from Figure 27) to determine the total cost (not including depreciation).

The upper curve in Figure 26 shows a decrease in rate of return from 0.22 at 40 km to 0.18 at 140 km. The lower curve shows a decrease from 0.23 at 40 km to 0.14 at 140 km. These represent reductions in the rate of return of 18 and 39% respectively. This difference in sensitivity to hauling distance is attributed to the greater operating cost savings obtained when comparing a tree-length cut-and-skid harvesting system to a fully-mechanized full-tree harvesting system rather than to a full-tree cut-and-skid system. The principal trade-off affecting centralized full-tree processing and harvesting is the increased unit hauling costs versus the decreased unit processing costs and the extra revenues earned from the use or sale of energy biomass. As operating cost savings increase, changes in unit hauling costs become comparatively less significant.

5.5.2 Sensitivity to Load Size

The rate of return on the incremental investment required for proposed harvesting systems can clearly be seen to be sensitive to load size in Figure 25. The return on investment for the same harvesting system comparison in two different hauling configurations is shown in Figure 25. The rate of return for the upper curve ranges between 0.22 at 40 km and 0.18 at 140 km, a difference of 0.04. The rate of return in the lower curve ranges between 0.15 at 40 km and 0.00 at 140 km, a difference of 0.15. The vertical distance between the curves ranges between 0.07 at 40 km and 0.18 at 140 km. The vertical distance between the two curves is the change in rate of return attributable to the different load sizes used in the off-highway versus on-highway hauling scenarios. The difference in rate of return is more than twice as large at 140 km as at 40 km. Two observations may be drawn from this discussion: firstly that the rate of return is sensitive to load size and secondly that the effect of load size on rate of return increases with increasing hauling distance.

Figure 29 shows the relationship between rate of return on extra investment and required selling price for energy biomass. The six curves represent this relationship for the change from the tree-length cut-and-skid and fully-mechanized systems to their full tree equivalents, in both off-highway and on-highway hauling configurations. As an example of the sensitivity to load size, we may look at the two curves for the change from the tree-length fully-mechanized system to its full-tree equivalent. It should be noted that the two curves differ mainly in load size. If we wish to maintain a rate of return of 0.08 in both cases, the difference in selling price required is $53.88 per oven-dry tonne of energy biomass (43.09-[-10.79]). In the case of the off-highway hauling configuration, the incremental investment will yield a return of 0.12 even if the cost of disposal of the energy biomass is $4.03 per oven-dry tonne. In the on-highway hauling configuration the energy biomass must fetch a price of $51.79 per oven-dry tonne to earn a 0.12 return on incremental investment (see Table 22 for these values).

5.5.3 Sensitivity to Energy Biomass Selling Price

It is clear from Figure 29 that energy biomass selling price will significantly affect return on incremental investment. The same information is shown in tabular form in Table 20. The slope of the curves indicates that for each change of $10 per oven-dry tonne of biomass, the rate of return will change by approximately 0.04. In Figure 30, the rates of return earned when biomass is valued between $0.00 and $50.00/o.d.t for three system comparisons are plotted. The curves in Figure 30 also indicate that rates of return change between 0.02 and 0.06 for each $10/o.d.t change in biomass value, depending on the assumptions used in each scenario. It is important to note that several of the system comparisons yield returns on investment in excess of 12% with energy biomass values set at zero. This implies that the decision to change harvesting systems may be less dependent on energy biomass prices than has been previously thought.

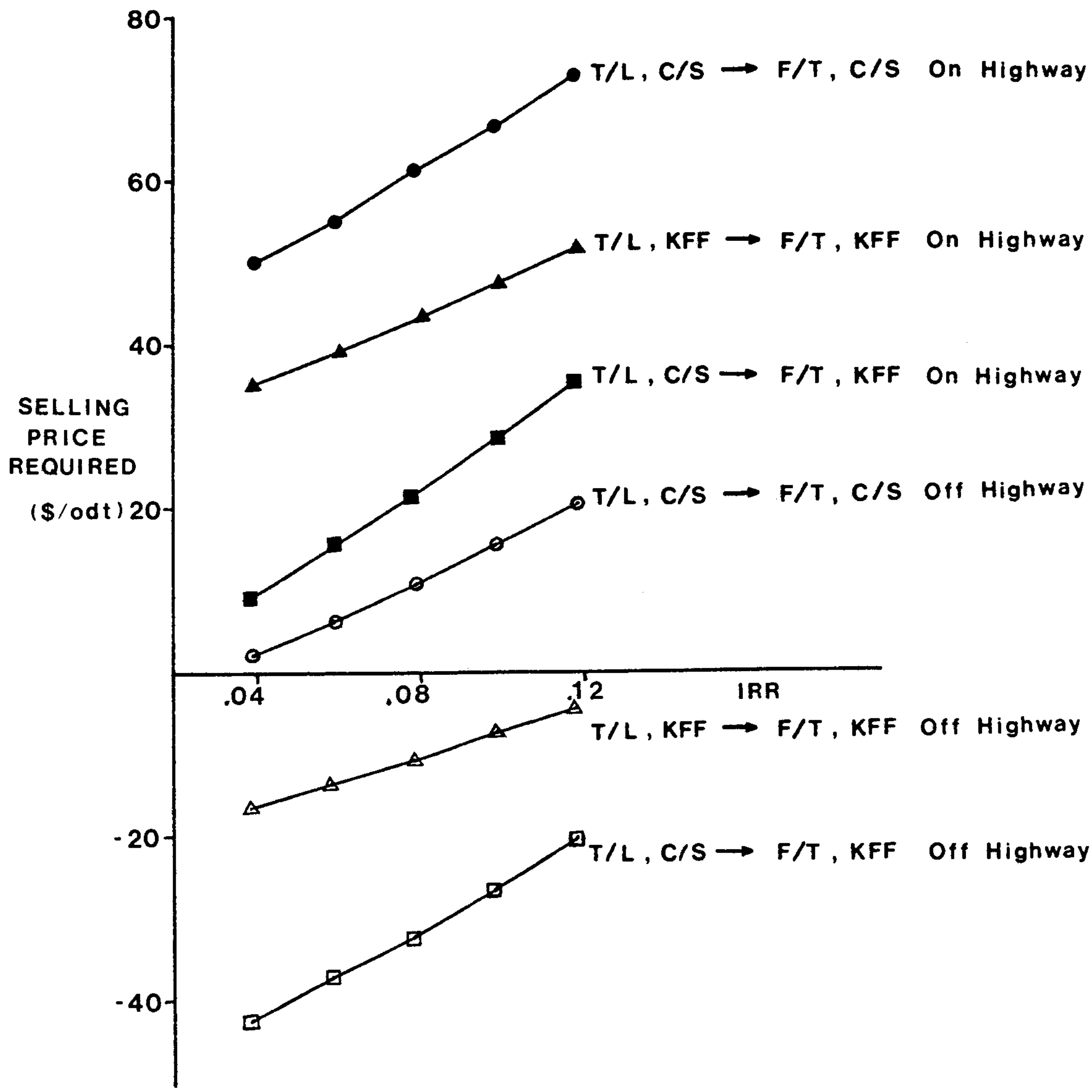


Figure 29. Energy biomass selling price versus return on investment for various harvesting system comparisons (hauling distance = 140 km).

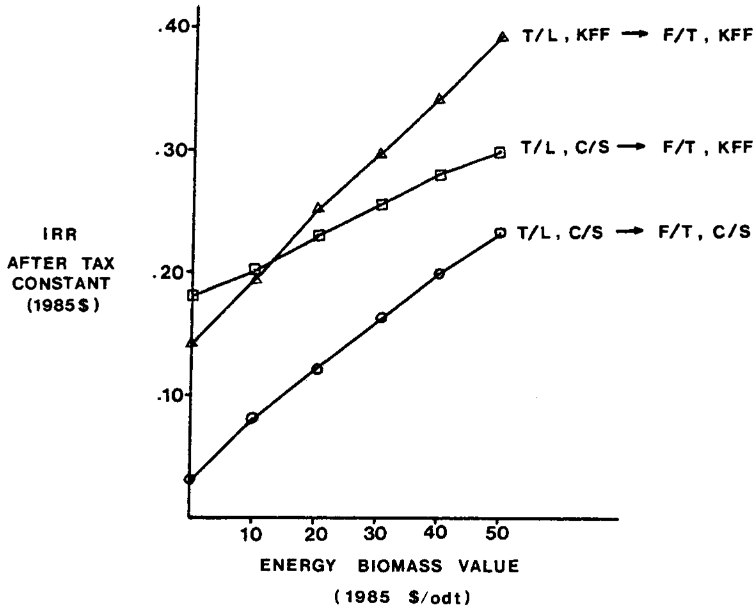


Figure 30. Rate of return versus energy biomass value. Hauling distance = 140 km. All scenarios considered above include off-highway hauling.

