Effects of Harvesting Technology Upon Optimal Stocking Regimes of Forest Stands in Mountainous Terrain

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Although one of the most common problems facing the forest manager is the determination of management regime, there has been little effort to explicitly recognize the effect of harvesting technology and topography in the analysis. This study introduces a unified theory of harvesting in mountainous terrain which brings together silvicultural method, harvesting technology, product yield, and product price to identify the optimal path through time for a forest stand managed for the objective of maximization of net present worth.

Techniques for predicting harvesting costs as a function of the specific diameter distribution to be removed from the stand have not been available. The first part of the research fills this gap by the development of a harvesting simulator for mountainous terrain. Considerable detail is devoted to discussing the validity of model assumptions including log distributions, heuristic rules for log gathering, and cost sensitivity with respect to the shape

of the diameter distribution. The harvesting simulator is tested against two detailed time studies of Douglas-fir thinning in mountainous terrain and is found to compare favorably with field observations.

To develop the relative harvesting costs for illustration in the stocking level analysis, two skyline yarders typical of the range expected to be operating in second growth Douglas-fir are evaluated using the simulator. Analysis of the harvesting cost results indicates that over the range of values analyzed, the elasticity of harvest cost with respect to volume removed is constant for a given mean diameter of material removed.

Costs from the harvest simulator are combined with a Douglas-fir growth model in a three descriptor dynamic programming structure. The potential effects of diameter growth acceleration are modeled through biometric relationships between the three descriptors; stand age, trees per acre, and basal area per acre.

The optimal thinning regime and optimal rotation age are determined simultaneously for a medium site Douglas-fir example under a predetermined set of average conditions. The sensitivity of optimal stocking level to harvest technology variables of yarding direction, yarding distance, truck transport cost, and log gathering strategies is examined. Under assumed cost differentials between uphill and downhill yarding, bare land values for downhill yarding are lower than for uphill yarding and the optimal management intensity is lower with less frequent, heavier entries. Increases in yarding cost with distance indicate that optimal stocking levels not only depend on traditional concepts of prices and costs, but that management intensity is also spatially oriented. It is demonstrated that under certain conditions substantial increases in net present worth can be made by treating portions of the stand in the same skyline road and with the same rotation age with different thinning regimes. Haul costs are exogenous to the harvesting cost simulation. However, reductions in haul cost increase bare land values by at least the magnitude of the present value of the haul cost decrease and may increase the optimal level of management intensity. The sensitivity of management regime to log gathering technique is examined by formulating a prebunching model which stratifies the log handling activity into two components. Logs are first gathered into bunches along the skyline corridor, and then the bunches are forwarded up the corridor to roadside. Prebunching and forwarding under the model assumptions is found not only to increase bare land values but in some circumstances to reduce the cost of handling early thinnings sufficiently to justify noncommercial entries to accelerate diameter growth. Constraints eliminating noncommercial thinning opportunities are shown to reduce present value.

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EFFECTS OF HARVESTING TECHNOLOGY UPON OPTIMAL STOCKING REGIMES OF FOREST STANDS IN MOUNTAINOUS TERRAIN

I. INTRODUCTION

One of the basic questions faced by forest resource managers is the determination of thinning regime and rotation age. Much recent attention has been given to the use of theoretical optimization approaches for solving the problem of joint determination of thinning regime and rotation age. These approaches have included a variety of methods, such as complete enumeration (Hardie 1977), simple algebra (Deurr 1960), dynamic programming (Amidon and Akin 1968), inventory theory (Pelz 1977) and control theory (Naslund 1969).

There is in the literature, however, little evidence that these techniques have actually been used to determine the optimal strategy without many simplifying assumptions concerning net revenues resulting from management activities. Common among these assumptions are constant harvesting costs regardless of topography or unit geometry and no direct relationship between harvesting costs and the type or intensity of the silvicultural practice.

It is not apparent, in North American literature, that harvesting technology and the resulting costs have been explicitly considered in the joint determination of thinning regime and rotation age in <u>mountainous</u> terrain.

This study will introduce harvesting technology into the regime optimization process. As suitable harvest cost schedules are not available, the first part of the study will concentrate upon developing a harvesting model for mountainous terrain. Results from the harvesting model will be incorporated into a dynamic programming optimization scheme using the work of Brodie and Kao (1978) to simultaneously determine the optimal thinning regime and rotation age.

Typical Douglas-fir stands in mountainous terrain of the Pacific Northwest will be used for illustration. Douglas-fir is an important commercial species occupying approximately 30 million acres in the western United States, many in mountainous terrain. During the earlier years of this century, the more gentle ground was harvested first so that the proportion of final harvest from mountainous areas is increasing.

The question of management regimes in mountainous terrain is therefore an important problem. If forest managers are to manage these stands efficiently, additional study is required to more accurately assess the costs of management activities.

Objective

The purpose of this study is to examine the relationship between harvest technology and optimal management regimes for forest stands in mountainous terrain.

The intent of this study is to specifically address the questions:

1. What is the optimal management regime in mountainous terrain for a medium site Douglas-fir stand under a specific set of geometric, topographic, and economic conditions?

2. How sensitive is management regime to changes in these geometric, topographic and economic conditions? In particular, how might changes in yarding direction, yarding distance, haul cost, price-diameter relationships and discount rates affect management regime?

3. How sensitive is managment regime to work method? Can stratification of work tasks in conventional skyline yarding operations affect management regime in mountainous terrain?

4. Should management intensity be inversely proportional to distance from the truck road transportation system?

In order to adequately respond to the previous questions, the following questions must also be addressed:

(1) How are harvesting costs related to stand parameters?

(2) How does terrain affect harvesting costs?

The objective of this study is not to provide an inflexible management guide for stand management in mountainous terrain, but to identify relationships often overlooked by forest managers in making silvicultural prescriptions.

Scope

The primary focus of this research is on forest harvesting costs, their relationship to silvicultural operations, and the effect of harvesting technology on the choice of thinning regime and rotation age. The intent of the research has been to incorporate existing knowledge of forest growth models, harvesting production rates, costs, and optimization algorithms into a comprehensive decision model for determining management strategy in mountain terrain. As the research was constrained by both budget and time, certain assumptions had to be made about the system in order to assure feasibility of modeling the system. These assumptions include the following:

1. Only one species, Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) will be used for the yield simulator.
2. One site index, Site 140, 100 year basis (McArdle, Meyer, and Bruce 1961), will be used in the example calculations.
3. The silvicultural method may include both thinnings and regeneration harvests, but thinnings must be taken such that the stand mean and variance are not changed.
4. Only skyline yarding systems are to be used.
5. The harvest area is rectangular.
6. Topographic considerations will be limited to mountainous terrain and skyline payload will be the proxy for topography.
7. The timber within the unit is homogeneous with respect to species. Logs are assumed to be uniformly and randomly distributed on the unit.

8. The location of roads and landings within the area are fixed and exogenous.
9. Actions taken on the individual unit are not influenced by management actions on surrounding forest areas.
10. Product prices and the discount rate remain constant over time.
11. Reforestation costs and other management costs are exogenously determined.
12. The forest manager's objective is to maximize net present worth.

In the remainder of this section, certain assumptions will be discussed briefly to illustrate the motive for specifying them.

Growth Model

The Douglas-fir biometric stand model, DFIT,[1/] by Reukema, Demars and Bruce (1977) will be used as the yield simulator throughout the study. The DFIT model is a general model which can be used to simulate both natural stands and plantations. Silvicultural activities such as commercial and precommercial thinning, fertilization, and genetic improvement can be simulated and projected. DFIT, although a comprehensive yield simulator, does not directly provide all the stand information required for the harvest simulator. Additional information concerning diameter distributions required to

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1/ Acronym for Douglas-fir Interim Tables.

bridge the gap between the two simulators is drawn from Bulletin 201 (McArdle 1961) which provided much of the base information for the development of DFIT. This study will be restricted to the use of DFIT as the yield simulator, however, any simulator which provides growth response and stand table information could be used with the harvest simulator and optimization routines.

Site

The study will be limited to the investigation of management regimes for Site 140, a "mean" or average Douglas-fir site index. Inferences for other sites may be able to be drawn from these results.

Silvicultural Method

Both thinnings and regeneration harvests are considered in the model. Thinnings must be taken in such a manner that the mean stand diameter before thinning must equal the mean stand diameter after thinning and the stand variance is not changed. This requires the same proportion of trees be removed from each diameter class. This type of silvicultural operation precludes thinning from "above" or "below" but it is typical of the range of thinning ratios advocated for Douglas-fir (Reukema and Bruce 1977). The thinning ratio constraint is required for two reasons (1) it permits specification of the mean and variance of the diameter distribution to be removed, and (2) it considerably reduces the size of the optimization problem.

2/ The thinning ratio is defined as the ratio of the mean stand diameter before thinning to the mean stand diameter after thinning.

The sensitivity of optimization results to thinning ratio is discussed later.

Harvest Systems

The harvest systems considered in this study are limited to small standing skyline systems (70 hp) and intermediate-sized standing skyline systems (300 hp), both with slackpulling capability and able to pass intermediate supports. Other skyline systems, namely live and running skylines, were not considered in this study as it has not been demonstrated that they have the ability to cross intermediate supports. This ability will generally be required for thinning young stands in steep terrain when spans exceed 600 feet, unless terrain is concave.

Tractors have not been considered in this study because although they have been used for thinning Douglas-fir on slopes up to 50 percent more economically than skylines (Aulerich 1974), concern for soil and watershed protection will generally preclude their use under such conditions.

Balloons have not been considered due to their relative rarity (only three balloons were operating in North America in 1978), and their inability to protect the residual stand during thinning.

Helicopters are not considered because although they have been demonstrated to have the ability to both thin and final harvest, the cost of using helicopters where there is road access within 2000 feet is usually prohibitive. Comparative costs for yarding by skyline, balloon, and helicopter are given by Dykstra (1976a).

Harvest Unit Geometry

The planning unit is assumed to be rectangular. Harvest units are of two general shapes, rectangular and fan-shaped. Unless the slope is very dissected with many lateral ridges the rectangular unit is the most common. The preferred yarding direction is perpendicular to the contour. Fan-shaped units could also easily be simulated with only minor changes in the simulator code to include triangular density distributions.

Topography

Topography considered will be limited to mountainous terrain. In the Pacific Northwest the slope demarcation between gentle and mountainous terrain is roughly 30 percent and a value of 40 percent will be assumed throughout this study.

