DETERMINATION OF ECONOMICALLY MARGINAL TREE SIZE THROUGH THE APPLICATION OF CONVENTIONAL AND LINEAR PROGRAMMING TECHNIQUES

by

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ABSTRACT

Various investigators of logging operation efficiency have stated that the harvesting of small trees is inevitably associated with higher operating costs. A comprehensive survey of literature has been presented to substantiate this fact.

The cited information was supplemented, for the purpose of this thesis, by a time study conducted at the University Research Forest, near Haney, B. C., in June, 1961. During this study felling, bucking, yarding and loading of timber was studied at two different operations in that Forest. These studies supplied basic data for the computation of the size of the zero marginal tree. It was found that, under existing conditions, the indicated sizes were 12 and 14 in. d.b.h. for Douglas fir and hemlock trees, respectively. Further it was shown that the milling operation constituted the largest cost component, especially penalizing the small dimensions.

A new schedule, with certain proposed improvements in operating efficiency, was established. Under this schedule the milling operation was omitted, and the logs were assumed to be the final, marketable product. The solution of this computation revealed that, under the assumed conditions, the

zero marginal limit in terms of d.b.h. for Douglas fir and hemlock was lowered to 7 and 8 in., respectively, provided the logs from such small trees could be sold at the same price as # 3 sawlogs. The shape of the net return function suggests, however, that only around and above 15 in. d.b.h. could the operation be regarded as safely paying its way, under current market conditions and restrictions as to minimum log size and length.

The technique of linear programming (LP) has been successfully employed in other sectors of manufacturing and transportation. It is demonstrated in this thesis that the LP technique may be applied to certain forest harvesting situations. Progressing through three problem situations of increasing complexity, it is shown how an optimum strategy of action may be established in terms of the economically marginal tree size.

The difficulty of obtaining precise time and cost values in sufficient quantity was encountered throughout this work. Consequently, the main purpose of these computations is to illustrate the underlying principles of the application of LP, and to demonstrate its applicability to certain aspects of forest harvesting problems. This area offers wide scope for future investigation and for improvement of techniques.

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INTRODUCTION

The Coastal Region of British Columbia has for decades produced lumber products in sizes and quantities matched only in a few locations elsewhere in the world. The wealth of old-growth stands has created a tradition of logging on a gigantic scale. Both the equipment and methods in the coastal operations have been adapted for handling of large dimensions and high volumes per acre. Accessible locations on tidewater and low stumpage prices created a favourable economic climate allowing a generous profit margin in spite of the relative isolation of this region from the major consuming centres of the world.

As the old-growth stands on the most accessible areas became depleted and loggers moved up the hills and farther inland, distances from tidewater or railroad spur lines increased. Growing transportation problems raised new economical implications: in order to make a profit, which trees should be taken and which should be ignored because they would not pay their way? The loggers felt intuitively that the largest trees are the best money-earners whereas the handling of smaller trees is less profitable if not entirely undesirable.

In the early days of forest operations in this province this kind of reasoning, together with a relative abundance of unexploited forest areas, and a lack of governmental enforcement of a firm forest policy, gave rise to a period of indiscriminate removal of old-growth trees. In many instances this was accompanied by destruction of the residual stand. However, with the dwindling availability of virgin stands and increased public knowledge about the situation in the forests, these conditions obviously could not continue to prevail.

Logging practices have changed considerably since the early days of lumbering. Changed economic conditions have imposed new problems on the operators in the woods and sawmills. One basic fact that has remained unchanged is: the removal and subsequent manufacture of a small tree is still far more expensive, per unit volume, than an equivalent volume manufactured from a larger tree. It has become apparent that each tree has a unique value under specified conditions such as its location, available harvesting and milling technology, and the state of markets for the particular products extracted from that tree.

Harvesting of timber is a business enterprise and if conducted under the "free enterprise" system, is subject to the profit maximization principle. This principle is equally valid if the forest is operated as a public enterprise where in addition to declared monetary profits a number of intangible returns may be included. Under the "free enterprise" system these returns may also be met by legislation controlling the operation of companies for the "public good". In general, the determination of marginal values of trees of various sizes becomes the basis for subsequent planning of an operation. The determination of these values, using various computational approaches, is the chief purpose of this thesis.

Although these computations strive to approach actual conditions encountered in the field, the difficulty in obtaining accurate data often made it necessary to resort to certain assumptions. Thus an element of approximation and compromise was introduced wherever no other avenue of approach was possible.

Because the author was mainly concerned with a development of system and method, this approach should not diminish the value of the work. At this time only a reasonable model was looked for, which could easily be improved as more detailed basic data become available.

REVIEW OF LITERATURE

One of the earlier scientific investigations into the effects of tree size on logging and manufacturing costs was conducted by Ashe (1916) in Tennessee, Virginia and North Carolina. This study was intended to lend strength to the argument in favor of leaving the small, unprofitable trees to grow to larger sizes for future cutting. The results of this investigation are in principle quite comparable to the operations of later days, allowing for the changed technology. Ashe found that for felling and bucking the optimum size for trees was between 30 and 38 inches in diameter and that the cost increased rapidly for trees below 18 inches in d.b.h. In skidding, conducted with teams of horses, logs averaging 8 inches in diameter were nearly three times as costly as logs averaging 24 inches in diameter. Similar trends were also noted in sawing logs of different diameters.

In the Douglas Fir Region, one of the first comprehensive studies on the cost of felling and bucking by different tree sizes was published by Rapraeger (1931). In his study, which primarily was concerned with the establishment of realistic rates of pay for the workers in the woods, Rapraeger established production rate schedules for Douglas fir and hemlock trees of various stump diameters and also investigated the effect of different wage systems on the rate of output. In a separate study carried out in Eastern Oregon, Rapraeger (1932) investigated the efficiency in sawmilling and the most economic use of timber. Within this broader framework of study, consideration was given also to the effect of log size on sawing time. It was found that the cost of making lumber from a 6-inch log was more than three times the unit cost for a 30-inch log.

In a later study in Idaho, Rapraeger (1936) compared the output of fallers and buckers in the Idaho White Pine Area with loggers working in the Douglas Fir Region. He found that, whereas in the latter region a daily output of two fallers and two buckers was 30,000 to 40,000 f.b.m. of logs, giving a per-man-day output of 7,500 to 10,000 f.b.m., at that time in western white pine camps a daily production of 5,000 to 6,000 f.b.m. was considered an excellent day's work. This difference was shown to arise directly from the difference in tree sizes of the two species.

Several time studies have been reported for the Southern Pine Region. Garver and Cuno (1932), working in loblolly pine forests of North Carolina, concluded that it is five times more costly per thousand f.b.m. gross log scale to log 9-inch trees than 21-inch trees. A trend of decreasing costs with increasing log size was noted also for milling of loblolly pine trees. By combining the value of lumber in each tree and production cost for a particular d.b.h. class, Garver was able to tabulate the size at which the trees began paying their way. In that particular study, a 13-inch d.b.h. loblolly pine tree proved to be marginal, if a 20 per cent profit was to be earned on the operation.

A comprehensive treatment of logging and milling costs, as affected by tree and log size, was given by Reynolds et al. (1944) for the second growth pine-hardwood forests in Arkansas, Louisiana, Texas and Oklahoma. Guttenberg and Duerr (1949) illustrated the application of conversion surplus methods as a guide for determining the most profitable products obtainable from a tree.

In the "Inland Empire" region, Bradner et al. (1933) conducted extensive studies over a period from 1919 to 1928. The data were collected to show the effects of species, size of timber, slope and season of the year, on logging cost. In felling and bucking operations the effect of season was found to be minor. Species, however, had considerable effect on the rate of output. Also the incentive created through contract payment, as compared to daily wage system, was aptly illustrated in their study. According to the surveys, the contract crew exceeded the day crew by 300 f.b.m. per hour when sawing 20-log-per-thousand ponderosa pine. As the timber increased in size, the difference in output between the two crews also increased. The results of skidding studies indicated consistently that the output, regardless of methods employed, increased with decreasing skidding distance and increasing log size. In general, as the size of material decreased, the smaller output was attributed to the increased handling time in making up and unhooking the load. With a tractor, a limit in the number of pieces which could be skidded per load was reached in the smaller material before the weight had an appreciable effect. Therefore, a greater difference was found between the output for small and large timber in tractor skidding than in horse skidding. In handling of logs with trucks, the bulk rather than the weight was found to be the limiting factor. It precluded the handling of enough small logs to equal the scale of larger logs that could be carried. Long distance also increased the loss in output of small, as compared with larger, timber. The gross output per hour for all sizes of timber decreases as the handling distance increases: regardless of the scale per load, fewer trips are made per hour or per day.

The effect of road type on pulpwood and log production cost has been investigated by Reynolds (1936) in the pine-hardwood regions of Louisiana, Arkansas and Texas. His results showed that the handling costs per M f.b.m. decreased with increasing quality of road surface and increasing log size.

McClary (1953), also working in the Southern Pine Region, conducted time studies in pulpwood cutting and log making. His chief interest was the effect of tree size on the production rate, using a chainsaw instead of the then conventional hand cross-cut saws. McClary found that, if it takes 100 man-hours to cut a given amount of pulpwood from 10-inch, 7-bolt (bolt = 5¼ ft.) trees, it would take 145 man-hours to cut the same amount from 7-inch 5-bolt trees.

High-lead yarding costs in a 100-year-old Douglas fir, sitka spruce and hemlock stand in Oregon were investigated by Tennas <u>et</u> <u>al</u>. (1955). In their work they observed the effects of crew size, haul-in distance, volume per turn, slope, length of yarding roads and number of logs per acre on production rate and cost.

In a cost analysis comparing two areas of pulpwood operations in Eastern Canada, Holt (1949) demonstrated that a selective cutting, where small immature trees are left to grow to maturity, was a more profitable method of harvesting than the accepted clearcutting method. More recent work in logging and milling studies has also been done in Eastern Canada by Doyle (1957) and Doyle and Calvert (1961). In these investigations the whole range of conversion operations from stump through to the sawn board has been investigated for spruce, balsam fir and jack pine. In both reports the main object of the research has been the effect of tree (and log) size on the cost of the various stages in harvesting and milling operations. Again small logs and trees were much more expensive to log and saw.

METHODS AND DEFINITIONS

Chapman and Meyer (1947) outlined in considerable detail the computational procedures used in determination of tree stump values for various sizes, grades and species. This method, which will be used later in this thesis, approaches the estimated value of a tree in steps from the direction of the final product. It considers methodically all intervening operational steps. After allowing for the various costs involved, it arrives at a schedule of values which indicates the profitability of a given logging chance and determines the tree of zero margin.

The profit of an operation is obviously the difference between the total revenue from the sale of all outputs, in this case the lumber products, and the expenditure upon all inputs such as labor, operating cost of equipment, taxes and so forth. As will be shown, profit is a function of the variable inputs and is maximized with respect to these variables alone. Consequently, the evaluation of the functional relationships between the variable inputs and the outputs associated with them becomes of primary importance in the profit maximization analysis. Often the required information is not available, or it may be scanty and not sufficiently reliable.

Some underlying principles of production function and the nature of profit maximization will be briefly outlined in the following sections.

I. PRODUCTION FUNCTION

The entrepreneur's production function gives mathematical expression to the relationships between the quantities of inputs he employs and the quantity of output he produces. Thus in a simple production process of two variable inputs (X_1 and X_2), and one or more fixed inputs producing a single output Q, the production function states the quantity of output (q) as a function of the quantities (X_1) and (X_2) :

$$q = f(X_1, X_2) \ldots\ldots (1)$$

Here (1) is assumed to be a single-valued continuous function with continuous first and second-order partial derivatives. It should be emphasized that a production function pre-supposes technical efficiency and states the maximum output obtainable under every possible input combination.

Since the function (1) is continuous, the number of possible combinations of X_1 and X_2 to the entrepreneur is infinite. The best utilization of any particular input combination is a technical, not an economic, problem. The <u>selection</u> of the best input combination for the production of a particular output level depends upon input and output prices and is the subject of economic analysis.

II. MARGINAL PRODUCTIVITY

The total productivity of variable X_1 in the production of output Q is defined as that quantity of Q that can be secured from the input of X_1 if X_2 is held fixed at an assigned level

$$q = f(X_1 \; X_2^o) \quad \text{.................(2)}$$

The average productivity of X_1 is its total productivity divided by its quantity:

$$AP = \frac{q}{X_1} = \frac{f(X_1 \; X_2^o)}{X_1} \quad \text{...........(3)}$$

Finally, the marginal productivity of X_1 is the rate of change of its total productivity with respect to variations of its quantity, i.e., the partial derivative of (1) with respect to X_1:

$$MP = \frac{\partial q}{\partial X_1} = f_1(X_1 \; X_2^o) \quad \text{........(4)}$$

Families of AP and MP curves can be constructed by assigning different values to X_2^o.

III. ISOQUANTS AND COST FUNCTION

For a fixed output level of q^o the production function becomes

$$q^o = f(X_1, X_2) \quad \text{..............(5)}$$

The locus of all the combinations of X_1 and X_2 which satisfy (2) forms an isoquant. It is apparent that along an isoquant the ratio of X_1 to X_2 changes continuously, whereas the output remains constant. Consequently the income remains constant but the costs of the inputs are varying. Since the entrepreneur wishes to maximize the difference between his income and expense, he attempts to choose X_1 and X_2 at such a point that the cost function should attain an absolute minimum relative to the isoquant passing through that point.

The cost function is expressed as:

$$C = P_1X_1 + P_2X_2 + B \text{...........}(6)$$

where: C is the total cost of production,

P_1 and P_2 are the respective prices of X_1 and X_2 and

B is the cost of fixed inputs.

IV. PROFIT MAXIMIZATION

The profit (π) of the entrepreneur is the number of units sold (q) multiplied by the fixed unit price (p) less the total cost of production:

$$\pi = pq - C \text{....................}(7)$$

The following substitutions are made: $q = f(X_1\ X_2)$ from (1) and $C = P_1\ X_1 + P_2\ X_2 + B$ from (3). Then

$$\pi = pf(X_1\ X_2) - P_1 X_1 - P_2 X_2 - B \ldots\ldots (8)$$

Thus profit is a function of X_1 and X_2 and is maximized with respect to these variables.

Setting partial derivatives of (8) with respect of X_1 and X_2 equal to zero:

$$\frac{\partial \pi}{\partial X_1} = pf_1 - P_1 = 0$$

$$\frac{\partial \pi}{\partial X_2} = pf_2 - P_2 = 0$$

Moving the input price terms to the right side of the equations -

$$\left.\begin{aligned} pf_1 &= P_1 \\ pf_2 &= P_2 \end{aligned}\right\} \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

The first-order conditions for profit maximization require <u>that each input be utilized up to a point at which the value of its marginal product equals its price</u>.

DETERMINATION OF CONVERSION RETURNS

The above statement implies that the entrepreneur can increase his profit as long as the addition to his revenue from the employment of an additional unit of X_1 exceeds its cost. This principle underlines the marginal analysis of profit maximization.

Literal application of this formula in a real situation gives rise to many severe complications. Firstly, the inputs and their interrelations are so complex that even a reasonable approximation necessarily entails severe over-simplification. This, however, diminishes the significance of the partial derivatives and also of the marginal values of the various inputs. The above is especially true for logging operations where wide variability is the rule rather than the exception.

Chapman and Meyer (1947) circumvented this difficulty by analyzing one specific situation at a time, using the best available time study and cost accounting data available. Their analysis is arbitrarily divided into steps which follow and complement each other in a logical sequence. These steps, somewhat modified, are enumerated below and discussed in detail in the following chapters:

Step 1. Determination of selling value of lumber of varying grades and dimensions.

Step 2. Lumber grade output of logs of varying size and quality.

Step 3. Milling costs for logs of varying sizes.

Step 4. Combination of Steps 1, 2 and 3 will give net value of logs by varying size as they arrive at the mill.

Step 5. Determination of logging and transportation costs by size of log.

Step 6. Combination of Steps 4 and 5 to obtain net value of logs by size as they lie on the ground after felling and bucking.

Step 7. Felling and bucking costs by size of tree.

Step 8. Combination of Steps 6 and 7 and part of Step 5 to arrive at net value of single standing trees of different sizes.

A more recent technique in handling complex problems, where some profit function must be maximized subject to a set of economic restrictions, has been developed under the designation of <u>linear programming</u> (LP). Although LP has been used with remarkable success in agricultural, industrial and even military problems, its application to forestry and forest industry has been only slight. It will be shown in this thesis that LP methods are suitable for the solution of certain problems in forest harvesting operations.

SELLING VALUE OF LUMBER OF VARYING GRADES AND DIMENSIONS

The price of lumber has a decisive effect on the entire subsequent analysis. Minor variations in price take place constantly over short periods of time and, over long periods, the value of products may change considerably. As an illustration of this point, in Table 1 is shown the changes in price of coast Douglas fir lumber between the years 1944 to 1955.

TABLE 1

AVERAGE VALUE OF COAST DOUGLAS FIR LUMBER

PER THOUSAND (M) BOARD FEET (f.b.m.)

Year	Dollars per M f.b.m.
1944	33.59
1947	63.63
1950	70.94
1953	75.39
1955	78.75

Whereas the price levels may change quite substantially, relative price levels between various grades and dimensions tend to remain more constant. This should not imply that differential price changes do not take place, because locally they may be highly significant. There is considerable merit, after defining a base-price, to establishing a relative price schedule which then may be modified for specific cases. McBride has presented such price schedules for small Douglas fir (1949) and young hemlock (1951) which can be shown in Table 2.

TABLE 2

RELATIVE LUMBER PRICES BY GRADES FOR

SMALL DOUGLAS FIR AND YOUNG HEMLOCK

Grade	Douglas Fir Gangmill	Douglas Fir Circular Mill	Hemlock Circular Mill
	Price as a percentage of 1" No. 1 Common Lumber		
Clears	201	199	205
Select Com. 1"	107	107	107
" " 2"	111	111	111
Sel. Com. Timbers	147	139	120
No. 1 Common 1"	100	100	100
" " " 2"	104	104	104
No. 1 Com. Timbers	135	130	115
No. 2 Common	93	93	98
No. 3 Common	71	71	69
No. 4 Common	49	49	40

Average selling prices for dressed lumber from the Interior of British Columbia were reported by the B. C. Forest Service in its Annual Report for 1960. For the last quarter of 1960 the Report quoted the following prices by various species:

TABLE 3

AVERAGE DRESSED-LUMBER PRICES FOR

OCTOBER - DECEMBER 1960 - INTERIOR B. C.

Species	Basis M f.b.m.	Average Price
Fir-larch	144,706	$51.29
Spruce	185,821	50.72
Cedar	4,451	49.70
White pine	5,328	92.39
Yellow pine	2,044	49.93

Accepting $51 per M as the price of 1 inch Common No. 1 stock, then the following price schedule may be set up. A mill with a circular saw is contemplated (Table 2).

TABLE 4

PROPOSED PRICE SCHEDULE FOR

DOUGLAS FIR AND HEMLOCK LUMBER

Lumber Grade	Douglas Fir	Hemlock
Clears	$101	$94
Select Common 1"	55	49
" " 2"	57	51
" " Timbers	71	55
No. 1 Common 1"	51	46
" " " 2"	53	48
" " " Timbers	66	53
No. 2 Common	47	45
No. 3 Common	36	41
No. 4 Common	25	18

As the prices change from week to week, these values should be replaced with the latest and most accurate estimates available. In this thesis all calculations will be carried out with this mill price schedule. Increasing width increases the price in higher grades, but in lower grades (No. 3 and No. 4 Common) the price falls for wider boards, mainly due to lack of strength and greater amount of defects present. The base price of hemlock was set 10 per cent below that of Douglas fir, *viz.* .90(51) = $46.

LUMBER GRADE OUTPUT FROM LOGS OF VARYING SIZE AND QUALITY

The grade output of lumber varies with log quality and size and with the equipment and practices used in any particular mill where the studies are conducted. Because regional differences make it inadvisable to rely on values too far away from the locality where the analysis is to be applied, the large number of U. S. studies will not be drawn upon. McBride has given lumber recovery values for small Douglas fir and young hemlock which can be shown as in Table 5.

TABLE 5

LUMBER RECOVERY VALUES (PER M f.b.m.) BY LOG DIAMETER FOR SMALL DOUGLAS FIR AND YOUNG HEMLOCK

Log Diam. In.	Douglas Fir				Hemlock
	Gangmill		Circular Mill		Circ. Mill
	Dollars per M f.b.m. lbr. tally as per cent of that from 12" logs				
	Log # 2	# 3	# 2	# 3	# 3
6	-	-	-	-	90
9	-	97	-	98	92
12	100	100	100	100	100
15	103	100	104	102	108
18	106	96	107	102	113
21	109	94	111	101	117
24	112	93	114	99	-
27	115	98	117	98	-

For second-growth Douglas fir in the Pacific Northwest, Matson (1952) presented the following grade recovery distribution for various diameter classes.

TABLE 6

GRADE RECOVERY FROM SECOND-GROWTH DOUGLAS FIR LOGS

IN PER CENT OF GREEN-CHAIN TALLY

Log Dia. In.	Lumber Grade Recovery (%)			
	Select Structural	No. 1	No. 2	No. 3
8	24.9	67.8	5.6	1.7
10	29.5	59.2	9.5	1.8
12	32.9	52.2	12.8	3.1
14	35.4	46.8	15.5	2.3
16	37.0	42.9	17.2	2.9
18	37.4	40.9	18.1	3.6
20	36.7	40.5	18.4	4.4
Average:	31.9	53.8	12.1	2.2

For spruce in Prince George district, McBride (1956) found that the percentage of No. 2 and Better Common decreases with increase in diameter, and the percentage of Clears, No. 3 Common, No. 4 Common and No. 5 Common increases as the diameter increases. The average lumber grade recovery values are given in Table 7.

TABLE 7

AVERAGE PERCENTAGE OF LUMBER GRADE RECOVERY BY DIAMETER CLASSES (ROUGH GREEN BASIS) FOR INTERIOR SPRUCE

Log Dia. In.	Lumber Grade Recovery, (%) D & Btr Clear	No. 2 & Btr.Com.	No. 3 Com.	No. 4 Com.	No. 5 Com.	Value $/M f.b.m.
6	-	46	45	9	-	78.00
9	1	45	46	8	-	83.75
12	2	43	47	8	-	84.55
15	3	38	49	10	-	84.05
18	4	33	51	11	1	83.10
21	4	28	54	13	1	81.75
24	5	21	58	14	2	80.35

Matson and Rapraeger (1950), working in second-growth Douglas fir region of the Willamette National Forest, Oregon, reported on the grade recovery percentages by log diameters. In their study, all logs under 12 inches in diameter were classed as No. 3 logs and those of larger diameters were all No. 2 sawmill quality logs. Their results are summarized in Table 8.

TABLE 8

AVERAGE PERCENTAGE OF LUMBER GRADE RECOVERY BY

DIAMETER CLASSES FOR SECOND-GROWTH DOUGLAS FIR

Log Dia. In.	Lumber Grade Recovery (%) Select Structural	No. 1	No. 2	No. 3
6	10.6	79.4	5.5	4.5
8	21.8	69.6	5.2	3.4
10	29.8	61.8	5.9	2.5
12	34.7	55.8	7.6	1.9
14	36.4	51.8	10.4	1.4
16	34.9	49.9	13.8	1.4
18	30.3	50.0	18.6	1.1
20	22.5	52.5	23.6	1.4
Average:	30.0	59.2	8.9	1.9

A similar evaluation of grade recovery by diameter classes for second-growth hemlock has been reported by McBride (1951). The sawmill studied was a small portable type, with circular headsaw cutting 10 M f.b.m. per eight-hour shift. The values have been summarized in Table 9. All logs belonged to Grade No. 3.

TABLE 9

AVERAGE PERCENTAGE OF LUMBER GRADE RECOVERY BY

DIAMETER CLASSES FOR SECOND-GROWTH HEMLOCK

Log Dia. In.	Lumber Grade Recovery (%) Clear	Selected Comm. Boards & Dim.	Selected Com. Timber	No. 1 Com.	No. 2 Com.	No. 3 Com.	No. 4 Com.
6	-	9	-	63	25	3	-
9	2	16	-	57	22	3	-
12	6	23	18	35	16	2	-
15	11	5	46	26	10	2	-
18	16	5	49	20	8	2	-
21	22	5	50	15	7	1	-
Average:	12	8	43	24	11	2	-

Worthington (1955) reported grade recovery for young Douglas fir in Washington, cut in a mill using a 30-inch round-log Swedish gang. These values are given in Table 10.

TABLE 10

LUMBER GRADE RECOVERY IN PER CENT OF

GREEN-CHAIN TALLY - YOUNG DOUGLAS FIR

Log Dia. In.	Grade Recovery (%) No. 1 & Better	No. 2	No. 3	No. 4
6	28	40	27	5
8	45	38	13	4
10	53	35	9	3
12	56	33	8	3
14	57	32	8	3
16	56	32	9	3
18	54	32	11	3

Grade recovery values were tabulated for about 300 second-growth Douglas fir logs from some unpublished data gathered by the Vancouver Forest Products Laboratory, Canada Department of Forestry. The results are given in Table 11. From these results it may be seen that smaller logs produce a relatively larger percentage of No. 1 Common lumber than do larger logs. No. 2 Common Grade is relatively constant over the various diameter classes and constitutes about 15 per cent of the volume recovered. No. 3 Common is low for smaller logs but increases rapidly with increasing log size.

TABLE 11

GRADE RECOVERY IN SMALL DOUGLAS FIR

(UNPUBLISHED DATA FROM V.F.P.L.)

	Log Top Diameter Classes - In.			
	6-9	9-12	12-15	15-18
Grade	Per Cent of Total Recovered Volume			
Clears	0.8	1.2	2.7	5.1
No. 1	77.7	66.3	57.2	35.1
No. 2	13.9	16.6	14.3	17.1
No. 3	7.5	13.5	24.4	37.6
No. 4	0.1	2.4	1.4	5.1

Kirkland and Brandstrom (1936) studied the recovery of lumber grades. Their results, based on a sample of 1,336 logs, show that the percentage of No. 1 Common decreases with increasing log diameter, whereas Select grade and No. 3 Common lumber increase over the same diameter range.

The various grade recovery tables presented so far indicate the great variability which is found between the different investigations. A comparison of the studies shows that, although they all follow similar patterns, individual values exhibit very wide variation. Obviously there are no two identical tracts of forest in respect of recovery possibilities.

In this thesis a reasonable compromise is attempted between the various studies. For lumber recovery values, Table 6 by Matson (1952) has been used. The over-run values for Douglas fir have been adopted from McBride (1949) and for hemlock from McBride (1951). Using the price schedule in Table 4, the lumber recovery value for a 16-foot, 12-inch Douglas fir log is found to be \$70.63 per M f.b.m., and the corresponding value for hemlock was taken 10%* lower, or \$63.57.

In Table 12, the lumber realization values per M f.b.m. and the value of single logs have been computed for logs of various lengths and top diameters.

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* suggested by L. B. Dixon, Chief Inspector, British Columbia Lumber Manufacturers Association (B.C.L.M.A.).

TABLE 12

LUMBER REALIZATION VALUE PER M f.b.m. AND PER LOG OF VARIOUS SIZES

DOUGLAS FIR (F) HEMLOCK (H)

Log D.i.b. in.	Vol. of 16-ft. log B.C. f.b.m.	% Overrun F[1]	% Overrun H[2]	Lumber tally f.b.m. F	Lumber tally f.b.m. H	No. of logs per M F	No. of logs per M H	Lumber realiz. Value $/M F	Lumber realiz. Value $/M H	Value per 16-ft. log F	Value per 16-ft. log H
6	15	85	77	28	27	35.7	37.0	64.17	57.75	1.80	1.56
7	23	60	55	37	36	27.0	27.8	65.36	58.82	2.42	2.12
8	32	50	41	48	45	20.8	22.2	65.47	58.92	3.15	2.65
9	43	43	29	61	55	16.4	18.2	67.81	61.03	4.13	3.35
10	55	33	25	73	69	13.7	14.5	68.94	62.05	5.03	4.28
11	69	27	22	88	84	11.4	11.9	69.83	62.85	6.13	5.28
12	84	23	19	103	100	9.7	10.0	70.63	63.57	7.28	6.36
13	101	21	17	122	118	8.2	8.5	71.32	64.19	8.70	7.55
14	119	19	15	142	137	7.0	7.3	71.86	64.67	10.27	8.86
15	139	18	14	164	158	6.1	6.3	72.33	65.10	11.86	10.33
16	160	17	12	187	179	5.3	5.5	72.56	65.30	13.69	11.87
17	183	16	11	212	203	4.7	4.9	72.59	65.33	15.44	13.33
18	207	15	9	238	226	4.2	4.4	72.62	65.36	17.29	14.85
19	233	15	8	268	252	3.7	4.0	72.41	65.17	19.57	16.29
20	261	14	6	297	277	3.4	3.6	72.07	64.86	21.20	18.02
21	290	14	5	331	304	3.0	3.3	71.47	64.32	23.82	19.49
22	320	14	4	365	333	2.7	3.0	70.91	63.82	26.26	21.27
23	352	13	4	398	366	2.5	2.7	70.72	63.65	28.29	23.57
24	386	13	3	436	397	2.3	2.5	70.45	63.41	30.63	25.36
25	421	13	3	476	434	2.1	2.3	70.08	63.07	33.37	27.42

Log D.i.b. in.	Vol. of 24-ft. log B.C. f.b.m.	Lumber tally f.b.m. F	Lumber tally f.b.m. H	No. of logs per M F	No. of logs per M H	Value per 24-ft. log F	Value per 24-ft. log H	Vol. of 32-ft. log B.C. f.b.m.	Lumber tally f.b.m. F	Lumber tally f.b.m. H	No. of logs per M F	No. of logs per M H	Value per 32-ft. log F	Value per 32-ft. log H
6	23	43	41	23.2	24.4	2.76	2.37	31	57	55	17.5	18.2	3.67	3.17
7	35	56	54	17.9	18.5	3.65	3.18	46	74	71	13.5	14.1	4.84	4.17
8	48	72	68	13.9	14.7	4.71	4.01	64	96	90	10.4	11.1	6.30	5.31
9	64	92	83	10.9	12.0	6.22	5.09	86	123	111	8.1	9.00	8.37	6.78
10	83	110	104	9.1	9.6	7.57	6.46	110	146	137	6.8	7.30	10.14	8.50
11	103	131	126	7.6	7.9	9.19	7.96	137	174	167	5.75	5.99	12.14	10.49
12	126	155	150	6.5	6.7	10.87	9.49	168	207	200	4.83	5.00	14.62	12.71
13	151	183	177	5.5	5.6	12.97	11.46	201	243	235	4.12	4.26	17.31	15.07
14	178	212	205	4.7	4.9	15.29	13.20	238	283	274	3.53	3.65	20.36	17.72
15	208	245	237	4.1	4.2	17.64	15.50	278	328	317	3.05	3.15	23.71	20.67
16	240	281	269	3.6	3.7	20.16	17.65	320	374	358	2.67	2.79	27.18	23.41
17	274	318	304	3.1	3.3	23.42	19.80	366	424	406	2.36	2.46	30.76	26.56
18	311	358	339	2.8	2.9	25.94	22.54	415	477	452	2.10	2.21	34.58	29.57
19	350	403	378	2.5	2.6	28.96	25.06	466	536	503	1.87	1.99	38.72	32.75
20	391	446	414	2.2	2.4	32.76	27.02	521	594	552	1.68	1.81	42.90	35.83
21	434	495	455	2.0	2.2	35.73	29.24	579	660	608	1.52	1.64	47.02	39.22
22	480	548	499	1.8	2.0	39.39	31.91	640	730	666	1.37	1.50	51.76	42.55
23	528	597	549	1.7	1.8	41.60	35.36	704	796	732	1.26	1.36	56.13	46.80
24	578	653	595	1.5	1.7	46.97	37.30	771	871	794	1.15	1.26	61.26	50.33
25	631	713	650	1.4	1.5	50.06	42.05	841	950	978	1.05	1.02	66.74	61.83

1 McBride (1949)

2 McBride (1951)

MILLING COSTS FOR LOGS OF VARYING SIZES

It has been demonstrated through numerous investigations that smaller logs are more costly to handle than larger logs. Ashe (1916), in his investigation in Tennessee, Virginia, and North Carolina, showed that sawing time increased rapidly for logs 16 inches in diameter and less, and also that species and log length affect the rate of production.

A study by Rapraeger (1932) in ponderosa pine region in Eastern and Central Oregon showed that the making of lumber from 6-inch logs was more than three-fold of the cost for 30-inch logs. In Table 13 are summarized the sawing times per M f.b.m., rough green lumber tally basis.

TABLE 13

SAWING TIME IN MINUTES PER M f.b.m. OF LUMBER FOR PONDEROSA PINE LOGS OF VARIOUS DIAMETERS

Log Dia. In.	Min. per M f.b.m.	% of 12 in. times
6	20.4	187.1
8	17.5	160.5
10	12.6	115.6
12	10.9	100.0
14	9.9	90.8
16	9.0	82.6
18	8.4	77.1
20	8.0	73.4
24	7.3	67.0
28	6.8	62.4
32	6.6	60.6

A similar trend was found by Doyle and Calvert (1961) in their mill study on jack pine in Northern Ontario. In Table 14 are shown the average times in man-minutes required to produce one M f.b.m. of lumber.