It is not unreasonable to expect energy biomass values of at least $0.00-$20.00/o.d.t. Routhier (1981) assumed a value of 1981 $44.00/o.d.t, including a 1981 $10.00 allowance for the depreciation of extra capital investment in burning facilities. Stone (1984) described a process for the conversion of cellulosic wastes into fuel ethanol for use as a gasoline octane enhancer and extender or as an industrial chemical. It would be economical, at $0.35 per liter of ethanol (a conservative price), to pay between $0.00 and $20.00 per tonne of energy biomass to be used as an ethanol production feedstock. This energy biomass value would allow four of the six main scenarios to earn rates of return in excess of 0.08 (after-tax and net of inflation) or three of six to earn rates of return of at least 0.12 (see Figure 29).

Routhier (1981) reported much higher required selling prices of energy biomass than are reported in this study. The difference in results is due largely to the use of a central processing plant in both the tree-length and full-tree systems in Routhier (1981). This study uses a central processing plant only in the full-tree system. Another factor causing the difference in rates of return is the higher productivity assumed for the central processing plant when the feedstock is jack pine (owing to the larger average tree size).

5.5.4 Sensitivity to Central Processing Plant Capital Costs

Table 21 summarizes the prices required per tonne of energy biomass to earn the rates of return on incremental investment in the proposed harvesting system configuration where the capital cost of the central processing plant has been increased by 10%. The proposed systems are limited to those involving the off-highway hauling configuration. This limitation is imposed to simplify the analysis and because the higher rates of return earned by the off-highway systems make them more likely to be interesting to the forest industry. Table 21 should be compared with Table 20. The comparison of the tree-length cut-and-skid system with its full-tree equivalent in Table 20 indicates that the energy biomass price required to earn a rate of return of 0.12 is $20.23/o.d.t. When the cost of the central processing plant is increased by 10% (see Table 21), the required energy price jumps to $24.26/o.d.t. The rate of return at $0.00/o.d.t falls from 0.03 to 0.02. Taking into account the nature of the components used in the central processing plant design and the contingency increase in capital expenditures of 10%, it is unlikely that capital costs would vary greatly from those predicted in Routhier (1981) and Hamilton (1982).

Table 21. Required selling prices of energy biomass ($/o.d.t) at various rates of return on extra investment. Central processing plant capital costs increased by 10%. Hauling distance = 140 km

BENCHMARK HARVESTING SYSTEM - TREE-LENGTH		PROPOSED HARVESTING SYSTEM - FULL TREE			
		OFF-HIGHWAY HAUL			
		cut-and-skid method	fully-mechanized method	cut-and-skid method	fully-mechanized method
CUT-AND-SKID	IRR				
	.04	4.16	-40.31		
	.06	8.72	-34.85		
	.08	13.59	-28.94		
	.10	18.75	-22.59		
	.12	24.16	-15.82		
	IRR at $0/o.d.t	0.02	0.16		
FULLY-MECHANIZED	IRR				
	.04		-14.61		
	.06		-11.27		
	.08		-7.67		
	.10		-3.84		
	.12		0.18		
	IRR at $0/o.d.t		0.12		

5.5.5 Sensitivity to Central Processing Plant Machine Utilization Rate

Table 22 summarizes the effect of reducing central processing plant machine utilization by 5% on required energy biomass prices. The proposed systems are limited to those involving the off-highway hauling configuration. This limitation is imposed to simplify the analysis and because the higher rates of return earned by the off-highway systems make them more likely to be interesting to the forest industry. Table 22 should be compared with Table 20. The comparison of the tree-length cut-and-skid system with its full-tree equivalent in Table 20 indicates that the energy biomass price required to earn a rate of return of 0.10 is $15.34/o.d.t. When the central processing plant machine utilization rate is reduced by 5% (see Table 22), the required energy price jumps to $15.47/o.d.t. The rate of return at $0.00/o.d.t falls from 0.03 to 0.02.

It should be noted that the reduction in machine utilization rate reduces the annual throughput of the central processing plant from 502 330 to 472 781 m^3. The volumes required from the harvesting and hauling operations have been adjusted accordingly. This assumption does not limit the conclusions reached in this analysis since the marginal cost of increasing central processing plant capacity is lower than the cost of establishing the original capacity. An interesting effect of this reduction in annual volume harvested can be seen in the comparison of the tree-length cut-and-skid system with the full-tree fully-mechanized system. The energy biomass selling prices required are lower and the rate of return is higher than they were with the higher central processing plant machine utilization rather than the opposite, which would be expected. As the volume harvested per year was reduced, the utilization of the integrated full-tree harvesting equipment increased relative to the utilization of the tree-length equipment. This occurred because of the excess productive capacity in the full-tree harvesting system. The excess capacity existed because the full-tree harvesting equipment (Koehring feller-forwarder) is bought in large production capacity increments. Tree-length cut-and-skid equipment may be bought in much smaller production capacity increments owing to the lower production per machine. For this reason, this anomalous effect was not observed when comparing the two cut-and-skid systems or the two fully-mechanized systems. The anomalous effect would not continue to be felt if annual production were to be decreased further.

The magnitude of the change in rates of return indicates that the economic worth of the proposed harvesting system changes would not be significantly affected by variations likely to be observed in machine utilization rates. Given that the central processing plant described in Routhier (1981) and Hamilton (1982) uses proven technology and that the delimbing units operate independently of each other, it is unlikely that the plant will exhibit unusually low machine utilization rates.

5.5.6 Effect of Two-Stage Hauling Configuration

Many hauling operations must transport wood over both private and public roads before it reaches the mill. The basic analysis performed for this report considered the cases in which tree lengths are hauled directly to the mill or in which full trees are hauled directly to the central processing plant which is located at the mill. This section presents the results of an analysis in which the transportation step is broken down into two stages, as

Table 22. Required selling prices of energy biomass ($/o.d.t) at various rates of return on extra investment. Central processing plant machine utilization reduced by 5%. Hauling distance = 140 km

BENCHMARK HARVESTING SYSTEM - TREE-LENGTH			PROPOSED HARVESTING SYSTEM - FULL TREE: OFF-HIGHWAY HAUL, cut-and-skid method	PROPOSED HARVESTING SYSTEM - FULL TREE: OFF-HIGHWAY HAUL, fully-mechanized method	PROPOSED HARVESTING SYSTEM - FULL TREE: cut-and-skid method	PROPOSED HARVESTING SYSTEM - FULL TREE: fully-mechanized method
	CUT-AND-SKID	IRR				
		.04	2.74	-44.49		
		.06	6.71	-39.82		
		.08	10.96	-34.74		
		.10	15.47	-29.26		
		.12	20.21	-23.40		
		IRR at $0/o.d.t	0.02	0.19		
	FULLY-MECHANIZED	IRR				
		.04		-15.13		
		.06		-12.35		
		.08		-9.33		
		.10		-6.12		
		.12		-2.75		
		IRR at $0/o.d.t		0.14		

described in section 5.2.2. Table 23 lists the energy biomass selling prices required to earn various rates of return for a hauling distance of 140 km. Table 23 should be compared with Table 20. It becomes clear that the required selling prices for the comparisons involving the two-stage hauling configuration are much higher than those listed in Table 20. Figure 27 shows a lower hauling cost for the two-stage haul than for the on-highway full-tree configuration. This might appear to be at odds with the much higher required prices listed in Table 23. It should be noted that the major difference between the two-stage hauling configuration and the others is in the loading and unloading steps, where much greater investments are required to load and unload the shortwood. Additional costs would also be incurred to move energy biomass from the central plant to the mill. These costs have not been calculated here since the required selling prices are higher than any foreseeable value for the biomass.