Slopes can be broadly grouped into the categories of concave, uniform and convex slopes. Concave slopes can usually be yarded with a single span. Uniform slopes and convex slopes usually require intermediate supports if slopes greater than 600 to 800 feet are being yarded. Convex slopes require intermediate supports.

Topography establishes an upper unit on skyline payload for a specific machine and rigging configuration. As such, skyline payload will be used as a <u>proxy</u> for topography. Payloads will be determined exogenously. Details on the calculation of skyline payload are covered by Sessions and Binkley (1977).

Although skyline payload is not constant along the length of the skyline, it will be defined as the maximum load which can be transported along the skyline from the unit boundary to the landing. For standing skylines, this maximum payload is constrained to the largest payload which can be transported past midspan and is a good representative payload as most of the volume on the unit must pass this point.

Typical production or cycle time equations such as those by Dykstra (1975, 1976a), Aulerich (1974), Neilsen (1977) and Kramer (1978) do not include skyline payload as an independent variable. Skyline payload, however, often not only provides the motivation for the particular equipment selected for the job, but is also a direct determinant of the amount of rigging time required for such activities as the rigging of tail trees and intermediate supports.

Homogeneity of Timber

Timber on the unit is homogeneous with respect to species and logs are assumed to be randomly distributed over the unit. Few quantifiable data are available concerning actual log distributions in the field. The implications of this assumption are more carefully examined in a later section. As far as the simulation is concerned, the choice of log distribution is not a constraint. For units where the change in biological site is not extreme, the uniform log distribution assumption may be justified. On other units, for example, a west-facing slope where the unit begins at the ridge top and ends near the stream zone, there is usually a pronounced change in site accompanied by an increase in larger logs and the number of logs as the stream is approached.

Transportation System

The transportation system, meaning road location and landing spacing, is assumed to be fixed and exogenous. This is a "second-growth" model; it is assumed that the transportation system was constructed to harvest the old-growth. In moutainous terrain there are usually only a few feasible alternatives for access road construction. In general, the densest economical road system was constructed initially when old-growth volumes justified the road costs. In addition, considering the growing environmental pressures against road building and the costly environmental protection measures required when new roads are built (EPA 1977), it is doubtful that increases in road density will be permitted in many situations. In areas where there is a flexibility to consider additional road development, output from the harvesting cost model developed in this study could be used to establish cost tradeoffs for road optimization models similar to Carter, Gardner, and Brown (1973).

Landing spacings used in the harvest model are typical of those which have been found to be most efficient. Most recently, road and landing spacing models have been formulated by Peters (1978) as extensions of earlier work by Matthews (1942) and Lussier (1961).

Incorporation of Peters' algorithm might improve cost efficiency but experience suggests that the total cost curve is relatively flat with respect to lateral yarding distance, and optimization of this variable was not attempted.

Haul and road maintenance costs associated with removing the merchantable volume are assumed to be exogenous to the model. Maintenance costs are expressed in haul units and added to the haul cost. Haul costs for the unit are assumed to be constant and the sensitivity of management strategy to haul cost is examined.

Independence of the Harvest Area

The harvest area or unit is assumed to be the smallest common denominator or "building block" of the forest. It is assumed that areas outside this unit have no influence on the management regime selected for the unit. This is realistic if surrounding topography and stand conditions are sufficiently similar to the unit being considered that the same equipment and regime will be selected for other units in the area. By sufficiently similar, it is suggested that approximately 50 or more acres in the same general area will be subject to the same treatment in a given year. This will usually reduce move-in costs to the point where they can be effectively ignored for the purpose of this analysis.

Product Price and General Price Level

Product price, at the mill pond, by diameter is assumed known. Net value is determined by subtracting harvesting and haul costs from the product price. The Oregon Department of Revenue provided the pond values for western Oregon second-growth Douglas-fir logs based on the first quarter of 1978. All prices and costs are assumed to remain constant over the planning period. The discount rate has been deflated to reflect the long term real rate of growth. A long term real rate of growth of 3 percent has been used after studies by Yohe and Karnosky (1969). The effect of changing this discount upon management strategies is discussed later.

Regeneration Costs and Other Management Investments

The stand is assumed to be normally stocked at age 20. Regeneration and other management investments to assure this result are assumed to be determined exogenously and to have a present net cost of $200 per acre. Buongiorno and Teeguarden (1973) have developed a methodology to rank reforestation projects in an attempt to weigh costs and benefits of alternative regeneration plans. They correctly point out that regeneration cost-initial stocking relationships may affect both the thinning regime and rotation age. Buongiorno and Teeguarden express regeneration cost as the sum of a fixed plus a variable cost. The fixed cost reflects administrative costs concerned primarily with the size of the project and the variable cost considers the number of seedlings planted per acre. Maederer (1978) feels that, in addition to these variables, slope, degree of access, and the size of stock affect the planting cost. A summary of Maederer's estimated planting costs for conditions in the Coast Range of Oregon are given in Table 1 for 2-1 stock.

If the diameter distribution parameters for the mean diameter of a non-normally stocked stand do not differ appreciably from the normally stocked stand, the harvesting costs from the harvest simulator will remain valid. A plot of net present worths from additional optimization runs with alternative starting conditions and regeneration costs would then identify the "optimum optimorum" with respect to the regeneration variable. This extension is considered beyond the scope of the current study.

Table 1. PLANTING COSTS FOR 2-1 STOCK ($/ACRE)
NOT INCLUDING COST OF STOCK

	Walk in Distance (feet)		
Slope (%)	500	1500	3000
30	55	60	90
60	55	65	95
90	60	70	120

Standard Conditions

The standard conditions for this study are, unless otherwise stated:

Harvest unit geometry	=	rectangular
Cutting unit length	=	1200 feet horizontal distance
Cutting unit width	=	200 feet for large yarder
	=	160 feet for small yarder
Cutting unit slope	=	40 percent
Yarding direction	=	Uphill
Yarding system	=	Skyline with slackpulling carriage, preset chokers
Discount rate	=	3 percent
Haul cost	=	$150 per Mcf

The sensitivity of the conclusions reached in this study for the standard conditions will be discussed in Chapter VI. Emphasis will be placed upon the sensitivity of optimal thinning regime to changes in yarding distance, yarding direction, haul cost, and log gathering techniques.

Synthesis

The assumptions and limitations discussed in this section have important implications for the determination of optimal management regimes. It is assumed that adequate forest growth models exist to predict the response of silvicultural activities and that harvesting will be restricted to skyline systems.

To determine optimal management regimes, the following detailed information must be available:

1. Stand yield information for natural and managed stands.
2. Stand table information, particularly the mean stand diameter class distribution before and after the management activity, for all physically feasible activities.
3. The spatial distribution of logs on the harvest area.
4. Cost and production information for each skyline yarding system.
5. Skyline payload, the proxy for topography, for each cable yarding system for the topography under consideration.
6. Product price by diameter class interval.

Much of this information is presently available to the forest manager. Information relating growth response to the diameter class distribution and the spatial log distribution after cutting are the two strongest assumptions which must be made. Optimization over only three descriptors: time, number of trees per acre, and basal area per acre, is another limitation of the study.

The preceding discussion should satisfy questions concerning the type of data required and the assumptions which have been made. Several of the points are discussed in greater detail in subsequent sections. With this information, the study should provide:

1. The simultaneous determination of optimal thinning regime and rotation age for a typical stand of Douglas-fir Site 140 in mountainous terrain under certain average conditions.

2. The sensitivity of optimal management regime to changes of yarding direction, yarding distance, haul cost, log gathering technique, discount rate, and price assumptions.

Study Procedure

To accomplish the objectives of the study within the scope outlined above, the following tasks were undertaken:

1. The specific problem to be solved was defined.
2. Harvest cost relationships were formulated.
3. A harvesting simulator was developed.
4. Stand parameters required for the harvesting simulator were derived from growth models.
5. The harvesting simulator was validated against studies of completed harvest operations.
6. Harvest simulations for various thinning intensities and conditions at final harvest were completed.
7. A response surface providing harvesting cost as a function of mean stand diameter and volume removed was constructed.
8. The growth and harvest model were combined in a dynamic programming framework.
9. The optimization model was used to determine the optimal management regime for a Site 140 Douglas-fir example in mountainous terrain.
10. The sensitivity of the management regime to model assumptions was examined and alternative strategies were discussed.

II. PROBLEM DEFINITION

Planning Thinning Regime and Rotation Age in Mountainous Terrain

The determination of thinning regime and rotation age are common problems to the forest resource manager. A considerable number of theoretical optimization approaches to the problem have been formulated, but applications to determine the optimal stocking level over time for stands in mountainous terrain have been rare. The few optimization models that consider species common to mountainous terrain do not explicitly consider terrain or harvesting technology. As such, management plans resulting from the model assumptions may be neither physically possible nor economically accurate. Attempts such as Buongiorno and Teeguarden (1973) and Randall (1974) express stumpage value of final harvests as some linear function of tree diameter and treat the value of thinnings as a constant fraction of the final harvest stumpage to account for some combination of lower product values or greater harvest cost. No attempt is made to distinguish between management opportunities based on harvest area characteristics or thinning intensity. Harvesting costs on the other hand are known to be highly dependent upon log size, volume per acre removals, and yarding distance. Conway (1976) reports that skyline yarding costs in the Pacific Northwest depend upon topographic conditions, volume per acre, log size, and yarding distance, with volume per acre being the most important consideration. Lisland

(1975) reports similar relationships for harvesting smaller trees in Norway. This study will treat topography, thinning intensity, and harvest area geometry explicitly in the determination of thinning regime and rotation age. The harvesting costs will be derived in such a framework that future changes in cost elements can be incorporated without changing the basic structure of the model. Harvesting technology will be described to the extent necessary to permit an understanding of derivations.

The calculation of thinning regime and rotation age require definition of five elements: a growth model, a cost model, a price model, a method of generating alternatives, and a method of choosing between alternatives efficiently. The remainder of this section briefly describes these elements and their importance in solving the overall problem.