TABLE 14

EFFECT OF LOG DIAMETER ON THE TIME REQUIRED TO SAW M f.b.m. OF LUMBER

Log Dia. In.	Man-Min. M f.b.m.	% of 12" times
5	460	191.6
6	320	133.3
7	230	95.8
8	200	83.3
9	180	75.0
10	180	75.0
11	200	83.3
12	240	100

Doyle and Calvert's results indicate that the sawmill used was specifically designed for small material, but even in this case, sawing of logs less than 7 inches in diameter becomes rapidly more time-consuming and consequently more expensive.

For the Douglas fir region, Matson and Rapraeger (1950) have given the times required to produce a specified amount of lumber from logs of various sizes. Sawing times at the headrig of a 24-inch Swedish gang-saw for 16-foot logs are shown in Table 15.

TABLE 15

NET SAWING TIME OF 16-FOOT LOGS

PER M f.b.m. OF LUMBER TALLY

Log Dia. In.	Minutes (Fir)	% of 12 in. times
6	53.1	363.6
8	30.7	210.2
10	20.1	137.6
12	14.6	100
14	12.7	86.9
16	11.5	78.7
18	10.4	71.2
20	10.0	71.2

The setting of cost figures requires that the analyst must have access to the accounting figures of a sawmill. Because such information is usually kept secret, it is difficult to deal here with specific figures. Only approximate figures will be used in the present instance.

In establishing the price schedule for lumber products, the prices from the B. C. Interior for autumn 1960 (Table 4) were used. For the same region and the same period of time, average sawmilling costs figures were suggested by Mr. L. B. Dixon of B. C. L. M. A. as reasonable approximations. These cost values are presented in Table 16.

TABLE 16

LUMBER MANUFACTURING COST IN THE

SOUTHERN INTERIOR SELLING PRICE ZONE (SPRING 1960)

(STATIONARY MILLS)

Species	Cost of Sawing Per M f.b.m.	Cost of Planing Per M f.b.m.	Cost of Kiln Drying Per M f.b.m.	Total Cost Per M f.b.m.
Fir & Other	$14.00	$ 8.70	$ -	$22.70
Spruce	15.30	11.70	2.90	29.90
Cedar	15.00	11.20	-	26.30
W. Pine	15.60	12.60	3.60	31.80
Y. Pine	15.10	11.50	2.50	29.10

Assuming that no planing is considered and that the average value in the above tables refers to a log with a diameter of 18 inches*, the cost schedule shown in Table 17 may be set up, based on distribution of sawing times as given by Matson and Rapraeger (1950) in Table 15.

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* This may overestimate the average log size.

TABLE 17

COST OF SAWING PER M f.b.m. LUMBER TALLY OF 16, 24 and 32 FOOT LOGS

Log	Sawing time per M - minutes						$ Cost/M f.b.m.						$ Cost per Log					
Dia.	16-ft. Logs		24-ft. Logs		32-ft. Logs		16-ft.		24-ft.		32-ft.		16-ft.		24-ft.		32-ft.	
In.	F	H	F	H	F	H	F	H	F	H	F	H	F	H	F	H	F	H
	100%		79.2%		65.6%													
6	53.1	55.0	42.1	43.6	34.8	36.1	84.76	87.80	67.13	69.54	55.60	57.60	2.37	2.37	2.89	2.85	3.18	3.16
7	39.5	40.6	31.3	32.2	25.9	26.6	63.50	64.81	50.29	51.33	41.66	42.52	2.35	2.33	2.81	2.77	3.08	3.02
8	30.7	32.8	24.3	26.0	20.1	21.5	49.00	52.36	38.81	41.47	32.14	34.35	2.36	2.36	2.79	2.82	3.09	3.09
9	24.5	27.2	19.4	21.5	16.1	17.8	39.11	43.42	30.98	34.39	25.66	28.48	2.38	2.39	2.84	2.87	3.17	3.16
10	20.1	21.3	15.9	16.9	13.2	13.9	32.07	34.00	25.40	26.93	21.04	22.30	2.34	2.34	2.79	2.81	3.09	3.05
11	16.9	17.6	13.4	13.9	11.1	11.5	26.97	28.09	21.36	22.25	17.69	18.43	2.37	2.36	2.81	2.82	3.08	3.08
12	14.6	15.1	11.6	12.0	9.6	9.9	23.31	24.10	18.46	19.09	15.29	15.81	2.40	2.41	2.84	2.85	3.17	3.16
13	12.9	13.4	10.2	10.6	8.5	8.8	20.58	21.39	16.30	16.94	13.50	14.03	2.51	2.52	2.96	3.03	3.28	3.29
14	12.7	13.1	10.1	10.4	8.3	8.6	20.26	20.91	16.05	16.56	13.29	13.72	2.89	2.86	3.41	3.38	3.76	3.76
15	12.0	12.5	9.5	9.9	7.9	8.2	19.14	19.50	15.16	15.44	12.56	12.79	3.14	3.09	3.70	3.68	4.12	4.06
16	11.5	11.9	9.1	9.4	7.5	7.8	18.00	18.50	14.26	14.65	11.81	12.14	3.40	3.36	3.96	3.96	4.42	4.35
17	10.5	10.9	8.3	8.6	6.9	7.2	17.20	17.60	13.62	13.94	11.28	11.54	3.66	3.59	4.39	4.22	4.78	4.69
18	10.4	10.8	8.2	8.6	6.9	7.1	16.60	17.00	13.15	13.46	10.89	11.15	3.95	3.86	4.70	4.64	5.19	5.05
19	10.4	10.5	8.2	8.3	6.9	6.9	16.60	16.60	13.15	13.15	10.89	10.89	4.49	4.15	5.26	5.06	5.82	5.47
20	9.8	10.2	7.8	8.1	6.4	6.7	15.60	16.10	12.36	12.75	10.23	10.56	4.59	4.47	5.62	5.31	6.09	5.83
21	9.4	10.1	7.4	8.0	6.2	6.6	15.00	15.95	11.88	12.63	9.84	10.46	5.00	4.83	5.94	5.74	6.47	6.38
22	9.3	9.8	7.4	7.8	6.1	6.4	14.90	15.50	11.80	12.28	9.77	10.17	5.52	5.17	6.56	6.14	7.13	6.78
23	9.1	9.6	7.2	7.6	6.0	6.3	14.60	15.15	11.56	12.00	9.58	9.94	5.84	5.61	6.80	6.67	7.60	7.31
24	8.9	9.5	7.0	7.5	5.8	6.2	14.20	15.00	11.25	11.88	9.32	9.84	6.17	6.00	7.50	6.99	8.10	7.81
25	8.8	9.5	7.0	7.5	5.8	6.2	14.00	14.90	11.09	11.80	9.18	9.77	6.67	6.48	7.92	7.87	8.74	9.58

DETERMINATION OF NET VALUE OF LOGS IN THE MILL POND

Manufacturing costs shown in Table 17 are subtracted from the lumber realization values of Table 12. The net values per M f.b.m. (lumber tally basis) are shown in Table 18.

TABLE 18

CONVERSION RETURN PER M f.b.m. AND PER LOG

OF VARIOUS LENGTHS AT THE MILL POND

Log Top	$ Value per M f.b.m.						Net Value of One Log $					
D.i.b.	16 ft.		24 ft.		32 ft.		16 ft.		24 ft.		32 ft.	
In.	F	H	F	H	F	H	F	H	F	H	F	H
6	-20.59	-30.05	-2.96	-11.79	8.57	0.15	-0.57	-.81	-.13	-.48	.49	.01
7	1.86	- 5.99	15.07	7.49	23.70	16.30	0.07	-.21	.84	.41	1.76	1.15
8	16.47	6.56	26.66	17.45	33.33	24.57	0.79	0.29	1.92	1.19	3.21	2.22
9	28.70	17.61	36.83	26.64	42.15	32.55	1.75	0.96	3.38	2.22	5.20	3.62
10	36.87	28.05	43.54	35.12	47.90	39.75	2.69	1.94	4.78	3.65	7.05	5.45
11	42.86	34.76	48.47	40.60	52.14	44.42	3.76	2.92	6.38	5.14	9.06	7.41
12	47.32	39.47	52.17	44.48	55.34	47.76	4.88	3.95	8.03	6.64	11.45	9.55
13	50.74	42.80	55.02	47.25	57.82	50.16	6.19	5.03	10.01	8.43	14.03	11.78
14	51.60	43.76	55.81	48.11	58.57	50.95	7.38	6.00	11.88	9.82	16.60	13.96
15	53.19	45.60	57.17	49.66	59.77	52.31	8.72	7.24	13.94	11.82	19.59	16.61
16	54.56	46.80	58.30	50.65	60.75	53.16	10.29	8.51	16.20	13.69	22.76	19.06
17	55.39	47.73	58.97	51.39	61.31	53.79	11.78	9.74	19.03	15.58	25.98	21.87
18	56.02	48.36	59.47	51.90	61.73	54.21	13.34	10.99	21.24	17.90	29.39	24.52
19	55.81	48.57	59.26	52.02	61.52	54.28	15.08	12.14	23.70	20.00	32.90	27.28
20	56.47	48.76	59.71	52.11	61.84	54.30	16.61	13.55	27.14	21.71	36.81	30.00
21	56.47	48.37	59.59	51.69	61.63	53.86	18.82	14.66	29.79	23.50	40.55	32.84
22	56.01	48.32	59.11	51.54	61.14	53.65	20.74	16.10	32.83	25.77	44.63	35.77
23	56.12	48.50	59.16	51.65	61.14	53.71	22.45	19.96	34.80	28.69	48.53	39.49
24	56.25	48.41	59.20	51.53	61.13	53.57	24.46	19.36	39.47	30.31	53.16	42.52
25	56.08	48.17	58.99	51.27	60.90	53.30	26.70	20.94	42.14	34.18	58.00	52.25

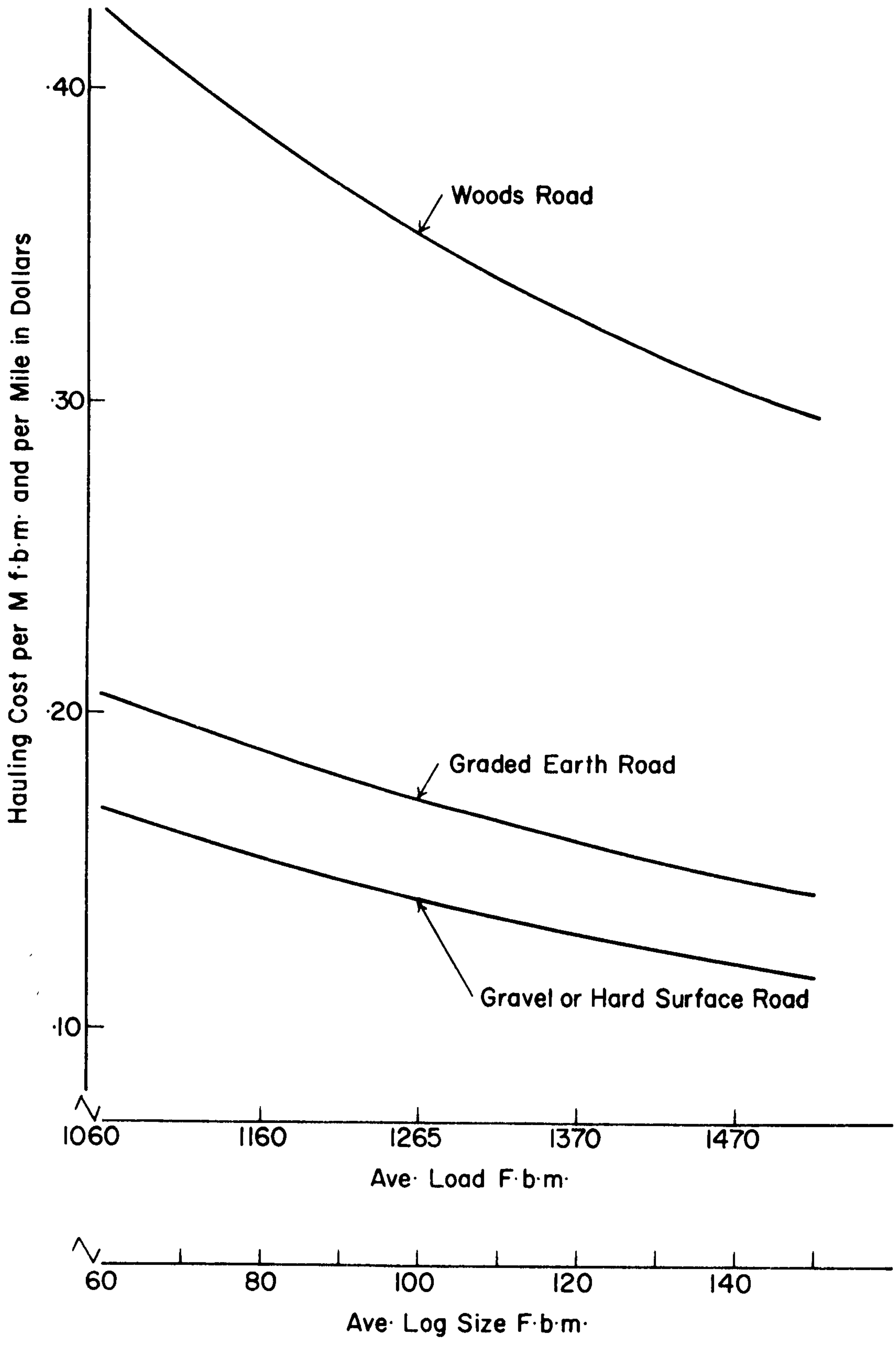
TRANSPORTATION AND LOGGING COSTS BY LOG SIZE

Logging is conducted under operating conditions which vary constantly. Each individual logging unit, however small, presents a different problem to the operator. Fortunately, a large number of systematic logging studies have been carried out throughout the years and these records afford a means of estimating the performance for a defined set of logging conditions.

In addition to published data which will be presented in subsequent paragraphs, the author has conducted some original time studies in the University Research Forest near Haney, B. C. These various sources will be used to establish costs for hauling, loading, yarding, bucking and falling operations.

A. THE EFFECT OF TYPE OF ROAD ON HAULING COST

The effect of road type on pulpwood and log production costs has been investigated by Reynolds (1936) in the pine-hardwood region of Louisiana, Arkansas and Texas. He demonstrated in this study that the hauling cost per M f.b.m. decreased with increasing quality of road surface and increasing average log size. The costs per M f.b.m. of hauling logs for one mile over three types of roads are shown in Figure 1. Cost data of this nature may be used as a basis for determining whether construction of a certain type of road is justified,



Fig· I Effect of Road Type on Hauling Cost provided the volume to be hauled over that road is known approximately.

Tessier and Knapp (1961) reported a road construction cost of $16,452 per mile for the University Research Forest. The hauling on the same road was later done by contract at a rate of $6.25 per M f.b.m. The total hauling distance was 18.1 miles, with 14.1 miles on surfaced highway and the remaining 4 miles on a Forest logging truck road. This contract hauling represents a cost of $0.35 per M f.b.m. per mile.

B. THE EFFECT OF LOG SIZE ON HAULING COST

In addition to hauling distance and road surface, hauling cost depends on log size. Doyle and Calvert (1961) reported that the hauling cost of jack pine logs in Ontario decreased with increasing log size, and that the rate of decrease was most rapid in the smallest log sizes. Thus the cost of hauling five-inch logs was more than twice that for logs eleven inches in diameter. These costs included both hauling and loading.

During June, 1961 the loading of 18 truckloads of logs was observed and timed by the author in the University Research Forest. The mean load was 2,589 f.b.m. with a standard deviation of 248 f.b.m., although the number of logs in these loads ranged from 6 to 36. The relative consistency of the load volume meant that the hauling cost per load and per mile did not differ much with the varying log size. Using the previously quoted figure of 35 cents per M f.b.m. per mile, the cost of an 18-mile trip would have ranged from \$12.19 to \$29.85 per load, varying directly with the load volume.

Bradner et al. (1933) reported hauling studies for ponderosa pine logs with a 7½-ton truck. It was found in hauling that the bulk, rather than weight, was the limiting factor. This precludes the handling of enough small logs to equal the scale of larger logs that could be carried. Hauling distance also increases the loss in output of small as compared with large timber. The gross output per hour for all sizes of timber decreases as the hauling distance increases; regardless of the scale per load, fewer trips are made per hour or day.

Reynolds et al. (1944) presented the number of man-hours required for a 4-mile truck haul in the second-growth pine-hardwood forest in the Southern U. S. A. The current cost figure may be obtained from that information by multiplying the number of man-hours by going hourly rate of pay (e.g. \$2), shown in Table 19.

TABLE 19

HAULING COST PER M f.b.m. ACCORDING TO

REYNOLDS *et al.* (1944)

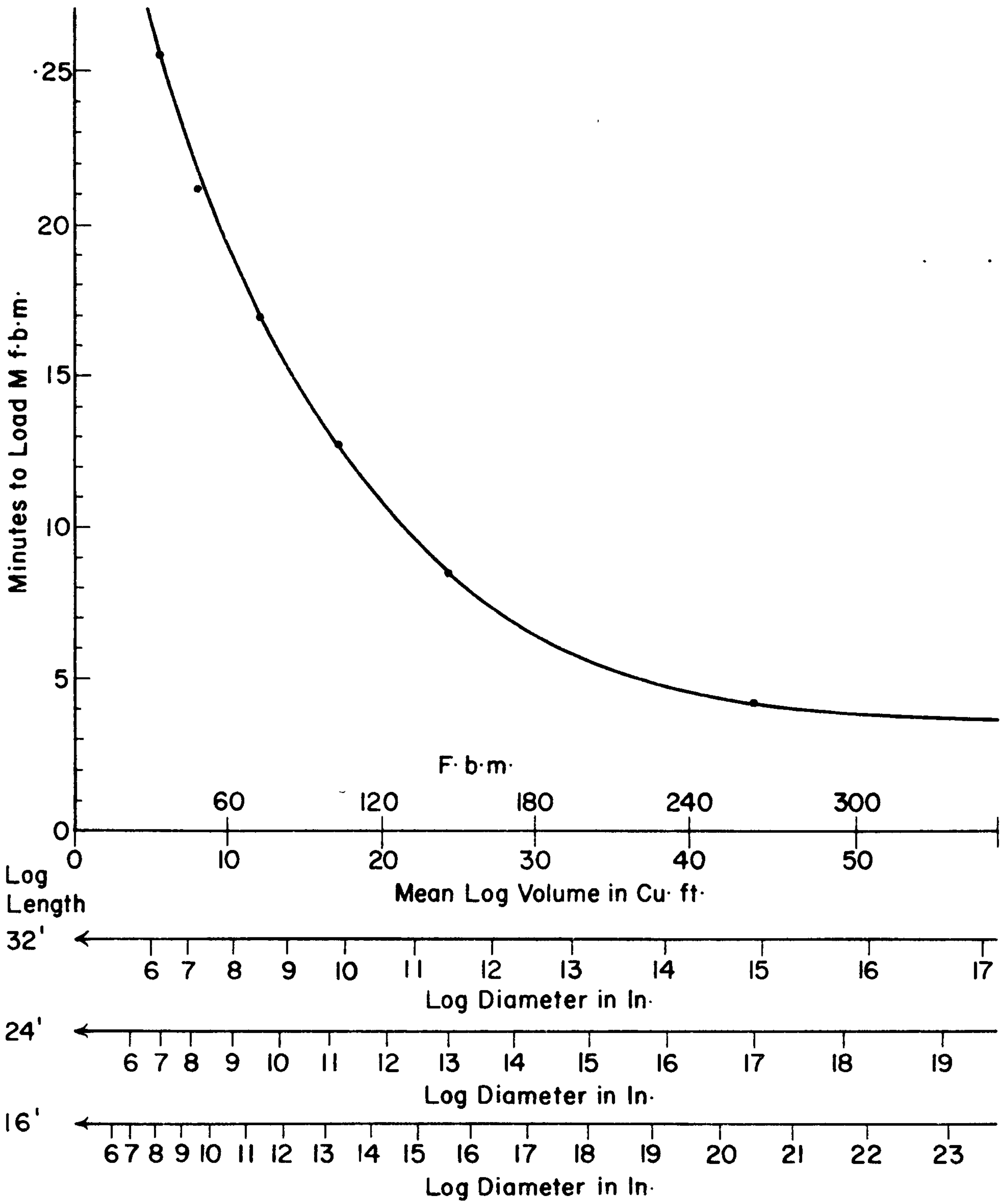
D.b.h.	Man-hours	Cost per 4 miles	Cost per 18 miles
12	2.917	$5.834	$26.25
14	2.148	4.296	19.33
16	1.740	3.480	15.66
18	1.564	3.128	14.08
20	1.433	2.866	12.90
24	1.156	2.312	10.40
30	.984	1.968	8.86

Reynolds' higher costs, as compared to today's rates, are the result of technological improvements in truck and road design.

C. LOADING COST

Although the hauling cost of full truckloads was found not to be influenced much by log diameters, the loading operation studied by the author was significantly influenced by log size. The performance of a 4-man crew at the University Research Forest is shown in Figure 2. This curve shows the time in minutes needed to load one M f.b.m. of logs of various lengths and diameters.

Tessier and Knapp (1961) reported an average loading cost $2.90 per M f.b.m. The size of the average log was 400 f.b.m. Assuming machine rental as $2.00 per hour and labourers' rate of pay as $2.00 per hour, a cost schedule may be set up for loading of logs of various sizes as shown in Table 20.



Fig· 2 Effect of Mean Log Volume on Loading Rate· University Research Forest, June 1961

TABLE 20

LOADING AND HAULING COSTS PER M f.b.m. AND LOG

FOR 16, 24 AND 32-FOOT LOGS

Top D.i.b. In.	Time to Load M f.b.m. min.			$ Cost of Loading per M f.b.m. *			Hauling Cost	Total Loading & Hauling Cost per M			Total Loading & Hauling Cost per Log $					
											16 ft.		24 ft.		32 ft.	
	16 ft.	24 ft.	32 ft.	16 ft.	24 ft.	32 ft.	18 mi.	16 ft.	24 ft.	32 ft.	F	H	F	H	F	H
6	33.2	29.5	26.5	5.53	4.92	4.42	6.30	11.83	11.22	10.72	.33	.32	.48	.46	.62	.59
7	29.5	25.5	22.6	4.92	4.25	3.77	"	11.22	10.55	10.07	.42	.40	.59	.57	.75	.71
8	26.3	22.2	19.0	4.38	3.70	3.17	"	10.68	10.00	9.47	.51	.48	.72	.68	.91	.85
9	23.4	19.0	15.2	3.90	3.17	2.53	"	10.20	9.47	8.83	.62	.56	.87	.79	1.09	.98
10	20.8	15.8	12.4	3.47	2.63	2.07	"	9.77	8.93	8.37	.71	.67	.98	.93	1.23	1.15
11	18.0	13.2	9.6	3.00	2.20	1.60	"	9.30	8.50	7.90	.82	.78	1.12	1.08	1.37	1.32
12	15.6	10.6	7.4	2.60	1.77	1.23	"	8.90	8.07	7.53	.92	.89	1.24	1.20	1.56	1.51
13	13.4	8.6	5.8	2.23	1.43	.97	"	8.53	7.73	7.27	1.04	1.00	1.41	1.38	1.76	1.71
14	11.3	6.9	4.8	1.88	1.15	.80	"	8.18	7.45	7.10	1.17	1.12	1.59	1.52	2.01	1.95
15	9.6	5.6	4.2	1.60	.93	.70	"	7.90	7.23	7.00	1.29	1.29	1.76	1.72	2.29	2.22
16	7.9	4.8	3.8	1.32	.80	.63	"	7.62	7.10	6.93	1.44	1.39	1.97	1.92	2.60	2.48
17	6.7	4.2	3.7	1.12	.70	.62	"	7.42	7.00	6.92	1.58	1.51	2.26	2.12	2.93	2.81
18	5.6	4.0	3.7	.93	.67	.62	"	7.23	6.97	6.92	1.72	1.64	2.49	2.40	3.30	3.13
19	5.0	3.8	3.7	.83	.63	.62	"	7.13	6.93	6.92	1.93	1.78	2.77	2.67	3.71	3.48
20	4.5	3.7	3.7	.75	.62	.62	"	7.05	6.92	6.92	2.07	1.96	3.15	2.88	4.12	3.82
21	4.1	3.7	3.7	.68	.62	.62	"	6.98	6.92	6.92	2.33	2.11	3.46	3.14	4.55	4.22
22	3.9	3.7	3.7	.65	.62	.62	"	6.95	6.92	6.92	2.57	2.32	3.84	3.46	5.05	4.61
23	3.7	3.7	3.7	.62	.62	.62	"	6.92	6.92	6.92	2.77	2.56	4.07	3.84	5.49	5.09
24	3.7	3.7	3.7	.62	.62	.62	"	6.92	6.92	6.92	3.01	2.77	4.61	4.07	6.02	5.49
25	3.6	3.7	3.7	.60	.62	.62	"	6.90	6.92	6.93	3.29	3.00	4.94	4.61	6.59	6.78

* Hourly Cost: 4-man Crew - $8 per hr.
Machine - $2 per hr.
Total $10 per hr. (or 16.67 cents per min.)

If the total cost per M f.b.m. of loading and hauling is subtracted from the net log value at the mill pond, net value at the woods landing is obtained. These values are presented in Table 21.

TABLE 21

NET VALUE OF LOGS AT THE WOODS LANDING SITE

Log Top D.i.b. In.	$ Value per M f.b.m. Scale						Net Value of One Log $					
	16 ft.		24 ft.		32 ft.		16 ft.		24 ft.		32 ft.	
	F	H	F	H	F	H	F	H	F	H	F	H
6	-32.42	-41.88	-14.18	-23.01	-2.15	-10.57	-.90	-1.13	-.61	-.94	-.13	-.58
7	- 9.36	-17.21	4.52	- 3.06	13.63	6.23	-.35	- .60	.25	-.16	1.01	.44
8	5.79	- 4.12	16.66	7.45	23.86	15.10	.28	- .19	1.20	.51	2.30	1.37
9	18.50	7.51	27.36	17.17	33.32	23.72	1.13	.40	2.51	1.43	4.11	2.64
10	27.10	18.28	34.61	26.19	39.53	31.38	1.98	1.27	3.80	2.72	5.82	4.30
11	33.56	25.46	39.97	32.10	44.24	36.52	2.94	2.14	5.26	4.06	7.69	6.09
12	38.42	30.57	44.10	36.41	47.81	40.23	3.96	3.06	6.79	5.44	9.89	8.04
13	42.21	34.27	47.29	39.52	50.55	42.89	5.15	4.03	8.60	7.05	12.27	10.07
14	43.42	35.58	48.36	40.66	51.47	43.85	6.21	4.88	10.29	8.30	14.59	12.01
15	45.29	37.70	49.94	42.43	52.77	45.31	7.43	5.95	12.18	10.10	17.30	14.39
16	46.94	39.18	51.20	43.55	53.82	46.23	8.85	7.12	14.23	11.77	20.16	16.58
17	47.97	40.31	51.97	44.39	54.39	46.87	10.20	8.23	16.77	13.46	23.05	19.05
18	48.79	41.13	52.50	44.93	54.81	47.29	11.62	9.35	18.75	15.50	26.09	21.39
19	48.68	41.44	52.33	45.09	54.60	47.36	13.15	10.36	20.93	17.33	29.19	23.80
20	49.42	41.71	52.79	45.19	54.92	47.38	14.54	11.59	23.99	18.83	32.69	26.18
21	49.49	41.39	52.67	44.77	54.71	46.94	16.49	12.55	26.33	20.36	36.00	28.62
22	49.06	41.37	52.19	44.62	54.22	46.73	18.17	13.78	28.99	22.31	39.58	31.16
23	49.20	41.58	52.24	44.73	54.22	46.79	19.68	15.40	30.73	24.85	43.04	34.40
24	49.33	41.49	52.28	44.61	54.21	46.65	21.45	16.59	34.86	26.24	47.14	37.03
25	49.18	41.27	52.07	44.35	53.98	46.38	23.41	17.94	37.20	29.57	51.41	45.47

D. YARDING COSTS

Many time studies of yarding by log sizes have been conducted over the years. A comprehensive study was carried out by Bradner et al. (1933) in the Inland Empire. In this study skidding output data were analysed for horse, tractor and donkey (groundline) skidding.

Results of their studies indicate consistently that output in skidding, for the various methods, increases with decreasing skidding distance and increasing log size. Thus when skidding with horses in the ponderosa pine type on 0 to 15 per cent slopes, the output in timber with 3 to 5 logs per thousand, skidded a distance of 100 feet, is three times as high as in timber with 18 to 25 logs per thousand. In general, it was found that a smaller output, as the size of material decreased, was attributable to the increased handling time in making up and unhooking the load. With the tractor, a limit in the number of pieces which can be skidded per load is reached in the smaller material before the weight has become an appreciable effect. Therefore, a greater difference is found between the output for small and large timber in tractor skidding than in horse skidding.

Tennas et al. (1955) studied high lead yarding costs in Western Oregon. They found that haul-in distance and volume per turn were the most significant factors on haul-in time. The haulback time, for a given speed, is determined by haul-in distance. Choker set time increased as the distance from the spar tree increased and obviously decreased when several choker setters were used. Finally, unhooking time was found to increase with number of logs yarded per turn. Tennas et al. summarized their findings in the following regression equation:

$$Y = 366.43 + .451D + .000265D^2 + .0000485DV$$
$$+ .00072VS - 49.25C + 8.60N\ldots\ldots.(10)$$

Where Y = Time per turn in 1/100 minute

D = Haul-in distance in feet

V = Volume per turn in board feet by the Scribner rule

S = Slope in per cent

C = Number of choker setters (including head rigger)

N = Number of logs per turn

No provision was made in their report to study the effect of individual log size on operating time and cost.

Stewart (1961) in his salvage study at the University Research Forest reported a yarding cost of \$16.16 per M f.b.m. as compared to the average cost of yarding of \$3.64 on West Coast Vancouver Island.

McIntosh and Gunn (1960) studied the performance of high-lead yarding in a pre-logging operation with a portable steel spar. Yarding time per 100 cubic feet, as related to net turn volume and yarding distance, is shown in Table 22.

TABLE 22

YARDING TIMES OF VARIOUS TURN VOLUMES

Turn Volume Cu. Ft.	Man-Minutes Per Cu. Ft.	
Yarding Distance	505 ft.	365 ft.
20	331.5	205.0
40	170.9	111.5
60	117.0	77.5
80	90.3	58.5
100	70.2	46.0
120	55.2	35.5
140	45.5	28.5
160	39.0	22.5
180	33.1	17.5
200	29.9	-
220	26.6	-
240	23.4	-

Time requirements for the various phases of yarding operations were distributed according to the time breakdown in Table 23.

TABLE 23

BREAK-DOWN OF YARDING TIME REQUIREMENTS

Operation	Per Cent of Total Time	
Yarding Distance	505 ft.	365 ft.
Haulback	5.7	6.1
Stop Chokers	4.7	5.8
Hook-up	26.1	24.6
Haul	19.0	15.0
Unhook Chokers	7.8	9.0
Hang-ups	11.3	3.3
Landing Delays	3.9	1.2
Other Delays	21.5	35.0

Tessier and Knapp (1961) reported on the operation of a Madill Mobile steel spar. The average cost was $4.76 per M f.b.m. and the average log size in this operation was 413 f.b.m.

The time studies which the author conducted at the University Research Forest also included a yarding study. The equipment used was a 10-10 Lawrence donkey, a 70-foot spar tree and a 4-man crew. The high-lead method of yarding was used. The haulback time was found to vary with the skidding distance as in Table 24.