It is, however, possible to reduce the capital cost of the two-stage hauling configuration by using the wood handling equipment which exists at the central plant to reduce the number of machines required to load shortwood. Little can be done to reduce the capital costs of the unloading process at the mill.

5.5.7 Cut-and-Skid Tree-Length Versus Fully-Mechanized Tree-Length

A separate comparison of the cut-and-skid tree-length system and the fully-mechanized tree-length harvesting system yielded a return of 0.22. The analysis was carried out for a distance of 140 km using an on-highway hauling configuration. This result indicates that the high rates of return earned when the two levels of harvesting mechanization are compared are largely earned by the mechanization of the harvesting process rather than by the centralization of processing functions. This is, of course, not the case where identical levels of harvesting mechanization are compared. As energy biomass prices increase, this effect becomes less significant.

5.5.8 General Discussion of Economic Analysis

The good rates of return earned by two of the six scenarios even without any revenue generated from the sale of energy biomass suggest that integrated full-tree harvesting and central processing systems will provide a higher return on investment than will tree-length systems. These results, however, are dependent on several factors. Firstly, merchantable volume per truck load must be maximized. Secondly, the energy biomass selling price required depends on the accuracy of the estimate of annual energy biomass production. Thirdly, the operation which was created for this study used only one harvesting technology, whereas site factors usually limit the use of fully-mechanized systems to less than 100% of a harvesting area.

Energy biomass recovery rates will affect the economics of the proposed system in two ways: Firstly, the quantity of energy biomass delivered to the central processing plant and, therefore, the revenues (or savings) from energy sales will vary with energy biomass recovery rates. Secondly, the merchantable truck load size will vary with the branchiness of the full trees.

Table 23. Required selling prices of energy biomass ($/o.d.t) at various rates of return on extra investment for a two-stage haul (60 km off-highway, 80 km on-highway). Hauling distance = 140 km

			PROPOSED HARVESTING SYSTEM - FULL TREE			
			TWO-STAGE HAUL			
			cut-and-skid method	fully-mechanized method	cut-and-skid method	fully-mechanized method
BENCHMARK HARVESTING SYSTEM - TREE-LENGTH	CUT-AND-SKID	IRR				
		.04	81.79	42.81		
		.06	88.75	50.83		
		.08	96.08	59.39		
		.10	103.77	68.45		
		.12	111.80	78.01		
		IRR at $0/o.d.t	-----	-----		
	FULLY-MECHANIZED	IRR				
		.04		68.50		
		.06		74.41		
		.08		80.66		
		.10		87.20		
		.12		94.01		
		IRR at $0/o.d.t		-----		

The first effect is easily quantified. The product of the required selling prices for energy biomass listed in Tables 15-23 and the annual production of energy biomass is the annualized net present value of the incremental costs of the proposed harvesting system. For example, in Table 20 the required energy biomass selling price for the comparison of the fully-mechanized tree-length system and its full-tree equivalent (off-highway hauling configuration), for a rate of return of .12, is $35.79/o.d.t. The annual energy biomass production for the fully-mechanized method is 26 557 o.d.t. The annualized net present value of the incremental costs of the proposed system is:

26 557 o.d.t x 35.79/o.d.t = $950 475

If the energy biomass recovery rate were considered too low, it could be changed in Section 5.3.5.2. If, for example, the new recovery rate were to increase annual biomass production from 26 557 to 30,000 o.d.t, the required selling price (for the comparison described above) would be:

$950 475/30 000 = $31.68/o.d.t

As long as the energy biomass value is assumed to be zero, the internal rate of return of the proposed project is not affected by the quantity of energy biomass produced. In effect, the values labelled "IRR at $0/o.d.t" in Tables 15-23 remain independent of the quantity of biomass produced as long as the biomass is not assigned a positive value.

The second effect of a change in biomass recovery rates is the effect on merchantable truck load size. This effect would have to be quantified empirically. Merchantable load size would be strongly affected by tree form characteristics like size of branches and branching angle, which vary significantly within a stand, between stands and regionally. The species mix would also affect the merchantable load size. Accurate assessment of the effect of biomass recovery rate on full-tree hauling costs will require extensive testing in local conditions.

5.5.9 Other Economic Considerations

In addition to the easily identifiable economic effects of integrated full-tree harvesting already discussed, there are economic effects which are more difficult to quantify. These may be significant in determining the degree to which the integrated full-tree harvesting and centralized processing concepts are implemented.

Conventional harvesting technology leaves branches and tops either in the stump area or at the roadside. The accumulation of these logging residues in the stump area may impede reforestation efforts by excessive shading of mineral soil or by hampering scarification, seeding or planting. The accumulation of logging residues in piles at the roadside or in windrows in the stump area may create a forest fire hazard. The piles of residue left at roadside would also impede reforestation efforts. Integrated full-tree harvesting and central processing would reduce the accumulation of logging residues at the roadside or at the stump. The lower accumulations of logging residues could, therefore, lead to lower reforestation costs and to lower fire prevention costs.

The integrated full-tree harvesting system could, when the fully-mechanized method is used, reduce the degree of soil contamination of the energy biomass recovered and of the merchantable wood. This would reduce the amount of 'clinker' formed in wood-using boilers and, thereby, reduce the boiler maintenance requirements.

The safety hazards associated with logging operations are significant. The transferral of some high-risk processing operations such as manual delimbing to a central plant would lead to reduced injuries and, therefore, lower compensation payments. The reduced labour component of the highly-mechanized integrated full-tree harvesting system would lead to lower supervision costs and lower fringe benefit costs.

The concentration of large numbers of unprocessed trees at a central processing plant capable of multi-product manufacturing (e.g., shortwood and sixteen-foot sawlogs) could lead to improved utilization of high grade portions of harvested timber which would normally be converted into shortwood at roadside or at the mill.

Several negative effects may also be experienced as a result of a switch from conventional harvesting and processing technologies to integrated full-tree harvesting. The first of these is the problem of nutrient depletion in sites harvested by any full-tree system (including those in which processing is done at roadside). Nutrient budget considerations are more important in sites where nutrient reserves are low. The sandy podzols on which jack pine is often found have low nutrient levels and low nutrient holding capacity.

It should, however, be noted that the lower energy biomass recovery values observed for jack pine indicate that the nutrient removal problem may be less severe than would be expected. It may nevertheless be necessary to fertilize jack pine cutovers to maintain long-term productivity.

The storage of full trees at a central processing plant may pose an unacceptable fire risk. It will be necessary to develop adequate fire prevention methods before large scale storage of full trees is undertaken.

6.0 CONCLUSIONS

The effect of temperature on biomass recovery was not identifiable from data on daily temperature and biomass recovery in the cut-and-skid phase of the winter study. The comparison of summer and winter data, however, clearly shows that higher yields can be expected in unfrozen conditions.

The results of the winter cut-and-skid phase are of dubious value owing to the high temperatures and other operating factors (e.g., the number of operators). The data gathered for the summer cut-and-skid phase are, however, considered representative within the limitations discussed in Section 1.0. The results of both fully-mechanized phases are considered representative, assuming that the sampling method (particularly the method of separating stems from KFF loads for weighing) does not introduce bias. This assumption is reasonable. A similar method was used by Routhier (1981) in his study of energy biomass yields in black spruce.

Figure 31. Shaggy load of jack pine and black spruce full trees would not be permitted on public roads.

Hauling full trees with tractor-trailer units designed for use with tree-lengths caused a 56.2% reduction in merchantable volume carried. This implies the need for larger trailers which can only be used on private roads, or the need to downsize tractor units to reduce the cost of hauling full trees in highway-sized trailers. The shape of the loads with protruding branches and tops (see Figure 31) dictates that hauling full trees with conventional trailers must only be carried out on private roads or that new trailers with enclosed tops and sides must be designed in order to meet highway size restrictions. Trailers with hydraulically or pneumatically operated compaction equipment could be used to increase the load density and bring the load within highway size restrictions.

The lower energy biomass yield obtained by harvesting by the fully-mechanized method when compared with the cut-and-skid method clearly show that tree form and species affect energy biomass recovery rates for different harvesting systems.

Changing harvesting systems to recover both conventional products and energy biomass appears to be promising in jack pine. The comparison of a tree-length cut-and-skid system with a full-tree cut-and-skid system seems to show promise where off-highway hauling is permissible. The comparison of the fully-mechanized tree-length system with its full-tree equivalent also show promise when off-highway hauling is feasible.