Growth Model

There have been numerous growth models for Douglas-fir including both single tree and stand models. Single tree models describe tree growth as a function of tree characteristics and the tree's physical environment. Once the behavior of a single tree has been described the response of a stand can be modeled using tree interactions. Models proposed by Newnham (1964), Curtis (1967) and Buongiorno and Teeguarden (1973) are examples of single tree models. Bulletin 201 (McArdle et al 1961) and the Douglas-fir Interim Tables (Reukema, Demars, and Bruce 1977) are examples of stand models which provide stand yield estimates without the detailed modeling of individual tree interactions. The essentials of a growth model for use with the harvesting cost and price models are that it must provide estimates of product yield and stand parameters which are compatible with the other model elements as well as being sufficiently flexible to simulate diverse silvicultural activities. For example, if harvest costs are known to be dependent upon the number of stems per acre before entry and after entry, the mean stand diameter, and the variance of the diameter distribution, then the growth model must provide these estimates. Similarly, the price model may require estimates of the number of logs by diameter class and grade.

DFIT was chosen as the growth model as it represents the most current, documented development in Douglas-fir modeling, as well as having a model structure easily adaptable to optimization.

Cost Model

Modeling of harvesting activities in mountainous terrain has been attempted, but a literature search has not revealed a framework of sufficient flexibility to predict harvesting costs as a function of silvicultural activity and topography. To be effective, a cost model must have the ability to predict costs for the full range of combinations of thinnings and final harvests which can feasibly occur. This would include harvesting costs resulting from such silvicultural methods as thinning from below, from above, and thinning uniformly throughout the distribution. It would include thinning to different stocking levels from small reductions in basal area to final harvest.

Harvesting operations usually result in highly nonlinear cost relationships. Consider, for example, the relationship between volume removed and harvesting cost. Small skyline yarders harvest more effciently than larger yarders when a low volume per acre of small trees is being removed. As the volume per acre increases the larger yarder often becomes more competitive and is eventually more efficient. This change in equipment often creates a discontinuity where the cost curves intersect. Even within the limits of operation of the small yarder different operating modes exist. Above certain volume removals per acre there are diseconomies of scale. When more than 2000 cubic feet of logs are accummulated at the landing from one setting Neilsen (1977) reports that productivity and safety at the landing are jeopardized and an auxiliary machine must be brought in to rehandle the logs, increasing cost. Figure 1 illustrates the type cost relationships which have been discussed above.

Price Model

Darr (1973) reported that stumpage values are highly diameter dependent. This relationship can arise from either greater product value or lower harvesting cost per unit for larger diameter material or from some combination of the two factors.

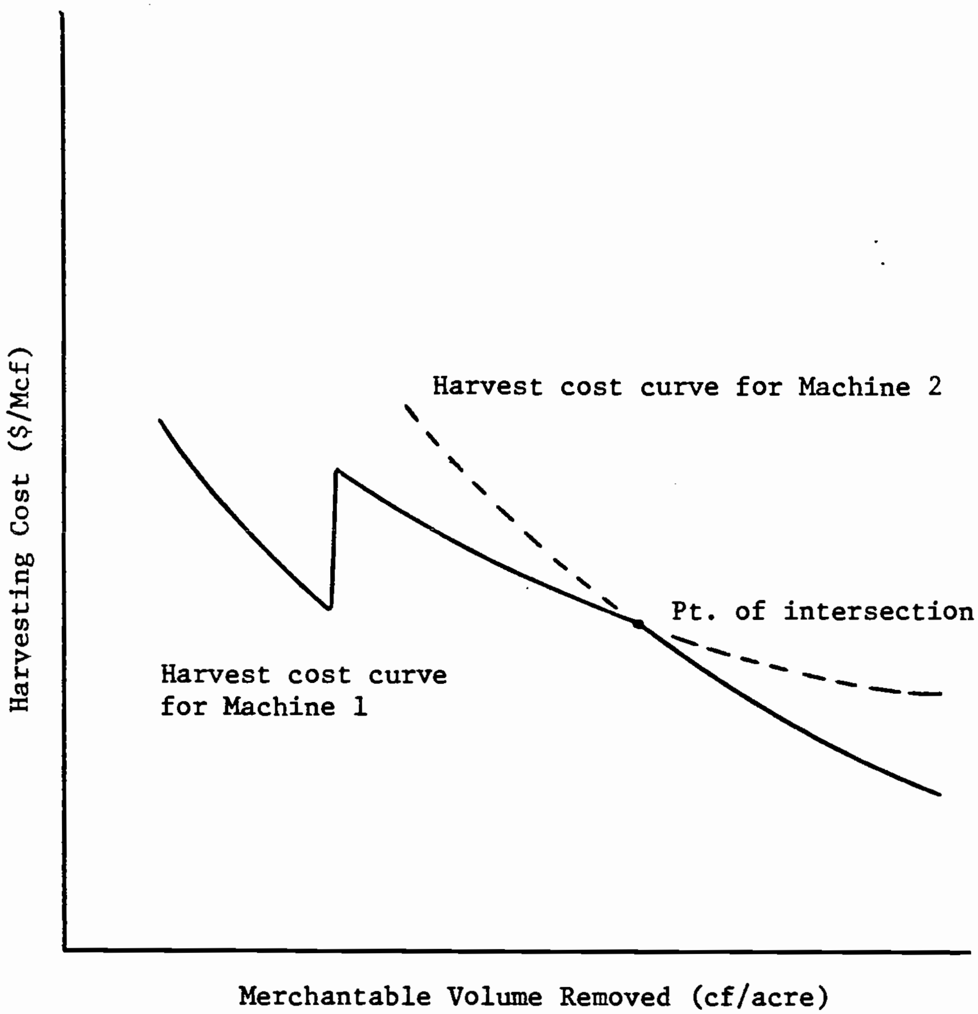


Figure 1. Generalized harvest cost relationships for two machines. Solid line indicates lowest cost operating range for each machine.

The price model used for management optimization must be able to quantify the price-diameter relationship. As Darr and Randall (1974) point out, assumptions concerning price-diameter relationships can influence not only an estimate of a project's benefits, but also the entire financial feasibility. In this particular problem, the choice of the price-diameter relationship can affect both the thinning regime and rotation age. The approach used in this price model will be to construct a relationship between mean stand diameter and pond value at the mill using diameter premiums from the Oregon State Department of Revenue, Timber Tax Division. Net value will then be determined by subtracting logging and haul cost from the pond value.

Alternative Generation

A necessary condition for finding an optimum solution to the stumpage maximization objective lies with the ability to generate the full range of alternatives so that the solution is not constrained in some arbitrary manner. Suboptimal solutions can arise from such diverse causes as artificially bounding the solution set, excessively aggregating values of the independent variables, or by improper structuring of the model. Generation of alternatives will be accomplished within the dynamic programming structure where the state descriptors will be basal area, number of trees, and stand age. Other than an upper limit on the percentage of trees which can be removed in the first possible thinning, based on silvicultural concerns over sunscald and windthrow, alternatives will be automatically generated over all physically accessible nodes which can be reached from the current period. Thinning alternatives will include all opportunities presented by state intervals of number of trees and basal area from no thinning to total harvest. State intervals of 15 trees per acre and 4 square feet of basal area per acre will be used as a compromise between accuracy and cost of computation. Time intervals between possible entries will be 10 years.

Optimization

Dynamic programming has been proposed as the optimization method. It is well suited to problems of this type with highly nonlinear objective functions and nonlinear structural equations. Dynamic programming has been applied to the thinning regime and rotation problem using both forward and backward recursions. The forward recursion has been chosen for this study as it produces the optimal thinning regime and optimal rotation age in a single pass. A discussion of other relative merits of forward versus backward recursion is in Chapter V.

Summary

This chapter has discussed factors which were considered during the problem definition phase of the study. To investigate management regime alternatives in mountainous terrain, the price and cost relationships resulting from silvicultural treatments will need to be explicitly determined. A flexible harvesting model will be required to simulate a wide range of silvicultural options. Price-diameter relationships will need to be derived to appropriately weight timber removals from silvicultural treatments. The cost and price relationships must be linked to a growth model. This link will be the dynamic programming structure which will provide automatic alternative generation and evaluation in an efficient manner.

III. HARVESTING SIMULATION

This section discusses harvest costs, harvest cost studies and harvest simulations which have been developed for evaluating harvest strategies in mountainous terrain. The harvesting simulator (YARDALL) is presented with a discussion of stand generation, falling and bucking, yarding and loading simulation. Validation tests are discussed. The first part of the section briefly reviews the literature on harvesting in mountainous terrain with emphasis on suggested limitations in methods of analysis and prediction.

Literature Review

The study of forest operations is not new. Brandstrom (1933) and Matthews (1942) pioneered the use of time studies for use in collecting information for the analysis of forest harvesting operations. Matthews particularly was concerned with the optimization of road and landing spacing which required detailed breakdown of forest operations in order to determine the variable costs per unit distance for yarding material. His basic work has been extended by Suddarth and Herrick (1964), Lysons and Mann (1965), and Peters and Burke (1972). Although the road spacing formulas developed by Matthews have only limited application in mountainous terrain due to the relatively few access road alternatives, his formulations of the fixed and variable costs of the harvesting operation did much to establish a framework for further analysis. Since Matthews, there have been literally dozens of studies measuring the productivity of logging operations. Studies in the West, in mountainous terrain, include measurements of highlead productivity by Tennas et al (1955), Binkley (1964), Adams (1965), Chamberlain (1965), and Schillings (1969). Measurements of large skylines have been reported by Binkley (1964), Campbell (1973), and Dykstra (1976a). Measurements of intermediate and small skylines include Dykstra (1975, 1976a), Peters (1973), Campbell (1974), Sinner (1973), Aulerich (1974), Neilsen (1977) and Kramer (1978), and Van Winkle (1976).

Common variables affecting yarding production were found to be yarding distance, lateral yarding distance, slope, log size, number of logs per turn, crew size, horsepower, and height of the log deck in front of the yarder. Two of the studies, taken in partial cuts, reported that the percentage of the stems removed also influenced production.

Interestingly, not one of the models include topography nor volume per acre as a primary determinant of production, but these two variables are among the first a logger considers when evaluating the economic feasibility of yarding a unit. Conway (1976), former logging division manager of a large industrial firm, lists topography, volume per acre, log size and yarding distance as the primary variables affecting production, with volume per acre being the most important variable. Why does this discrepancy exist? Which variables do affect yarding production? Additional insight requires examination of the objectives of cycle time analysis and the experimental design. Cycle time studies are generally very concentrated efforts to intensely study an operation at a single point in time to determine the variables which are affecting production at that point in time. The key to the analysis is "which variables were variable?". If variables do not vary during the study, data analysis will conclude the variables do not affect the production rate. On the other hand, there is a growing interest in gross time studies (Curtis 1978) which collect data daily over a long period of time so that there is a higher probability that all variables have had an opportunity to be sampled. In the case of the gross time study, however, the collection and analysis may aggregate the data to the extent that the effect of the individual variable cannot be segregated.