TABLE 24

HAULBACK TIMES AT UNIVERSITY RESEARCH FOREST

SALVAGE LOGGING OPERATION, JUNE 1961

Distance, Feet	Time, Minutes
60	.193
100	.215
200	.390
250	.370
300	.361
350	.450
400	.588
450	.716
500	.836

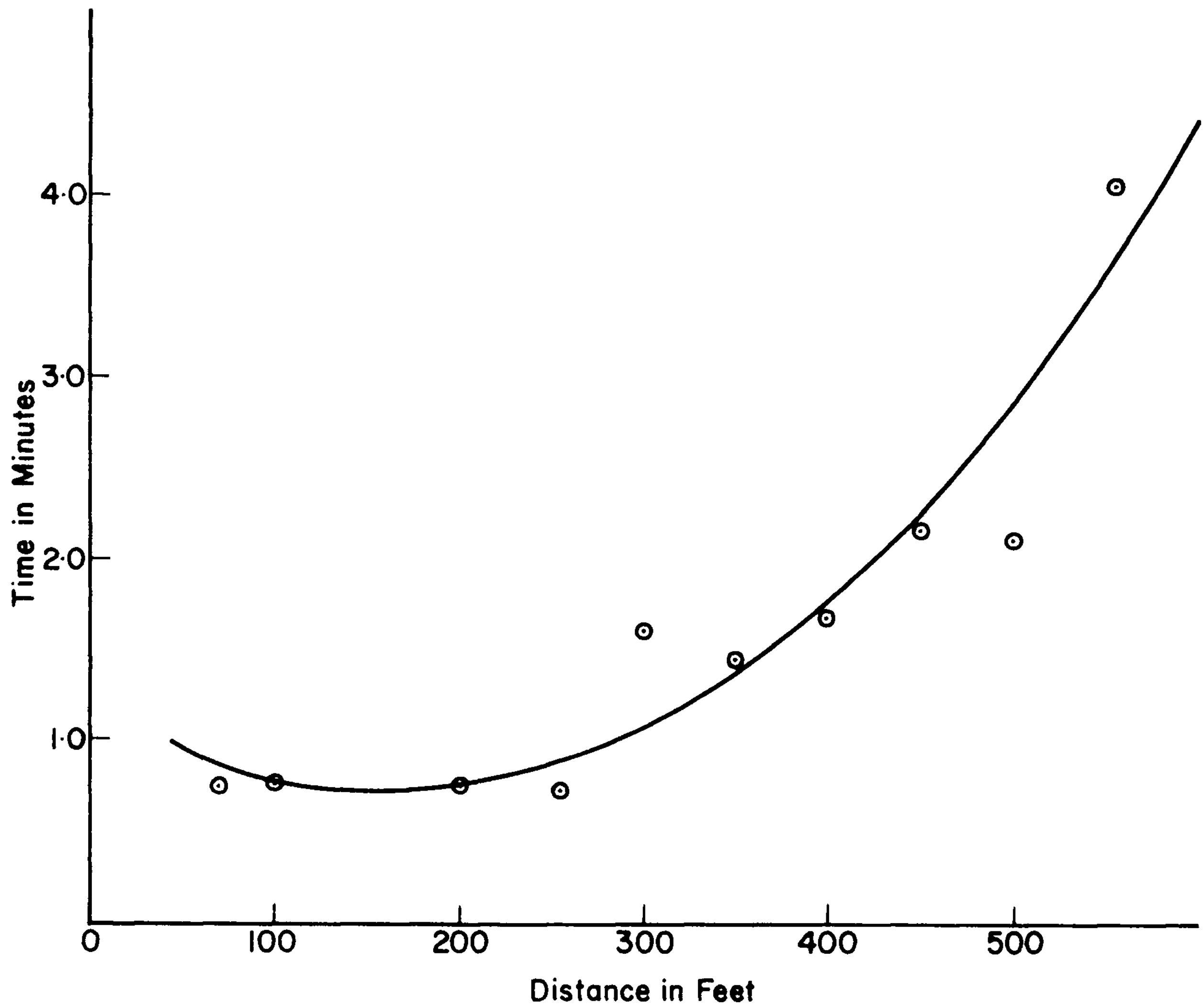
An attempt was made to correlate yarding time and log volume yarded. No correlation was detected between these variables. However, a definite relationship existed between yarding time (Y) and yarding distance (X). This relationship may be described by the following regression equation:

$$Y = 1.229 - 0.633X + 0.193X^2 \ldots\ldots(11)$$

This relationship is also shown in Figure 3.

The lack of correlation between yarding time and log volume seems to contradict the results of Tennas _et al_. (1955), who based their findings on a sample of 2,304 logs. The University Forest study included the yarding times of only 173 logs and consequently failed to show the effect of log volumes due to the much smaller sample.

If skidding distance is the major factor, skidding cost becomes a function of the mean length of yarding road. The relationship is not strictly linear, because with increasing yarding road length haulback time increases, and also the choker-set time increases, as shown by Tennas _et al_. At the University Research Forest, the mean choker-set time was 1.28 minutes and it did not vary significantly with haul-in distance. During the same operation, the mean skidding distance was 380 feet. At that distance the haul-in time equalled 1.60 minutes. Added to this are 1.28 minutes for choker-set, 0.5 minutes for unhooking, and 0.58 minutes for haulback, for a total of 3.96 minutes. The mean turn volume during the investigation was 26.66 cu. ft. so that the mean rate of production was 404 cu. ft. per hour. If the size of the log is varied, a whole schedule of production rates may be computed. These production rates fall under the following direct costs:



Fig· 3 Effect of Yarding Distance on Highlead Yarding Time·
University Research Forest, June 1961·

Labor: 4 men @ \$2.00 per hr. = \$ 8.00/hr.

Machine Rental: \$ 2.00/hr.

Total = \$10.00/hr.

In addition to directly productive time, the yarding operation requires time for changing yarding roads, changing corner blocks, swinging blocks on the spar tree and tightening guy lines. Times for changing yarding roads and corner blocks are fixed times per road. It is assumed here that it takes two days to move the donkey and erect a new spar tree.

The average cost of yarding may be based on following considerations. Assuming a setting with 600 ft. radius, the area thus covered equals 25.7 acres. If one acre contains 606 cu. ft. of yardable material (Stewart, 1961) then the total accessible material on this setting is 15,733 cu. ft. or 96,286 f.b.m. Assuming a working rate of 2,150 f.b.m. per hour, the total effective yarding time necessary is

$$\frac{96.286}{2,470} = 39 \text{ hr.}$$

Assuming further that there are 40 roads to the 360° of the setting and that each change of road requires one-half-hour, an additional 20 hours will be required. The total working time will be 59 hours, or approximately 60 hours.

Under ideal working conditions, where effective working time in an 8-hour day is 6 hours, the setting should be finished in $\frac{60}{6} + 2 = 12$ days. The daily cost of a crew of four and the donkey was assumed to be \$80.00. The total cost per setting then would be 12 x 80 = \$960 or $\frac{960}{96.286}$ = \$10.00 per M f.b.m.

The real situation at the University Research Forest showed an effective working time (yarding time and loading time) of only 3½ hours per 8-hour working day.* Then, instead of \$10.00, the apparent hourly cost will be $\frac{8 \times 10}{3\frac{1}{2}}$ = \$22.86, if the productive time alone is charged with the daily cost of \$80.00. At this rate, $\frac{60}{3\frac{1}{2}} + 2 = 19$ days are required to finish a setting. The cost for this time will be 19 x 80 = \$1,520 or $\frac{1,520}{96.286}$ = \$15.79 per M f.b.m. This hypothetical figure is fully comparable to Stewart's cost, quoted as \$16.16.

As a rule, two or more logs are hauled simultaneously, thereby increasing productivity and lowering unit cost. Thus the cost per M f.b.m. becomes a function of volume per turn, rather than the size of an individual log. Consequently the yarding cost will vary with the size of a load but remains constant if considered on a "per log" basis.

It is assumed that the mainline has two chokers and that the logs hauled have equal diameters. In Table 25 the volumes of such pairs of logs have been assembled and the cost of yarding per M f.b.m. The cost per log, which is constant for the mean yarding distance of 400 feet, is \$0.80 in this case.

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* All operations studied were "gyppo", working on a production contract basis only. They were not directly employed and supervised by the University Research Forest.

TABLE 25

HIGHLEAD YARDING COST PER M f.b.m. OVER A MEAN DISTANCE OF 400 FEET

Log Top	Volume of Two Logs, Lumber Tally						Yarding Cost per M f.b.m. *					
D.i.b.	16 ft.		24 ft.		32 ft.		16 ft.		24 ft.		32 ft.	
in.	F	H	F	H	F	H	F	H	F	H	F	H
6	56	54	86	82	114	110	28.44	29.49	18.52	19.42	13.97	14.48
7	74	72	112	108	148	142	21.52	22.12	14.22	14.74	8.80	11.21
8	96	90	144	136	192	180	16.59	17.69	11.06	11.71	8.29	8.85
9	122	110	184	166	246	222	13.05	14.48	8.65	9.59	6.47	7.17
10	146	138	220	208	292	274	10.91	11.54	7.24	7.66	5.45	5.81
11	176	168	262	252	348	334	9.05	9.48	6.08	6.32	4.58	4.77
12	206	200	310	300	414	400	7.73	7.96	5.14	5.31	3.85	3.98
13	244	236	366	354	486	470	6.53	6.75	4.35	4.50	3.28	3.39
14	284	274	424	410	566	548	5.61	5.81	3.76	3.88	2.81	2.91
15	328	316	490	474	656	634	4.85	5.04	3.25	3.36	2.43	2.51
16	374	358	562	538	748	716	4.26	4.45	2.83	2.96	2.13	2.22
17	424	406	636	608	848	812	3.76	3.92	2.50	2.62	1.88	1.96
18	476	452	716	678	954	904	3.35	3.52	2.22	2.35	1.67	1.76
19	536	504	806	756	1072	1006	2.97	3.16	1.98	2.11	1.48	1.58
20	594	554	892	828	1188	1104	2.68	2.87	1.79	1.92	1.34	1.44
21	662	608	990	910	1320	1216	2.41	2.62	1.61	1.75	1.21	1.31
22	730	666	1096	998	1460	1332	2.18	2.39	1.45	1.60	1.09	1.19
23	796	732	1194	1098	1592	1464	2.00	2.18	1.33	1.45	1.00	1.09
24	872	794	1306	1190	1742	1588	1.83	2.01	1.22	1.34	.91	1.00
25	952	868	1426	1300	1902	1956	1.67	1.83	1.12	1.22	.84	.81

* Full turn = 4.18 minutes
1 min. cost = $ .38095
4.18 = $1.5924

If these values are applied to the table of net log values at landing (Table 21), it becomes immediately apparent that the minimum fir log to be yarded is 10 inches in top diameter. For hemlock this size is 11 inches. Before net values after felling and bucking are computed, yarding costs for tractor- and horse-skidding will also be explored.

Gunn and Guernsey (1958) reported the results on five tractor operations in the B. C. Interior, in which it was pointed out that a notably long time was used for the hook-up phase of the work. Also, a relationship was found between turn volume and skidding distance. Thus it takes approximately the same time to skid 250 cu. ft. a distance of 280 feet as it does to skid 550 cu. ft. a distance of 2,720 feet, per unit volume. Consequently, per unit volume, it is more economical to skid larger volumes greater distances than to skid small volumes short distances. The distance factor could often be multiplied, or its effect reduced, by more effective supervision in regard to turn volume, according to the authors. For these five operations, the time was distributed between the various phases of yarding as follows:

1.	Make road and swamp....................	6.8%
2.	Return..................................	15.1
3.	Hook-up.................................	33.0
4.	Haul....................................	17.1
5.	Unhook..................................	6.6
6.	Hang-up.................................	1.1
7.	Non-productive time.....................	20.3
		100.0%

The effects of skidding distance and turn volume on skidding time in the five operations investigated are shown in Table 26.

TABLE 26

SKIDDING TIME - MACHINE MINUTES PER 100 CU. FT. (GUNN AND GUERNSEY)

Turn Vol. Cu. Ft.	Operation A				B			C		D	E
	Crew Size - 3				3			3		2	2
	Skidding Distance - feet										
	280	660	1640	2720	180	620	715	190	370	190	1280
50	-									17.7	-
100	-				15.6	17.4	19.0	13.8	-	11.9	-
150					10.9	12.8	14.3	11.8	14.9	8.5	-
200	12.9				7.4	9.2	10.5	10.2	12.9	-	-
250	10.7				5.3	7.7	8.8	9.2	11.5	-	18.5
300	8.8	10.6	14.6		4.3	6.9	8.2	8.4	10.3	-	16.0
350	7.4	9.2	12.8		3.7	6.4	7.7		9.1	-	13.7
400	6.4	8.0	11.2	14.1	3.2	6.0	7.1		7.9	-	11.7
450	5.8	7.3	10.0	12.5		5.6	6.6			-	10.3
500	5.2	6.7	9.2	11.3		5.4	6.0			-	9.6
550	4.8	6.2	8.5	10.5						-	9.0
600	4.5	5.7	7.8	9.8						-	8.6
650	-	-	-	9.4						-	-
700	-	-	-	8.9							

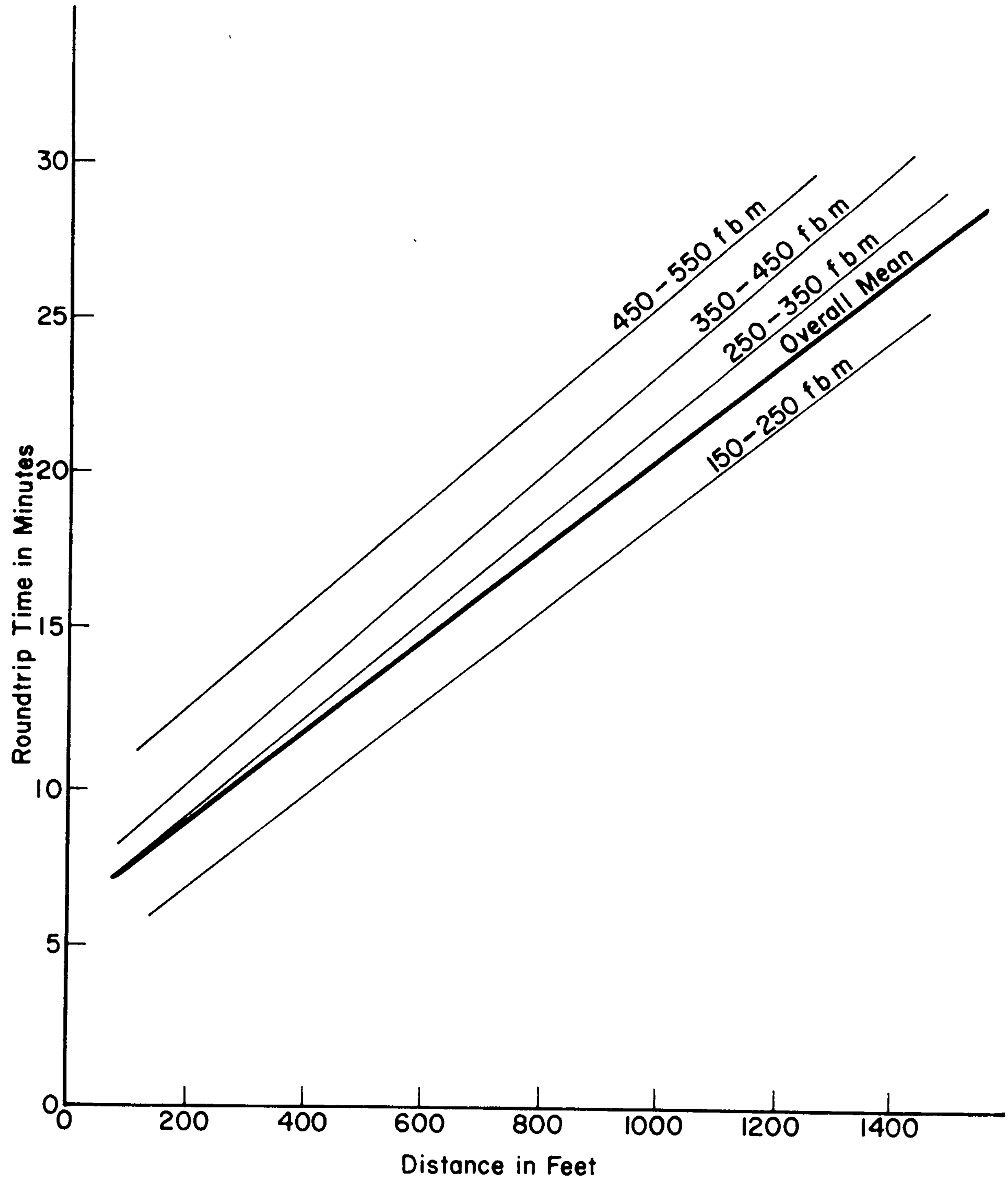


Fig. 4 Effect of Yarding Distance and Volume on Roundtrip Time; D-2 Tractor Operation, University Research Forest; March, 1961.

Tractor yarding was studied during alder logging in March 1961 at the University Research Forest. The volumes of single trips varied between 145 and 840 f.b.m. and the yarding distances varies between 150 and 1,400 feet. In Figure 4 is shown the effects of these two factors on the times of a roundtrip.

Cost of tractor yarding.

Machine rate	-	\$ 3.00 per hour
Driver "	-	\$ 2.00 per hour
Chokerman "	-	$\frac{1}{2}$ x \$2.00 per hour (used half the time)

Total Yarding Cost - \$ 6.00 per hour.

If it is assumed that out of the 8-hour working day only $5\frac{1}{2}$ hours are spent in active yarding, the apparent hourly rate is $\frac{6 \times 8}{5\frac{1}{2}} = \$8.73$. From Figure 4 the mean roundtrip for a 600 ft. skidding distance is 15 minutes. Assuming that three logs are hauled out simultaneously, the cost per turn would be $\frac{60 \times 8.73}{15} = \$3.49$ and the cost per log is \$1.16.

In this case the log size was ignored mainly because the original field measurements were not sufficiently numerous and showed a considerable variation about the mean value. Thus, the production rate for 12 in. d.i.b. logs 16 feet long would be $\frac{309 \times 60}{15} = 1235$ f.b.m. per hour and the cost $\frac{8.73 \times 1000}{1235} =$ \$7.07 per M f.b.m.

Computation shows that D-2 yarding is somewhat more economical than high-lead yarding (Table 25). This is true only if the high-lead works with the present low efficiency and that the D-2 will yard out at least three logs per turn. That, of course, is not always the case.

E. HORSE SKIDDING

Doyle (1957) and Doyle and Calvert (1961) have studied the performance of horse skidding in Eastern Canada. The reported average skidding cost varied from $3.26 to $5.50 per M f.b.m., and decreased with increasing log size.

Silversides (1960) gave the time study data in Table 27 on skidding pulpwood by bolt size and distance yarded.

TABLE 27

HORSE-SKIDDING TIMES PER CORD OF 100 IN. (OR 8 FT.) BOLTS, BY LOG DIAMETER CLASS AND DISTANCE

Log Dia.	Time Required per Cord with Skidding Distance of:		
In.	100 ft.	200 ft.	300 ft.
6	0.78	1.22	1.40
8	0.78	1.22	1.40
10	0.62	0.97	1.10
12	0.53	0.82	0.93
14	0.43	0.67	0.77

Worthington and Staebler (1961) showed that for products whose volume is less than 10 cu. ft., horses are most satisfactory for skidding, provided that the terrain is favourable and skidding distances are less than 600 feet. The time study results by these authors are given in Table 28.

TABLE 28

HOURLY PRODUCTION (CU. FT.) FOR HORSE-SKIDDING OF 8-FOOT LOGS, BY SKIDDING DISTANCE AND LOG DIAMETER

Log Dia.	Skidding Distance in Feet				
In.	100	200	400	600	800
7	32	26	20	16	13
8	41	33	26	20	16
10	62	50	39	30	24
12	82	65	48	36	29
14	105	80	57	42	33

The cost of owning and using a horse as given by Worthington (1957) is:

Fixed Cost per horse-hour..........	$0.119	
Variable " " " "	0.277	
Total " " " "	$0.396	$.40

This cost is based on an initial cost for a horse of $100 to $175, less salvage $25 and a working life of 4 years. The annual working time was assumed to be 1,600 hours per 200 days (8-hr. day). If the hourly wage of the teamster is $2.00 and it is assumed that a team produces 5½ hours of active yarding each day, then the cost for horse skidding can be estimated as shown in Table 29.

TABLE 29

COST OF HORSE-SKIDDING - DISTANCE 400 FEET

Log Dia. In.	Volume per hour (8-foot log) cu. ft.*	M f.b.m. Full Eff.	M f.b.m. Adj. for 68% Eff.	Yarding Cost/M (Hourly Cost $2.40)
10	39	0.245	0.168	$14.28
11	46	0.299	0.206	11.65
12	48	0.319	0.219	10.96
13	49	0.332	0.228	10.53
14	57	0.393	0.270	8.89

* from Table 28.

It is evident, by comparison with D-2 Caterpillar tractor, that yarding with a horse becomes somewhat more expensive.

F. NET VALUE OF LOGS IN THE WOODS

The foregoing cost figures have shown that, under the prevailing conditions in the University Research Forest in June, 1961, the yarding operation was carried out more economically with a D-2 Caterpillar tractor. The author felt that this result was not due to an inherent superiority on the part of the tractor, but rather due to inefficiency in the high-lead operation. It became apparent that, with some improvement in the high-lead yarding equipment, the efficiency of that operation could be raised sufficiently to make it comparable to or even better than tractor skidding. Consequently, in the following computations, the cost figures of a high-lead system will be used in the calculation of log values in the woods after falling and bucking. These values are given in Table 30.

TABLE 30

NET VALUE OF LOGS IN THE WOODS AFTER FELLING AND BUCKING

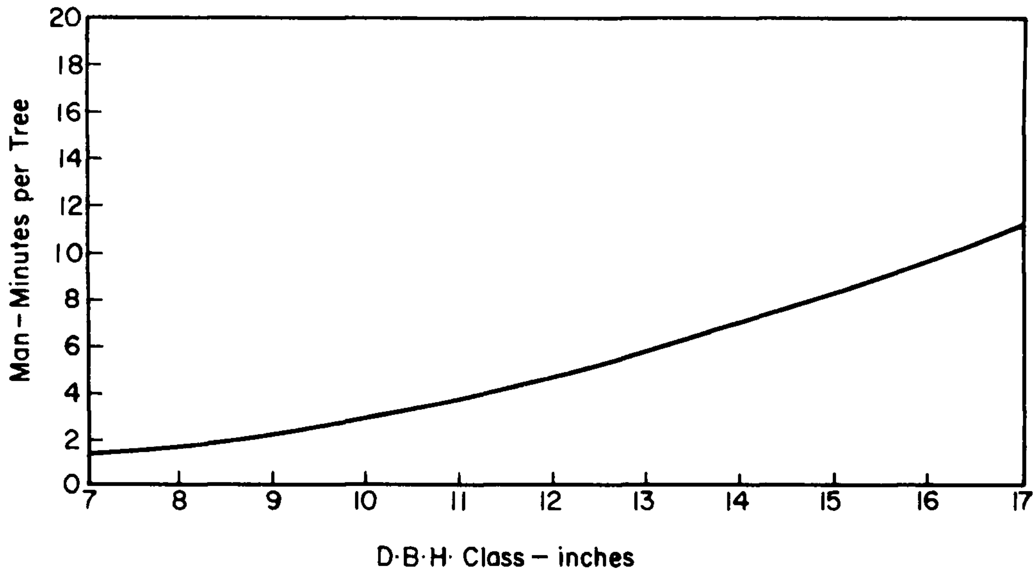
Log Top	$ Value per M f.b.m.						$ Net Value of One Log					
D.i.b.	16 ft.		24 ft.		32 ft.		16 ft.		24 ft.		32 ft.	
In.	F	H	F	H	F	H	F	H	F	H	F	H
6	-60.84	-71.37	-32.70	-42.43	-16.12	-25.05	-1.70	-1.93	-1.41	-1.74	- .93	-1.38
7	-30.88	-39.33	- 9.70	-17.80	- 4.83	- 4.98	-1.15	-1.40	- .65	- .96	0.21	- .36
8	-10.80	-21.81	5.60	- 4.26	15.57	6.25	- .52	- .99	.40	- .31	1.50	.57
9	5.45	- 7.07	18.71	7.58	26.85	16.55	.33	- .40	1.71	.83	3.31	1.84
10	16.19	6.74	27.37	18.53	34.08	25.57	1.18	.47	3.00	1.92	5.02	3.50
11	24.51	15.98	33.89	25.78	39.66	31.75	2.14	1.34	4.46	3.26	6.89	5.29
12	30.69	22.61	38.96	31.10	43.96	36.25	3.16	2.26	5.99	4.64	9.09	7.24
13	35.68	27.52	42.94	35.02	47.27	39.50	4.35	3.23	7.80	6.25	11.47	9.27
14	37.81	29.77	44.60	36.78	48.66	40.94	5.41	4.08	9.49	7.50	13.79	11.21
15	40.44	32.66	46.69	39.07	50.34	42.80	6.63	5.15	11.38	9.30	16.50	13.59
16	42.68	34.73	48.37	40.59	51.69	44.01	8.05	6.32	13.43	10.97	19.36	15.78
17	44.21	36.39	49.47	41.77	52.51	44.91	9.40	7.43	15.97	12.66	22.25	18.26
18	45.44	37.61	50.28	42.58	53.14	45.53	10.82	8.55	17.95	14.70	25.29	20.59
19	45.71	38.28	50.35	42.98	53.12	45.78	12.35	9.56	20.13	16.53	28.39	23.00
20	46.74	38.84	51.00	43.27	53.58	45.94	13.74	10.79	23.19	18.03	31.89	25.38
21	47.08	38.77	51.06	43.02	53.50	45.63	15.69	11.75	25.53	19.56	35.20	27.82
22	46.88	38.98	50.74	43.02	53.13	45.54	17.37	12.98	28.19	21.51	38.78	30.36
23	47.20	39.40	50.91	43.28	53.22	45.70	18.88	14.60	29.93	24.05	42.24	33.60
24	47.50	39.48	51.06	43.27	53.30	45.65	20.65	15.79	34.06	25.44	46.34	36.23
25	47.51	39.44	50.95	43.13	53.14	45.57	22.61	17.14	36.40	28.77	50.81	45.67

G. FELLING AND BUCKING

It is desirable to evaluate felling and bucking as distinct operations. In many otherwise complete time studies, however, felling and bucking have been lumped together and the quoted costs cover both operations.

A great number of time studies on felling and bucking had been conducted prior to the introduction of power-driven chain saws. Ashe (1916), Rapraeger (1931) (1936), Bradner _et al_. (1933), Reynolds _et al_. (1944), McClay (1953), Koroleff (1947) and Doyle (1957) have reported on the effects that the size of a log and tree have on fallers' and buckers' rate of output. Although the values from these studies are no longer applicable to present logging conditions, they nevertheless confirm the fact that handling of a small tree is relatively more costly than handling of a large one. Performance values on felling, limbing and bucking are given by Doyle and Calvert (1961). The results of their studies on the effect of power tools on the above-mentioned operations are shown in Figure 5, where the size of the jack pine tree, by d.b.h. classes, shows a definite effect on the time that is required to fell, buck and limb that tree.

Kurta (1961) investigated the performance of fallers and buckers in the University Research Forest. His results are shown in Table 32. Kurta found that the rate of production was highest for Douglas fir, followed by hemlock and cedar.



Fig· 5 Effect of Tree Size on Actual Time Required for Felling, Limbing, and Bucking· (Doyle and Calvert, 1961)

Consequently, the falling and bucking cost per M f.b.m. was lowest for Douglas fir and highest for cedar by \$1.00 and \$1.50 respectively for the 18-inch d.b.h. class trees. During the time studies, Kurta found that the eight-hour day was utilized by the 3-man working crews as in Table 31.

TABLE 31

AVERAGE DAILY PRODUCTIVE AND NON-PRODUCTIVE TIME FOR 3-MAN FALLING CREW

	Productive Time	Non-Productive Time
	Per Cent	
Faller	68	32
Marker	66	34
Bucker	81	19
Average:	72	28

The mean effective working time was 5½ hours per 8-hour day, or 72 per cent of the total time available. If a faller and bucker receive an hourly pay of \$5.00 or \$40.00 per day, the hourly rate over the effective working time would be $\frac{40}{5\frac{1}{2}} = \$7.28$. Applying this value to the man-minutes required to fell and buck trees of different sizes, a cost schedule may be compiled as shown in Table 32.

TABLE 32

THE EFFECT OF STUMP HEIGHT DIAMETER ON

FELLING AND BUCKING TIME AND COST (KURTA 1961)

Dia. @ Stump Ht. In.	Douglas Fir		W. Hemlock		W. R. Cedar	
	Man-min. per M	Cost $/M	Man-min. per M	Cost $/M	Man-min. per M	Cost $/M
14	-	-	-	-	36.9	4.46
16	-	-	28.9	3.50	30.9	3.74
18	16.5	2.00	21.8	2.64	24.8	3.00
20	13.9	1.68	16.5	2.00	19.7	2.38
22	11.7	1.42	12.8	1.56	16.0	1.94
24	10.2	1.24	10.9	1.32	13.4	1.62
26	9.0	1.10	9.7	1.18	11.4	1.38
28	8.0	0.96	8.8	1.06	10.0	1.32
30	7.3	0.88	8.3	1.00	8.8	1.06
32	6.6	0.80	7.8	0.94	8.0	0.98
34	6.1	0.74	7.5	0.90	7.3	0.88

Nixon and Gunn (1957) determined the productivity values shown in Table 33, for Interior Douglas fir, larch, and spruce.

TABLE 33

EFFECT OF TREE SIZE (D.B.H.) ON FELLING AND BUCKING TIMES

PER M f.b.m. GROSS VOLUME - LOGS 12 TO 22 FEET LONG

(NIXON AND GUNN)

D.b.h.	Time in Man-Minutes per M f.b.m.		
	D. Fir	Larch	Spruce
12	92.3	70.6	56.4
16	76.2	59.2	45.7
20	62.9	49.3	37.4
24	54.4	43.0	32.5
28	49.0	40.3	30.1
32	44.9	39.1	28.9
36	40.8	-	-
40	37.4	-	-

The cost of production per M f.b.m. may be computed from the foregoing table. The worker's wage rate is assumed to be $2.00 per hour and the total cost of operating and owning a power saw is $0.50 per hour (Worthington and Staebler, 1961). Results of this computation are shown in Table 34.

TABLE 34

HOURLY PRODUCTION PER MAN, AND COST PER M f.b.m., OF FELLING AND BUCKING OF INTERIOR FIR, LARCH AND SPRUCE (NIXON AND GUNN)

D.b.h.	Douglas Fir		Larch		Spruce	
In.	Prodn. Mfbm/h.	Cost $/Mfbm	Prodn. Mfbm/h.	Cost $/Mfbm	Prodn. Mfbm/h.	Cost $/Mfbm
12	.650	3.85	.849	2.94	1.064	2.35
16	.787	3.18	1.013	2.47	1.313	1.90
20	.954	2.62	1.217	2.05	1.604	1.56
24	1.103	2.27	1.395	1.79	1.846	1.35
28	1.224	2.04	1.489	1.68	1.993	1.25
32	1.336	1.87	1.534	1.63	2.076	1.20
36	1.470	1.70	-	-	-	-
40	1.604	1.56	-	-	-	-

It is immediately obvious that the Interior costs, as presented in the above table, based on the values of Nixon and Gunn, are higher than the values arrived at by Kurta. The chief reason for this difference is the much larger tree volume on the Coast as compared to a tree of similar d.b.h. in the Interior of this Province.

Felling and bucking of 8-foot logs of various sizes was investigated by Worthington and Shaw (1952). Their cost figures are presented here as percentages of the cost of felling and bucking 12-inch logs. If this cost is assumed to be $3.50, then the cost schedule of Table 35 may be set up.