For several harvesting system comparisons, the energy biomass produced at the central processing plant will be "free". In effect, the operating cost savings generated over the life of the central processing plant will pay a sufficiently high return on investment to justify its construction without considering revenues from the sale of energy biomass.

Although the rates of return obtained from integrated full-tree harvesting and central processing investments are high, it is important to note that in some cases some of the benefits may be available without requiring investment in a central processing plant. This is the case where the tree-length cut-and-skid system is compared with the full-tree fully-mechanized system.

Errors in the estimation of central processing plant capital cost and operating characteristics are, in the ranges tested, unlikely to cause large changes in the economic worth of the integrated full-tree harvesting and central processing system.

The two-stage hauling configuration does not appear economically attractive in the form used in this analysis. Increased utilization rates in the additional loaders required for this hauling configuration or increased use of the wood handling equipment available at the central processing plant could increase the worth of this hauling configuration. It is, however, unlikely that this hauling configuration could overcome its inherent inefficiencies to become economically attractive.

The results presented in this report indicate that operations having some or all of the following characteristics would be most likely to benefit from full-tree harvesting and central processing:

1) Off-highway hauls to:

   a) Mill
   b) Railhead
   c) Riverside jetty

2) Short hauling distances.

3) Terrain suited to large mechanized harvesting equipment.

4) High bush camp costs.

5) High energy prices (i.e., no natural gas service, no cheap electricity and no cheap energy biomass).

6) High slash disposal costs.

The highly variable nature of the forest harvesting and forest products manufacturing operations would require that each situation be analyzed separately to identify the economic worth of integrated full-tree harvesting and central processing in the proper context.

7.0 RECOMMENDATIONS

1) The economic benefits which this analysis has found indicate that integrated full-tree harvesting with central processing should be pursued as one means of reducing delivered wood costs and increasing energy self-sufficiency.

2) The importance of truck load size to economic viability of the change from conventional harvesting systems to the integrated full-tree system indicates the need to develop trucking equipment with the capacity to increase load density.

3) The relationship between tree species and energy biomass yield when harvesting by various systems merits further study. The variability in energy biomass recovery rates between species and harvesting systems indicates that every combination of species and harvesting method should be expected to have a different biomass energy recovery rates. Organizations analyzing the economics of integrated full-tree harvesting and central processing would be advised to perform sensitivity analyses to determine whether the energy biomass recovery rate is a critical factor. This would determine the need to perform tests to determine the biomass energy recovery rate in the specific conditions of the operations being analyzed.

4) Large piles of slash are left behind after trees harvested with a KFF are delimbed by sliding-boom delimbers. These piles represent a concentrated form of logging debris. The economics of harvesting this biomass needs to be studied. New concepts such as the FERIC Logging Residue Processor should be tested as an alternative to full-tree hauling.

5) The economic analysis performed depends heavily on the validity of the hypothetical costs and production parameters assigned to the central processing plant design. A prototype central processing plant should be constructed and operated to provide hard data on capital and operating parameters. This would also allow testing of the various on-highway and off-highway hauling configurations and the quantification of other costs and benefits associated with storage and handling of full trees. An ideal location for the test would be adjacent to existing biomass fired boilers where investment in burning equipment would not be necessary to run the experiment.

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SPECIES LIST

Balsam Fir - Abies balsamea (L.) Mill.

Black Spruce - Picea marianna (Mill.) B.S.P.

Jack Pine - Pinus banksiana Lamb.

Poplar - Populus tremuloides Michx.

White birch - Betula papyrifera Marsh.

APPENDIX 1

Regressions on Data Gathered in Frozen Conditions

Regression of stem volume on diameter squared.

VARIABLE	N	MEAN	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
	89	457.46708	47755.54663	218.53042	47.76965
	89	.27652	.01886	.13734	49.66696

CORRELATION = .970957758345

Selected degree of regression = 1
R-SQUARED = .942758968444
STANDARD ERROR OF ESTIMATE = 3.30464357826E-02

ADV

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE
TOTAL	88	1.65982		
REGRESSION	1	1.56481	1.56481	1432.89
X^1	1	1.56481	1.56481	1432.89
RESIDUAL	87	.09501	.00109	

VARIABLE	REGRESSION COEFFICIENTS STD. FORMAT	E-FORMAT	STANDARD ERROR REG. COEFFICIENT	T-VALUE
'CONSTANT'	-.00263	-.263303927500E-02	.00816	-.32
X^1	.00061	.610207605076E-03	.00002	37.85

	COEFFICIENT	95% CONFIDENCE INTERVAL LOWER LIMIT	UPPER LIMIT
'CONSTANT'	-.00263	-.01886	.01360
X^1	.00061	.00058	.00064

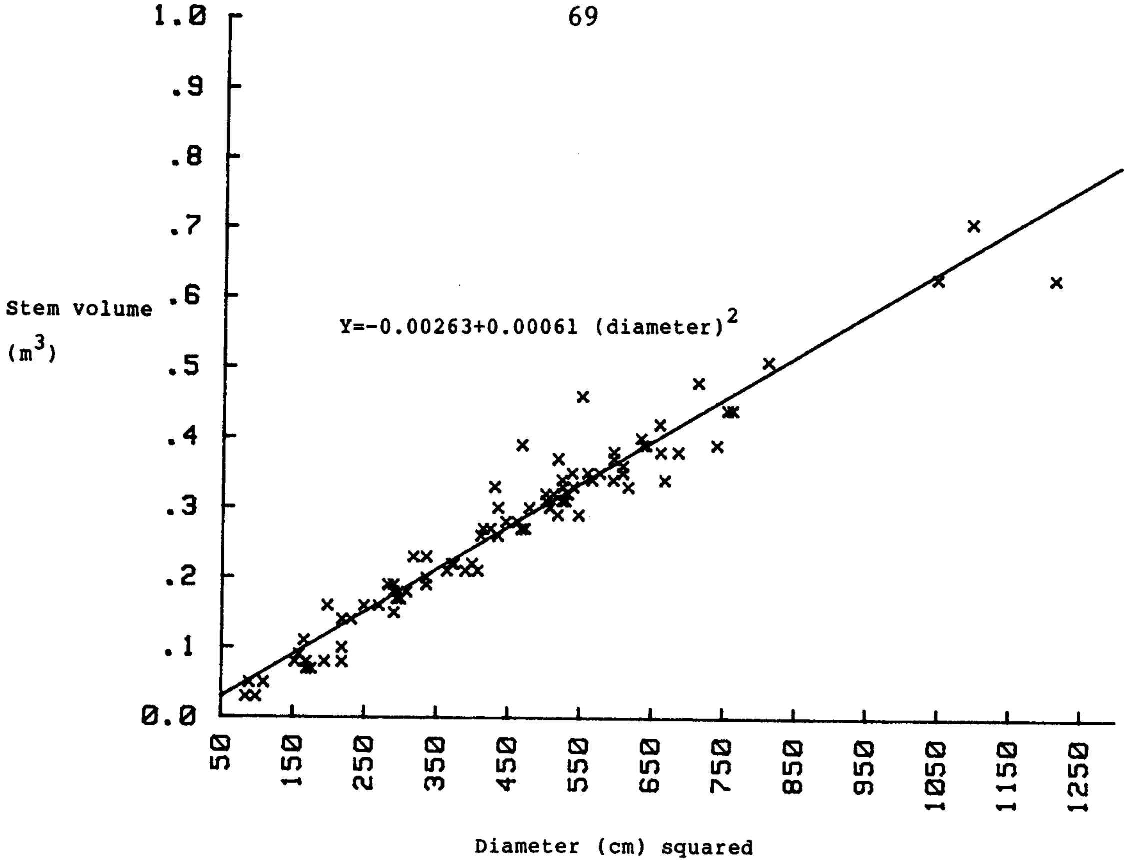

Figure A1.1: Regression of stem volume on diameter squared.