Logs per turn appears to be an important variable in cycle time models. It appears in a large number, if not the majority, of the models as having high explanatory power in predicting cycle time. Even if it were not in the cycle time model, it would have high explanatory power for production per hour since production per hour is a direct product of cycles per hour and logs per turn. Only three observers have commented on factors which might affect the number of logs hooked per turn.

Campbell (1973), in measuring the productivity of large skylines in rough topography in western Oregon, reported that the number of logs per turn was a function of log size and the number of logs per turn for clearcuts was higher than for partial cuts. Campbell, however, did not relate payload capability nor the intensity of the partial cut to the number of logs per load.

Neilsen (1977), in studying thinnings with a small skyline yarder in the Oregon State University school forest, noted that the logs per turn he observed were fewer than in an experiment performed in British Columbia by Maxwell and Oswald (1975). Neilsen concluded that the difference might be due to the number of additional stems removed in the Canadian experiment. Peters (1974) has probably made the most rigorous attempt to determine skyline loadings. Peters' hypothesis was that the average number of logs per turn was directly a function of average log size, log density per acre, and the payload capability of the system. Peters suggested that the load curve for a particular system could be constructed by observing as few as 90 turns and, once constructed, would be applicable over a wide range of terrain and timber conditions. This latter argument suggests work habits prevent the crew from responding to changing conditions. Peters did not make a direct correlation between silvicultural method and yarding productivity but his observations are among the first in the literature which identify skyline payload, log density, and log size as three of the primary elements in determining skyline loadings and skyline production.

Aulerich (1974) reported that, in thinning Douglas-fir to three residual basal areas, production increased when thinning intensity was increased and that cycle time decreased. Unfortunately, fewer chokers were used during the heavier thinnings than the lighter thinnings so that meaningful relationships between logs per turn and thinning intensity could not be identified.

Harvesting simulations have generally concentrated on modeling forest operations on gentle terrain, primarily in eastern Canada or the southeastern United States. Usually production rates are exogenous to the system being considered; for example, are attempts to improve machine scheduling by Woodland (1968), Hool et al. (1972), and Webster (1973). All involve ground skidding methods. The first cable harvest simulator identified in the literature is by Boyd and Lambert (1969) using a running skyline grapple yarder in British Columbia. The objective of the Boyd and Lambert study was to determine logging cost data so that when plotted against yarding distance the optimum yarding distance could be located by inspection. The simulation was deterministic, and it is not apparent that simulation was required to solve the set of equations describing the harvesting operation. Volumes per turn were arrived at in an interesting way. Arbitrary divisions of load size were made, in this case 300, 600, 1000, and 1500 bf, and the percentage of turns falling into each of these classes were measured in a field study. The simulation was then run for each volume per turn and the results were apparently weighted by their respective percentages for a final cost relationship. Skyline payload was not explicitly considered, except in that an "adequate" amount of deflection was assssumed. Sinner (1973) simulated thinning of Douglas-fir stands using GPSS. Stochastic elements of the model included random outhaul and lateral yarding distances to generate cycle times. The log distribution was permitted to vary over the unit, but in a deterministic manner. Log volume per turn was held constant. The objective was to determine the expected efficiency of alternative work methods in skyline yarding. Direct algebraic solution would have provided the same result. Burke (1976) developed a procedure caled "Automatic Yarding Cost Estimation" which was a deterministic attempt to determine the cost of skyline harvesting. The user specifies equipment unit costs, production rates, harvest area parameters of yarding distance and area, and the volume per turn. A desktop computer did the arithmetic.

Aulerich (1971) treats harvesting explicitly in a forest planning simulation model. He attempts to measure the desireability of logging a stand at any point in time by considering two opposing points of view: that of a forester (who wants to maximize net growth over mortality) and that of a logger (who wants to maximize net stumpage over logging costs). Skyline harvesting is not considered and the only apparent silvicultural practice permitted on the steeper terrain is clearcutting. Optimization over time is not attempted; regeneration costs and other stand management costs prior to the time of harvest are ignored.

Dykstra (1976b) considers the effects of topography explicitly in the optimal assignment of yarding machines to a forest unit considering a single entry final harvest model. Using the physical relationships between equipment characteristics and topography, Dykstra calculates the theoretical load carrying capacity of the system and compares this to an exogenously specified "maximum expected load" to check physical feasibility. He assumes that the appropriate number of logs can be assembled each turn to satisfy the constraints.

A brief survey of simulation efforts to date has been presented. An effort has been made to note limitations in present methods of analysis. It is evident that <u>none</u> of the previous models presents a <u>unified</u> framework relating harvesting cost to topographic and stand parameters. The purpose of the remaining section will be to propose a harvesting framework, develop a harvesting simulation model, and validate the model for use in the optimization study of stocking regime.

Harvesting Model Overview

The hypothesis of the harvesting model is that the cost of harvesting can be determined given equipment characteristics, terrain conditions, and a description of the components of the stand to be removed. Specifically, the harvesting model will require the following information:

1. Equipment characteristics including cycle time equations.
2. Allowable skyline payload based on the interaction between equipment characteristics and terrain.
3. Mean stand diameter and distribution parameters.
4. Silvicultural method.
5. Falling and bucking rule.

The data will be used in the harvesting model to:

1. Generate the log size and spatial log distribution of the logs to be yarded.
2. Assign logs to log loads in such a way that equipment constraints are not exceeded.
3. Determine the cost of felling, yarding, and loading based upon the relationships determined in the previous steps.

To develop a model to accomplish these objectives, some background material must be developed concerning stand simulation, falling and bucking simulation and yarding and loading simulation. Background subject matter concerning harvesting technology will be introduced as necessary to clarify model development.

Output from the harvesting model will be:

1. Harvesting cost relationships as a function of volume per acre removed and mean stand diameter given the equipment characteristics and terrain description.
2. Identification of the breakeven points between different machines operating in the same stand and terrain conditions.

The results of the harvesting simulation will permit identification of the locus of points connecting the minimum harvest costs of various machines under identical stand and terrain conditions. This locus of points, referred to as the minimum cost envelope, is shown in Figure 2 as a function of volume per acre removed for a given mean stand diameter. A similar relationship could be illustrated for various machines as a function of mean stand diameter for a given volume per acre.

Simulation begins with a description of the diameter distribution of the trees to be removed, the falling and bucking rule, the equipment characteristics, and the maximum skyline payload. The diameter distribution is generated and the trees felled and bucked. Yarding commences at the landing and progresses along the skyline until all logs have been brought to the landing. Log loads are assembled with the objective of maximizing load size subject to the spatial distribution of the logs, the number of chokers, the choker length, and the maximum payload. Logs are then either transported to a cold deck area for later reloading, or directly loaded

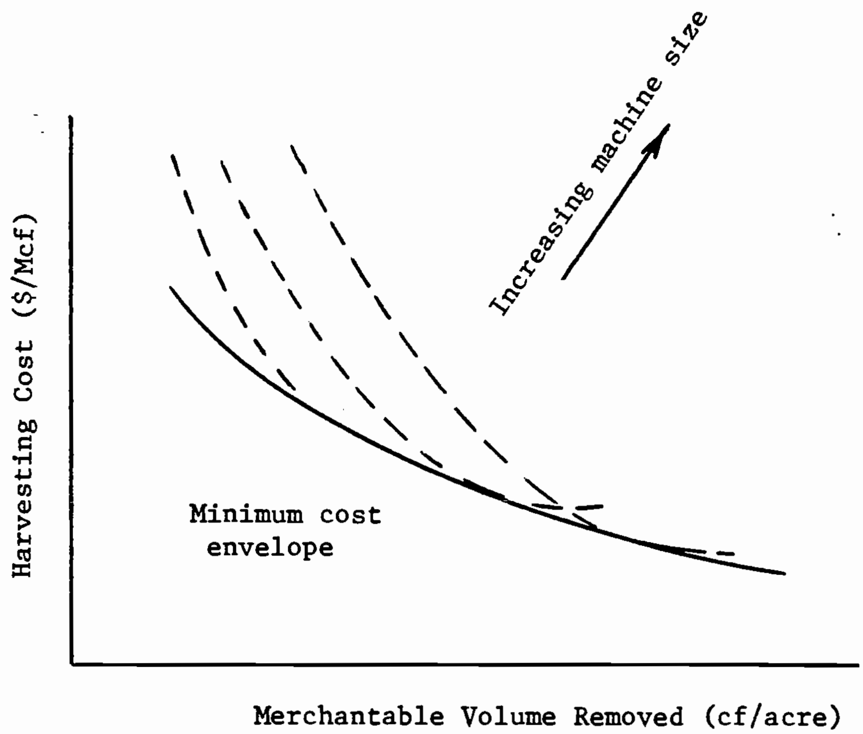


Figure 2. General form of the minimum cost envelope for harvesting cost as a function of machine size and volume per acre removed.

upon truck for transport to the mill. Felling, bucking, yarding, and loading times are accumulated, converted to cost, and output.

The simulations are repeated for various removals per acre from a light thinning to final harvest. The resulting harvest cost data are fit with a power curve model by least squares expressing harvesting cost as a function of volume per acre. Output includes the least squares estimates of the coefficients and the multiple coefficient of correlation.

A flow chart of the activities performed during the simulation is shown in Table 2. User documentation for the harvest simulator is in Appendix VIII. The remainder of the chapter will describe the model elements in detail.