TABLE 35

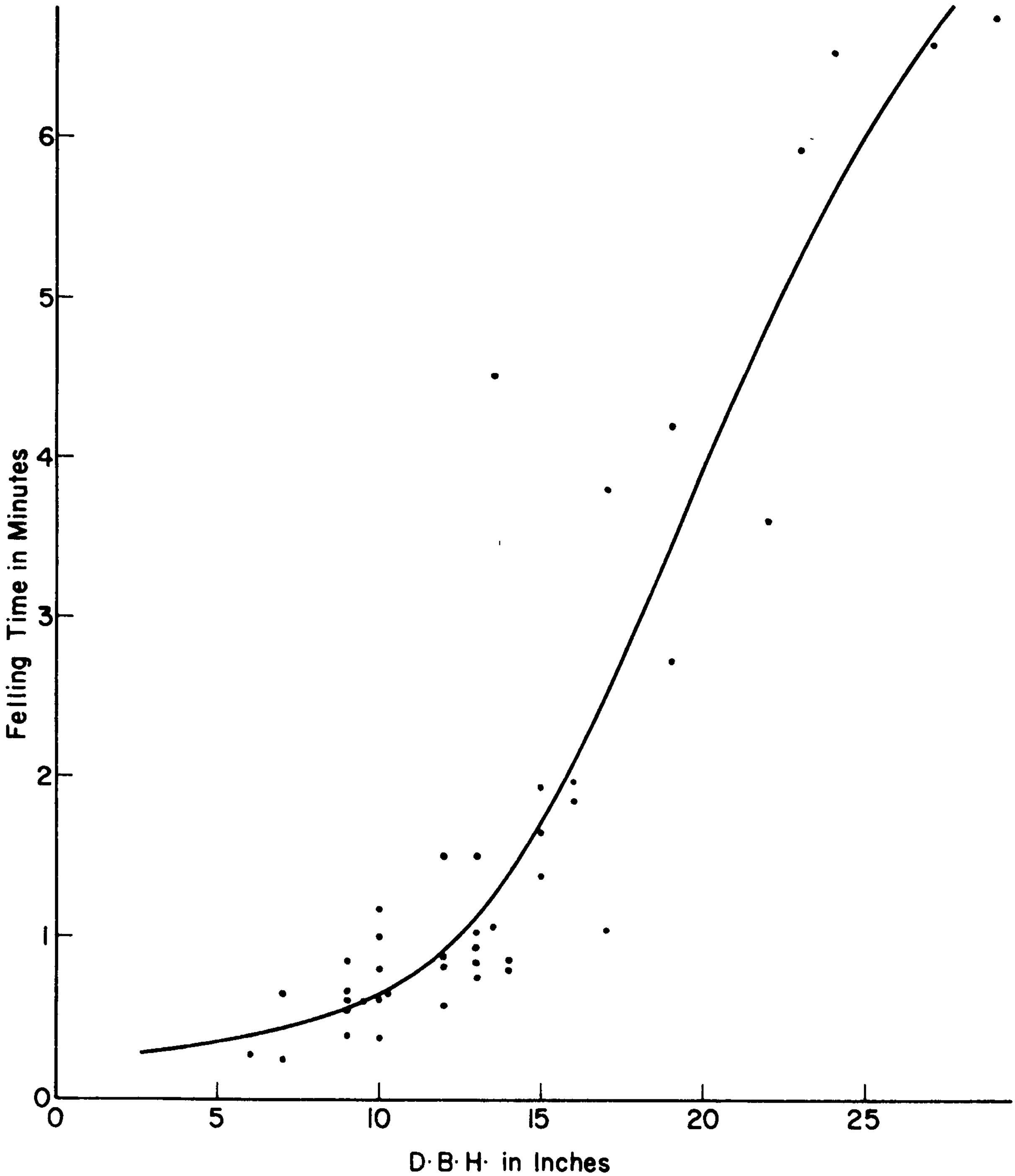
FELLING AND BUCKING COSTS FOR LOGS OF VARIOUS DIAMETERS (WORTHINGTON AND SHAW)

Log Top D.i.b. In.	Cost as Percentage of 12-inch logs	Cost $/M f.b.m.
7	160	5.60
8	148	5.18
9	130	4.55
10	118	4.13
11	109	3.82
12	100	3.50
13	91	3.18
14	82	2.87

These values are not comparable to the cost figures of Gunn and Dixon, which were based on tree sizes rather than log sizes.

A time study of limited extent on falling and bucking performance was conducted by the author at the University Research Forest. The 8-hour day of the faller and bucker was found to consist of following component times:

Preparing to fall and/or buck........	13.5%	
Falling..............................	18.2%	56.7%
Bucking, Limbing.....................	25.0%	
Saw Service..........................	17.9%	
Walking..............................	14.7%	
Resting..............................	10.7%	
	100.0%	



Fig· 6 Effect of Tree D·B·H· on Felling Time·
University Research Forest, June 1961·

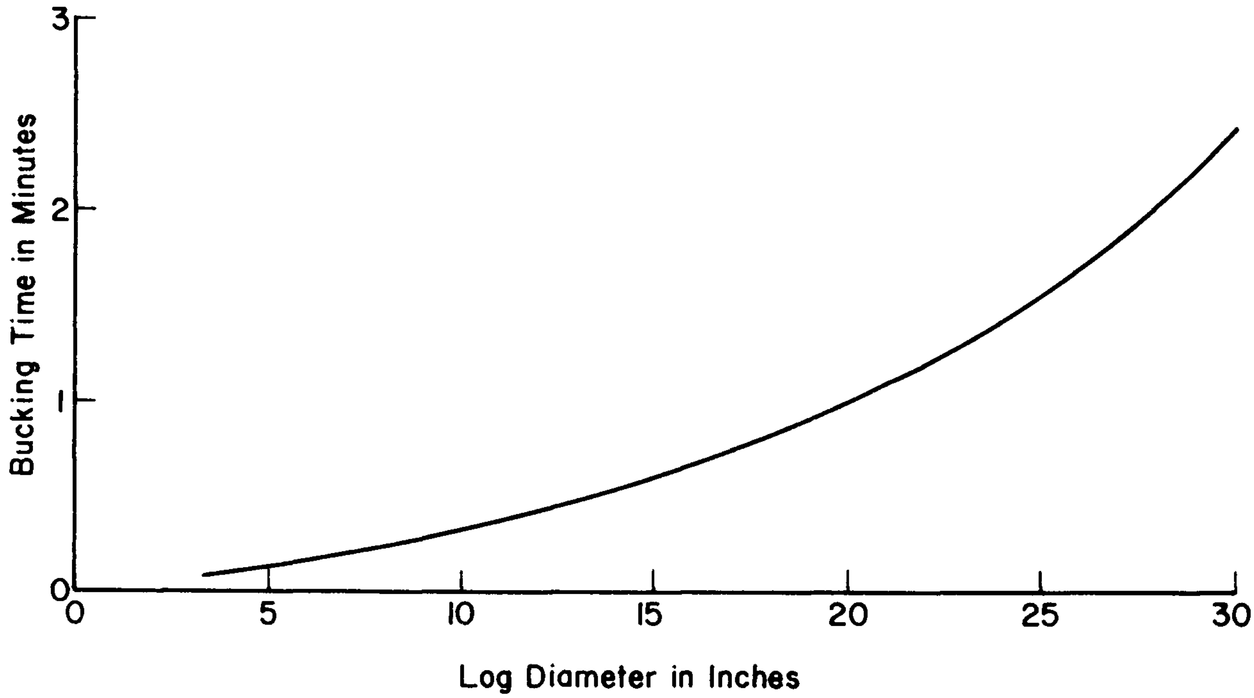


Fig. 7 Effect of Log Diameter on Bucking Time.
University Research Forest, June 1961.

Cutting times with a Pioneer 5.5 H.P. chain saw were recorded and plotted in Figure 6 and Figure 7. The curved data are given in Table 36.

TABLE 36

CUTTING TIMES IN FELLING AND BUCKING OPERATIONS

AT THE U. B. C. RESEARCH FOREST

D.b.h. In.	Felling Time Min.	Diameter at Cutting Position In. i.b.	Bucking Time Min.
6	0.40	6	0.14
8	0.50	8	0.22
10	0.63	10	0.32
12	0.90	12	0.42
14	1.40	14	0.52
16	2.10	16	0.68
18	3.00	18	0.82
20	3.9	20	1.00
22	4.9	22	1.20
24	5.7	24	1.41
26	6.3	26	1.70
28	6.9		
30	7.4		
32	7.8		
34	8.2		

During the felling and bucking operation, the observed practice of the faller was sometimes to buck in the woods. On other occasions it was only to top a tree and to buck it later at the landing. Because the latter procedure produces fewer logs to be skidded, this is a more economical way to operate. Bucking at the landing is safer and more convenient, although it requires more saw maintenance. This is due mainly to sand and rock imbedded in the bark of the logs, which dulls the saw faster than in the woods. In the following computations it will be assumed that all felled trees are bucked in the woods into 16, 24 and/or 32-foot lengths.

On the Coast, the faller and bucker are usually paid at a certain rate per M f.b.m. produced. This rate is adjusted according to the size of the timber in the stand to assure the workers a fair minimum daily wage. An introduction of changing rates of pay in this study, however, would serve no useful purpose. It will be assumed that the one-man crew, operating both as a faller and a bucker, receives a flat daily rate. When this amount is divided by the production rates resulting from different tree sizes, the costs associated with the various d.b.h. classes may be directly obtained.

In keeping with the traditionally high rates of pay that the coast fallers receive, it is assumed that the daily pay for the faller equals $40.00.* Further, it is assumed that 72 per cent of his time may be classified as productive, as found by Kurta's investigation. Felling and bucking costs are calculated and presented in Table 37.

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* Information supplied by J. A. McIntosh, Vancouver Laboratory, Forest Products Laboratories of Canada.

TABLE 37

DETERMINATION OF FELLING AND BUCKING COST FOR

DOUGLAS FIR TREES OF DIFFERENT SIZES

D.b.h. In.	(Curved) Utilized Volume in a Tree Lbr. tally f.b.m.	Felling Time min.	Bucking Time (per tree) min.	Necessary Unprod. Time min.	Total Time per Tree min.	Production Rate fbm/hour	Adjusted for 72% Efficiency	Daily Output (8 hr.) f.b.m.	Cost per M $	Cost per Tree $
6	-	-	-	-	-	-	-	-	-	-
7	28	.43	.14	3.0	3.57	471	339	2772	14.43	0.40
8	37	.50	.19	3.2	3.89	571	411	3288	12.17	0.45
9	42	.56	.22	3.5	4.28	589	424	3392	11.79	0.50
10	50	.63	.19	3.8	4.62	649	467	3736	10.71	0.54
11	60	.75	.22	4.0	4.97	724	521	4168	9.60	0.58
12	80	.90	.19	4.3	5.39	890	641	5128	7.80	0.62
13	100	1.10	.22	4.5	5.82	1031	742	5936	6.74	0.67
14	120	1.40	.22	4.8	6.42	1121	807	6456	6.20	0.74
15	150	1.73	.64	5.0	7.37	1221	879	7032	5.69	0.85
16	180	2.10	.74	5.3	8.14	1327	955	7640	5.24	0.94
17	220	2.50	.74	5.5	8.74	1510	1087	8696	4.60	1.01
18	260	3.00	.82	5.8	9.62	1622	1168	9344	4.28	1.11
19	310	3.4	.71	6.1	10.21	1822	1312	10496	3.81	1.18
20	377	3.9	.90	6.3	11.10	2038	1467	11736	3.41	1.29
21	430	4.4	.74	6.6	11.74	2198	1583	12664	3.16	1.36
22	505	4.9	1.64	6.8	13.34	2271	1635	13080	3.06	1.55
23	600	5.3	1.64	7.1	14.04	2564	1846	14768	2.71	1.63
24	699	5.7	1.91	7.4	15.01	2794	2012	16096	2.49	1.74
25	798	6.0	1.74	7.6	15.34	3121	2247	17976	2.23	1.78
26	897	6.3	1.64	7.9	15.84	3398	2447	19576	2.04	1.83
27	1020	6.6	2.99	8.1	17.69	3460	2491	19928	2.01	2.05
28	1140	6.9	3.24	8.4	18.54	3689	2656	21248	1.88	2.14
29	1260	7.2	2.87	8.6	18.67	4049	2915	23320	1.72	2.17
30	1390	7.4	2.87	8.9	19.17	4351	3133	25064	1.60	2.22
31	1520	7.6	2.93	9.1	19.63	4646	3345	26760	1.49	2.26
32	1660	7.8	3.29	9.4	20.49	4861	3500	28000	1.43	2.37

TABLE 38

BUCKING SCHEDULE OF TREES OF DIFFERENT SIZES

D.b.h. In.	Top Diameter of Logs Obtained[1] 16-ft. Logs	24-ft. Logs	32-ft. Logs	Utilized Length ft.	Top Left ft.	Total[2] Tree Length ft.
6	(5")			16	37	53
7	(6")			16	45	61
8	(7")			16	52	68
9	(8")			16	59	75
10		(7")		24	58	82
11		8		24	65	89
12			7	32	63	95
13			8	32	69	101
14			8	32	75	107
15	12	8		40	73	113
16	14	8		40	79	119
17	14	8		40	84	124
18	15		8	48	81	129
19		14	7	56	78	134
20		16	8	56	83	139
21			8, 14	64	80	144
22	19	14	8	72	76	148
23	20		8, 12	80	73	153
24	22		8, 13	80	77	157
25		21	8, 12	88	73	161
26			8, 12, 20	96	69	165
27	25	18	8, 12	104	65	169
28	25	19	8, 12	104	68	172
29		18, 24	8, 12	112	64	176
30		18, 24	8, 12	112	67	179
31		14, 26	8, 13	112	69	181
32		27	8, 12, 18	120	64	184

TABLE 38 (Continued)

1 Based on taper data supplied by Mr. J. A. McIntosh from V. F. P. L.

2 Based on Local Volume Tables of U. B. C. Research Forest. Species: Immature Douglas Fir. Maximum Height: 200 feet.

H. DETERMINATION OF NET VALUE OF STANDING TREES

It was assumed that the felled trees were bucked into 16, 24 or 32-foot lengths. In order to establish the "log-content" of trees of various d.b.h. sizes, the author consulted local volume tables, compiled for Douglas fir and hemlock trees of the University Research Forest. In addition to these tables, Douglas fir taper curves were constructed from some unpublished Vancouver Laboratory* data. The bucking schedule (Table 38) was assembled by applying the outlined sources of information. This table indicates the number of logs of 16, 24 and 32-foot length which may be obtained, on the average, from trees of various sizes.

Earlier, in Table 30, the net values of various logs after felling and bucking were assembled. The information from that source and from that in Table 38 can be combined to assign a net value for each tree after felling and bucking. This calculation, which involves the summation of the net values of the appropriate logs, has been shown in Columns 1 and 2 of Table 39.

This new schedule of values does not progress smoothly because of the stepwise increase of utilized volumes in the trees. Therefore, the values of Columns 1 and 2 have been smoothed out as shown in Figure 8. The curved values have been

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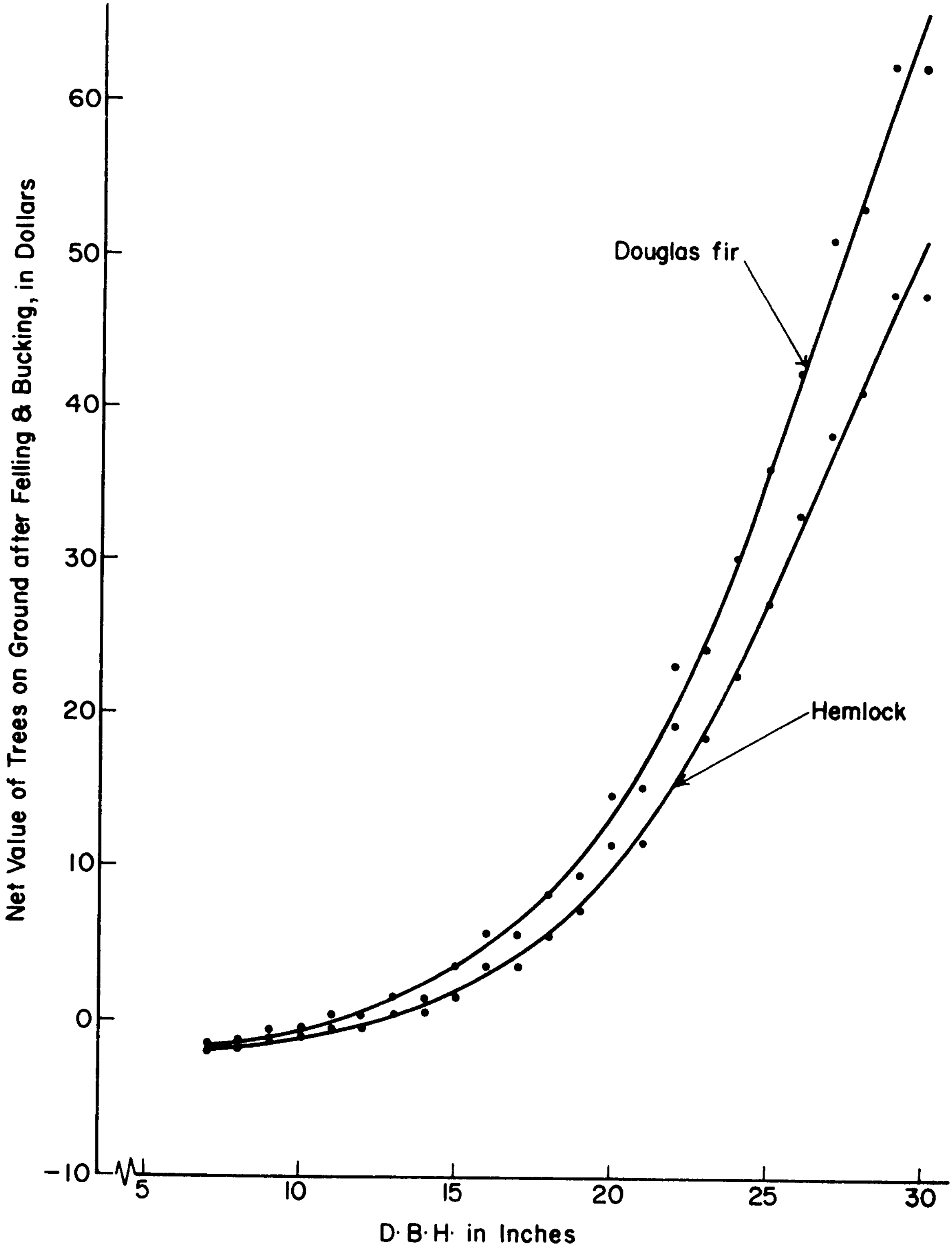
* Information supplied by J. A. McIntosh, Vancouver Laboratory, Forest Products Laboratories of Canada.

TABLE 39

NET VALUES OF STANDING TREES

D.b.h. In.	Net Value of All Utilized Logs in a Tree after Felling and Bucking		Curved Values		Felling & Bucking Cost Per Tree $	Net Value of Standing Tree		
	F	H	F	H		F	H	
6	-	-	-	-	-	-	-	
7	- 1.70	- 1.93	- 1.70	- 1.93	.40	- 2.10	- 2.33	
8	- 1.15	- 1.40	- 1.50	- 1.40	.45	- 1.95	- 1.85	
9	- .52	- .99	- 1.00	- 1.20	.50	- 1.50	- 1.70	
10	- .65	- .96	- .50	- 1.00	.54	- 1.04	- 1.54	
11	.40	- .31	0	- .70	.58	- .58	- 1.28	
12	.21	- .36	.75	- .10	.62	.13	- .72	Zero margin
13	1.50	.57	1.60	.40	.67	.93	- .27	Douglas Fir
14	1.50	.57	2.50	1.10	.74	1.76	.36	Zero margin
15	3.56	1.95	3.56	2.00	.85	2.71	1.15	Hemlock
16	5.81	3.77	5.00	3.00	.94	4.04	2.06	
17	5.81	3.77	6.60	4.25	1.01	5.59	3.24	
18	8.13	5.72	8.20	5.90	1.11	7.09	4.79	
19	9.70	7.14	10.08	7.80	1.18	8.90	6.62	
20	14.93	11.54	13.60	10.00	1.29	12.31	8.71	
21	15.29	11.78	17.00	12.80	1.36	15.64	11.44	
22	23.34	19.43	20.80	15.75	1.55	19.25	14.20	
23	24.33	18.60	25.00	19.20	1.63	23.37	17.57	
24	30.34	22.82	29.80	23.00	1.74	28.06	21.26	
25	36.12	27.37	36.00	27.50	1.78	34.22	25.72	
26	42.48	33.19	42.00	32.20	1.83	40.17	30.37	
27	51.15	39.65	48.00	36.90	2.05	45.95	34.85	
28	53.33	41.48	54.00	41.60	2.14	51.86	39.46	
29	62.60	47.95	60.00	46.10	2.17	57.83	43.93	
30	62.60	47.95	65.60	50.90	2.22	63.38	48.68	



Fig· 8 Net Value of Trees after Felling and Bucking entered in Columns 3 and 4 of Table 39. Next, the cost of felling and bucking per tree (Table 37, entered into Column 5 of Table 39) is subtracted from the values in Columns 3 and 4, giving the net values of standing trees. These final values are shown in Columns 6 and 7 of Table 39 and the net revenue values per tree in graph form in Figure 9.

It can be seen that 12-inch d.b.h. Douglas fir and 14-inch hemlock trees are the smallest sizes paying their way. They constitute the zero marginal tree size, provided the specified conditions hold and provided the natural variability in the estimates from the original data is ignored.

Results of the computations, leading to the quoted tree sizes, have been summarized in Table 40. The various cost items are shown on a per tree basis. Milling cost has been given a separate position because of its relative magnitude in respect of the other costs.

This tabulation emphasizes the fact that the smaller logs are unprofitable to saw and the conversion process becomes profitable only for the larger sizes. The various results obtained up to this stage may be summarized as follows:

1. The zero marginal size for Douglas fir is 12 in. d.b.h.

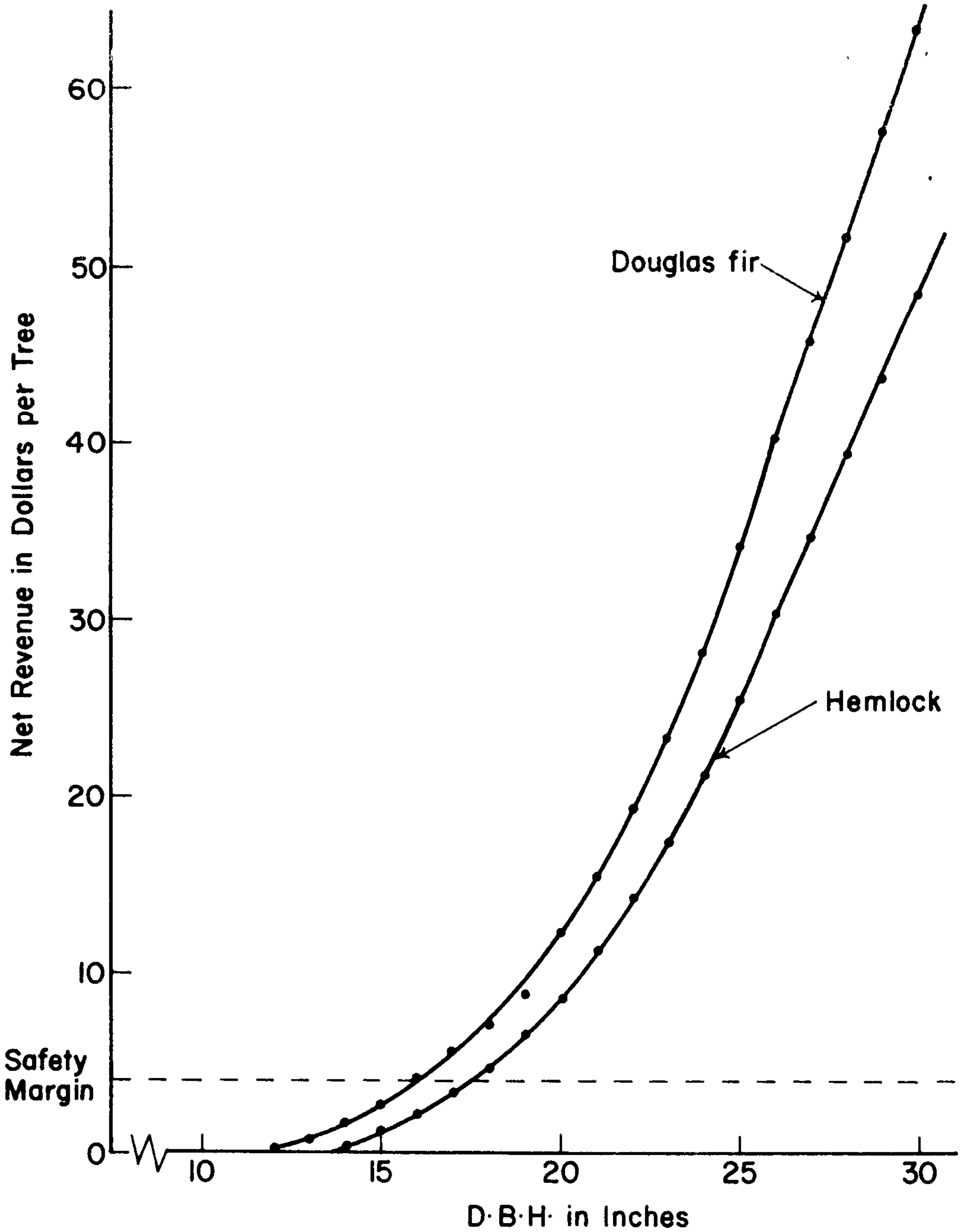
2. The zero marginal size for hemlock is 14 in. d.b.h.

3. It is more profitable to sell the logs obtained from trees of d.b.h. $<$ 21 in.

4. It is more profitable to mill the logs from trees with

d.b.h. $>$ 21 in., and to market the products.

This particular set of results, with the associated conditions and price schedules, will henceforth be referred to as Program I.



Fig· 9 Net Revenue per Tree ; Program I·

TABLE 40

SUMMARY OF PROGRAM I - COST ITEMS AND RETURNS

D.b.h. In.	Various Cost Items, Dollars Per Tree: Felling Bucking	Yarding Highlead	Loading Hauling	Royalty	Towing	Gov't. Scaling	Total	Milling	Grand Total
12	0.62	0.40	0.75	0.10	0.06	0.01	1.94	3.08	5.02
13	0.67	0.40	0.91	0.12	0.08	0.02	2.20	3.09	5.29
14	0.74	0.40	0.91	0.14	0.10	0.02	2.31	3.09	5.40
15	0.85	0.80	1.64	0.18	0.12	0.03	3.62	5.19	8.81
16	0.94	0.80	1.89	0.22	0.14	0.03	4.02	5.68	9.70
17	1.01	0.80	1.89	0.26	0.18	0.04	4.18	5.68	9.86
18	1.11	0.80	2.20	0.31	0.21	0.05	4.68	6.23	10.91
19	1.18	0.80	2.34	0.37	0.25	0.06	5.00	6.49	11.49
20	1.29	0.80	2.88	0.45	0.30	0.07	5.79	7.05	12.84
21	1.36	0.80	2.92	0.52	0.34	0.08	6.02	6.85	12.87
22	1.55	1.20	4.43	0.61	0.40	0.09	8.28	10.99	19.27
23	1.63	1.20	4.74	0.72	0.48	0.11	8.88	10.96	19.84
24	1.74	1.20	5.24	0.84	0.56	0.13	9.71	11.89	21.60
25	1.78	1.20	5.93	0.96	0.64	0.14	10.65	12.20	22.85

D.b.h. In.	Log Prices Per Tree $: # 2 Fir	# 3 Fir	# 2 Hemlock	# 3 Hemlock	Balsam	Net Revenue $: # 3 Fir Logging	Milling	# 3 Hemlock Logging	Milling	Balsam Logging
12	-	4.18	-	3.31	3.14	2.24	0.13	1.37	- 0.72	1.20
13	-	5.23	-	4.14	3.92	3.03	0.93	1.94	- 0.27	1.72
14	7.70	6.27	-	4.96	4.71	3.96	1.76	2.65	0.36	2.40
15	9.71	7.84	-	6.20	5.89	4.22	2.71	2.58	1.15	2.27
16	11.65	9.41	-	7.44	7.06	5.39	4.04	3.42	2.06	3.04
17	14.24	11.50	-	9.10	8.63	7.32	5.59	4.92	3.24	4.45
18	16.83	13.59	-	10.75	10.20	8.91	7.09	6.07	4.79	5.52
19	20.07	16.21	-	12.82	12.16	11.21	8.09	7.82	6.62	7.16
20	24.41	19.71	17.72	15.59	14.79	13.92	12.31	9.80	8.71	9.00
21	27.84	22.48	20.21	17.78	16.87	16.46	15.64	11.76	11.44	10.85
22	32.69	26.40	23.74	20.89	19.82	18.12	19.25	12.61	14.20	11.54
23	38.84	31.37	28.21	24.82	23.54	22.49	23.37	15.94	17.57	14.66
24	45.25	36.54	32.86	28.91	27.43	26.83	28.06	19.20	21.26	17.72
25	51.66	41.72	37.51	33.01	31.31	31.07	34.22	22.36	25.72	20.66

ZERO MARGINAL TREE SIZE FOR AN OPERATION WITH IMPROVED PERFORMANCE (PROGRAM II)

It appears from the results of Program I that the operations at the University Research Forest at the time of this study were not efficient. Although the theoretical zero margin lies at 12 inches d.b.h. for Douglas fir and 14 inches d.b.h. for hemlock, there is no allowance for a "safety factor" to counter the inevitable inaccuracies in the various measurements and the normal variability within the machine performance. The curves of Figure 9 show that the increase in net revenue, with increasing d.b.h. sizes, is small for the lower ranges, and increases more rapidly when larger trees are handled. This suggests the uncertainty associated with a precise determination of zero marginal trees. A safety margin of $4.00 per tree would increase the zero marginal size by approximately four inches, as shown in Figure 9.

After considering various ways in which the same operation could be improved, it was decided to recalculate the zero margin for an operation which is more efficient yet still realistic. The selling price of logs, rather than that of sawn lumber, was taken as the basis of the analysis. The following computations and solutions will henceforth be referred to as Program II and will occupy the next part of this thesis.

A. MARKET PRICES OF LOGS

Log price quotations are available and form a convenient basis for computations. The prices used in the following analysis are the Vancouver Log Prices, September 1961. The attached statement in the AppendixIdoes not take into consideration the size of logs. It is assumed here that the "small logs", e.g. below size 8 inches by 32 feet, may be sold at the same price as the large ones provided the percentage of such logs is not excessive.

Log grades are indicated by the following table, which shows the quality of the stand being harvested.*

TABLE 41

APPROXIMATE STAND QUALITY

D.b.h.	Percentage No. 2 Sawlogs	
In.	Douglas Fir	Hemlock
7 to 16	0	0
16	20	0
18	34	0
20	41	0
22	41	0
24	42	12
26	42	23
28	43	27
30	44	30

* Data supplied by Dr. J. H. G. Smith, Faculty of Forestry, University of British Columbia.

TABLE 42

BUCKING SCHEDULE FOR PROGRAM II

D.b.h.	Number of Logs	Bucked at Landing				Volume Yield Per Tree, f.b.m. Adjusted for Overrun	
In.	Hauled	Top - ins. x Length - ft.				Douglas Fir	Hemlock
7	1	6 x 16				24	23
8	1	7 x 16				37	36
9	1	7½ x 16				40	38
10	1	8 x 16				48	45
11	1	6½ x 32				58	56
12	1	7 x 32				74	71
13	1	7½ x 32				85	81
14	1	8 x 32				96	90
15	1	9 x 30				123	111
16	1	6½ x 16	10 x 32			175	165
17	1	7 x 16	10½ x 32			190	181
18	1	8 x 16	11 x 32			222	212
19	2	6½ x 32	11½ x 32			251	241
20	2	7 x 32	13½ x 32			338	326
21	2	6 x 16	8 x 32	14½ x 32		424	407
22	2	6½ x 16	8½ x 32	15½ x 32		492	461
23	2	8 x 32	12 x 32	20 x 16		600	555
24	2	6½ x 16	8 x 32	13 x 32	21½ x 16	716	670
25	2	7 x 32	11 x 32	19 x 32		784	741
26	2	8 x 32	12 x 32	20 x 32		897	842
27	2	6 x 16	8½ x 32	12½ x 32	21 x 32	1017	949
28	2	7 x 16	9 x 32	13 x 32	21½ x 32	1098	1016
29	2	7½ x 16	10 x 32	14 x 32	22½ x 32	1231	1151
30	2	8 x 16	10½ x 32	15 x 32	23½ x 32	1374	1273

B. THE UTILIZED VOLUME PER TREE

It is assumed that felled trees are bucked at a 6-inch top. They are yarded out full length, the limit for handling being set at 60 feet. The trees are bucked into logs at the landing. A bucking schedule has been prepared which shows the utilized volumes per tree for the various size classes (Table 42).

C. GROSS VALUES OF TREES

A schedule of gross values per tree can be set up as shown in Table 43, by combining the information of log market prices, stand quality in respect of # 2 and # 3 sawlog distribution, and the available volume per tree.