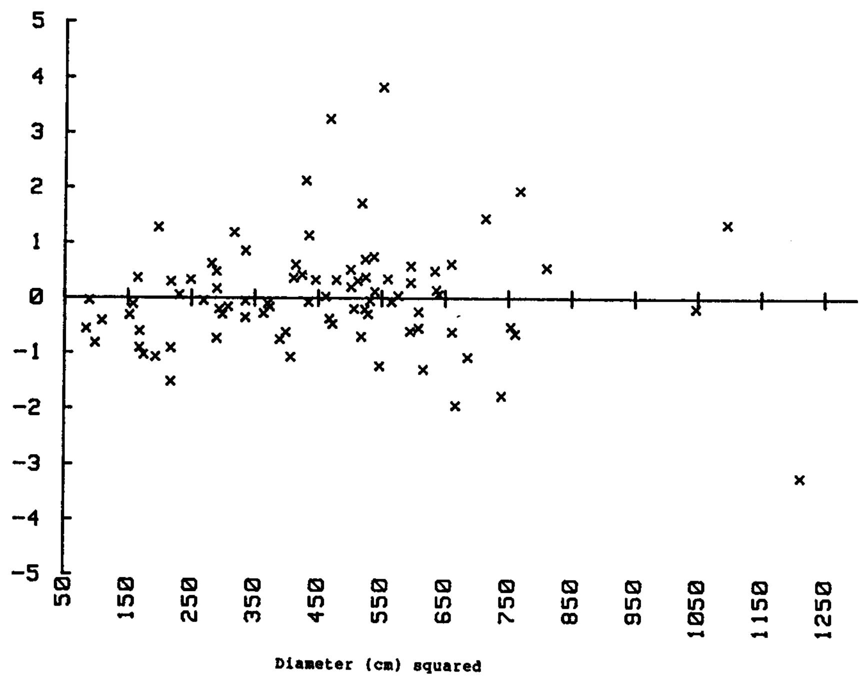

Figure A1.2: Regression of stem volume on diameter squared.

Regression of full tree weight at stump on stem weight.

VARIABLE	N	MEAN	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
	89	221.51348	11081.24573	105.26750	47.5219
	89	268.25955	16356.58562	127.89287	47.6750

CORRELATION = .992671161386

Selected degree of regression = 1
R-SQUARED = .985396034661
STANDARD ERROR OF ESTIMATE = 15.5440230706

ADV

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE
TOTAL	88	1439379.53438		
REGRESSION	1	1418358.88555	1418358.88555	5870.29
X^1	1	1418358.88552	1418358.88552	5870.29
RESIDUAL	87	21020.64883	241.61665	

VARIABLE	REGRESSION COEFFICIENTS STD. FORMAT	E-FORMAT	STANDARD ERROR REG. COEFFICIENT	T-VALUE
'CONSTANT'	1.10806	.110805842800E+01	3.85650	.29
X^1	1.20603	.120602813129E+01	.01574	76.62

	COEFFICIENT	95% CONFIDENCE INTERVAL LOWER LIMIT	UPPER LIMIT
'CONSTANT'	1.10806	-6.55888	8.77500
X^1	1.20603	1.17473	1.23732

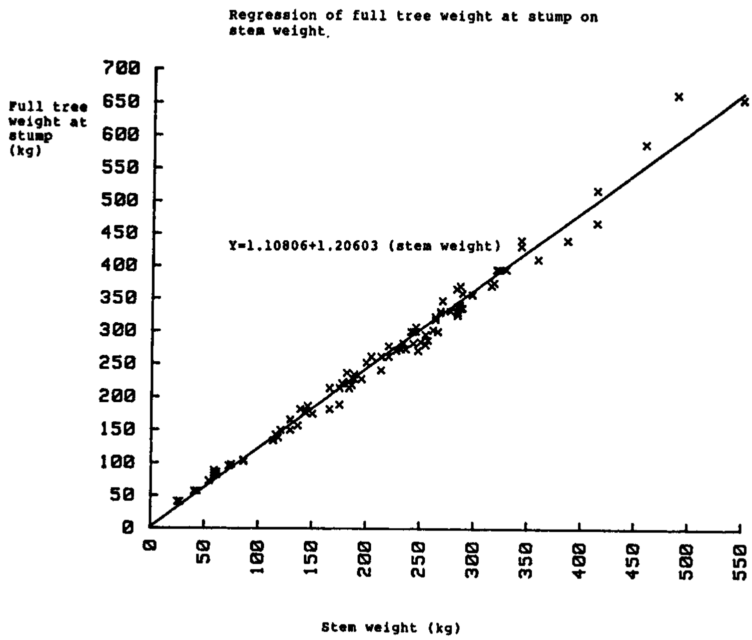

Figure A1.3: Regression of full tree weight at stump on stem weight.

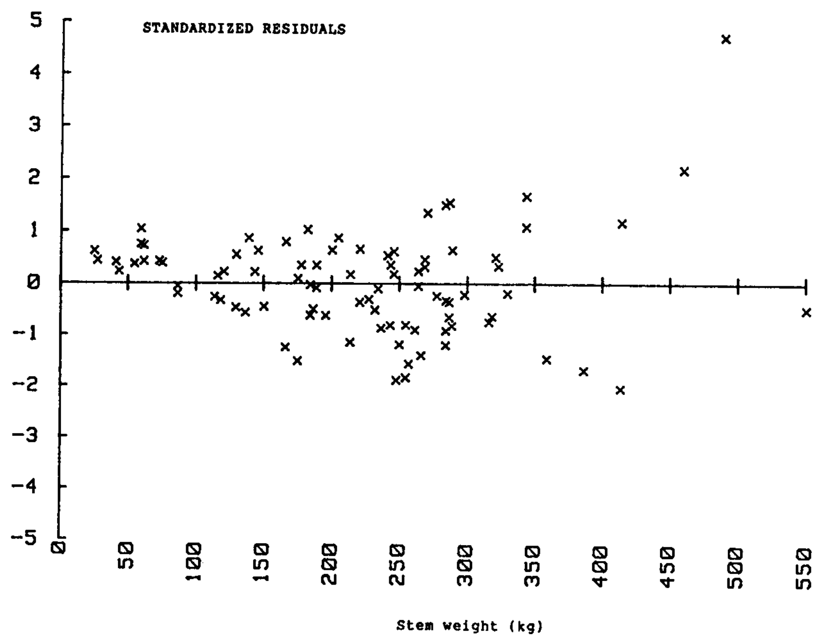

Figure A1.4: Regression of full tree weight at stump on stem weight.

APPENDIX 2

Regressions on Data Gathered in Unfrozen Conditions

Regression of stem volume on diameter squared.

VARIABLE	N	MEAN	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
	96	447.09552	37155.60573	192.75789	43.11336
	96	.26125	.01695	.13019	49.83432

CORRELATION = .955442669829

Selected degree of regression = 1
R-SQUARED = .912870695345
STANDARD ERROR OF ESTIMATE = 3.86335708414E-02

ADV

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE
TOTAL	95	1.61025		
REGRESSION	1	1.46995	1.46995	984.86
X^1	1	1.46995	1.46995	984.86
RESIDUAL	94	.14030	.00149	

VARIABLE	REGRESSION COEFFICIENTS STD. FORMAT	E-FORMAT	STANDARD ERROR REG. COEFFICIENT	T-VALUE
'CONSTANT'	-.02727	-.272711338260E-01	.01000	-2.73
X^1	.00065	.645323248347E-03	.00002	31.38