Stand Simulation

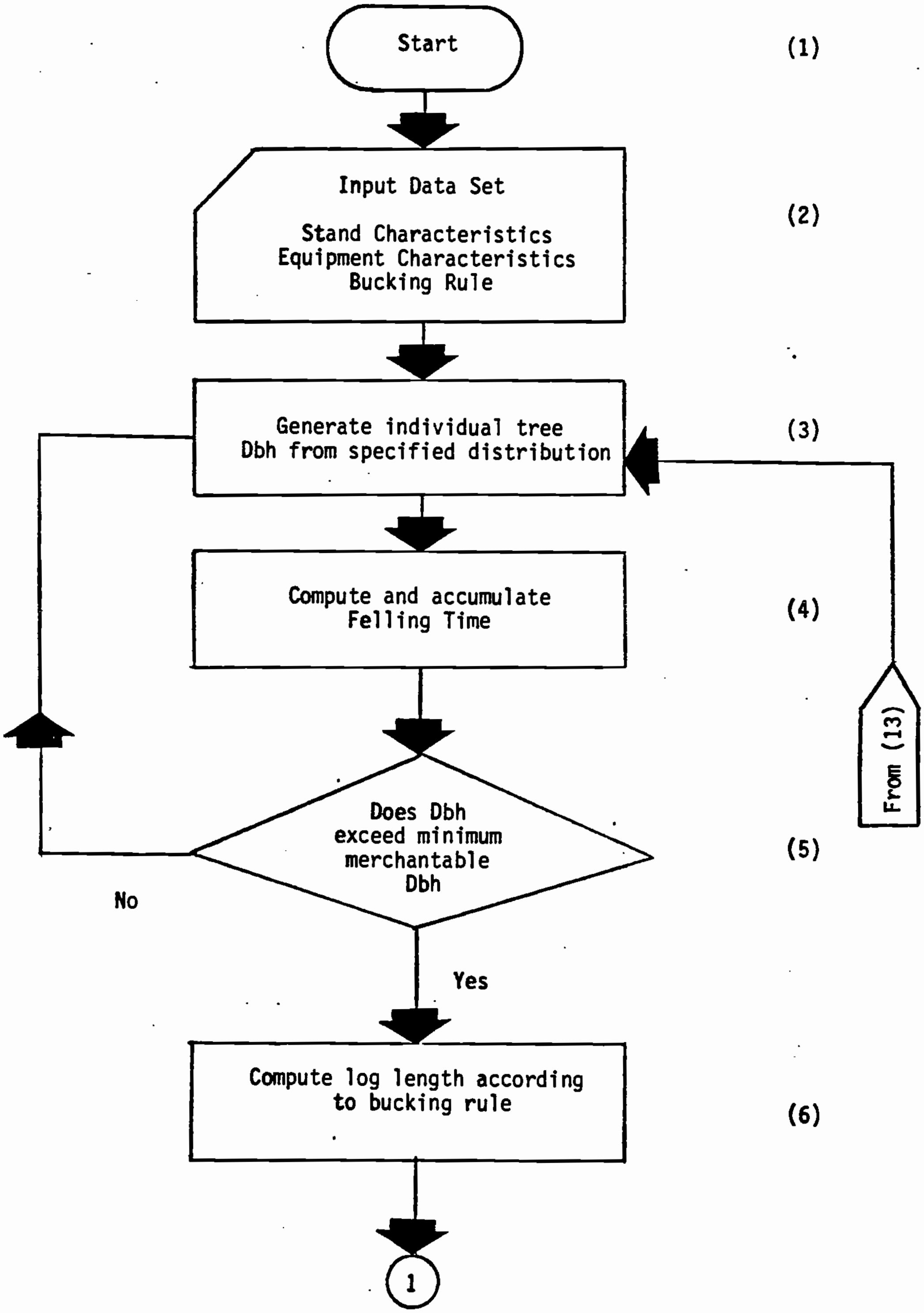
To simulate a forest stand, the stand parameters including the diameter distribution must be known. To simulate the harvest of this stand, the characteristics of the trees to be harvested must be known. This study resolves these questions by three assumptions:

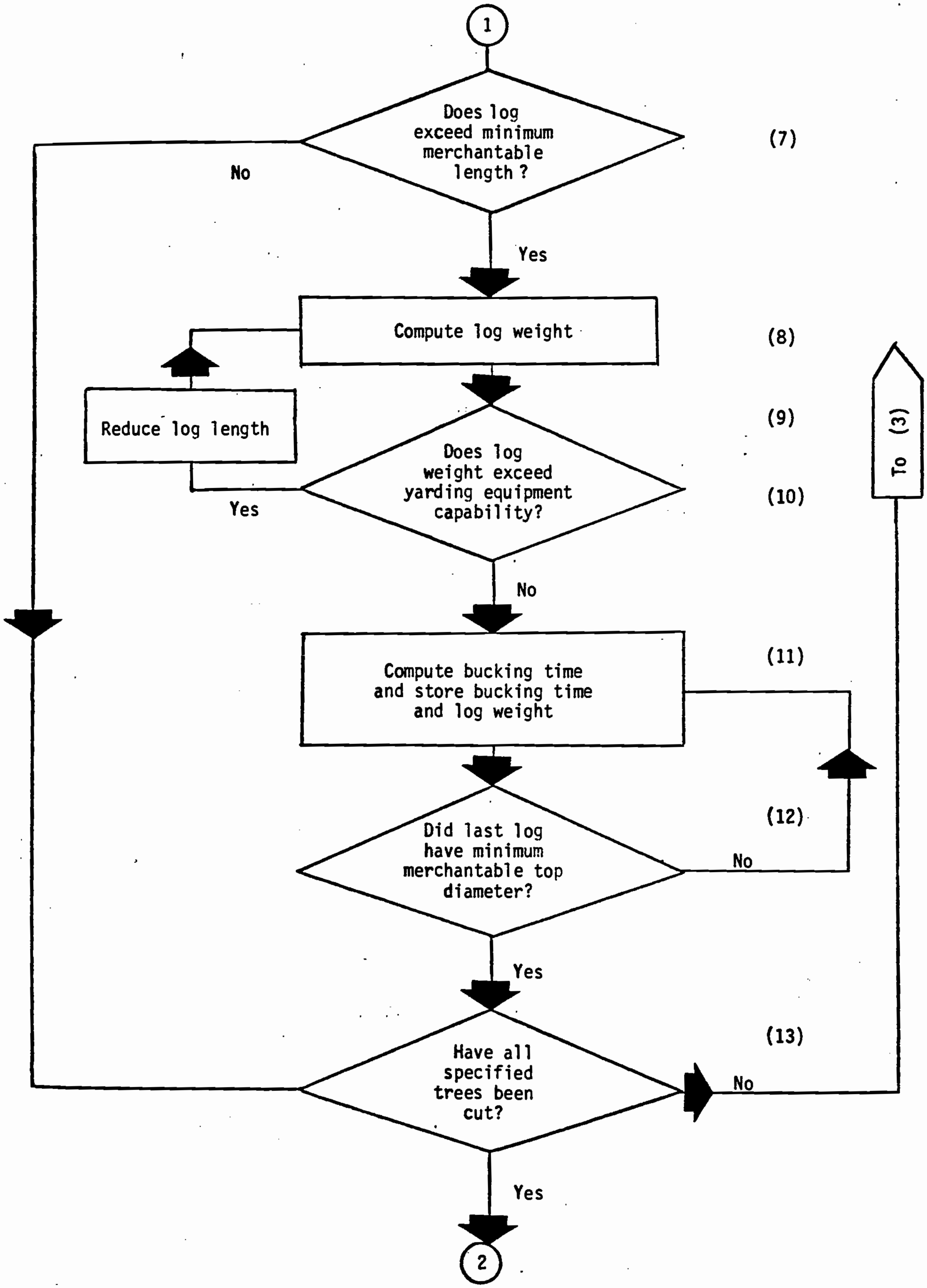
(1) The diameter distribution of an unthinned natural stand is normally distributed with known mean and variance.

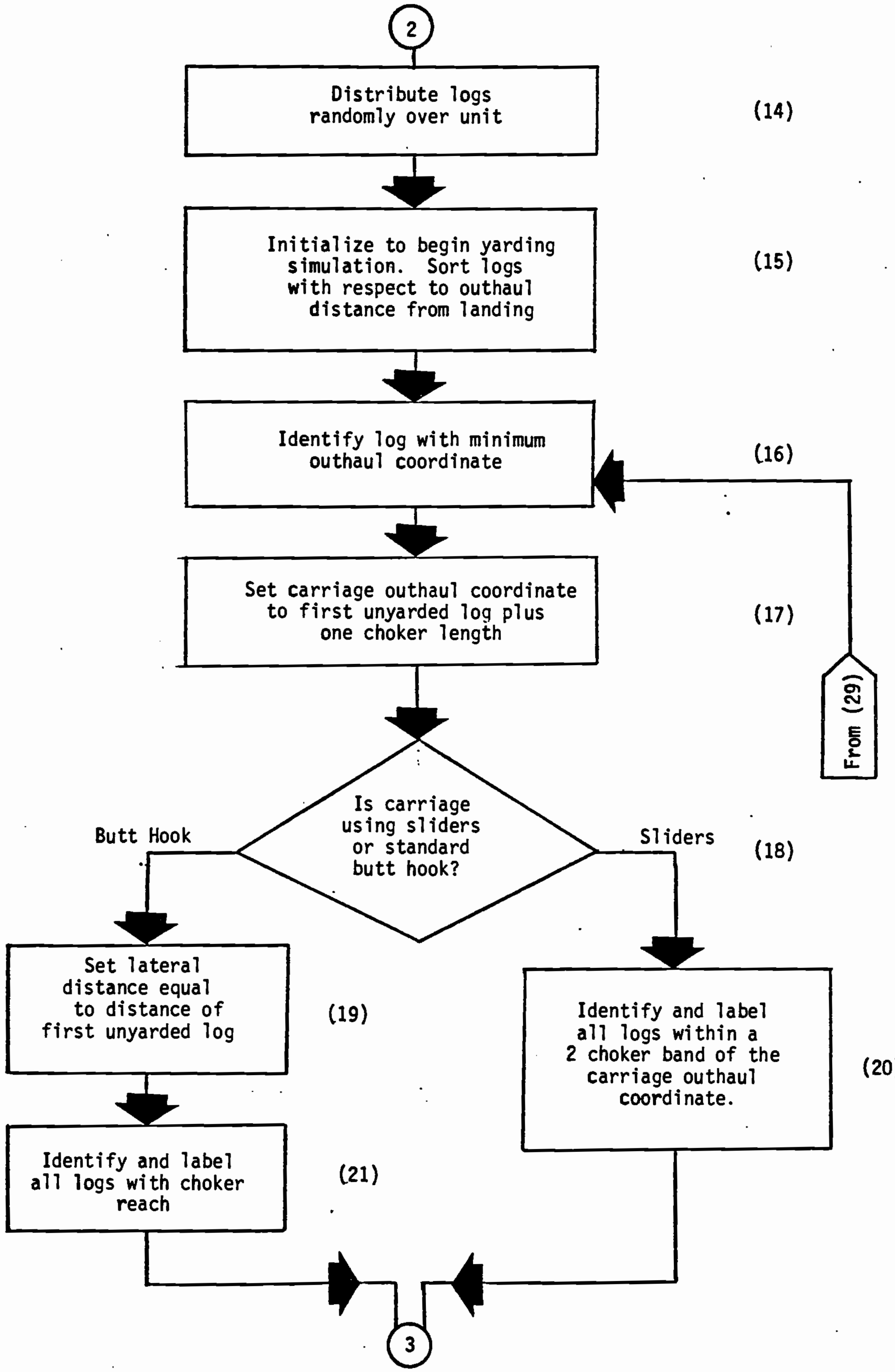
(2) The stand is cut in such a manner that the diameter of the stand before thinning and the diameter of the stand after thinning is unchanged.