TABLE 43

GROSS VALUES OF STANDING TREES

D.b.h.	Gross Value Per Tree, Dollars	
In.	Douglas Fir	Hemlock
7	1.25	0.95
10	2.51	1.86
12	3.87	2.94
14	5.02	3.72
16	9.58	6.82
18	12.55	8.77
20	19.40	13.48
25	45.09	31.36
30	79.36	54.82

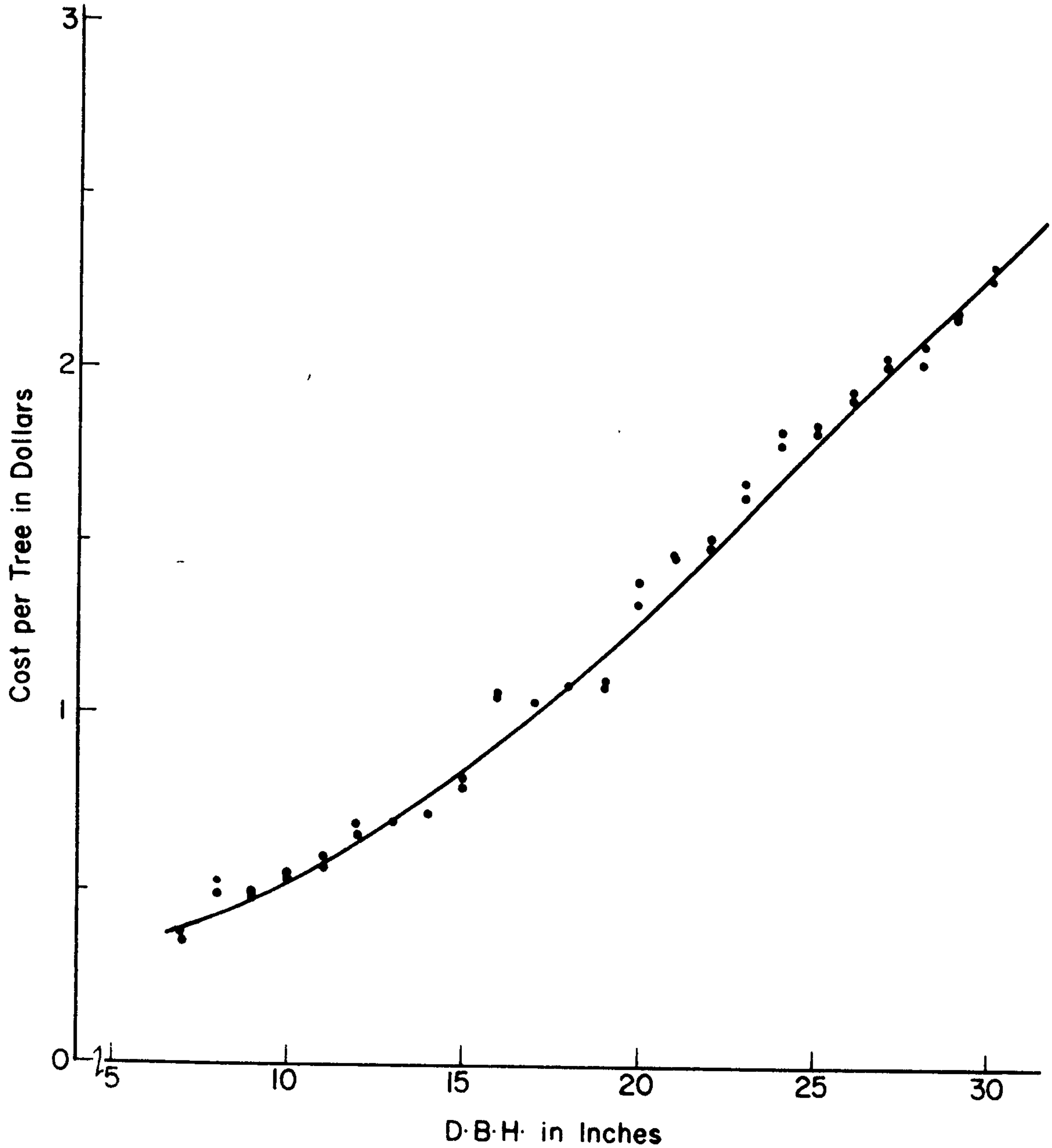


Fig. 10 Felling and Bucking Cost per Tree; Douglas Fir and Hemlock; Program 2.

D. FELLING AND BUCKING

Felling and bucking costs are based on the time studies of June, 1961 at the University Research Forest and have been assembled in Table 44 for the proposed new bucking schedule of Program II. The final per tree costs have been smoothed graphically to minimize variability in the measured data. (Figure 10.)

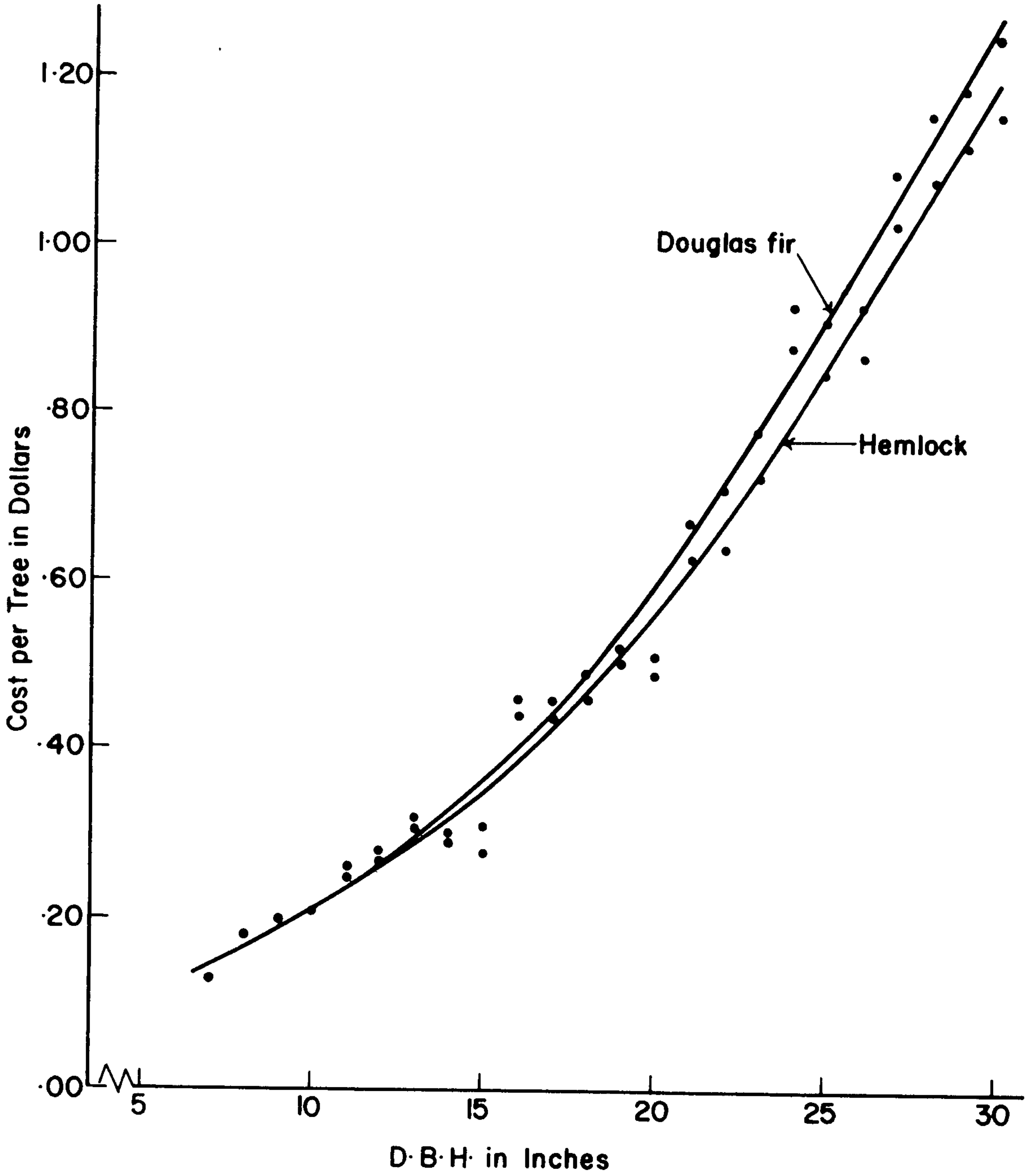
TABLE 44

FELLING AND BUCKING COST PER TREE

D.b.h. In.	Cost Per Tree, Dollars Douglas Fir	Hemlock
7	0.39	0.41
10	0.52	0.54
12	0.65	0.65
14	0.77	0.77
16	0.92	0.91
18	1.11	1.09
20	1.31	1.29
25	1.86	1.83
30	2.29	2.26

E. LOADING COST

This cost is based on the performance shown by the 4-man crew at a salvage operation in the University Research Forest in June, 1961. The computed values are shown in Table 45 and Figure 11.



Fig· 11 Loading Cost; Program 2·

TABLE 45

LOADING COST PER TREE

D.b.h.	Cost Per Tree, Dollars	
In.	Douglas Fir	Hemlock
7	0.15	0.15
10	0.21	0.21
12	0.27	0.26
14	0.33	0.32
16	0.40	0.39
18	0.49	0.47
20	0.60	0.56
25	0.93	0.86
30	1.27	1.20

F. COST OF YARDING

As a result of low efficiency in the yarding operation at the University Research Forest salvage operation, the apparent yarding cost per hour was \$22.86, or \$15.79 per M f.b.m. This cost figure is extremely high by any available comparison and a reduction of cost at this stage of operation is of great importance. In setting up Program II, it was assumed that the improvement would be achieved by a more effective use of the available time. Because that problem is regarded as purely a mechanical and organizational one, no specific solution will be offered within this work. It will be merely assumed that the yarding crew will be working effectively 5 hours out of 8 and that the various time requirements remain unchanged from Program I.

The total daily cost of $80.00 will then give an hourly cost of $\frac{80}{5}$ = $16.00. The setting will be finished in $\frac{60}{5} + 2 =$ 14 days, with a total cost of 14 x 80 = $1120. This in turn will give a unit cost $\frac{1120}{96.286}$ = $11.64. This value implies that, on the average, $4 per M f.b.m. will be saved by this new working rate.

Within the framework of Program II the logs are yarded out in full length up to 60 feet. This procedure will increase the production substantially and further lower the per unit cost.

If it is assumed that a full turn for an average yarding distance of 400 feet will take 4.18 minutes, then the yarding cost per tree will depend only on the number of turns necessary to haul it to the landing. The bucking schedule (Table 42) shows that trees of the size 7 to 18 inches d.b.h. are hauled out in one piece whereas trees of size 19 to 30 inches d.b.h. yield 2 logs. Consequently the lumped yarding cost for the first group (d.b.h. 7 to 18) is $0.49 per tree and for the second group $0.98. These values are based on an effective hourly cost of $\frac{80}{5}$ = $14. or 95¢ per 4.18 minutes. The high-lead mainline is assumed to be equipped with two chokers.

G. OTHER COSTS ASSOCIATED WITH PROGRAM II

1. Hauling

Hauling is done by contract and the set price for hauling one M f.b.m. 18 miles is $6.25. This haul will transfer the logs from the University Research Forest to a booming ground near the Pitt River Bridge.

2. Scaling and Royalty

The established fee for a government scaler is 18¢ per M f.b.m. The Royalty depends on log grade and is $1.00 per M f.b.m. for # 3 logs and $2.00 per M f.b.m. for # 2 logs.

3. Towing

The price quoted by a local towing company indicates that the cost for towing from Pitt River Bridge to Eburne Saw Mills would be 80¢ per M f.b.m.

The above costs have been recalculated on a per tree basis and are shown in Table 46.

TABLE 46

MISCELLANEOUS COSTS OF PROGRAM II

$ PER TREE

D.b.h.	Scaling		Royalty		Towing		Hauling	
In.	F	H	F	H	F	H	F	H
7	0.01	0.01	0.02	0.02	0.01		0.15	0.14
10	0.01	0.01	0.05	0.04	0.03		0.30	0.28
12	0.01	0.01	0.07	0.07	0.04		0.46	0.44
14	0.02	0.02	0.10	0.09	0.05		0.60	0.56
16	0.03	0.03	0.21	0.16	0.10		1.09	1.03
18	0.04	0.04	0.30	0.21	0.14		1.39	1.32
20	0.06	0.06	0.48	0.33	0.21		2.11	2.04
25	0.14	0.13	1.11	0.87	0.52		4.90	4.63
30	0.25	0.23	1.98	1.65	0.94		8.59	7.95

H. COMPUTATION OF NET REVENUES PER TREE

The various computed cost items are assembled in Table 47. For each d.b.h. class all cost items have been totalled and then subtracted from the revenue which each tree is expected to yield, according to its content of saleable logs. The difference, or the net revenue, has been shown in Figure 12.

TABLE 47

PROGRAM II - COSTS AND NET REVENUES PER TREE[1]

D.b.h.	Total Cost Per Tree $		Revenue Log Prices $		Net Revenue Per Tree $	
In.	F	H	F	H	F	H
7	1.22	1.23	1.25	0.95	0.03	-0.28
8	1.39	1.41	1.93	1.43	0.54	0.02
9	1.47	1.49	2.09	1.57	0.64	0.08
10	1.61	1.60	2.51	1.86	0.90	0.26
11	1.76	1.78	3.03	2.32	1.27	0.54
12	1.99	1.96	3.87	2.94	1.88	0.98
13	2.16	2.13	4.44	3.35	2.28	1.22
14	2.36	2.30	5.02	3.72	2.66	1.42
15	2.68	2.56	6.43	4.59	3.75	2.03
16	3.24	3.11	9.58	6.82	6.34	3.71
17	3.52	3.36	10.57	7.49	7.05	4.13
18	3.96	3.76	12.55	8.77	8.59	5.01
19	4.84	4.62	14.28	9.97	9.44	5.35
20	5.75	5.47	19.40	13.48	13.65	8.01
21	6.69	6.29	24.33	16.83	17.64	10.54
22	7.43	6.89	28.24	19.07	20.81	12.18
23	8.53	7.85	34.43	22.95	25.90	15.10
24	9.67	9.03	41.18	28.17	31.51	19.14
25	10.44	9.82	45.09	31.36	34.65	21.54
26	11.54	10.87	51.59	35.92	40.05	25.05
27	12.73	11.90	58.74	40.59	46.01	28.69
28	13.58	12.68	63.42	43.58	49.84	30.90
29	14.87	13.99	71.10	49.49	56.23	35.50
30	16.30	15.21	79.36	54.82	63.06	39.61

I. RESULTS

Program II computations suggest that the zero marginal Douglas fir has a d.b.h. of 7 inches and hemlock of 8 inches. The relatively flat net revenue curve implies, for the smaller

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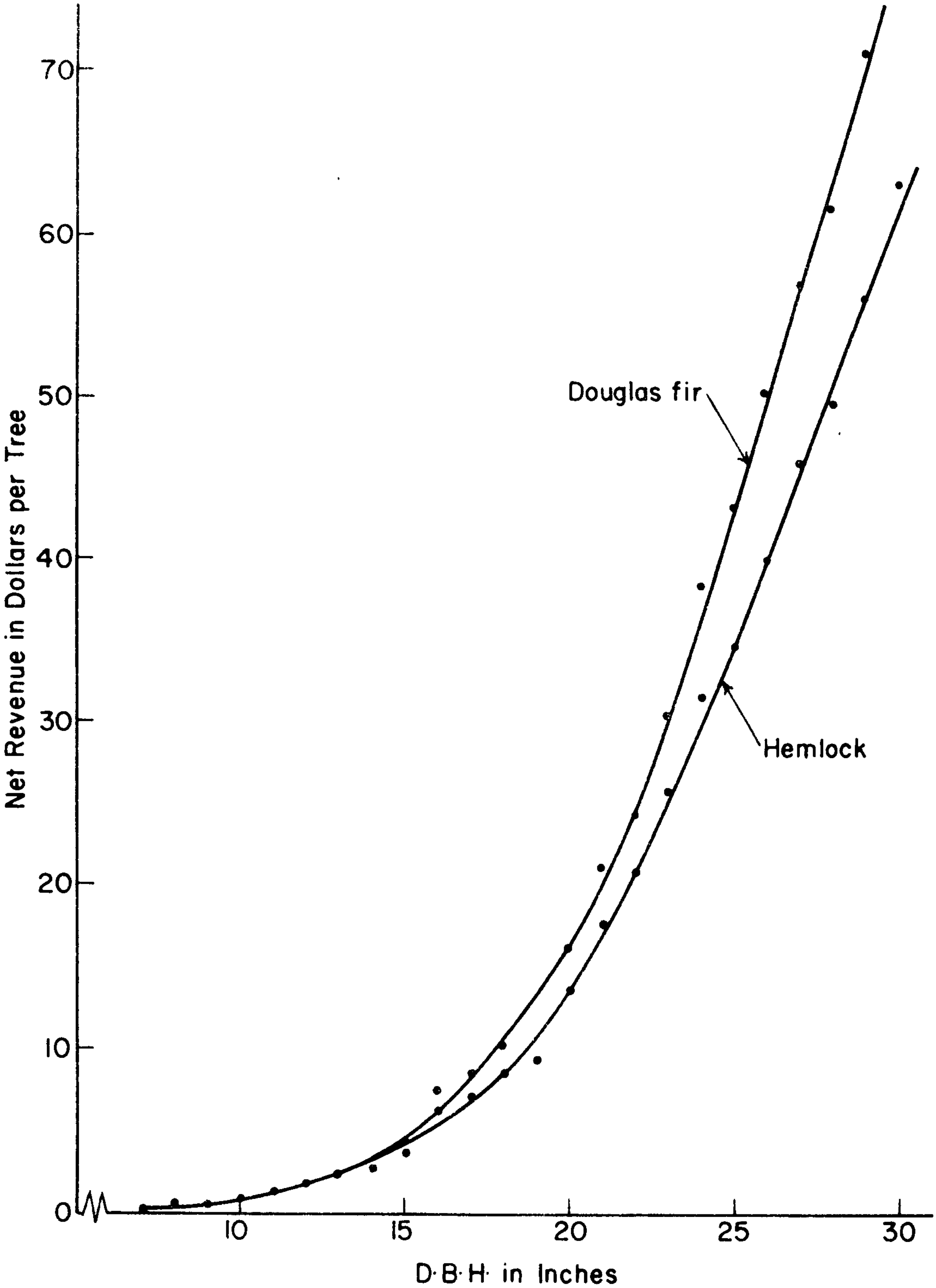
1 Assuming no penalty for logs under 8 inches top d.i.b.



Fig· 12 Net Revenue per Tree; Program 2·

sizes, that the increase in net revenue is small, and over the range of 7 to 15 inches, the exact value of net revenue is somewhat in doubt. It should be realized that the curve shown is only a best estimate of highly variable factors and probably has a wide range of variation which does not appear in the graph.

Around 15 inches d.b.h. the slope of the curve becomes steeper and it may be assumed that the profitability of the operation is no longer subject to an excessive amount of uncertainty.

The preceding interpretation of the revenue curves is far too subjective. Undoubtedly, with more basic data available, the estimates may be made more precise and both the theoretical and economically safe zero marginal tree size may be determined with a greater degree of certainty.

LINEAR PROGRAMMING

A. INTRODUCTION

In the foregoing discussion, the determination of zero marginal tree has been approached in a very general manner. No emphasis was given to the actual size of the available timber stand, available number of machine-hours or capital. A consideration of this aspect is obviously important when a specific operation is to be evaluated.

The introduction of material restrictions or capital restrictions will limit the number of possible choices of action on the part of the operator. The problem will become that of optimization under a given set of restrictive factors. The technique of linear programming (LP) is often useful in solving complex problems of this nature.

B. PRINCIPLES

LP encompasses problems in which the quantity to be maximized (e.g. profit) or minimized (e.g. cost) is stated as a linear function of the independent variables, and is subject to a system of linear inequalities stated in terms of these variables. Thus, an LP problem has three quantitive components:

1. An objective;
2. Alternative methods or processes for attaining the

objective, and

3. Resource or other restrictions.

A problem which has these three components can always be expressed as a LP problem. Thus it is easy to construct a logging situation, expressed in terms of linear equations, and maximized according to LP methods.

PROBLEM AND SOLUTION NO. 1

An area of one acre is to be logged. Stand composition for this area is given in Table 48.

TABLE 48

STAND COMPOSITION AND VOLUME

D.b.h. In.	No. of Trees Per Acre D. Fir	Hemlock	Cedar	Total	F.b.m. Vol. Per Tree	Vol. Per D.b.h. Class/ac.	Group No.
6	24	26	21	71	20	1420	I
8	21	17	10	47	37	1739	I
10	12	19	4	25	48	1200	I
12	12	5	3	21	74	1554	I
14	8	4	2	14	96	1344	II
16	4	3	1	8	175	1400	II
18+	5	1	1	7	250	1750	II

It was demonstrated in the earlier chapters that all the various tree sizes have different unit costs which decrease with increasing tree diameter. If it were possible to carry out a computation whereby each tree was treated as a distinct unit, and provided that sufficiently detailed information were available to charge a proper amount of cost against each individual tree, then it would be possible to arrive at a completely correct estimate of the net values of the trees in that area. Such a calculation obviously is quite impractical.

At the other extreme, it is possible to treat the whole stand in terms of averages - viz. average size trees and average hauling distances. A calculation based on this approach is quite feasible and very often the one used in practice. It is apparent that, due to oversimplification, much detail is lost and the result is at best an approximation. This solution cannot find the optimum course of action unless through pure chance. Obviously a compromise must exist between these two opposite approaches. It is suggested that the stand should be divided into a number of d.b.h. classes. The average tree of each such class will be used as an entity, or a "process" as such units are often designated in LP context.

After the various technical coefficients and restrictions are determined for each process, the regular LP techniques are applied. The resulting solutions suggest how much of each "process" must be taken in order to maximize the overall profit function.

As an initial approach to a solution of the harvesting intensity of the indicated one acre, the tree diameters are divided into two groups, large and small. Within each group the mean d.b.h. value (weighted by volumes and numbers of trees) is calculated to represent that group:

Group	Mean d.b.h.	Trees per Acre	Vol. per Acre	Vol. per Tree
1	8	164	5913	36
2	16	29	4494	155

As a further simplification, it is assumed that all trees are Douglas fir.

The problem is to determine how many of the available trees in each group should be cut in order to maximize the returns from the operation. The profit equation is:

$$C = p_1x_1 + p_2x_2 - (x_1s_1 + x_2s_2)$$

where p_1 = the price of 8-in. tree = \$1.93/tree

p_2 = the price of 16-in. tree = \$9.58/tree

x_1 = No. of trees cut in Group I

x_2 = No. of trees cut in Group II

s_1 and s_2 = miscellaneous charges (towing, royalty, etc.) per respective group.

The restrictions in this problem are the number of available machine-hours per day for the various phases of operation, as well as the required number of machine-hours per tree to execute the various operations. These values are available from time study data which have been discussed earlier in this thesis.

Assume the following available number of machine-hours per day:

Felling and bucking.....7 hr. (= 420 min.)
Yarding (500 ft.).......5 hr. (= 300 min.)
Loading................5 hr. (= 300 min.)

The machine-hour requirements per tree are:

	Felling	Yarding	Loading (min.)
Group I	3.89	3.00	0.9
Group II	8.14	3.00	1.24

Contract hauling per tree: Group I - \$0.23
Group II - 1.09

Miscellaneous charges per tree are:

	Royalty	Scaling	Towing	Hauling	Total
Group I	0.04	0.01	0.02	0.23	0.30
Group II	0.21	0.03	0.10	1.09	1.43

The profit equation becomes:

$$C = 1.93X_1 + 9.58X_2 - 0.30X_1 - 1.43X_2$$

or

$$C = 1.63X_1 + 8.15X_2$$

subject to the following restrictions:

$$3.89X_1 + 8.14X_2 \leqslant 420$$

$$3.00X_1 + 3.00X_2 \leqslant 300$$

$$0.9X_1 + 1.24X_2 \leqslant 300$$

$$X_1 \leqslant 164$$

$$X_2 \leqslant 29$$

$$X_1 \geqslant 0$$

$$X_2 \geqslant 0$$

Because there are only two variables in the problem, a graphic solution may be carried out as in Figure 13. The seven inequalities are represented by a number of lines and the area

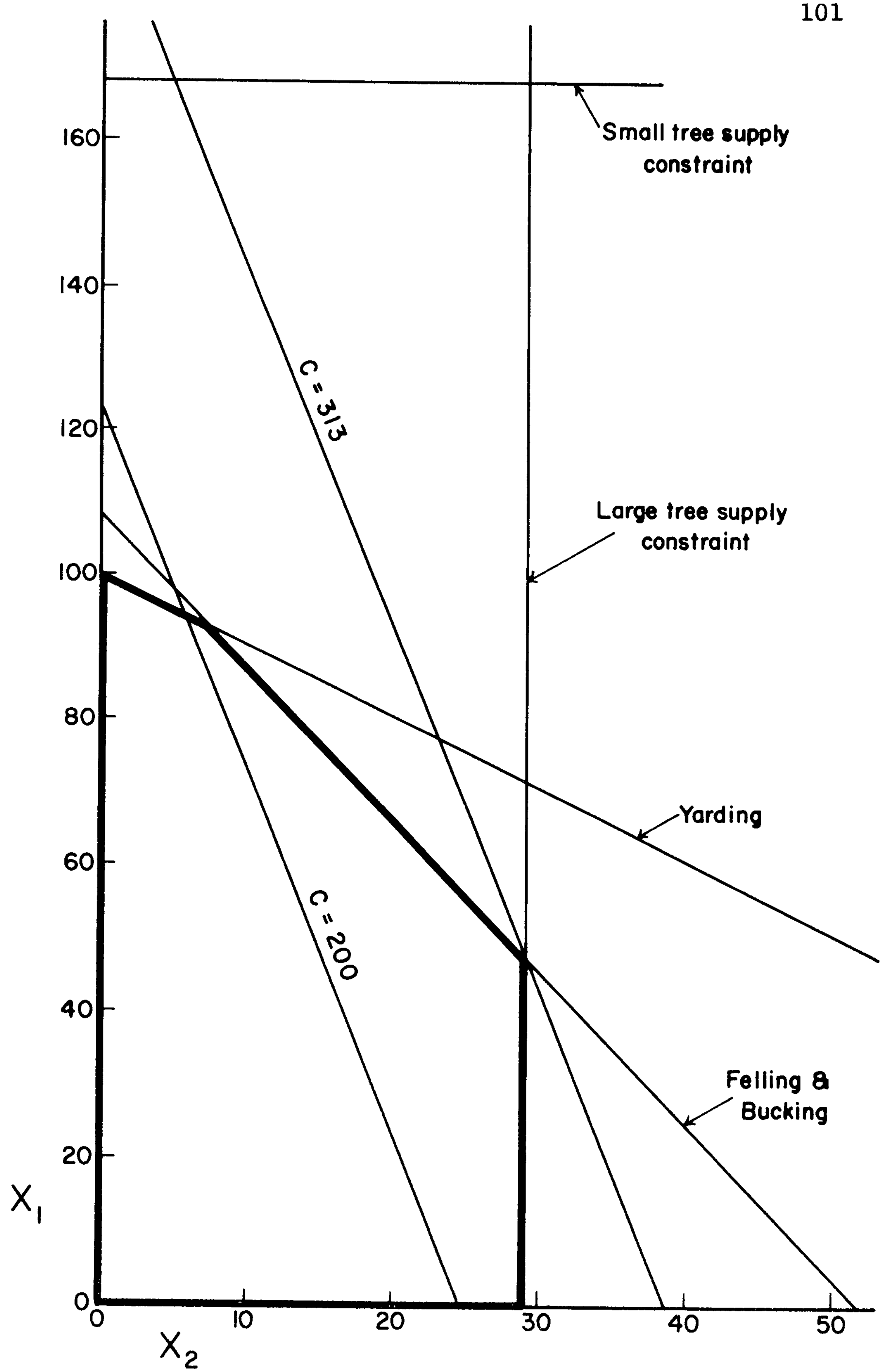


Fig. 13 Graphical solution of two-dimensional Problem No. 1

of feasible solutions is determined. To find the optimum solution among the feasible solutions, the profit function

$$C = 1.63X_1 + 8.15X_2$$

is plotted for various values of C, e.g. C = 200. This line is then moved, parallel to its original position, away from the origin until it is tangent to the farthest point of the constrained region. From Figure 13 it may be seen that this point is located at the crossing of the lines of felling and supply restriction of Group II. The solution for the optimum strategy may thus be obtained by solving the following equations:

$$3.89X_1 + 8.14X_2 = 420$$

$$X_2 = 29$$

then

$$X_1 = 47$$

$$X_2 = 29.$$

This gives the profit equation the following value:

$C = (1.63 \times 47) + (8.15 \times 29) = \$312.96$. The real net returns are obtained after fallers wages, yarding and loading costs have been subtracted from this value.

The solution shows that out of 164 available trees in Group I, only 47 should be taken. The solution does not indicate which these trees are, since all trees within a group are treated as equals. It seems most likely that the largest ones are taken and the smaller ones left behind.

The stand composition table (Table 48) lists 21 and 25 trees in the 12 and 10-inch d.b.h. groups respectively. Consequently all trees 10-inch d.b.h. and larger should be harvested and all others left behind.

The graphical solution for this Problem No. 1 was possible because the inequalities were given for two variables. Two-dimensional representation has the great advantage in making the nature of LP problems better understood by the reader. The solution may be made more accurate by extending this two-dimensional problem into the *n*th dimension. In the present instance, n would indicate the number of size classes into which the stand has been divided. Obviously, the larger n is, the closer the zero marginal tree can be determined, although the need for more detailed information will grow and hence also the cost of the whole project.

The solution of a n-dimensional LP problem is usually obtained by the Simplex Method. This method, which was developed by G. B. Dantzig (Koopmans, 1951), is an iterative procedure, which approaches the optimum solution in a systematic manner by testing and rejecting feasible solutions until the maximum (or minimum) value has been reached. Because the computations are long and repetitive, the use of electronic computers facilitates the application of this technique to a very considerable degree.

PROBLEM AND SOLUTION NO. 2

Once more one acre of forest is considered for harvesting. The composition of the stand is given in Table 49.

TABLE 49

STAND COMPOSITION AND THE EXPECTED PERCENTAGE OF # 2 LOGS

D.b.h. In.	No. of Trees Per Ac.	% # 2 Logs	Price Per Tree (DF)
6	71	0	1.00
88	47	0	1.93
10	25	0	2.51
12	21	0	3.87
14	14	0	5.02
16	8	20	9.58
18+	7	40	19.40

The available number of machine-hours is unchanged from the previous problem (No. 1) and the machine-hour requirements per tree for each d.b.h. class are given in Table 50. All values are based on time study data outlined in the first parts of this thesis.

TABLE 50

FELLING, BUCKING, YARDING AND LOADING TIMES

ASSOCIATED WITH PROBLEM NO. 2

D.b.h. In.	Felling & Bucking min.	500' Yarding min.	Loading min.
6	3.50	1.5	0.6
8	3.89	1.5	0.9
10	4.62	1.5	0.95
12	5.39	1.5	1.2
14	6.42	1.5	1.3
16	8.14	3	1.3
18+	12.0	3	1.5

TABLE 51

MISCELLANEOUS CHARGES PER TREE

PROBLEM NO. 2

D.b.h. In.	Royalty	Scaling	Towing	Contract Hauling	Total
6	$0.01	$0.01	$0.01	$0.13	$0.16
8	0.04	0.01	0.02	0.23	0.30
10	0.05	0.01	0.03	0.30	0.39
12	0.07	0.01	0.04	0.46	0.58
14	0.10	0.02	0.05	0.60	0.77
16	0.21	0.03	0.10	1.09	1.43
18+	0.48	0.06	0.21	2.11	2.86

The objective function is:

$$C = 1.00X_1 + 1.93X_2 + 2.51X_3 + 3.87X_4 + 5.02X_5 + 9.58X_6 + 19.40X_7 - 0.16X_1 - 0.30X_2 - 0.39X_3 - 0.58X_4 - 0.77X_5 - 1.43X_6 - 2.86X_7 ;$$

$$C = 0.84X_1 + 1.63X_2 + 2.12X_3 + 3.29X_4 + 4.25X_5 + 8.15X_6 + 16.54X_7.$$

Subject to the following restrictions:

$$
\begin{array}{lllllllll}
3.50X_1 & + 3.89X_2 & + 4.62X_3 & + 5.39X_4 & + 6.42X_5 & + 8.14X_6 & + 12.0X_7 & \leqslant & 420 \\
1.5X_1 & + 1.5X_2 & + 1.5X_3 & + 1.5X_4 & + 1.5X_5 & + 3.0X_6 & + 3.0X_7 & \leqslant & 300 \\
0.6X_1 & + 0.9X_2 & + 0.95X_3 & + 1.2X_4 & + 1.3X_5 & + 1.3X_6 & + 1.5X_7 & \leqslant & 300 \\
1X_1 & & & & & & & \leqslant & 71 \\
 & 1X_2 & & & & & & \leqslant & 47 \\
 & & 1X_3 & & & & & \leqslant & 25 \\
 & & & 1X_4 & & & & \leqslant & 21 \\
 & & & & 1X_5 & & & \leqslant & 14 \\
 & & & & & 1X_6 & & \leqslant & 8 \\
 & & & & & & 1X_7 & \leqslant & 7
\end{array}
$$

By adding disposal activities or so-called slack variables, the above inequalities are converted to a system of equalities, shown in Appendix II. This Simplex Tableau or Computational table is the starting point for the computation steps which comprise the Simplex Method.

The solution for Problem No. 2 was obtained using the Alwac III E electronic computer at the Computing Centre of the University of British Columbia. A standard program for the solution of Simplex problems is available at the Centre's tape library. In Appendix V are outlined briefly the procedures followed in using the computer for the solution of a Simplex problem.

SOLUTION OF PROBLEM NO. 2

A summary of the information in the problem and the optimum solution is shown in the attached copy of the original worksheet from the computer (Appendix III). Beneath the original matrix, which for technical reasons has a different order as compared to the standard Simplex Tableau, are given the net return values for the objective function. It can be seen that the optimum value $340.7) was reached in five iterations. The last column on the worksheet indicates the input levels for the optimum solution. The "p" designates a factor to be used and the "q" stands for a discarded value. Thus the first figure, p03-14.67748856 means that the third input in the objective function (≡ d.b.h. class 10 inches) should be utilized at a level of 14.68. These results are summarized in Table 52.