	COEFFICIENT	95% CONFIDENCE INTERVAL LOWER LIMIT	UPPER LIMIT
'CONSTANT'	-.02727	-.04714	-.00740
X^1	.00065	.00060	.00069

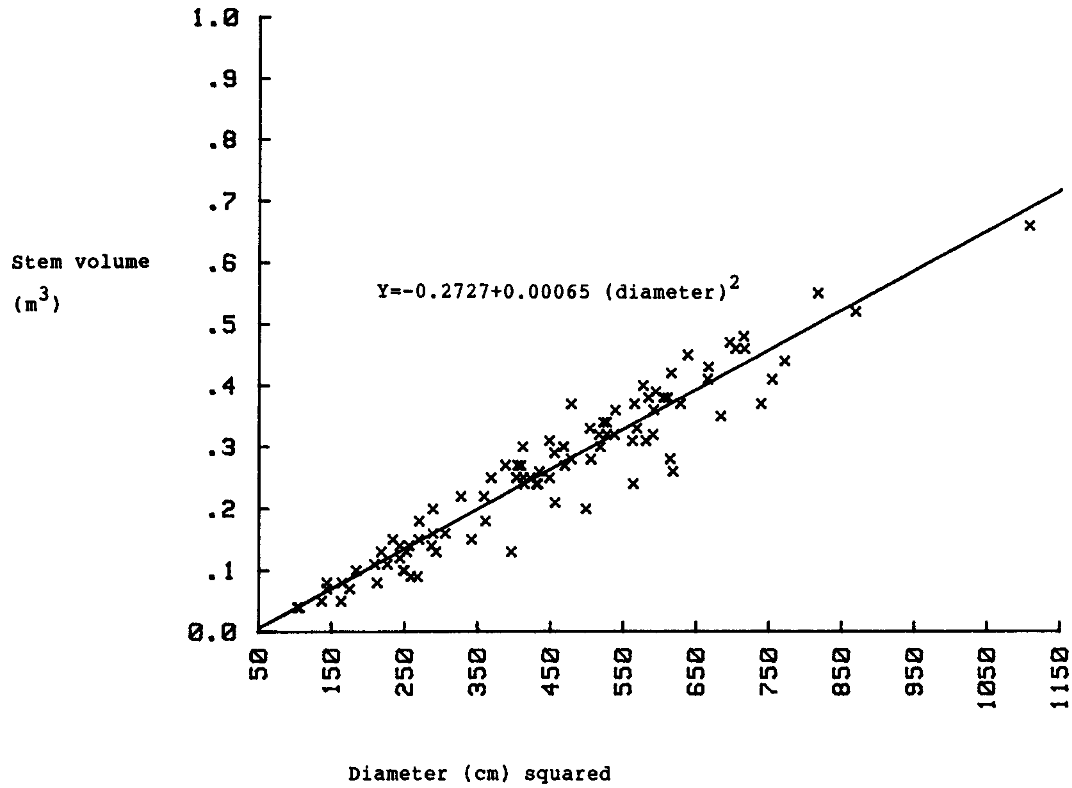

Figure A2.1: Regression of stem volume on diameter squared.

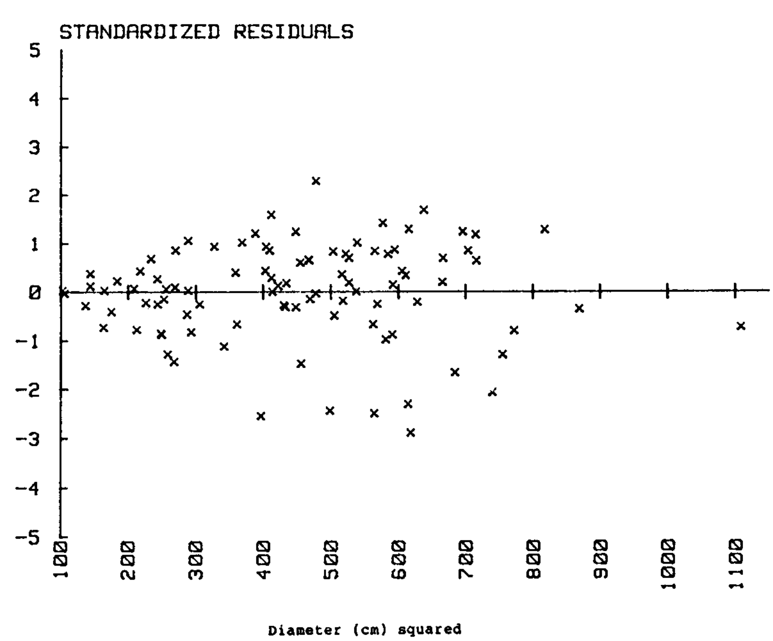

Figure A2.2: Regression of stem volume on diameter squared.

Regression of stem volume on stem weight.

VARIABLE	N	MEAN	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
	96	213.37604	10403.76058	101.99883	47.80238
	96	.26125	.01695	.13019	49.83432

CORRELATION = .984427305934

Selected degree of regression = 1
R-SQUARED = .969097120677
STANDARD ERROR OF ESTIMATE = 2.30081764905E-02

ADV

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE
TOTAL	95	1.61025		
REGRESSION	1	1.56049	1.56049	2947.79
X^1	1	1.56049	1.56049	2947.79
RESIDUAL	94	.04976	.00053	

VARIABLE	REGRESSION COEFFICIENTS STD. FORMAT	E-FORMAT	STANDARD ERROR REG. COEFFICIENT	T-VALUE
'CONSTANT'	-.00686	-.686388552100E-02	.00547	-1.26
X^1	.00126	.125653134919E-02	.00002	54.29

	COEFFICIENT	95% CONFIDENCE INTERVAL LOWER LIMIT	UPPER LIMIT
'CONSTANT'	-.00686	-.01772	-.00400
X^1	.00126	.00121	.00130

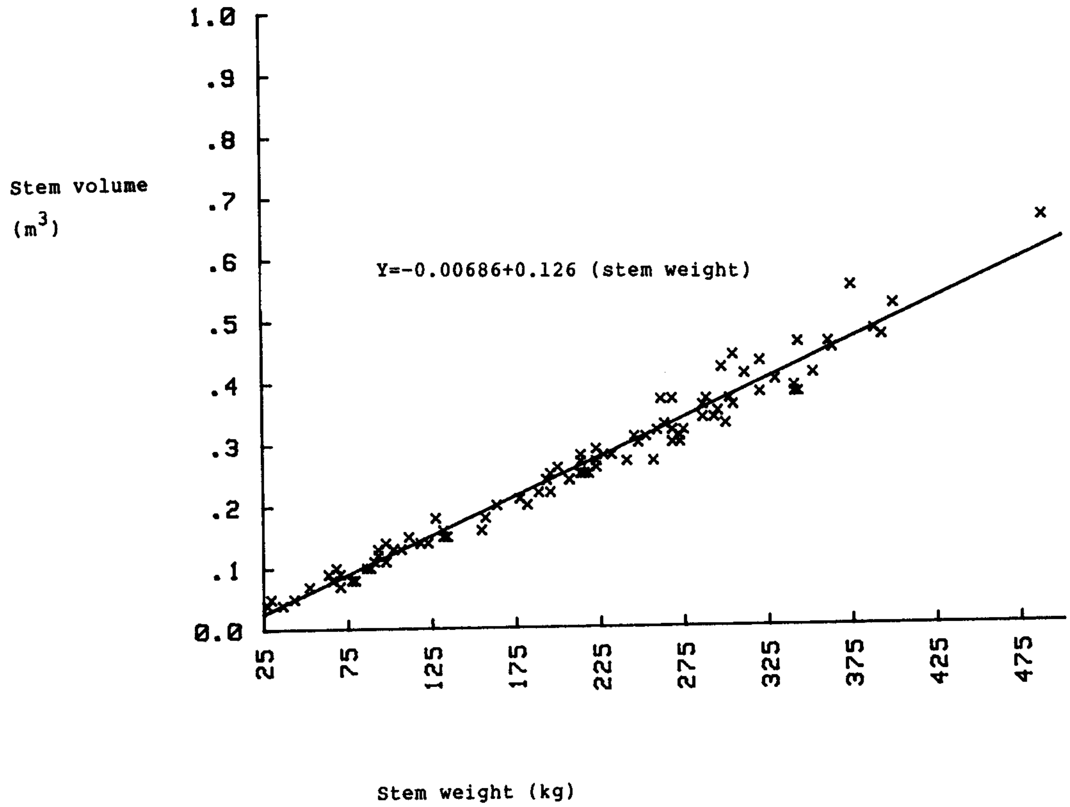

Figure A2.3: Regression of stem volume on stem weight.