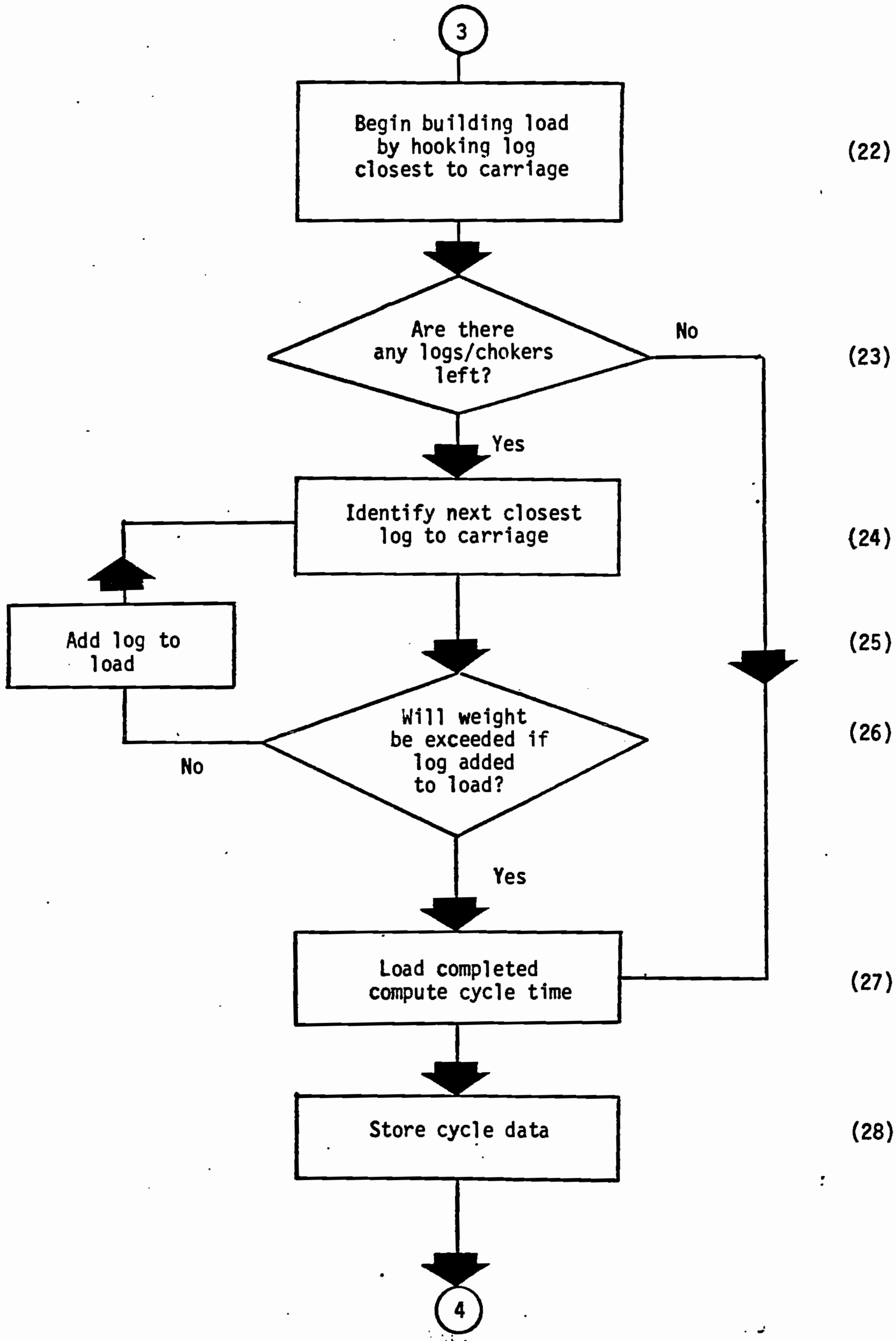
(3) The growth of a thinned stand progresses in such a manner that the variance of its diameter distribution would be

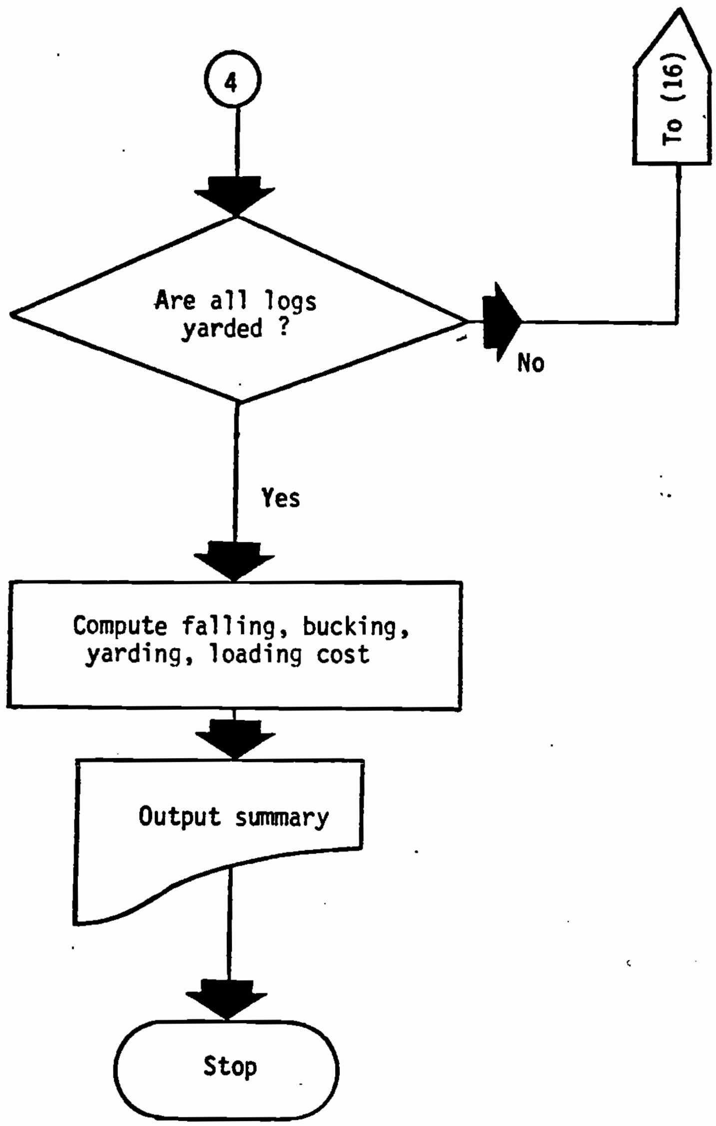
TABLE 2. FLOWCHART FOR HARVEST SIMULATOR.




1
Does log exceed minimum merchantable length ?
(7)
No
Yes
Compute log weight
(8)
Reduce log length
(9)
Does log weight exceed yarding equipment capability?
(10)
Yes
To (3)
No
Compute bucking time and store bucking time and log weight
(11)
Did last log have minimum merchantable top diameter?
(12)
No
Yes
Have all specified trees been cut?
(13)
No
Yes
2


2
Distribute logs randomly over unit
(14)
Initialize to begin yarding simulation. Sort logs with respect to outhaul distance from landing
(15)
Identify log with minimum outhaul coordinate
(16)
Set carriage outhaul coordinate to first unyarded log plus one choker length
(17)
From (29)
Is carriage using sliders or standard butt hook?
Butt Hook
Sliders
(18)
Set lateral distance equal to distance of first unyarded log
(19)
Identify and label all logs within a 2 choker band of the carriage outhaul coordinate.
(20)
Identify and label all logs with choker reach
(21)
3


3
Begin building load by hooking log closest to carriage
(22)
Are there any logs/chokers left?
No
(23)
Yes
Identify next closest log to carriage
(24)
Add log to load
(25)
Will weight be exceeded if log added to load?
No
(26)
Yes
Load completed compute cycle time
(27)
Store cycle data
(28)
4



4
Are all logs yarded ?
No
To (16)
Yes
Compute falling, bucking, yarding, loading cost
Output summary
Stop

(29)

(30)

(31)

(32)

the same as the variance of a natural stand of the same mean diameter.

A discussion of these assumptions follows.

Diameter Distribution

Bulletin 201 (McArdle 1961) presents a stand table for fully stocked Douglas-fir stands, designating the approximate number of trees in each 2-inch diameter class at 20-year intervals. Histograms of the number of trees by diameter class for ages 40 to 160 for unthinned normally stocked natural stands are shown in Appendix IV. Means and variances were calculated from the stand table and are listed in Table 3.

TABLE 3. DIAMETER DISTRIBUTION PARAMETERS AS A FUNCTION OF STAND AGE.

Age Years	Mean (inches)	Variance ($inch^2$)	Total Trees
40	6.58	5.85	585
60	10.39	11.83	337
80	13.69	17.79	232
100	16.22	23.35	184
120	18.36	29.58	152
140	20.19	34.96	131
160	21.95	40.11	117

A linear relationship between variance and age was derived using least squares. The stand variance of an unthinned, fully stocked natural stand can be expressed as

$$V = -5.367 + 0.287 * t$$

where

V = variance of the diameter distribution, square inches

t = stand age, years

The correlation coefficient for the regression (R^2) was 0.999. It is apparent that the original data from which the Bulletin 201 stand tables were derived have been smoothed.

Chi-squared (X^2) tests were performed on the stand data for goodness of fit to a normal distribution. The expected number of trees in a normal distribution was compared to the number of trees in each 2-inch class for the ages 40 to 160. The X^2 values follow the method outlined by Brunk (1975). These results are shown in the Table 4. None could be rejected at the 2 percent level.