TABLE 52

THE SOLUTION FOR PROBLEM NO. 2

D.b.h. In.	Number Trees Available	Program Solution	Price $	Total Gross Revenue
6	71	0	0.84	0
8	47	0	1.63	0
10	25	14.7	2.12	31.16
12	21	21	3.29	69.09
14	14	14	4.25	59.50
16	8	8	8.15	65.20
18+	7	7	16.54	115.78
				$340.73

Consequently the gross returns per one acre and one day's work were $340.73. The net return for this time and area is obtained by subtracting the pertinent costs from this value:

Gross return	$340.73
Faller & bucker wages	40.00
Highlead & crew cost	80.00
Loader & crew cost	80.00
Net revenue	$140.73

It is obvious that a change in the size of the area or time constriction will alterate the results. Thus, if a large area is considered but the total time allowed is short, the zero marginal limit will not be reached; the optimum program specifies that the largest trees be harvested first. A further refinement in the formulation of the problem can consider this time factor along with the others. Problem No. 3 illustrates such an application.

PROBLEM AND SOLUTION NO. 3

According to the solution of Problem No. 2, the zero marginal size refers to a tree of 10 inches d.b.h. The program suggests that about half of the available trees in that size group should be used. Although it is not made explicit, it is safe to assume that those 10 in. trees should be taken, which require shorter yarding. The trees situated farther away from the spar tree become sub-marginal. This consideration immediately suggests the incorporation of further factors into the LP matrix. It must be remembered, however, that the addition of new factors increases the number of "processes" and consequently also the size of the matrix. The limit is obviously set by the computer's capacity.

A more detailed solution for the determination of the zero marginal tree may be construed where in addition to tree size, the effect of various species, yarding distances and number of days operated will be included. In principle there is no difference between this and the earlier problems: the various sizes, species, yarding distances and time limits will only multiply the number of variables. The solution of the new matrix will only be longer and more laborious.

Because yarding distances are treated as variables in Problem No. 3, it is suggested at this stage that tractor skidding, rather than highlead yarding, be considered. During the time studies at the University Research Forest, the author obtained some performance values for the D-2 Caterpillar tractor. These results had been featured earlier in Figure 4. In this program, three yarding distances will be examined: 200, 600 and 1,000 feet. The species are Douglas fir and hemlock and the stand composition is assumed to be as shown in Table 53.

TABLE 53

STAND COMPOSITION FOR PROBLEM NO. 3*

D.b.h.	No. of trees on 20 acres	
In.	Douglas fir	Hemlock
8	410	522
10	246	256
12	256	170
14	150	118

The roundtrip times for a D-2 for the three distances are shown in Figure 4. Because of considerable variability in those data, the effect of load size is subject to considerable uncertainty. This effect will nevertheless be incorporated into the equations because future work is most likely to produce better time study data on this factor.

* Source: Smith, Ker, Csizmazia, 1961, p. 22.

The tractor is equipped with 3 chokers and the cost of machine operation is \$48.00 per day. If the machine works 5½ hours out of 8, then the hourly cost becomes \$8.75.

TABLE 54

YARDING TIME PER TREE FOR VARIOUS YARDING DISTANCES

D.b.h. In.	Logs Per Tree	Distance: 200 ft. — Time, minutes, per: Turn	200 ft. Tree	600 ft. Turn	600 ft. Tree	1,000 ft. Turn	1,000 ft. Tree
8	1	7	2.3	13	4.3	19	6.3
10	1	7	2.3	13	4.3	19	6.3
12	1	9	3	15	5	21	7
14	1	9	3	15	5	21	7

The time requirements for felling and bucking are taken from Table 38. Because of insufficient information, the time requirements for hemlock are assumed to be 10% higher than for Douglas fir; both are shown in Table 55.

TABLE 55

FELLING, BUCKING AND LOADING - TIME REQUIREMENTS PER TREE

D.b.h. In.	Machine-minutes: Felling & Bucking — Douglas Fir	Felling & Bucking — Hemlock	Loading — All Species
8	3.89	4.28	0.9
10	4.62	5.08	0.95
12	5.39	5.93	1.2
14	6.42	7.05	1.3

The direct charges against the trees such as Royalty, scaler's fee, towing and contract hauling are assumed to be equal for all species and have been adopted from Table 51 without change.

The revenues, shown in Table 52, are based on the log price schedule in Appendix I. This schedule is extended in this problem with a specification that the price for "small" logs be $25.00 per M f.b.m. for hemlock and $27.50 for Douglas fir. These are all logs obtained from trees with 13 inch d.b.h. or less.*

TABLE 56

REVENUES FROM LOG SALES

DOLLARS PER TREE - PROBLEM NO. 3

D.b.h. In.	Douglas Fir	Hemlock
8	1.02	0.90
10	1.32	1.12
12	2.02	1.77
14	5.02	3.66

Whereas in Problems 1 and 2 one day was the allowable time, an additional dimension will be added to Problem No. 3 by making this time limit a variable.

While the additional operating days show diminishing gross

* Modification suggested by Dr. J. H. G. Smith.

income because the best trees are removed first, the daily cost figure will still remain constant. It is of special interest, therefore, to establish for an operation the number of days at which the income is maximized.

To follow this lead, three operations were considered on that 20-acre area, each of them lasting 1, 5 and 20 days, respectively.

The machine-hours available for these operations are:

	1 day	5 days	20 days
Loading - 5 hours per day	300 min.	1500 min.	6000 min.
Yarding - 7 " " "	420 min.	2100 min.	8400 min.
Felling & bucking - 7 hours per day	420 min.	2100 min.	8400 min.

The objective function is:

$$
\begin{aligned}
C = {} & 1.02(X_1 + X_2 + X_3) + 1.32(X_4 + X_5 + X_6) + 2.02(X_7 + X_8 + X_9) \\
& + 5.02(X_{10} + X_{11} + X_{12}) + 0.90(X_{13} + X_{14} + X_{15}) \\
& + 1.12(X_{16} + X_{17} + X_{18}) + 1.77(X_{19} + X_{20} + X_{21}) \\
& + 3.66(X_{22} + X_{23} + X_{24})
\end{aligned}
$$

where

X_1 = no. of D. fir trees yarded 200 ft. - of 8 in. d.b.h. class

X_2 = " " " " " " 600 ft. - of 8 in. " "

X_3 = " " " " " " 1000 ft. - of 8 in. " "

X_4 = " " " " " " 200 ft. - of 10 in. " "

X_5 = " " " " " " 600 ft. - of 10 in. " "

.
.
.

X_{23} = no. of hemlock trees yarded 600 ft. - of 14 in. d.b.h. class

X_{24} = " " " " " 1000 ft. - of 14 in. " "

The system of inequalities stating the restrictions of this problem becomes an extensive one and the subsequent addition of slack variables will extend it even more. Because of the capacity limit of Alwac III E, which cannot handle Simplex matrices larger than 32 x 160, the number of factors must be kept down. This is partly the reason why only two species and four d.b.h. classes were included in this analysis.

The system of inequalities has not been given in the Appendices because of its size. It may be seen coded on the computer working sheet of Appendix IV.

SOLUTION OF PROBLEM NO. 3

From the appended worksheets, the following results were obtained as summarized in Table 57. Owing to a shortcoming in the programming, where the stand density had not been considered, the computer could not distinguish between the trees designated for short hauls and long hauls. Actually, the number of available trees within a certain size class grows with the increasing radius of an operating area provided the stocking is uniform.

TABLE 57

SUMMARY OF SOLUTIONS FOR PROBLEM NO. 3

1. One-day Operation

D.b.h.	No. trees available		Progr. Solution		Price		Total Gross Revenue			
In.	F	H	F	H	F	H	F	H	All	
8	410	522	-	-	-	-	-	-	-	
10	246	256	-	-	-	-	-	-	-	
12	256	170	-	-	-	-	-	-	-	
14	150	118	65	-	5.02	-	328	-	328	$ 328

2. Five-day Operation

D.b.h.	No. trees available		Progr. Solution		Price		Total Gross Revenue			
In.	F	H	F	H	F	H	F	H	All	
8	410	522	-	-	-	-	-	-	-	
10	246	256	-	-	-	-	-	-	-	
12	256	170	56½	-	2.02	-	114	-	114	
14	150	118	150	118	5.02	3.66	754	432	1186	$1300

3. Twenty-day Operation

D.b.h.	No. trees available		Progr. Solution		Price		Total Gross Revenue			
In.	F	H	F	H	F	H	F	H	All	
8	410	522	410	43	1.02	0.90	418	39	457	
10	246	256	246	256	1.32	1.12	325	284	609	
12	256	170	256	170	2.02	1.77	517	301	818	
14	150	118	150	118	5.02	3.66	754	432	1186	$3070

It may be seen from Table 57 that as the time limit is increased, more small trees may be hauled out. As this size decreases the net revenue diminishes because the daily operating costs remain constant. In other words, a series of such programs allows the operator to determine the longest time he should spend on a tract of land and also indicates the lowest size which should be cut during that operation.

Under the given situation, the daily cost was assumed to be:

Tractor operation......	\$ 48
Faller's wages.........	\$ 40
Driver's wages.........	\$ 18
Loader & Crew cost.....	\$ 80
Total	\$186

Consequently, the net revenue from one day's operation is 328 - 186 = \$142; but for the five-day operation 1300 - 5(186) = \$360 or $\frac{360}{5}$ = \$72 per day; and for the twenty days' operation the net revenue is 3070 - 20(186) = \$650 loss or $\frac{-650}{20}$ = \$32 loss per day.

A graphical extrapolation (Figure 14) shows that the average daily net revenue falls continuously as the time spent on the area increases. At the same time, the cumulative net revenue (Figure 15) increases, reaching a maximum at the 5th day and then decreasing to become zero on the 13th day of operation.

The five-day operation consequently constitutes the most

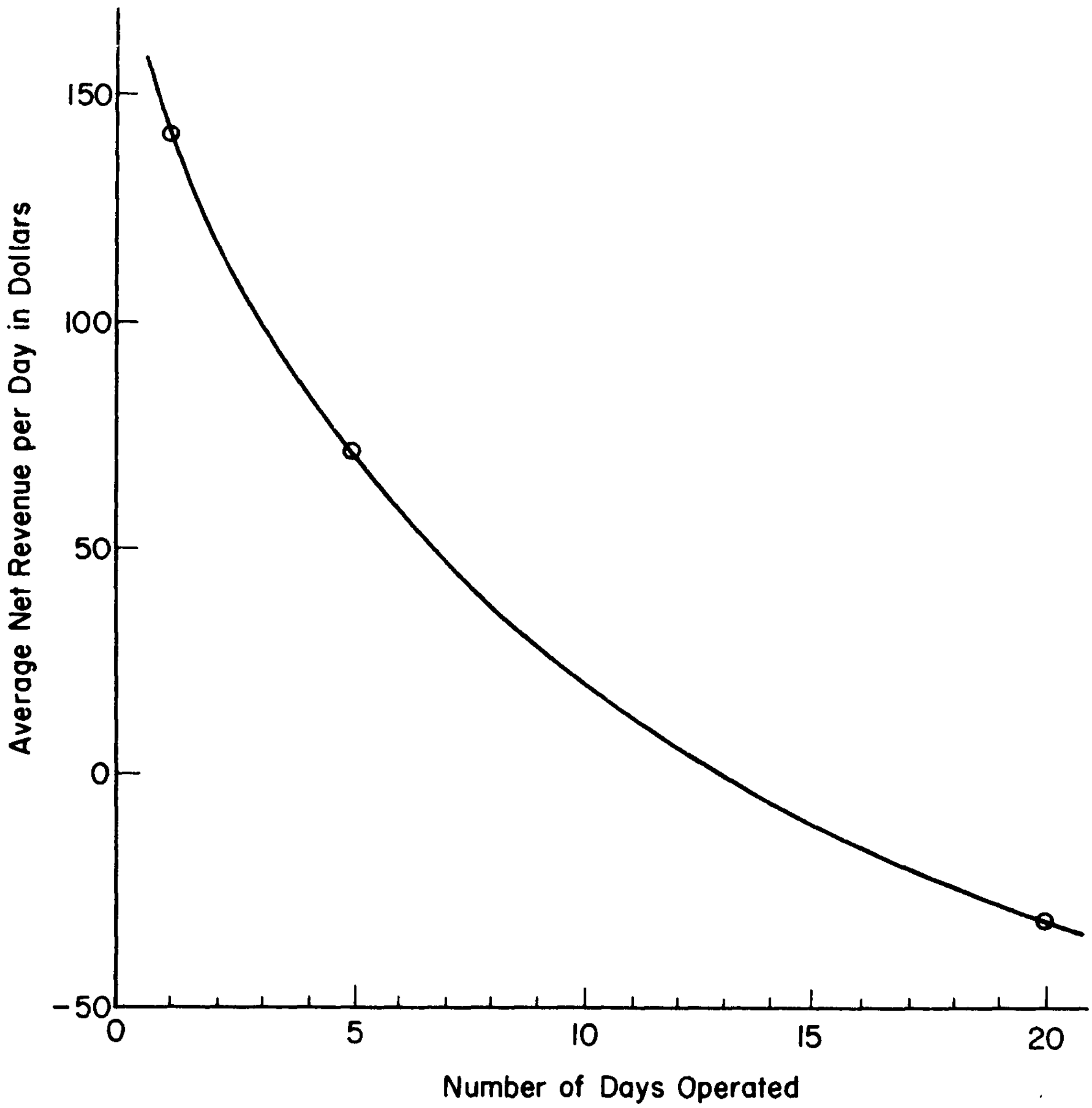


Fig. 14 Extrapolation of Net Revenues for Operations of various Durations. Problem No. 3.

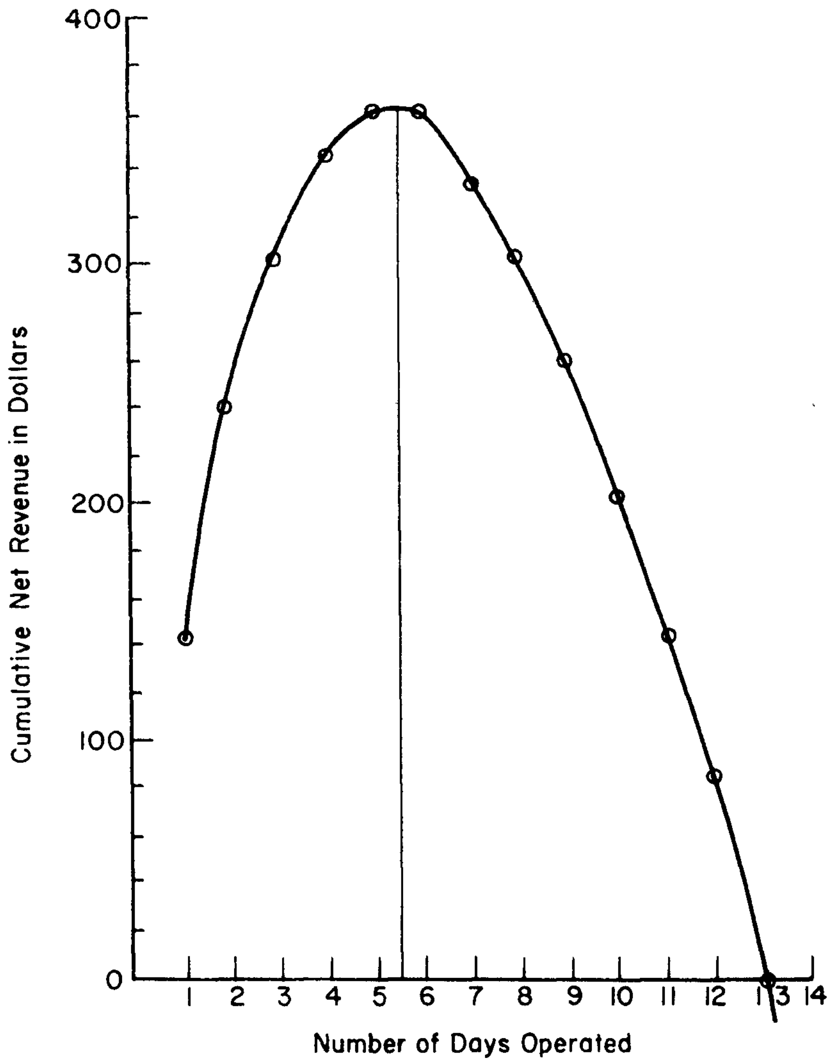


Fig. 15 Most Profitable Time-expenditure on the Operation. Problem No. 3.

profitable duration for this area and it is seen that the marginal tree sizes are 12 inches d.b.h. for Douglas fir and 14 inches d.b.h. for hemlock.

A maximum of thirteen days could be spent on the area if for some reason all profit in the larger trees is to be dissipated in logging the smaller trees. To obtain a precise size-limit on the trees for that period, a fourth set of Simplex solutions was solved, substituting the times available at the 12-day levels. This means that the available number of hours for the three operations are as follows:

Loading.................	3900 hours
Yarding.................	5460 "
Falling & Bucking.......	5460 "

With the modified program now available for the U. B. C. Alwac III E electronic computer*, it is possible to process several such systems in rapid succession.

The fourth part of Problem No. 3 was solved and the results are summarized in Table 58. For the worksheet, see Appendix IV.

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* Modified by J. Csizmazia.

TABLE 58

FOURTH SOLUTION OF PROBLEM NO. 3

4. Twelve-day Operation

D.b.h.	No. trees available		Progr. Solution		Price		Total Gross Revenue			
In.	F	H	F	H	F	H	F	H	All	
8	410	522	(36)	-	1.02	-	(37)	-	(37)	
10	246	256	246	-	1.32	-	325	-	325	
12	256	170	256	170	2.02	1.77	517	301	818	
14	150	118	150	118	5.02	3.66	753	432	1185	$2365

The net revenue from this operation is very close to zero:

$$2365 - 12(186) = \$133 \text{ or } \frac{133}{20} = \$6.65 \text{ per day.}$$

The solution shows, that at this rate of operation, the zero marginal tree size for Douglas fir is 10 in. d.b.h. (the 36 trees in 8 inch class are ignored) and for hemlock is 12 inches, two inches below the most profitable operating level.

These results confirm those arrived at previously in this thesis.

DISCUSSION

The collection and analysis of data on logging can be used to a great advantage in planning the profitability of new harvesting operations. Such information may serve as a basis for a comparison of the relative advantages of several methods of conducting the various operations in the woods and during log transportation.

Often the major transportation methods are adopted without adequate consideration of their effect on the cost from stump to landing. The effect of individual tree size is seldom considered as a factor in a real logging situation. Practical considerations often must overrule the theoretically optimal solutions and a compromise is usually achieved through the intuitive experience of the practical logger. However, a wider appreciation of the underlying basic factors is an area which should not be ignored by the practical woods operator as it has a direct bearing on the profit potentiality of a given logging system.

Logging is full of uncertainty. New situations arise continually which must be solved on the spot and which seem to defy clearcut classification and evaluation in terms of simple time-motion studies. Nevertheless, if the operating conditions were already so well standardized that little or no new knowledge could be added over that acquired through cost accounting, then output studies would become entirely unnecessary. Therefore it is the purpose of an investigator to distinguish the major factors affecting the output and to bring out their significance by studying their effects under a wide range of conditions.

Data must be collected, segregated and compiled on the basis of different natural factors which may be identified and classified. Variation in the data should be recognized and allowed for in the subsequent computations.

The extent of the time studies in the University Research Forest, in the summer of 1961, was such as to warrant no sweeping conclusions nor recommendations. Rather, it emphasized the extent of problems and shed some light on the shortcomings in the present state of operations. The subsequent computations, which occupied the main part of this thesis, further showed the difficulties in economic decision-making in connection with the harvesting and marketing of small trees.

Although many earlier studies have conclusively proven the higher cost associated with the harvesting of smaller trees, the actual values for any specific condition must be obtained through an independent investigation.

The time studies at the University Research Forest indicated that the 10 to 12 inch d.b.h. size class was the lower limit for trees still paying their way. It also showed that some improvement in yarding efficiency could, lower this size limit for Douglas fir down to 7 inches, at least in theory. This low diameter limit is unrealistic from many points of view. It must be assumed that the market absorbs these small logs at full market price and that the estimates of operating parameters are subject to very little variation. The general "safe" lower limit, established rather empirically from the solutions of the three Programs, is around 14 to 15 inches d.b.h. for Douglas fir and 16 to 17 inches for hemlock. Furthermore, in light of the available cost data on sawmilling, which was only a rough estimate obtained from the B.C.L.M.A. personnel, it seemed to be unwise to convert the small logs into lumber products.

Throughout this investigation, the lack of precise time and cost data has been the most serious problem. However, this shortcoming does not diminish the value of the general approach to the problem on hand. It is particularly true with regard to the application of LP methods in a fictitious logging operation.

Whereas the LP techniques have undergone considerable sophistication and refinement in such areas as airline routing and the solution of refinery and electrical networks, the inherent uncertainty of a logging situation poses a serious challenge to the user of LP techniques in this field. According to Lussier (1961), the great complexity of large-scale logging calls for the application of a variety of Operating Research methods, of which LP is only one of the available techniques. As a rule, the topics of Operation Research in general and LP in particular must be approached as complete and independent subjects in their own rights. It is not possible to explore the many subtle possibilities of this new research tool in a work of this general nature.

SUMMARY AND CONCLUSIONS

A survey of the literature dealing with logging and milling efficiency studies shows that, regardless of methods employed, the smaller trees are associated with higher harvesting and processing costs. Improved logging techniques have made it possible to lower the size limit for profitable operation, but even presently this marginal size is sufficiently high on the Pacific Coast to seriously curtail efficient utilization of trees smaller than a d.b.h. of 12 inches.

A time study conducted on the University Research Forest estimated the performances of felling, bucking, yarding and loading operations. It was found that especially the high-lead yarding was inefficient and realistic improvements were recommended in subsequent calculations (Program II).

The application of linear programming technique to some harvesting problems has been shown to be feasible. During the exposition and discussion of this methodology, three problem situations were thoroughly covered. A two-dimensional problem was solved by graphical technique and two multi-dimensional problems were solved by the use of the Alwac III E electronic computer. The results of the time study and the computations may be summarized as follows:

1. The present working efficiency, as existing in the University Research Forest in July 1961, is subject to some shortcomings. Especially serious was the lack of efficiency in the high-lead yarding operation.

2. The theoretical zero marginal size for Douglas fir and hemlock was found to be 12 and 14 inches d.b.h. respectively. A reasonable improvement in operating efficiency could lower this value by several inches; however the present market would probably not be willing to absorb this small material at the price of No. 3 logs.

3. The application of LP may provide a faster method for analysing various harvesting situations. More refined programs may show new approaches to the study of harvesting profitability.

4. Because of the large variability of typical time study data from logging operations, the field sampling must be relatively extensive. Only in that way may final results be secured within reasonably narrow confidence limits. The time studies carried out at the University Research Forest were in the opinion of the author not of sufficient size to give the results satisfactory precision.

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APPENDIX I

THE UNIVERSITY OF BRITISH COLUMBIA

INTERDEPARTMENTAL

MEMORANDUM

TO Dr. J. H. G. Smith ✓	FROM Prof. F. M. Knapp
Mr. J. P. Tessier	Faculty of Forestry
	October 25, 1961

Vancouver Log Prices September 1961

Fir Peelers

#1 -	$109.92
2 -	100.71
3 -	90.70
4 -	75.39
Av.	$90.31

Sawlogs

#1 -	$75.38
2 -	64.74
3 -	52.28
Av.	$58.89

Av.All Grades

#1 -	$94.41
2 -	69.50
3 -	52.28
Av.	$63.26

Cedar Lumber

#1 -	$58.99
2 -	48.66
Av.	$52.78

Shingle

#1 -	$51.92
2 -	41.43
3 -	30.89
Av.	$38.61

Merch.Cedar

#1 -	$46.03
2 -	39.78
3 -	30.11
Av.	$31.88

Av.All Grades

#1 -	$56.75
2 -	42.60
3 -	30.36
Av.	$38.99

Hemlock

#1 -	$52.17
2 -	47.01
3 -	41.36
Av.	$42.91

Balsam

#1 Peeler -	$50.00
2 Lumber -	39.24
3 Pulp -	32.50
Av.	$39.38

Pine

#1 -	$65.00
2 -	53.06
3 -	41.15
Av.	$46.70

Spruce

#1 -	$47.17
2 -	44.76
3 -	36.51
Av.	$39.73

APPENDIX II

SIMPLEX TABLEAU FOR PROBLEM NO. 2

Activity	Disposal Activities										Real Activities						
Level	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}	P_{17}	P_1 .84	P_2 1.63	P_3 2.12	P_4 3.29	P_5 4.25	P_6 8.15	P_7 16.54
420	/	0	0	0	0	0	0	0	0	0	3.50	3.89	4.62	5.39	6.42	8.14	12.0
300	0	/	0	0	0	0	0	0	0	0	1.5	1.5	1.5	1.5	1.5	3.0	3.0
300	0	0	/	0	0	0	0	0	0	0	0.6	0.9	0.95	1.2	1.3	1.3	1.5
71	0	0	0	/	0	0	0	0	0	0	/	0	0	0	0	0	0
47	0	0	0	0	/	0	0	0	0	0	0	/	0	0	0	0	0
25	0	0	0	0	0	/	0	0	0	0	0	0	/	0	0	0	0
21	0	0	0	0	0	0	/	0	0	0	0	0	0	/	0	0	0
14	0	0	0	0	0	0	0	/	0	0	0	0	0	0	/	0	0
8	0	0	0	0	0	0	0	0	/	0	0	0	0	0	0	/	0
7	0	0	0	0	0	0	0	0	0	/	0	0	0	0	0	0	/

APPENDIX III

```
8020
1007
420 300 300 71 47 25 21 14 8 7
0 0 0 0 0 0 0 0 0 0
.84 3.5 1.5 .6 1 0 0 0 0 0 0
1.63 3.89 1.5 .9 0 1 0 0 0 0 0
2.12 4.62 1.5 .95 0 0 1 0 0 0 0
3.29 5.39 1.5 1.2 0 0 0 1 0 0 0
4.25 6.42 1.5 1.3 0 0 0 0 1 0 0
8.15 8.14 3.0 1.3 0 0 0 0 0 1 0
16.54 12.0 3.0 1.5 0 0 0 0 0 0 1

     $ 0.000000000
p07q0a                  $ 115.7794685
p06q09                  $ 180.9791984
p05q08                  $ 240.4792175
p04q07                  $ 309.5690841
p03q01                  $ 340.6852951  ≈ $340.7


p03
 14.67748856
q02
 180.4837646
q03
 221.7563781
q04
 71.00000000
q05
 47.00000000
q06
 10.32251119
p04
 21.00000000
p05
 14.00000000
p06
 8.000000000
p07
 7.000000000
```

ALWAC III-E WORKSHEET - PROBLEM NO. 2

APPENDIX IV

```
1124
8400 6000 8400 410 246 256 150 522 256 170 118
0 0 0 0 0 0 0 0 0 0 0
1.02 3.89 0.90 2.30 1 0 0 0 0 0 0 0
1.02 3.89 0.90 4.30 1 0 0 0 0 0 0 0
1.02 3.89 0.90 6.30 1 0 0 0 0 0 0 0
1.32 4.62 0.95 2.30 0 1 0 0 0 0 0 0
1.32 4.62 0.95 4.30 0 1 0 0 0 0 0 0
1.32 4.62 0.95 6.30 0 1 0 0 0 0 0 0
2.02 5.39 1.20 3.00 0 0 1 0 0 0 0 0
2.02 5.39 1.20 5.00 0 0 1 0 0 0 0 0
2.02 5.39 1.20 7.00 0 0 1 0 0 0 0 0
5.02 6.42 1.30 3.00 0 0 0 1 0 0 0 0
5.02 6.42 1.30 5.00 0 0 0 1 0 0 0 0
5.02 6.42 1.30 7.00 0 0 0 1 0 0 0 0
0.90 4.28 0.90 2.30 0 0 0 0 1 0 0 0
0.90 4.28 0.90 4.30 0 0 0 0 1 0 0 0
0.90 4.28 0.90 6.30 0 0 0 0 1 0 0 0
1.12 5.08 0.95 2.30 0 0 0 0 0 1 0 0
1.12 5.08 0.95 4.30 0 0 0 0 0 1 0 0
1.12 5.08 0.95 6.30 0 0 0 0 0 1 0 0
1.77 5.93 1.20 3.00 0 0 0 0 0 0 1 0
1.77 5.93 1.20 5.00 0 0 0 0 0 0 1 0
1.77 5.93 1.20 7.00 0 0 0 0 0 0 1 0
3.66 7.05 1.30 3.00 0 0 0 0 0 0 0 1
3.66 7.05 1.30 5.00 0 0 0 0 0 0 0 1
3.66 7.05 1.30 7.00 0 0 0 0 0 0 0 1
```

#2 Sw on
clear
8004 0c 17a8f142 10 3128f142
clear
8008 0c 10

Clear
8004 05 2800f301 04 290ef301
Clear
8008 05 04

ALWAC III-E WORKSHEET - PROBLEM NO. 3

Soln III

```
8020
1124
8400 6000 8400 410 246 256 150 522 256 170 118


         $ 0.000000000
p0cq07         $ 752.9987945
p18q0b         $ 1184.877746
p09q06         $ 1701.995239
p15q0a         $ 2002.894897
p06q05         $ 2327.614868
p12q09         $ 2614.333923
p03q03         $ 2675.760375
p13p15         $ 2785.855285
p10p12         $ 2951.645202
p04q04         $ 3032.532531
p0dq01         $ 3071.488952
p14p13         $ 3071.488952
p13p14         $ 3071.488952
p14p13         $ 3071.488952
p13p14         $ 3071.488952

p0d
 43.28499889
q02
 4255.542968
p03
 409.9999923
p04
 149.7888641
p06
 96.21113014
p09
 256.0000000
p0c
 150.0000000
q08
 478.7149963
p10
 256.0000000
p13
 170.0000000
p18
 118.0000000
     $ 3071.488952
```

ALWAC III-E WORKSHEET - PROBLEM NO. 3

$ 0.000000000

p0cq07	$ 752.9987945
p18q0b	$ 1184.877746
p09q03	$ 1249.517456
p16q01	$ 1299.218933
p17p16	$ 1299.218933
p16p17	$ 1299.218933
p17p16	$ 1299.218933
p16p17	$ 1299.218933

✓ p16
43.05844116
q02
1083.674133
✓ p09
56.60482311
q04
410.0000000
q05
246.0000000
q06
199.3951759
✓ p0c
150.0000000
q08
522.0000000
q09
256.0000000
q0a
170.0000000
✓ p18
74.94155693
$ 1299.218933

p16
4

ALWAC III-E WORKSHEET - PROBLEM NO. 3

I

8020
$ 0.000000000

420, 300, 420

p0cq03	$ 301.1995162
p0aq01	$ 328.4106826
p0bp0a	$ 328.4106826
p0ap0b	$ 328.4106750
p0bp0a	$ 328.4106750
p0ap0b	

✓ p0b
18.97196388
q02
214.9532699
✓ p0c
46.44859600
q04
410.0000000
q05
246.0000000
q06
256.0000000
q07
84.57943725
q08
522.0000000
q09
256.0000000
q0a
170.0000000
q0b
118.0000000
$ 328.4106750

p0b
~~18.97196388~~
q

ALWAC III-E WORKSHEET - PROBLEM NO. 3

```
1124
5460 3900 5460


tttt
1124
5460 3900 5460 410 246 256 150 522 256 170 118
0 0 0 0 0 0 0 0 0 0 0
1.02 3.89 0.90 2.30 1 0 0 0 0 0 0 0
1.02 3.89 0.90 4.30 1 0 0 0 0 0 0 0
1.02 3.89 0.90 6.30 1 0 0 0 0 0 0 0
1.32 4.62 0.95 2.30 0 1 0 0 0 0 0 0
1.32 4.62 0.95 4.30 0 1 0 0 0 0 0 0
1.32 4.62 0.95 6.30 0 1 0 0 0 0 0 0
2.02 5.39 1.20 3.00 0 0 1 0 0 0 0 0
2.02 5.39 1.20 5.00 0 0 1 0 0 0 0 0
2.02 5.39 1.20 7.00 0 0 1 0 0 0 0 0
5.02 6.42 1.30 3.00 0 0 0 1 0 0 0 0
5.02 6.42 1.30 5.00 0 0 0 1 0 0 0 0
5.02 6.42 1.30 7.00 0 0 0 1 0 0 0 0
0.90 4.28 0.90 2.30 0 0 0 0 1 0 0 0
0.90 4.28 0.90 4.30 0 0 0 0 1 0 0 0
0.90 4.28 0.90 6.30 0 0 0 0 1 0 0 0
1.12 5.08 0.95 2.30 0 0 0 0 0 1 0 0
1.12 5.08 0.95 4.30 0 0 0 0 0 1 0 0
1.12 5.08 0.95 6.30 0 0 0 0 0 1 0 0
1.77 5.93 1.20 3.00 0 0 0 0 0 0 1 0
1.77 5.93 1.20 5.00 0 0 0 0 0 0 1 0
1.77 5.93 1.20 7.00 0 0 0 0 0 0 1 0
3.66 7.05 1.30 3.00 0 0 0 0 0 0 0 1
3.66 7.05 1.30 5.00 0 0 0 0 0 0 0 1
3.66 7.05 1.30 7.00 0 0 0 0 0 0 0 1
80
81
```

ALWAC III-E WORKSHEET - PROBLEM NO. 3

Prob No 4.