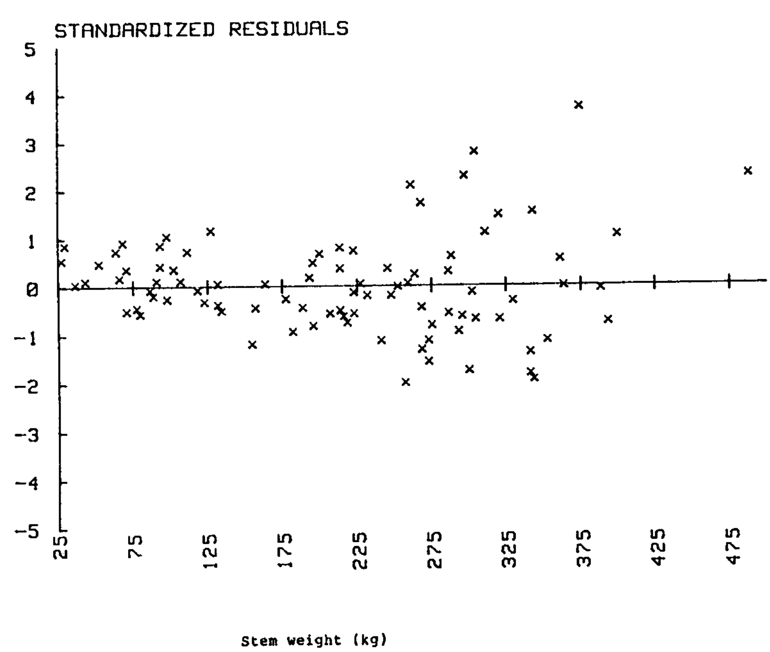

Figure A2.4: Regression of stem volume on stem weight.

Regression of full tree weight at stump on stem weight.

VARIABLE	N	MEAN	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
	96	213.37604	10403.76058	101.99883	47.80238
	96	265.78750	15769.00805	125.57471	47.24628

CORRELATION = .992755833499

Selected degree of regression = 1
R-SQUARED = .98556414501
STANDARD ERROR OF ESTIMATE = 15.1677554793

ADV

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE
TOTAL	95	1498055.76500		
REGRESSION	1	1476430.04921	1476430.04921	6417.56
X^1	1	1476430.04921	1476430.04921	6417.56
RESIDUAL	94	21625.71579	230.06081	

VARIABLE	REGRESSION COEFFICIENTS STD. FORMAT	E-FORMAT	STANDARD ERROR REG. COEFFICIENT	T-VALUE
'CONSTANT'	4.99499	-.499498963000E+01	3.60477	1.39
X^1	1.22222	.122222020960E+01	.01526	80.11

	COEFFICIENT	95% CONFIDENCE INTERVAL LOWER LIMIT	UPPER LIMIT
'CONSTANT'	4.99499	-2.16397	12.15395
X^1	1.22222	1.19192	1.25252

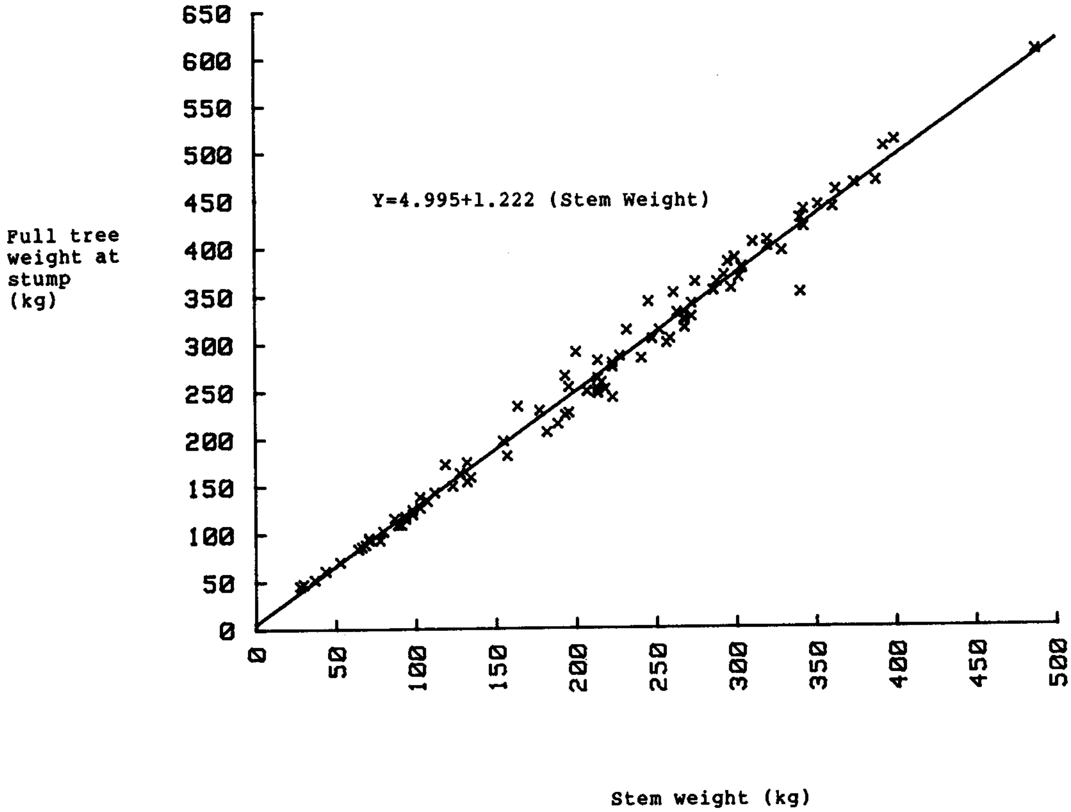

Figure A2.5: Regression of full tree weight at stump on stem weight - summer phase.

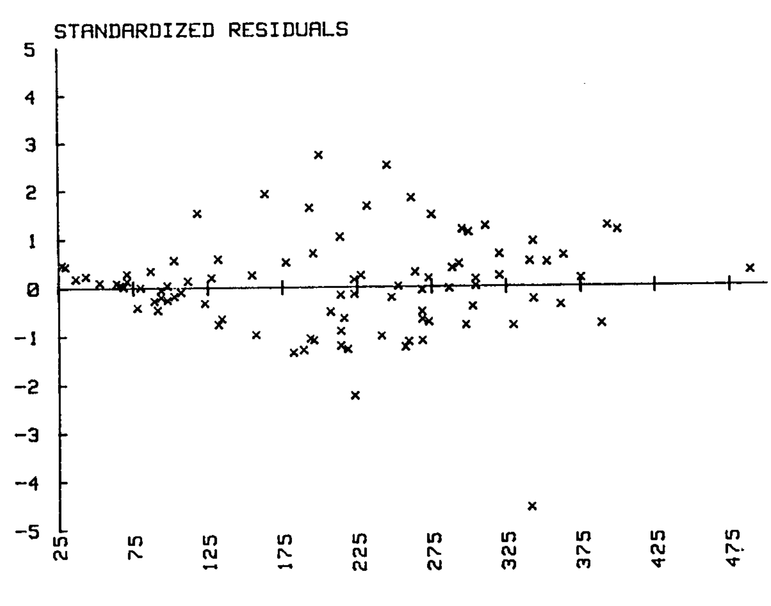

Figure A2.6: Regression of full tree weight at stump on stem weight - summer phase.

Polynomial regression of stem volume on butt diameter.

VARIABLE	N	MEAN	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
	96	20.61771	22.24148	4.71609	22.87396
	96	.26125	.01695	.13019	49.83432

CORRELATION = .94999126564

Selected degree of regression = 2
R-SQUARED = .913787191442
STANDARD ERROR OF ESTIMATE = .038635903824

ADV

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE
TOTAL	95	1.61025		
REGRESSION	2	1.47143	.73571	492.86
X^1	1	1.45322	1.45322	973.53
X^2	1	.01820	.01820	12.19
RESIDUAL	93	.13882	.00149	

VARIABLE	REGRESSION COEFFICIENTS STD. FORMAT	E-FORMAT	STANDARD ERROR REG. COEFFICIENT	T-VALUE
'CONSTANT'	-.08462	-.846194496210E-01	.05856	-1.45
X^1	.00586	.585720477550E-02	.00589	.99
X^2	.00050	.503483480438E-03	.00014	3.49

	COEFFICIENT	95% CONFIDENCE INTERVAL LOWER LIMIT	UPPER LIMIT
'CONSTANT'	-.08462	-.20093	.03169
X^1	.00586	-.00585	.01756
X^2	.00050	.00022	.00079