TABLE 4. CHI-SQUARED TESTS FOR GOODNESS OF FIT.

Age	X^2	Degrees of Freedom
40	9.83	3
60	9.19	5
80	10.92	6
100	12.97	7
120	5.94	9
140	6.70	10
160	4.31	11

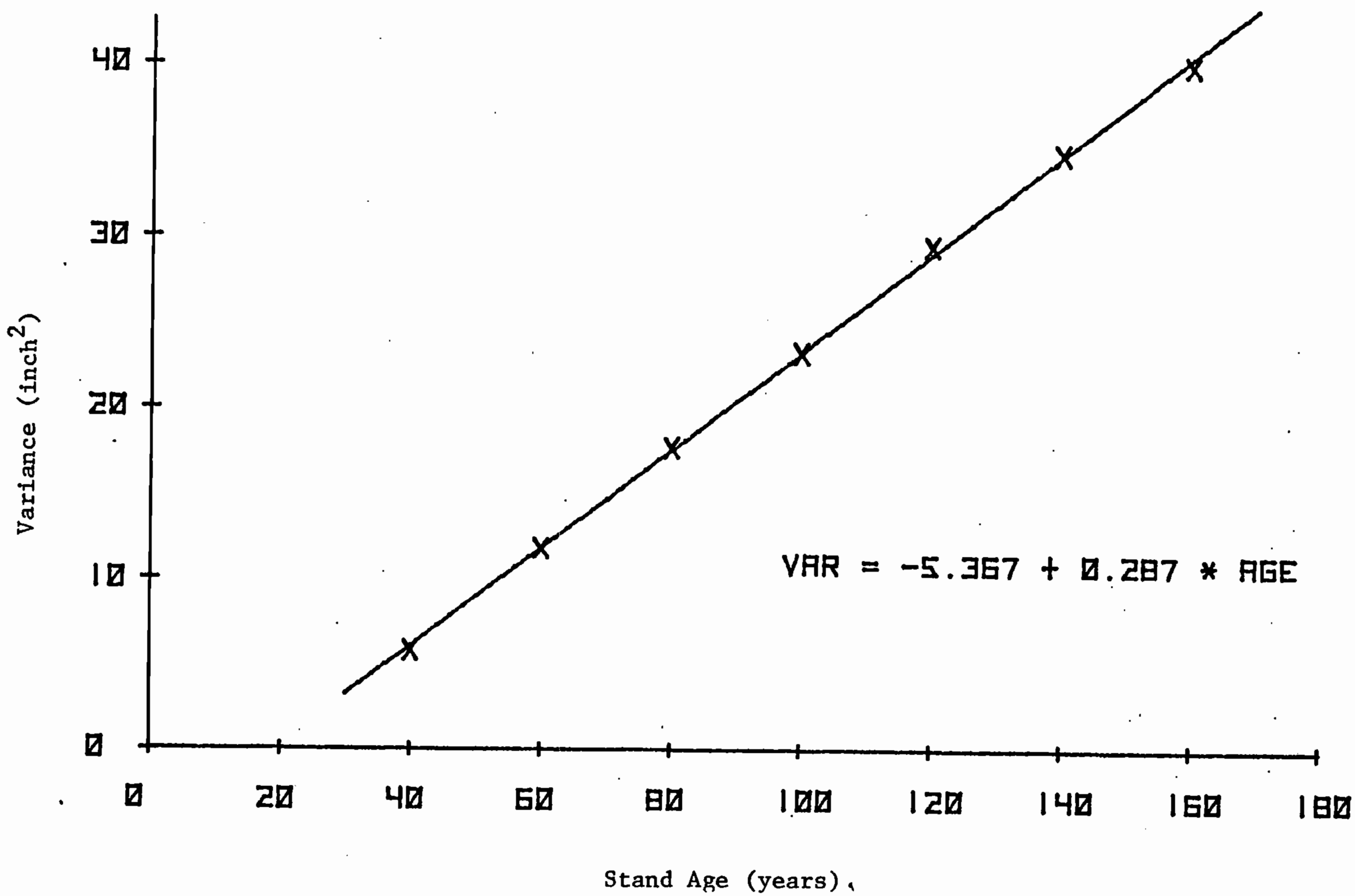


Figure 3. Variance of the diameter distribution as a function of stand age.

Thinning Ratio

The thinning ratio was assumed to be 1.0. Inclusion of the thinning ratio as a variable would have increased the complexity of the model, requiring four state descriptors. Reukema and Bruce (1977) after performing many simulations using DFIT, advocate an initial thinning with a thinning ratio of 1.0 followed by subsequent thinnings from below with a thinning ratio of 0.8. Results of optimization from Chapter VI indicate that entries will generally be delayed until year 60 with one or two additional light thinnings. The stand response between a thinning ratio of 0.8 and 1.0 will probably not be significant in these circumstances.

A thinning ratio of 1.0 facilitates the simulation of trees to be thinned. The proportion of trees removed from each diameter class is the same. Removal of trees in this manner leaves the mean and variance of the diameter distribution unchanged.

Reaction to Thinning

The assumption that the growth of a thinned stand progresses in such a manner that the variance of its diameter distribution would be the same as the variance of a natural stand of the same mean stand diameter is the most tenuous of the three assumptions. Although the thinning ratio of 1.0 assumes that the variance before and after entry is unchanged, the assumption that the stand then grows along a trajectory such that the relationship between variance and age is the same as an unthinned stand is speculation. Convincing arguments could be given that the growth following thinning could either accelerate the change in stand variance over time or reduce the rate of change with respect to an unthinned stand. Increasing the growing space of the remaining trees may release the suppressed trees relatively more than the dominant trees, depending on the age of the stand and crown condition. Or, the opposite may be true. For lack of additional information, the middle road has been chosen and the variance of thinned stands has been set equal to the variance of unthinned stands of the same mean diameter.

Fortunately, it will be shown that although harvesting costs are extremely dependent on <u>mean</u> stand diameter, costs are not particularly sensitive to the <u>variance</u> of the diameter distribution over a wide range.

Variate Generation

Diameter distributions were generated using deviates from a Uniform (0,1) distribution. Transformations available in the harvesting simulator include uniform, exponential, and normal distributions. Although the normal distribution was used as the standard diameter distribution, a discussion of the sensitivity of harvest cost to other distributions is included in Chapter IV.

The remainder of this section discusses the transformations used to develop alternative diameter distributions.

Uniform (A,B)

A variate from the Uniform (A,B) distribution is generated from a deviate of the Uniform (0,1) distribution (Fishman 1973) by the transformation,

$$U\ (A,B) = A + (B - A) * U\ (0,1)$$

where

$U\ (A,B)$ = uniform variate on the interval (A,B)

A = lower bound (diameter) of the distribution

B = upper bound (diameter) of the distribution

$U\ (0,1)$ = deviate from Uniform $(0,1)$

Exponential (K)

The generation of the exponential variate (Fishman 1973) is accomplished by

$$Exp\ (K) = -K * \ln\ (U)$$

where

$Exp\ (K)$ = exponential variate on the interval $(0,\infty)$

K = mean of the distribution

U = variate from $U\ (0,1)$ distribution

To obtain exponential variates over the truncated interval (A,B), variates on the interval $(0,\infty)$ were generated and those outside of the limits (A,B) ignored.

Normal (K,σ^2)

Variates of the Normal (K,σ^2) are generated from independent deviates of the $U\ (0,1)$. The procedure is as follows:

Let U_1 and U_2 be independent deviates from $U\ (0,1)$. The variates of the Normal $(0,1)$ will be (Box 1958)

$$X_1 = (-2 \ln U_1)^{\frac{1}{2}} \cos\ (2\pi U_2)$$

$$X_2 = (-2 \ln U_1)^{\frac{1}{2}} \sin\ (2\pi U_2)$$

To generate the variates from Normal (K,σ^2), the variates U_j and U_{j+1} are generated and then X_j, X_{j+1}

$$X_j = K + (-2\sigma^2 \ln U_j)^{\frac{1}{2}} \cos (2\pi U_{j+1})$$

$$X_{j+1} = K + (-2\sigma^2 \ln U_j)^{\frac{1}{2}} \sin (2\pi U_{j+1})$$

$$j = 1, 3, 5, \ldots .$$

To obtain normal variates over the truncated interval (A,B), variates over the interval $(-\infty,\infty)$ are generated and variates outside the limits (A,B) ignored.

Falling and Bucking

Falling and bucking involves the cutting down and conversion into logs of trees to be thinned or final harvested. This section is procedural; describing the falling and bucking rules, volume determinations, and falling and bucking time calculations used in the harvest simulator for steps 1 through 13 in the flow diagram.

The data required prior to felling and bucking simulation are:

1. Average total stand height.
2. Minimum merchantable diameter inside bark.
3. Minimum merchantable log length.
4. Average log density including bark.
5. Maximum log load that will be permitted to travel along the skyline.

Volume Calculations

Volume and weight calculations are based on the volume of a right circular cone of constant taper. Taper is calculated for each tree by the assumed relationship:

$$T_i = \bar{H} / Dbh_i$$

where,

T_i = Reciprocal of tree taper of tree i, feet per inch

$\bar{H}$ = Average total stand height, feet

Dbh_i = diameter, breast high outside bark, inches, for tree i

For simplicity T will be referred to as the "taper."

The volume of each log is calculated as

$$V_j = .005454\ L_j\ (D_j + L_j/(2 * T_i))^2$$

where,

V_j = cubic volume of log j, cubic feet

L_j = length of log j, feet

T_i = taper of tree i, feet/inch

D_j = small end diameter over bark for log j

This formula for log volume frequently underestimates 3/ the true volumes due to the nonlinear taper of logs. The longer the log, the more serious the underestimate.

Tait (1948) compared the relative accuracy for values T = 8,10 in second growth Douglas-fir and found that T = 8 resulted in an average underestimate of 5 percent while T = 10 resulted in an average underestimate of 14 percent. 4/

3/ The formula also slightly underestimates the true volume of a right circular cone of constant taper. The percent error of the underestimate can be expressed as

$$\text{Percent Error} = 100 - 75 * (r+R)^2/\ ((r+R)^2-rR)$$

where R = D/2, R = r + L/(2T)

4/ T = 8 is the basis of the "Rapreager rule" and T = 10 is the "Sorensen rule" (Dilworth 1973).