Max time limit = 12 days


```
8020
    $ 0.000000000
p0cq07        $ 752.9987945
p18q0b        $ 1184.877746
p09q06        $ 1701.995239
p15q0a        $ 2002.894897
p06q03        $ 2129.028198
p13p15        $ 2271.504394
p04q05        $ 2327.614868
p12q01        $ 2358.621948
p03p12        $ 2364.492065
p14p13        $ 2364.492065
p13p14        $ 2364.492065


p03
 36.15423011
q02
 2774.161010
p06
 122.1070766
q04
 373.8457641
p04
 123.8929100
p09
 256.0000000
p0c
 150.0000000
q08
 522.0000000
q09
 255.9999961
p13
 170.0000000
p18
 118.0000000
    $ 2364.492065


p03
```

ALWAC III-E WORKSHEET

APPENDIX V

THE USE OF ALWAC III-E FOR SIMPLEX METHOD COMPUTATION

THE PROCEDURE - GENERAL

The Program is in the Computing Center's Program Library under Code No. 03.

To use the program: The program can be loaded through the highspeed reader by typing 0E00 CR on the Flexowriter. At the same time on the Control Panel all switches have to be in Normal position, and Isolation-Free switch on the top of the panel should be on Free.

The Data Tape should be loaded through the Flexowriter.

Preparation of the Data Tape

The data should be stated in the following manner as outlined:

MMM.......	MM.......	M.......	CR	(for λ_o)
0........	0.......	0.......	CR	
C_1.......	C_2.......	....	CR	
nn.......	n.n......	-n......	CR	(for λ_1)
n........	nnn......	.n......	CR	(for λ_2)
.	.	.	.	
.	.	.	.	
.	.	.	.	
n.nn	-n	nn......	CR	

Note: MM stands for coefficients in the Requirements Vector. May contain any number of digits.

In row 2, the number of zeros, separated by spaces, equals the number of (MM).

C_1.....are the net prices. May be any digit, with decimals, positive or negative.

nn.....are the coefficients in the Structural Column vectors (λ_1, λ_2....λ_i....λ_n). May be any digit, with decimals, positive or negative.

Loading the Data Tape

Insert the data tape into Flexowriter's reading devices. Set J.S. No. 2 (Jump Switch) on Jump position.

Press Clear button.

Type 8020 CR (= keyword)

Type yyzz CR

Note: yy $\rightarrow$ no. of equations (here 10).

zz $\rightarrow$ no. of variables (here 20).

Press Start Read button.

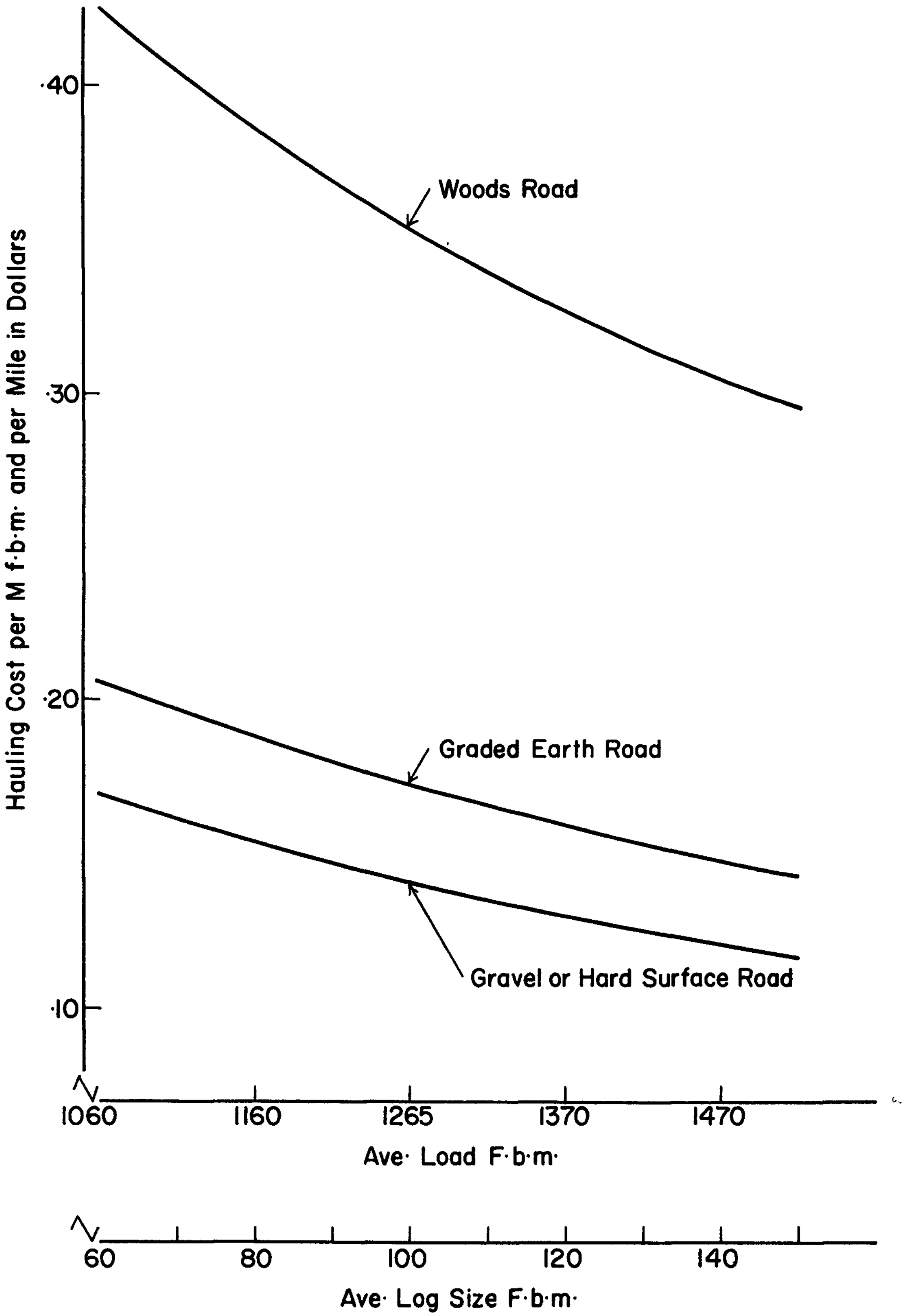
Now the machine will start reading in data and stops at lb command. After the lb occurs on the control panel, switch J. S. No. 3 to Jump and back to Normal.

The machine proceeds to compute and will out-put the results on the Flexowriter in a form as illustrated on the attached sheets.

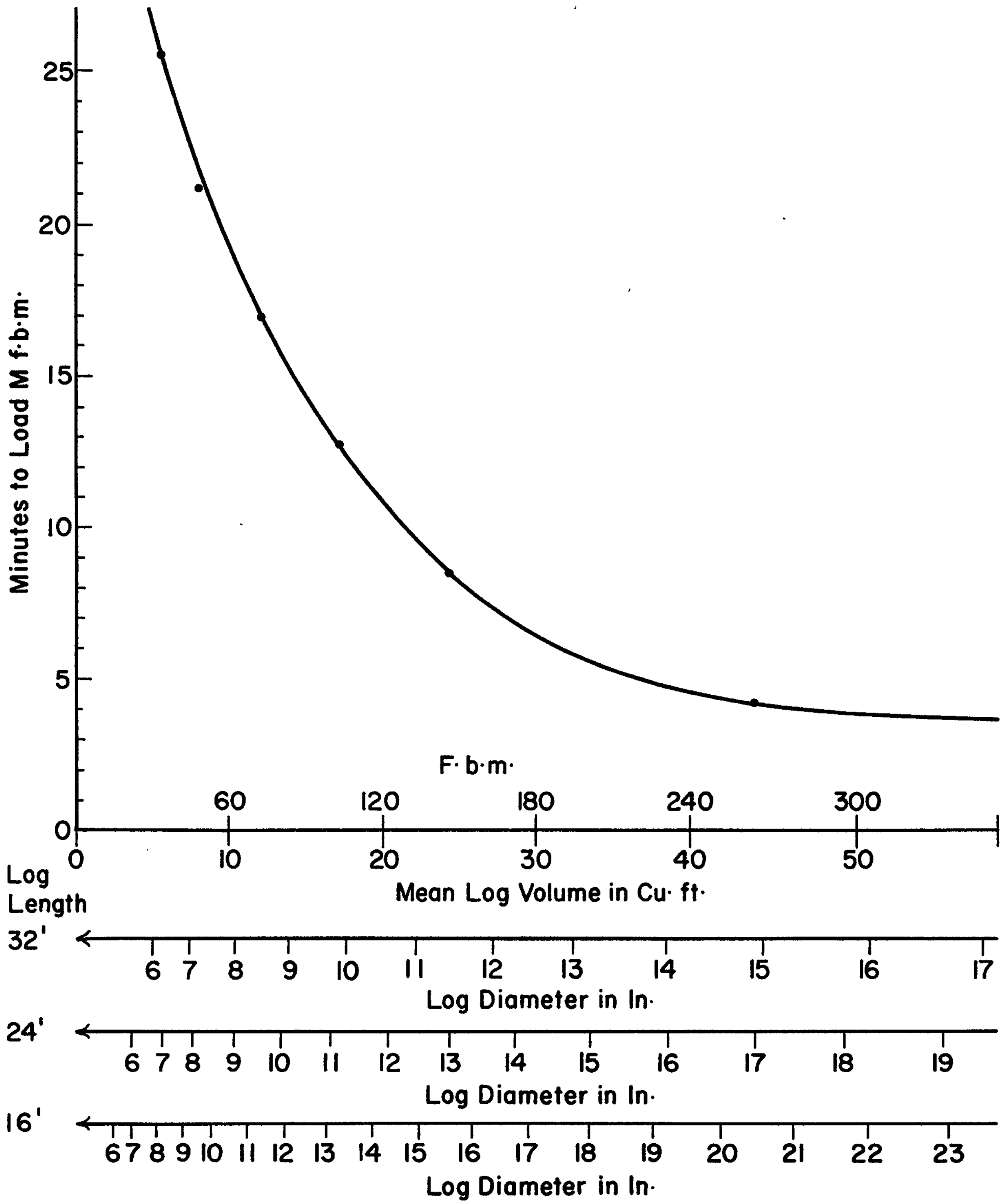
Note: Because the program uses the Isolated Memory, No. 2's and No. 3's have to be reloaded to the Main Memory through the highspeed reader. Press the Clear-Normal Switch (located on side of highspeed reader) to Clear and back to

Normal. Now the tape is read.

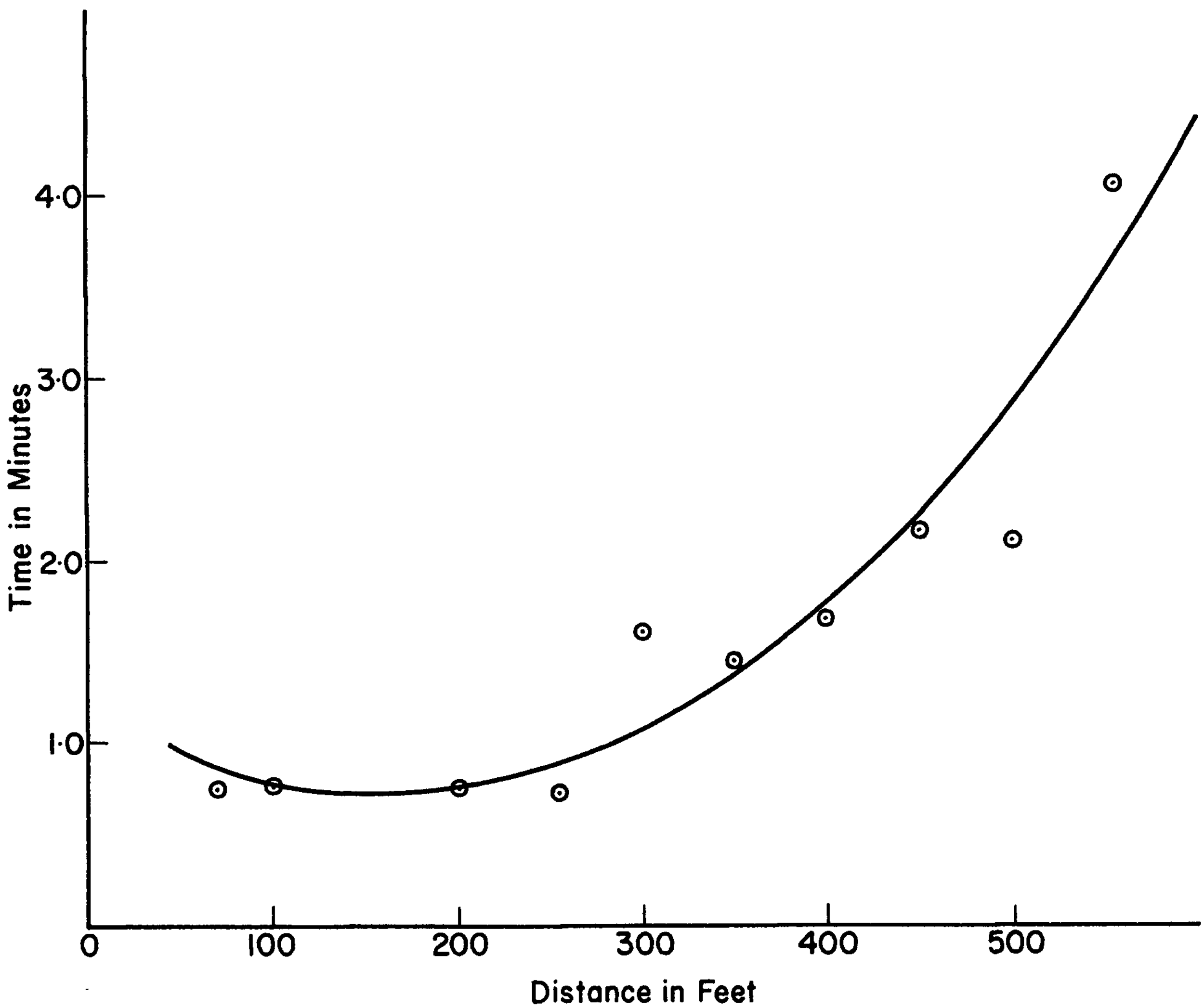
To test that the program has gone into the Main Memory properly, type on Flex. 0400 . If the machine types out OKAY , everytning is in order. Also check the Free-Isolated Switch which now must be at Isolated position.



Fig· I Effect of Road Type on Hauling Cost



Fig· 2 Effect of Mean Log Volume on Loading Rate· University Research Forest, June 1961



Fig· 3 Effect of Yarding Distance on Highlead Yarding Time·
University Research Forest, June 1961·

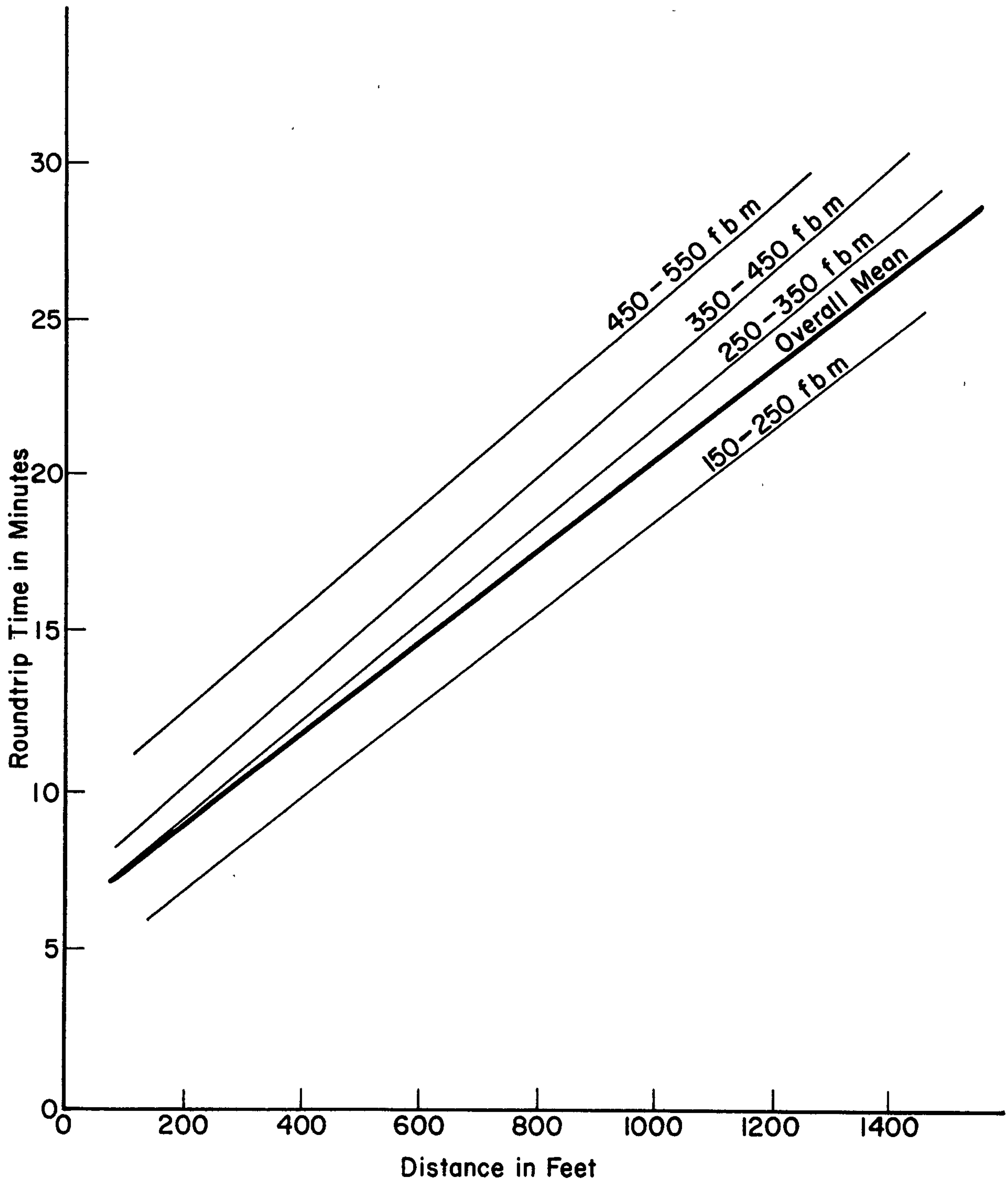
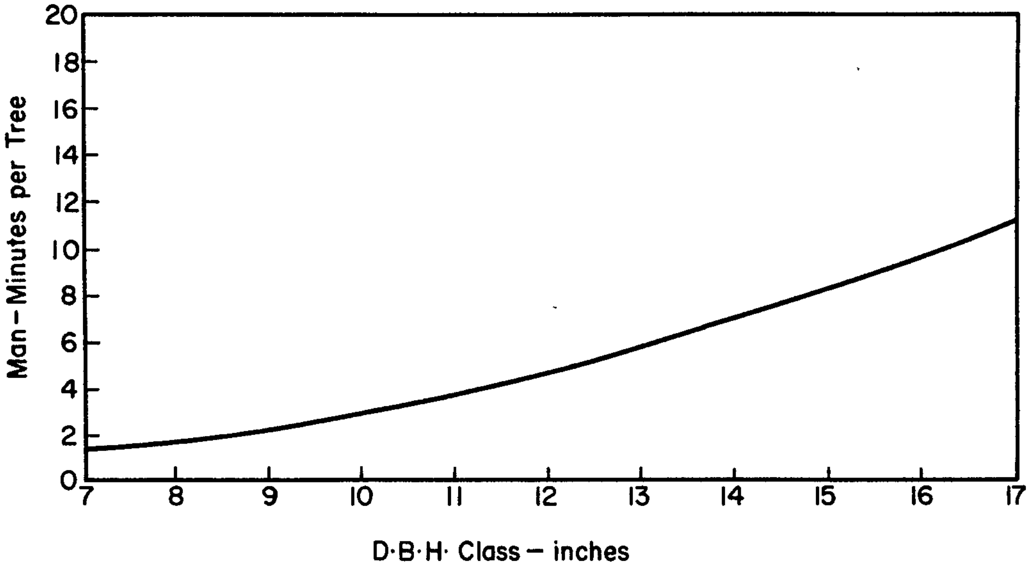
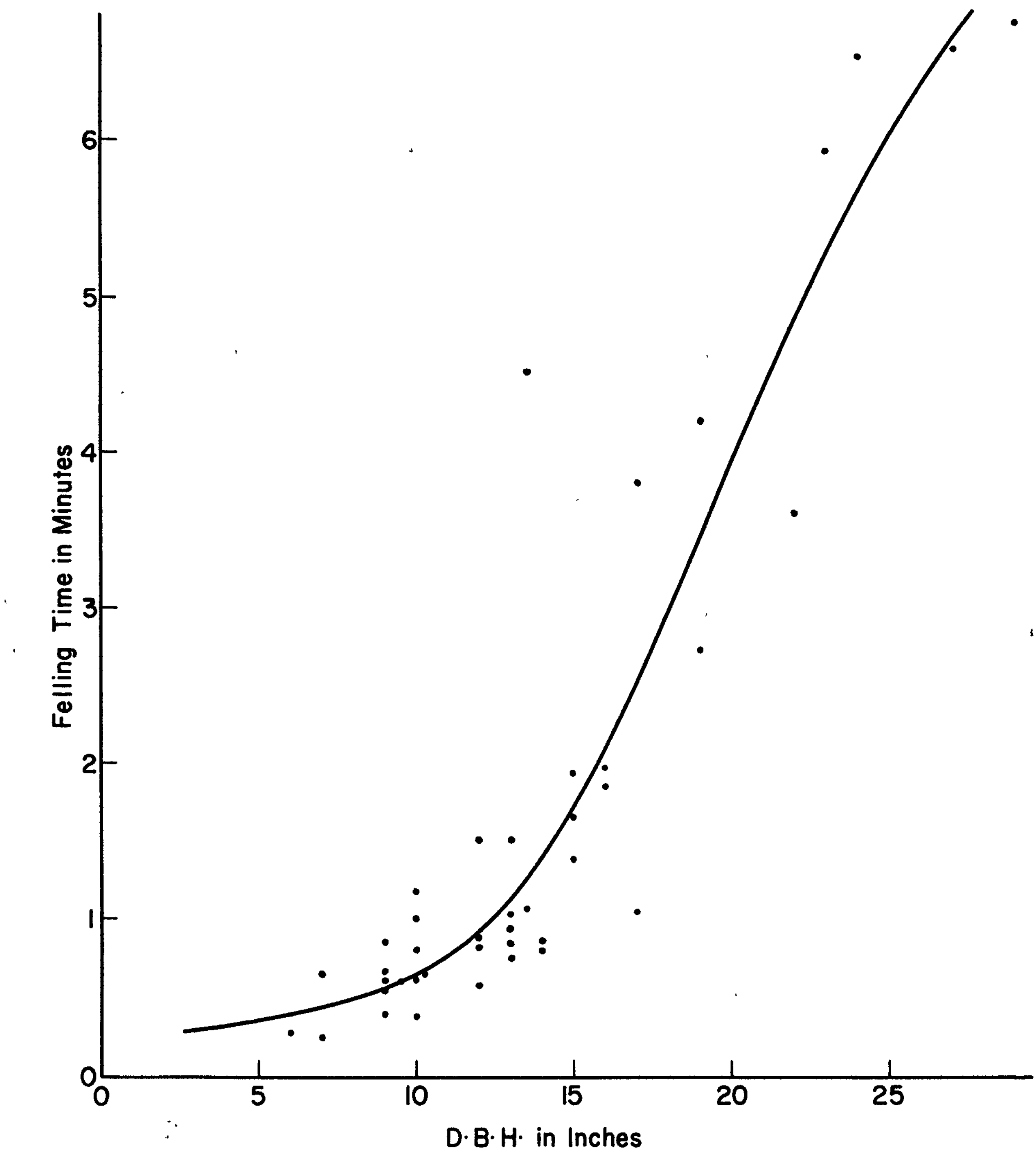


Fig. 4 Effect of Yarding Distance and Volume on Roundtrip Time; D-2 Tractor Operation, University Research Forest; March, 1961.



Fig· 5 Effect of Tree Size on Actual Time Required for Felling, Limbing, and Bucking· (Doyle and Calvert, 1961)



Fig· 6 Effect of Tree D·B·H· on Felling Time·
University Research Forest, June 1961·

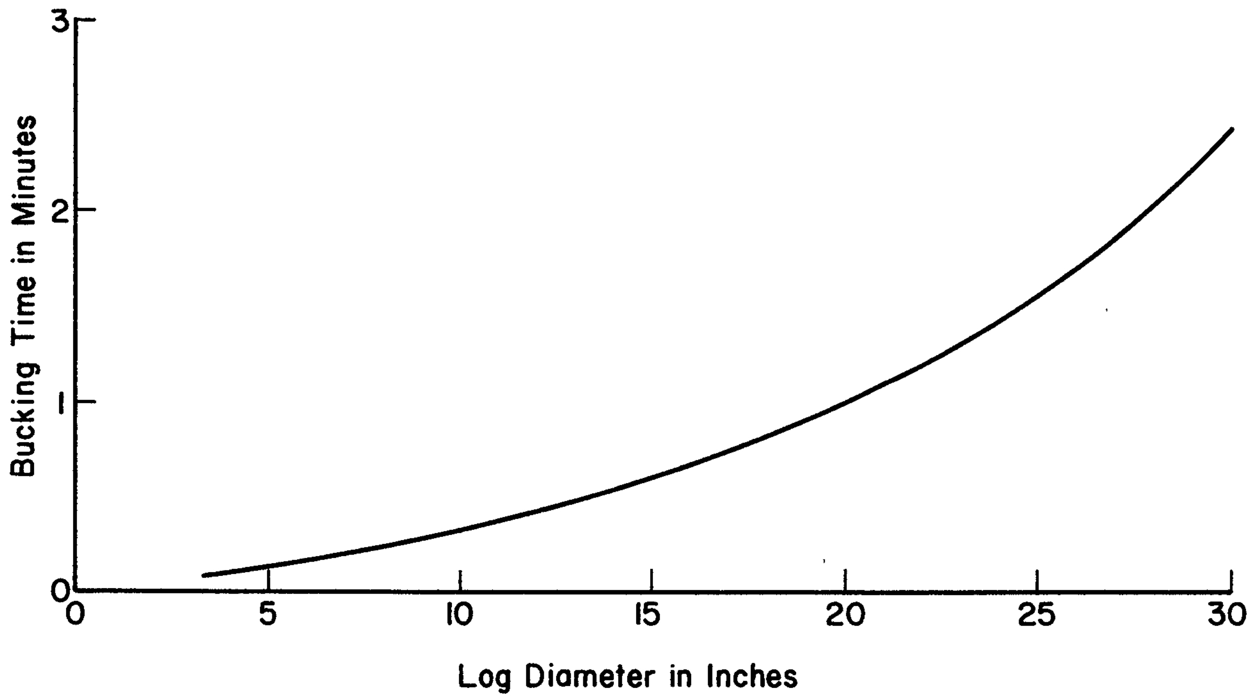
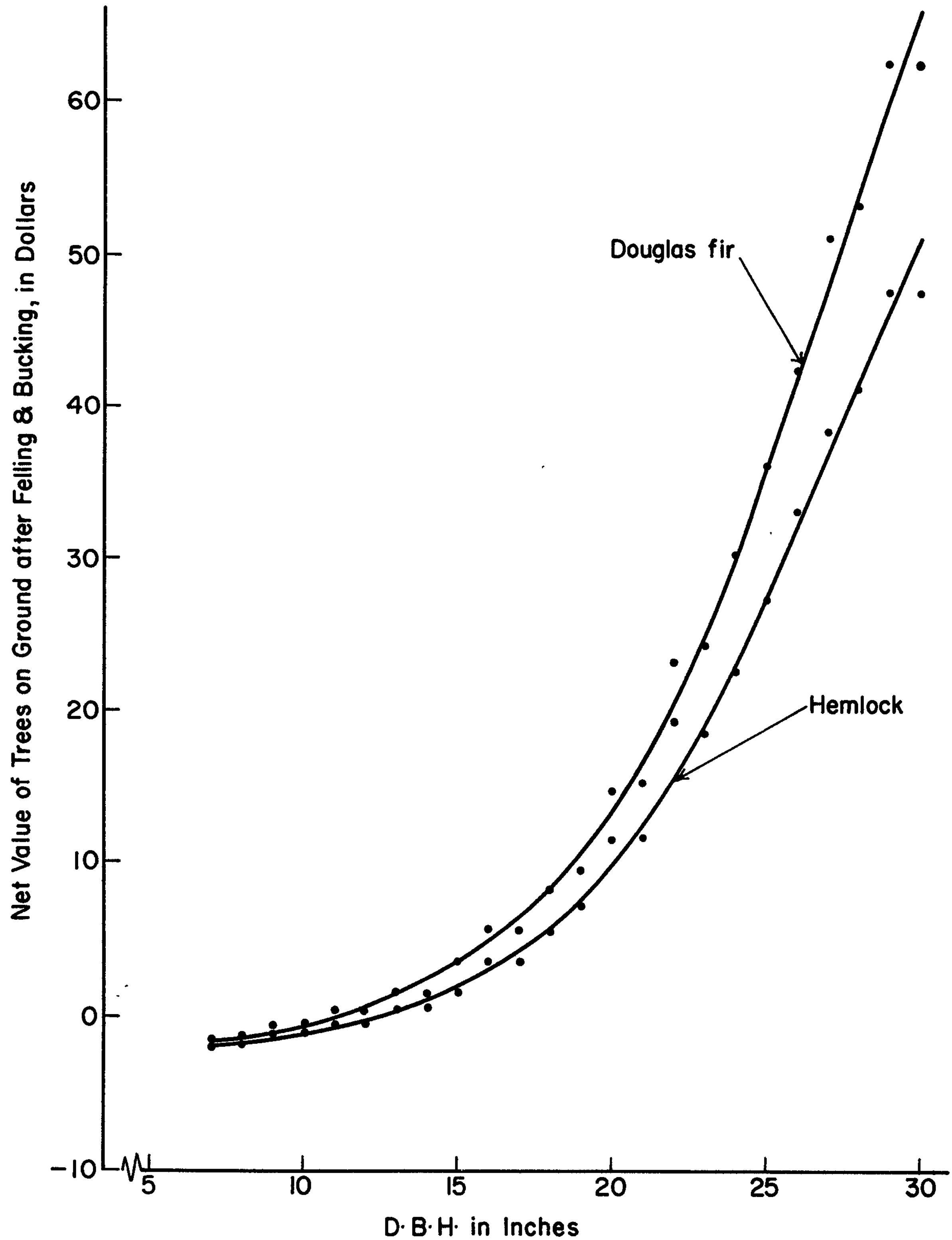
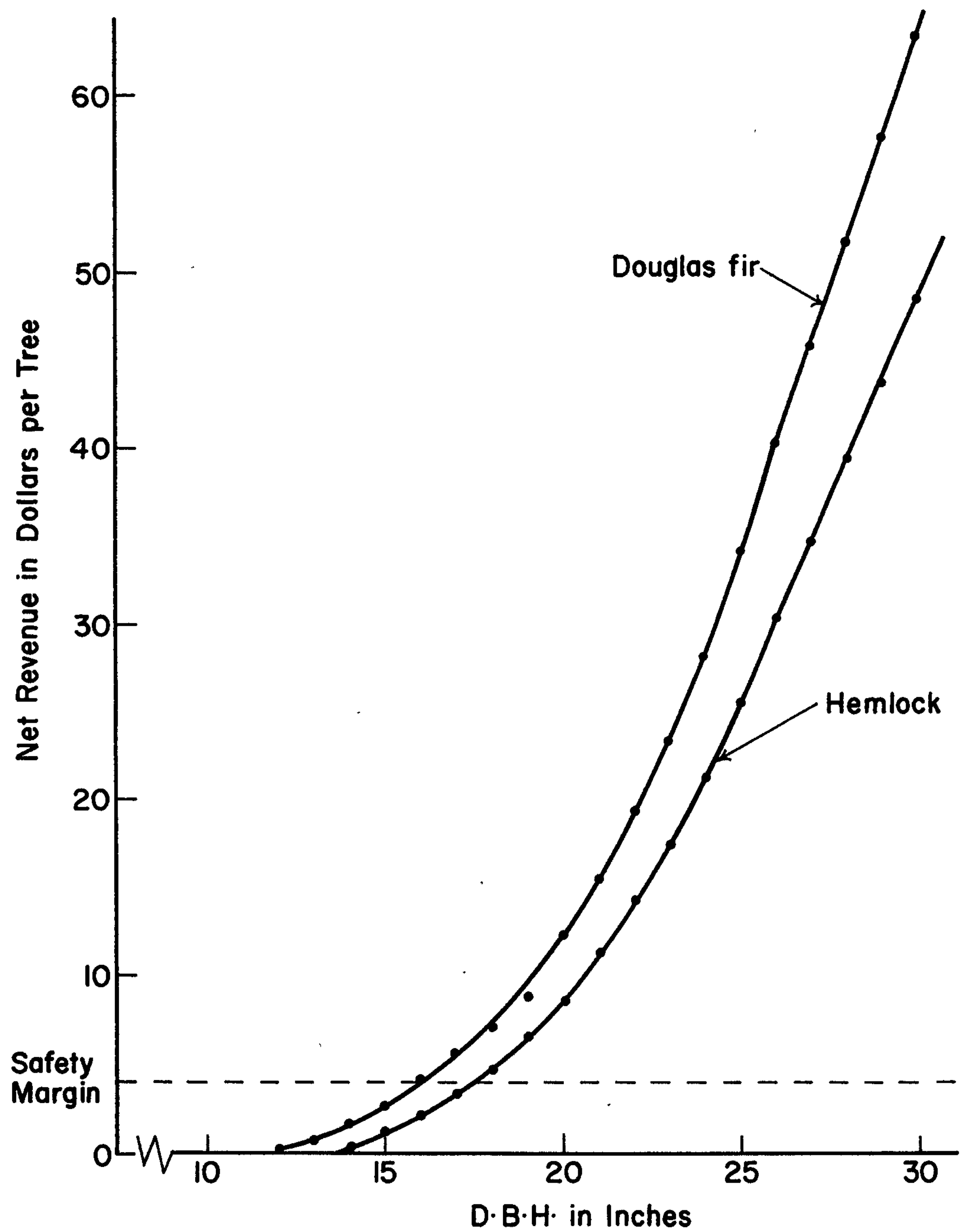