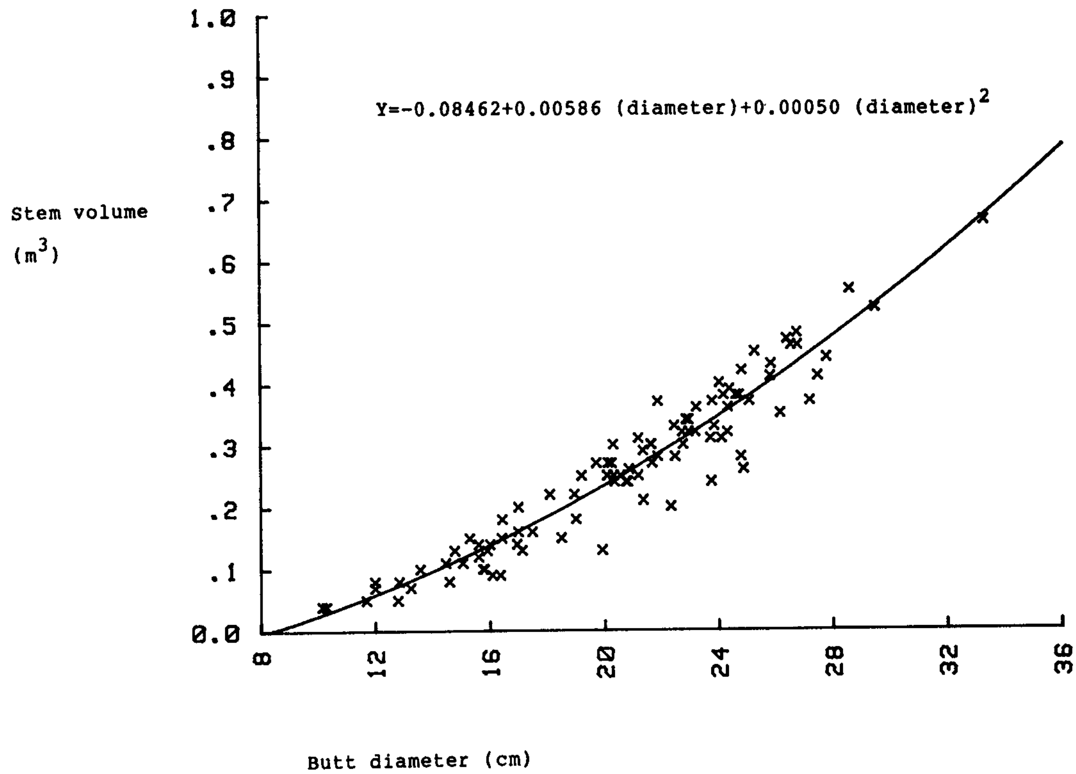

Figure A2.7: Polynomial regression of stem volume on butt diameter.

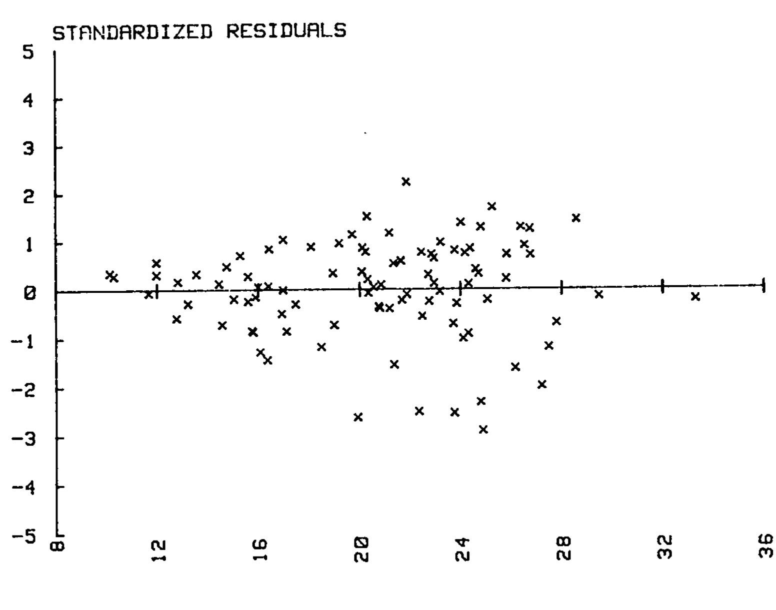

Figure A2.8: Polynomial regression of stem volume on butt diameter.

APPENDIX 3

Sample Output for Investment Analysis Program

The detailed cost analysis program produces (as explained in Section 5.2.1.3.) an investment table and other data used in the investment analysis program. These data are produced for both the benchmark system and the proposed system. Examples of these "System Data Summary" tables are found on page 97. The column labeled "t/l, c/s" refers to the tree-length cut-and-skid system and the column labeled "f/t, kff(2)" refers to the full tree fully mechanized system (large truck load scenario). The tables on pages 98 and 99 show the calculations performed by the investment analysis program based on the data at the AB and BE columns of page 97, respectively. These calculations are explained in Sections 5.2.1.1. to 5.2.1.4. Under the heading "SYSTEM COMPARISON" on page 99 we find a summary of the analysis. The value entitled "$/o.d.t" corresponds to the energy biomass selling price required for the following: the comparison of the cut-and-skid tree-length system with the fully-mechanized full-tree system (off-highway hauling configuration), an 'IRR' value of 0.10 and a hauling distance of 140 km. This value, -$26.24, can be found in the appropriate location in Table 20. Each of the values in Tables 15 to 23 were calculated in an analogous manner.

	AB	BE
System data summary	t/l, c/s	f/t, kff(2)
Tot $/m³	20.20642460	16.03622937
Annual op. $	10150293.27	8055479.101
O.d.t resid./yr	0	26567
Investment at intervals of:		
5 years	2340000	3225000
6 years	3500000	0
7 years	1320000	6000000
8 years	3000000	2319000
15 years	0	5949000
Employment		
Woods	169	46
Other		
Total	236	105

	A	B	C	D	E	F
1	Investment analysis	Investment	Residual	Net invest.	After tax inv.	
2	spreadsheet					
3	benchmark system					
4	year					
5	1	10160000	0	10160000	6731000	
6	2	0	0	0	0	
7	3	0	0	0	0	
8	4	0	0	0	0	
9	5	0	0	0	0	
10	6	2340000	234000	2106000	1395225	
11	7	3500000	350000	3150000	2086875	
12	8	1320000	132000	1188000	787050	
13	9	3000000	300000	2700000	1788750	
14	10	0	0	0	0	
15	11	2340000	234000	2106000	1395225	
16	12	0	0	0	0	
17	13	3500000	350000	3150000	2086875	
18	14	0	0	0	0	
19	15	1320000	1813562.9	-493562.9	-326985.42125	
20						
21	discount rate =	.1				
22	fixed dep. rate =	.2				
23	mobile dep. rate =	.3				
24	taxation rate =	.45				
25	fixed cap. fact. =	.7				
26	mobile cap. fact. =	.6625				
27				A.T. PV cap. inv. =		11130414.50
28				after tax op. $/yr =		5582661.297
29				npv (AT) op. $/yr =		42462165.68

	AD	AE	AF	AG	AH	AI
1	Investment analysis	Investment	Residual	Net invest	After tax inv.	
2	spreadsheet					
3	proposed system					
4	year					
5	1	17493000	0	17493000	11812200	
6	2	0	0	0	0	
7	3	0	0	0	0	
8	4	0	0	0	0	
9	5	0	0	0	0	
10	6	3225000	322500	2902500	1922906.25	
11	7	0	0	0	0	
12	8	6000000	600000	5400000	3577500	
13	9	2319000	231900	2087100	1382703.75	
14	10	0	0	0	0	
15	11	3225000	322500	2902500	1922906.25	
16	12	0	0	0	0	
17	13	0	0	0	0	
18	14	0	0	0	0	
19	15	6000000	1708379.622	4291620.378	2843198.50062375	
20						
21	discount rate =	.1				
22	fixed dep. rate =	.2				
23	mobile dep. rate =	.3				
24	taxation rate =	.45				
25	fixed cap. fact. =	.7				
26	mobile cap. fact. =	.6625				
27				A.T. PV cap. inv. =		16977104.79
28				after tax op. $/yr =		4430513.506
29				npv (AT) op. $/yr =		33698837.98
30						
31				SYSTEM COMPARISON		
32						
33				npv (AT) extra inv. =		5846690.292
34				npv (AT) extra op. $ =		-8763327.70
35				TOTAL =		-2916637.41
36				tot. as annuity (BT) =		-697202.430
37				o.d.t resid./year =		26567
38				$/o.d.t =		-26.24