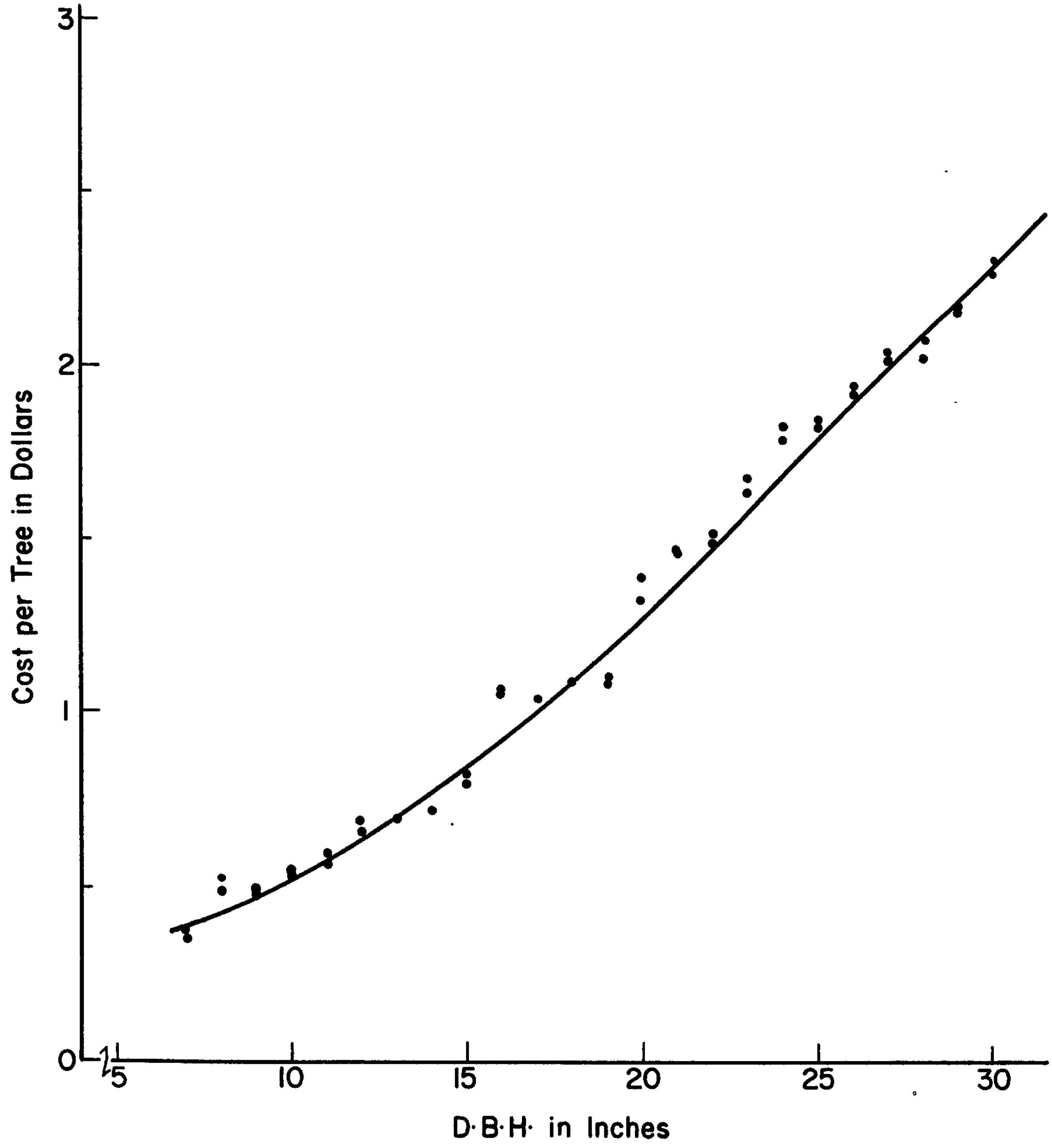
Fig. 7 Effect of Log Diameter on Bucking Time.
University Research Forest, June 1961.



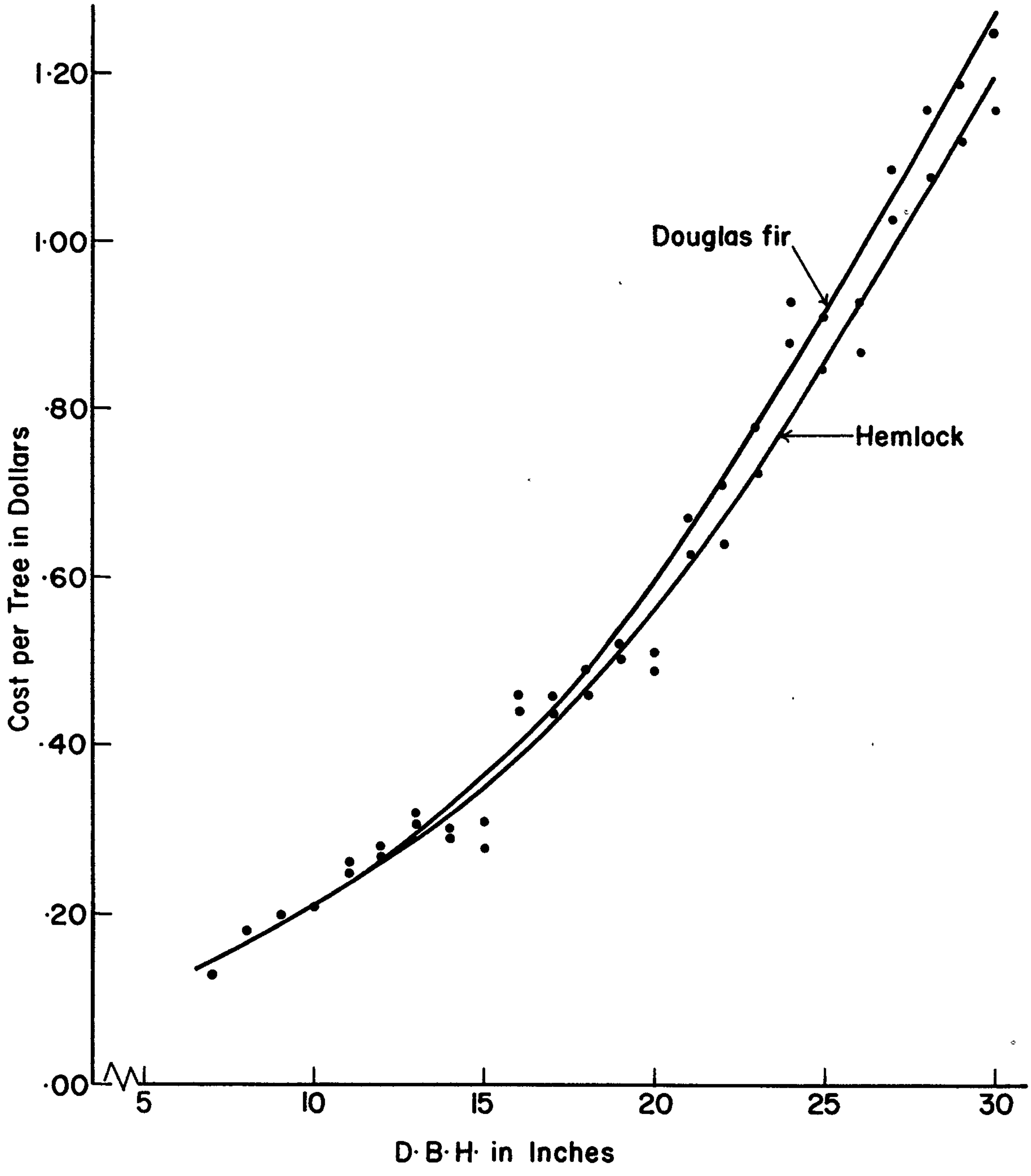
Fig· 8 Net Value of Trees after Felling and Bucking



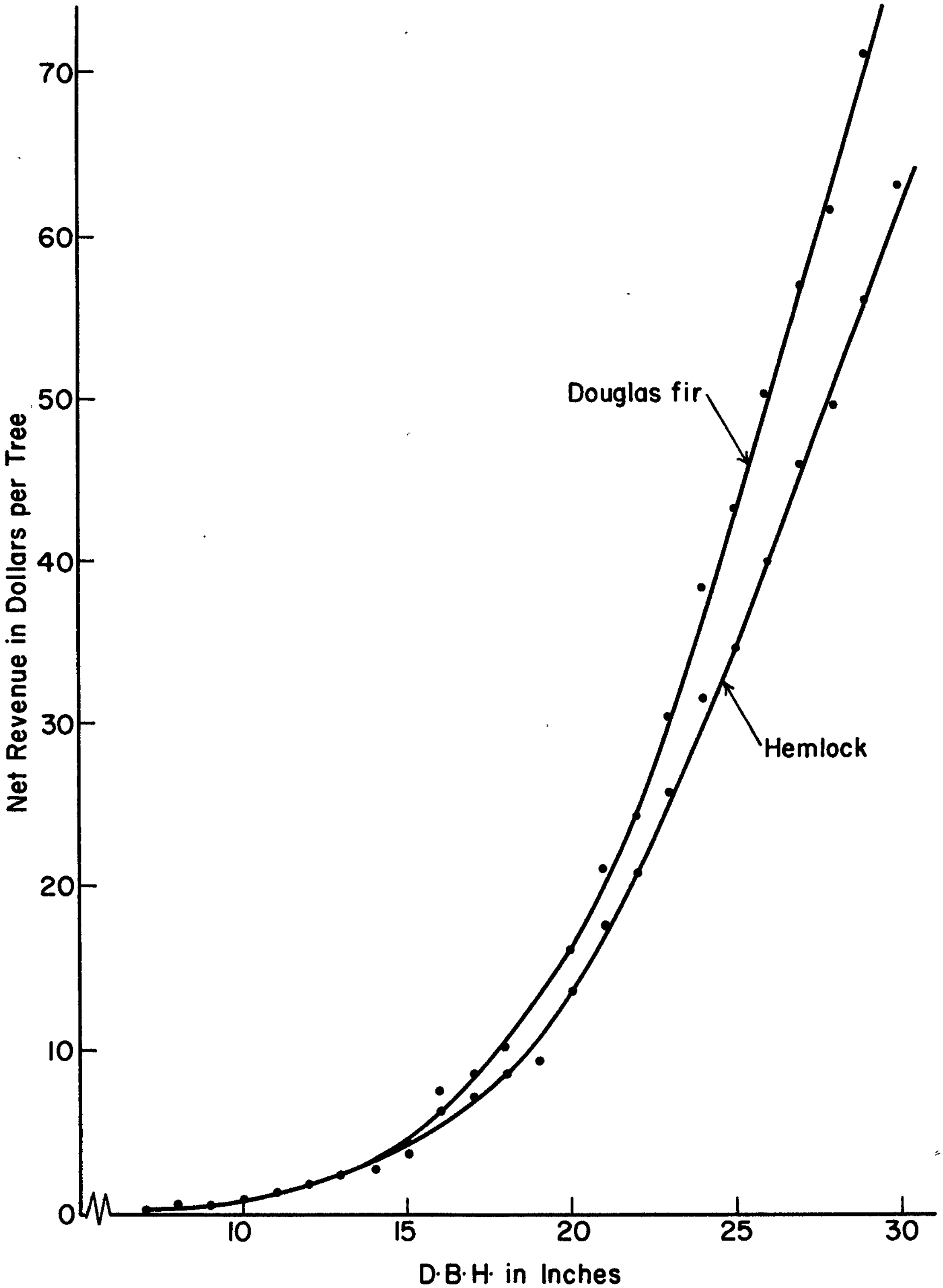
Fig· 9 Net Revenue per Tree; Program I·



Fig· 10 Felling and Bucking Cost per Tree; Douglas Fir and Hemlock; Program 2·



Fig· II Loading Cost; Program 2·



Fig· 12 Net Revenue per Tree; Program 2·

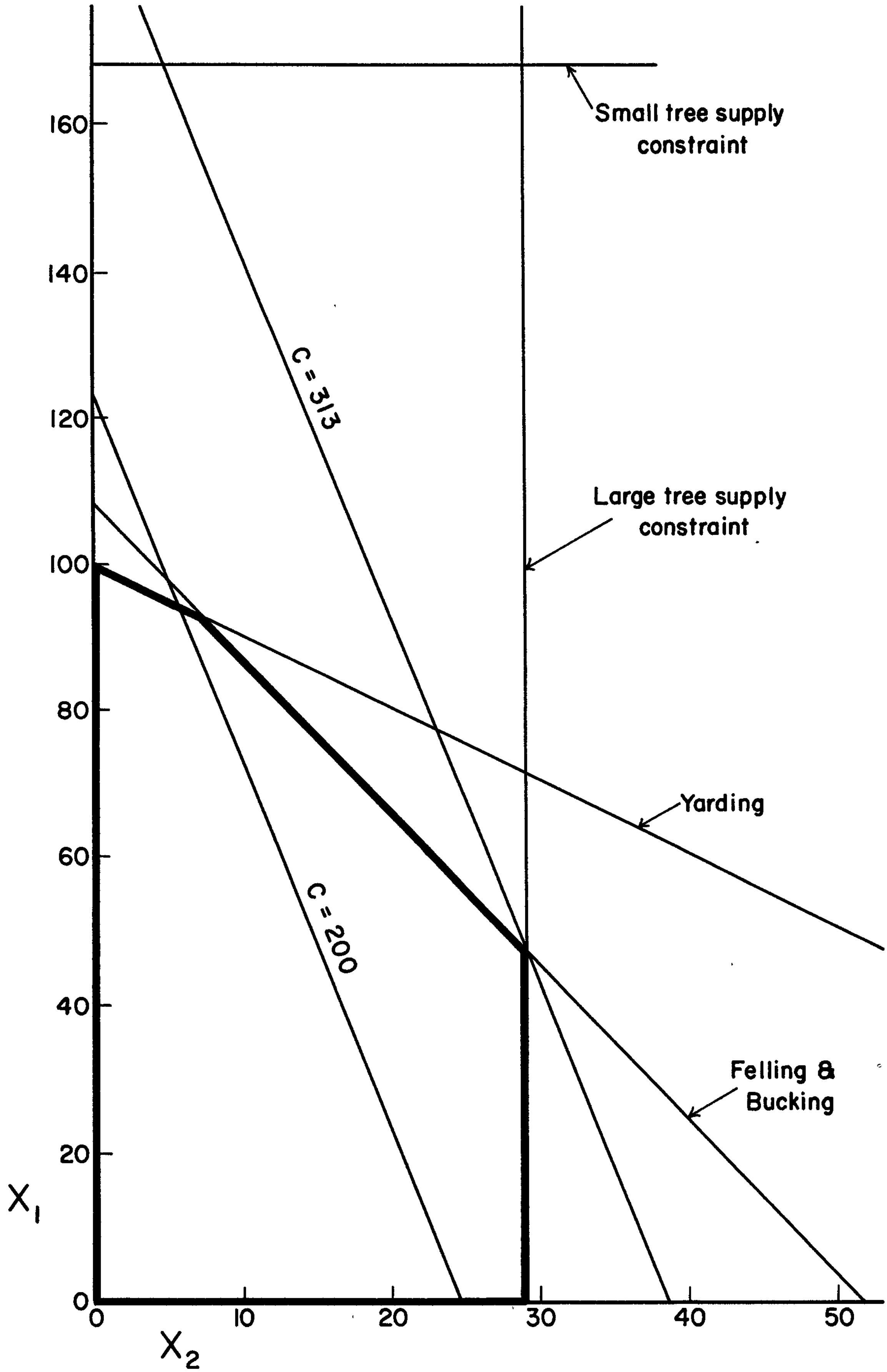


Fig. 13 Graphical solution of two-dimensional Problem No. 1

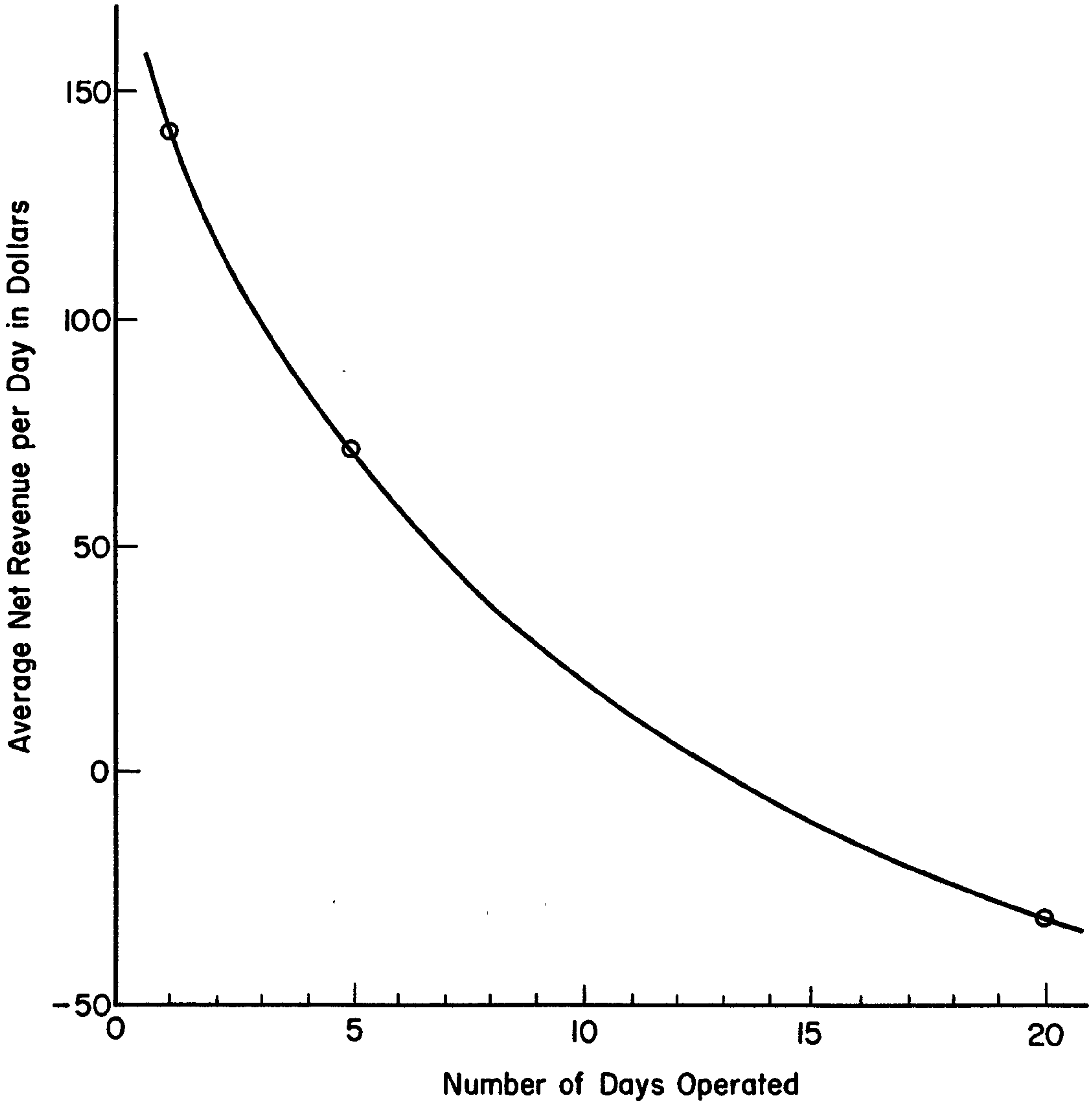


Fig. 14 Extrapolation of Net Revenues for Operations of various Durations. Problem No. 3.

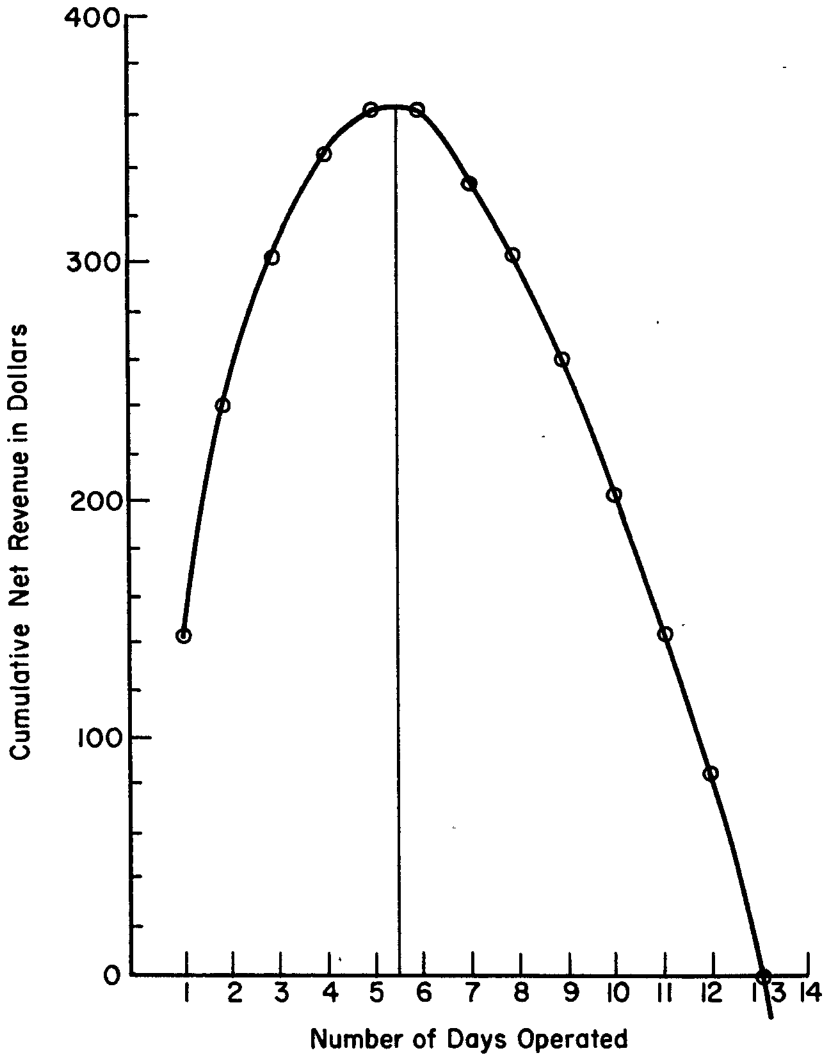


Fig. 15 Most Profitable Time-expenditure on the Operation. Problem No. 3.

THE UNIVERSITY OF BRITISH COLUMBIA

INTERDEPARTMENTAL

MEMORANDUM

TO Dr. J. H. G. Smith	FROM Prof. F. M. Knapp
Mr. J. P. Tessier	Faculty of Forestry
	October 25, 1961

Vancouver Log Prices September 1961

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Av.	$58.89

Av.All Grades

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3 -	30.89
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3 -	30.36
Av.	$38.99

Hemlock

#1 -	$52.17
2 -	47.01
3 -	41.36
Av.	$42.91

Balsam

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2 Lumber -	39.24
3 Pulp -	32.50
Av.	$39.38

Pine

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2 -	53.06
3 -	41.15
Av.	$46.70

Spruce

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2 -	44.76
3 -	36.51
Av.	$39.73

8020
1007
420 300 300 71 47 25 21 14 8 7
0 0 0 0 0 0 0 0 0 0
.84 3.5 1.5 .6 1 0 0 0 0 0 0
1.63 3.89 1.5 .9 0 1 0 0 0 0 0
2.12 4.62 1.5 .95 0 0 1 0 0 0 0
3.29 5.39 1.5 1.2 0 0 0 1 0 0 0
4.25 6.42 1.5 1.3 0 0 0 0 1 0 0
8.15 8.14 3.0 1.3 0 0 0 0 0 1 0
16.54 12.0 3.0 1.5 0 0 0 0 0 0 1

$ 0.000000000

p07q0a	$ 115.7794685
p06q09	$ 180.9791984
p05q08	$ 240.4792175
p04q07	$ 309.5690841
p03q01	$ 340.6852951 ≃ $340.7

p03
14.67748856
q02
180.4837646
q03
221.7563781
q04
71.00000000
q05
47.00000000
q06
10.32251119
p04
21.00000000
p05
14.00000000
p06
8.000000000
p07
7.000000000

Soln III

8020
1124
8400 6000 8400 410 246 256 150 522 256 170 118

$ 0.000000000

p0cq07	$ 752.9987945
p18q0b	$ 1184.877746
p09q06	$ 1701.995239
p15q0a	$ 2002.894897
p06q05	$ 2327.614868
p12q09	$ 2614.333923
p03q03	$ 2675.760375
p13p15	$ 2785.855285
p10p12	$ 2951.645202
p04q04	$ 3032.532531
p0dq01	$ 3071.488952
p14p13	$ 3071.488952
p13p14	$ 3071.488952
p14p13	$ 3071.488952
p13p14	$ 3071.488952

✓ p0d
43.28499889
q02
4255.542968
✓ p03
409.9999923
✓ p04
149.7888641
✓ p06
96.21113014
✓ p09
256.0000000
✓ p0c
150.0000000
q08
478.7149963
✓ p10
256.0000000
✓ p13
170.0000000
✓ p18
118.0000000
$ 3071.488952

1124
8400 6000 8400 410 246 256 150 522 256 170 118
0 0 0 0 0 0 0 0 0 0 0

1.02	3.89	0.90	2.30	1	0	0	0	0	0	0	0
1.02	3.89	0.90	4.30	1	0	0	0	0	0	0	0
1.02	3.89	0.90	6.30	1	0	0	0	0	0	0	0
1.32	4.62	0.95	2.30	0	1	0	0	0	0	0	0
1.32	4.62	0.95	4.30	0	1	0	0	0	0	0	0
1.32	4.62	0.95	6.30	0	1	0	0	0	0	0	0
2.02	5.39	1.20	3.00	0	0	1	0	0	0	0	0
2.02	5.39	1.20	5.00	0	0	1	0	0	0	0	0
2.02	5.39	1.20	7.00	0	0	1	0	0	0	0	0
5.02	6.42	1.30	3.00	0	0	0	1	0	0	0	0
5.02	6.42	1.30	5.00	0	0	0	1	0	0	0	0
5.02	6.42	1.30	7.00	0	0	0	1	0	0	0	0
0.90	4.28	0.90	2.30	0	0	0	0	1	0	0	0
0.90	4.28	0.90	4.30	0	0	0	0	1	0	0	0
0.90	4.28	0.90	6.30	0	0	0	0	1	0	0	0
1.12	5.08	0.95	2.30	0	0	0	0	0	1	0	0
1.12	5.08	0.95	4.30	0	0	0	0	0	1	0	0
1.12	5.08	0.95	6.30	0	0	0	0	0	1	0	0
1.77	5.93	1.20	3.00	0	0	0	0	0	0	1	0
1.77	5.93	1.20	5.00	0	0	0	0	0	0	1	0
1.77	5.93	1.20	7.00	0	0	0	0	0	0	1	0
3.66	7.05	1.30	3.00	0	0	0	0	0	0	0	1
3.66	7.05	1.30	5.00	0	0	0	0	0	0	0	1
3.66	7.05	1.30	7.00	0	0	0	0	0	0	0	1

#2 Sw on
clear
8004 0c 17a8f142 10 3128f142
clear
8008 0C 10

Clear
8004 05 2800f301 04 290ef301
Clear
8008 05 04

Soln II

$ 0.000000000

p0cq07	$ 752.9987945
p18q0b	$ 1184.877746
p09q03	$ 1249.517456
p16q01	$ 1299.218933
p17p16	$ 1299.218933
p16p17	$ 1299.218933
p17p16	$ 1299.218933
p16p17	$ 1299.218933

✓ p16
43.05844116
q02
1083.674133
✓ p09
56.60482311
q04
410.0000000
q05
246.0000000
q06
199.3951759
✓ p0c
150.0000000
q08
522.0000000
q09
256.0000000
q0a
170.0000000
✓ p18
74.94155693
$ 1299.218933

p16
4

1

I

8020
$ 0.000000000
p0cq03 $ 301.1995162
p0aq01 $ 328.4106826
p0bp0a $ 328.4106826
p0ap0b $ 328.4106750
p0bp0a $ 328.4106750
p0ap0b

420, 300, 420

✓ p0b
18.97196388
q02
214.9532699
✓ p0c
46.44859600
q04
410.0000000
q05
246.0000000
q06
256.0000000
q07
84.57943725
q08
522.0000000
q09
256.0000000
q0a
170.0000000
q0b
118.0000000
$ 328.4106750

p0b
~~18.97196388~~
q

```
1124
5460 3900 5460


tttt
1124
5460 3900 5460 410 246 256 150 522 256 170 118
0 0 0 0 0 0 0 0 0 0 0
1.02 3.89 0.90 2.30 1 0 0 0 0 0 0 0
1.02 3.89 0.90 4.30 1 0 0 0 0 0 0 0
1.02 3.89 0.90 6.30 1 0 0 0 0 0 0 0
1.32 4.62 0.95 2.30 0 1 0 0 0 0 0 0
1.32 4.62 0.95 4.30 0 1 0 0 0 0 0 0
1.32 4.62 0.95 6.30 0 1 0 0 0 0 0 0
2.02 5.39 1.20 3.00 0 0 1 0 0 0 0 0
2.02 5.39 1.20 5.00 0 0 1 0 0 0 0 0
2.02 5.39 1.20 7.00 0 0 1 0 0 0 0 0
5.02 6.42 1.30 3.00 0 0 0 1 0 0 0 0
5.02 6.42 1.30 5.00 0 0 0 1 0 0 0 0
5.02 6.42 1.30 7.00 0 0 0 1 0 0 0 0
0.90 4.28 0.90 2.30 0 0 0 0 1 0 0 0
0.90 4.28 0.90 4.30 0 0 0 0 1 0 0 0
0.90 4.28 0.90 6.30 0 0 0 0 1 0 0 0
1.12 5.08 0.95 2.30 0 0 0 0 0 1 0 0
1.12 5.08 0.95 4.30 0 0 0 0 0 1 0 0
1.12 5.08 0.95 6.30 0 0 0 0 0 1 0 0
1.77 5.93 1.20 3.00 0 0 0 0 0 0 1 0
1.77 5.93 1.20 5.00 0 0 0 0 0 0 1 0
1.77 5.93 1.20 7.00 0 0 0 0 0 0 1 0
3.66 7.05 1.30 3.00 0 0 0 0 0 0 0 1
3.66 7.05 1.30 5.00 0 0 0 0 0 0 0 1
3.66 7.05 1.30 7.00 0 0 0 0 0 0 0 1
80
81
```

Prob No. 4.
Max time limit = 12 days

```
8020
     $ 0.000000000
p0cq07        $ 752.9987945
p18q0b        $ 1184.877746
p09q06        $ 1701.995239
p15q0a        $ 2002.894897
p06q03        $ 2129.028198
p13p15        $ 2271.504394
p04q05        $ 2327.614868
p12q01        $ 2358.621948
p03p12        $ 2364.492065
p14p13        $ 2364.492065
p13p14        $ 2364.492065

✓ p03
  36.15423011
  q02
  2774.161010
✓ p06
  122.1070766
  q04
  373.8457641
  p04
✓ 123.8929100
✓ p09
  256.0000000
✓ p0c
  150.0000000
  q08
  522.0000000
  q09
  255.9999961
  p13
  170.0000000
  p18
  118.0000000
     $ 2364.492065


p03
```