Bucking Rules

The bucking rule used in the simulator to generate the cost curves in Appendix V and VI was to buck to 40-foot lengths whenever possible to a minimum top diameter inside bark of four inches. If the top was less than 12 feet long, the preceding log was shortened to a length such that the two top logs were of equal length. If a 40-foot log exceeded the allowable log load specified for the skyline, the log length was reduced in two-foot increments until the weight limitation was satisfied.

To test the accuracy of the stand generation procedure, natural unthinned stands were generated with variances derived from Bulletin 201 and mean diameters from DFIT. Net log volumes were corrected for bark by multiplying log volumes by a bark ratio factor referred to by mensurationists as the "mean squared bark thickness ratio." Dilworth (1973) recommends a net to gross factor of 0.85 for Douglas-fir 50 years of age and less and a factor of 0.81 for older age classes. The stand simulation and DFIT values are shown in Table 5 with total tree volumes in cubic feet per acre. Sample size for each simulation was 60 trees.

A minimum top diameter of one inch inside bark was specified. On the basis of this test, and the preceding reference to Tait (1948) a factor of 1.14 was used to correct all net and gross log volumes generated by YARDALL.

It is often of interest to know the log frequency for logging planning. Supplementary output from YARDALL includes a breakdown of logs per acre in ten weight classes. A histogram of log frequency as a function of log size for a regeneration harvest of an unthinned natural stand at age 100 is shown in Figure 4.

TABLE 5. COMPARISON OF DFIT STAND VOLUMES WITH YARDALL SIMULATIONS

Age (years)	YARDALL Gross Volume (cf/acre)	YARDALL Net Volume (cf/acre)	DFIT Net Volume (cf/acre)	Net YARDALL/ Net DFIT
40	5,192	4,414	4,883	0.88
60	8,055	6,524	7,872	0.83
80	10,189	8,253	10,037	0.82
100	12,556	10,170	11,740	0.87

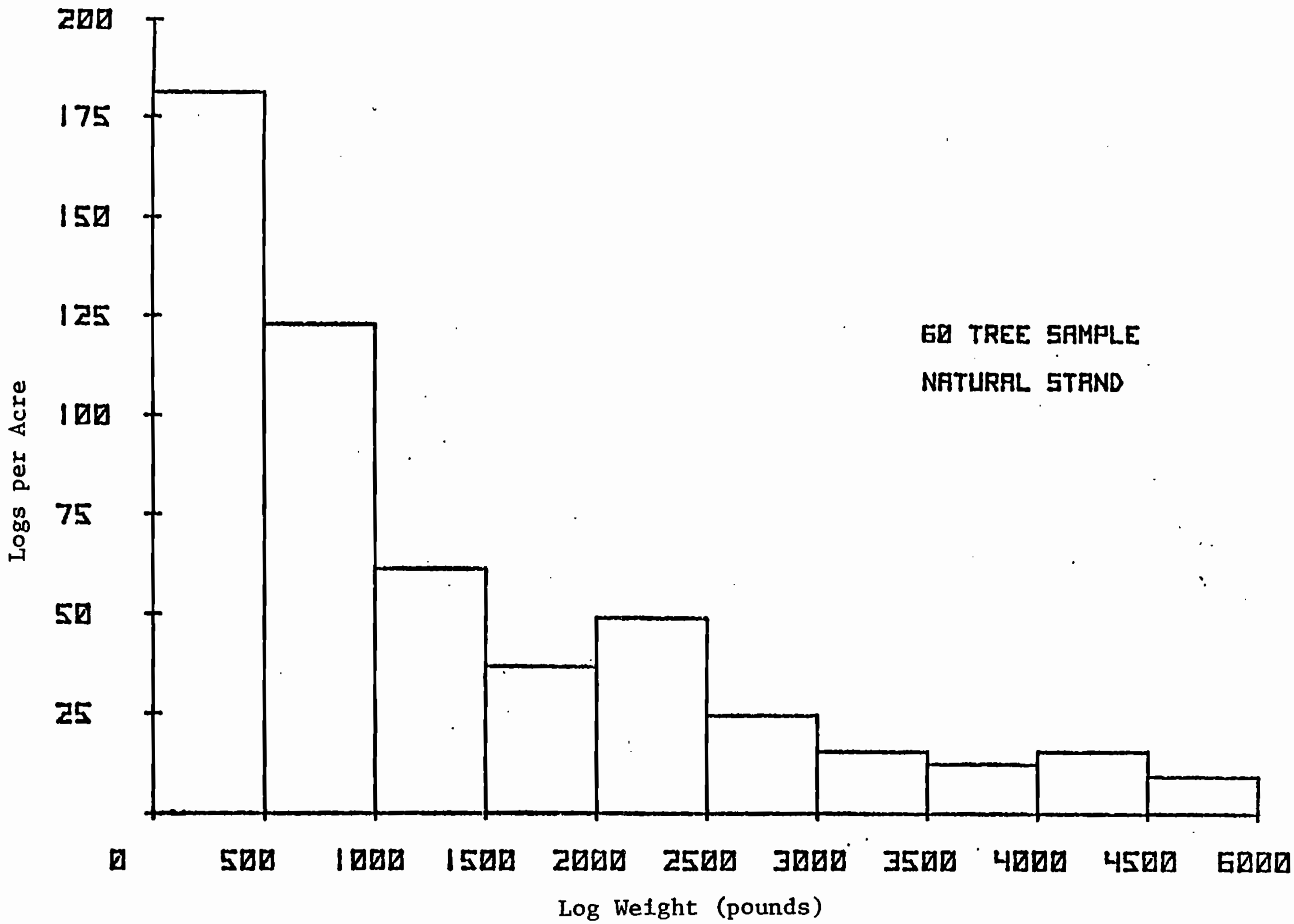


Figure 4. Histogram of logs per acre as a function of log weight for a regeneration harvest in an unthinned 100 year-old stand.

Fall and Buck Time

The time to fell and buck each tree is calculated and accummulated using the felling and bucking relationships from Adams (1967).

Adams divides falling and bucking time for commercial thinning of Douglas-fir into three components: the time to walk to each tree, the time to swamp around the tree prior to beginning cutting, and the time to actually fall, buck, and limb the tree.

Defining:

Y_1 = time to walk to each tree, minutes

Y_2 = time to swamp around the tree, minutes

Y_3 = time to fell, buck, and limb the tree, minutes

T_1 = number of trees per acre before cutting

T_2 = number of trees per acre cut

H = Dbh, inches

B = number of bucking cuts after felling

Adams finds that

$$Y_1 = 2.332 - (.01033)(T_1) + (0.0000182)(T_1^2) - (0.01235)(T_2)$$

$$Y_2 = 0.21$$

$$Y_3 = 1.3805 + (0.1134)(H^2) + (1.179)(B)$$

or, the total time to walk to each tree, swamp, fell, buck, and limb becomes

$$Y_4 = Y_1 + Y_2 + Y_3$$

An average of 30 trees per acre were cut from a stand of 212 trees per acre in the Adams study. Tree diameters varied from 6 inches dbh to 35 inches dbh. Normally stocked natural Douglas-fir stands on Site 140 will have a considerably larger number of initial stems per acre until year 80. This results in a negative value for the time to walk between trees. Since the actual time is small, generally less than 0.5 minutes, the time to walk between trees and to swamp around the trees were grouped and assumed to be constant at 0.62 minutes.

The total time to walk between trees, swamp, fell, buck and limb then becomes,

$$Y_4 = 2.0 + (0.1134)(H^2) + (1.179)(B)$$

The total time to fell and buck the stand is the sum for the individual trees.

Yarding

Spatial Log Distribution

Little information is available considering the spatial distribution of individual logs resulting from thinnings or final harvests. Existing research deals primarily with the spatial distribution of trees. Studies by Payandeh (1974) in eastern Canada indicate that natural coniferous or mixed hardwood stands have highly clustered spatial patterns while hardwood stands show nearly random spatial patterns. Daniels (1978) observed similar results in Loblolly pine. Stand development models incorporating the spatial distribution of individual trees include formulations by Newnham (1964), Curtis (1967), Arney (1974), Hegyi (1974), Ek and Monserud (1974), Daniels and Burkhardt (1975) and Mitchell (1975). The models by Newnham, Curtis, Arney, and Mitchell were developed for Douglas-fir.

The effects of spatial tree distribution patterns in mechanized thinning and final harvesting operations on gentle terrain have been studied by researchers including Almquist (1969, 1970), Newnham (1967, 1968, 1970), Newnham and Maloley (1970), Newnham and Sjunnesson (1969) and Sjunnesson (1970). It is not apparent that similar studies have been conducted in mountainous terrain.

Some preliminary analytical work on spatial log distributions was done by Ohmstede (1977) in an attempt to assign trees to log landings in tractor productivity studies in eastern Oregon. Ohmstede's procedure was to identify potential tractor logging landings on aerial photographs, transfer their locations to a grid and then digitize the location of the trees to be removed. Felling was simulated and log locations were stored in polar coordinates relative to the stump. A transformation was then made to cartesian coordinates relative to the log landing. No field follow up was undertaken. Falk (1978) currently is gathering detailed field data on log distributions.

Since few quantitative data are available, the assumption in this study is that the logs are randomly distributed over the unit following a UNI (0,1) distribution in both cardinal directions. This certainly is not the case for logs coming from an individual tree since the location of the top log is determined by the location of the butt log. However, if all trees on the unit are considered including those which are falling into the unit from adjacent units and out of the unit into adjacent units, the assumption may not be too strong. The assumption is probably poorest when only a few trees are being removed. Randomly distributing the logs over the unit permits the opportunity for two logs from an individual tree to be hooked in the same turn, an unlikely event in practice since trees are being hooked from the front end only to reduce hangups and residual stand damage.

The strongest argument in support of the assumption of random distribution is that model predictions of logs per turn compared favorably with field observations.

The procedure used to distribute the logs introduces a small bias which could result in an underestimate of the yarding productivity and consequent overestimate of the yarding cost. This error is introduced by yarding the unit in subsections referred to as "outhaul blocks." Prior to yarding it is necessary to identify log locations by ordering the logs by their perpendicular, or outhaul distance from the landing. Since simulations of a 1000-foot skyline corridor may require yarding of 1500 or more logs, the sort time can be substantial. To shorten the sort time the simulation is divided into subsections, generally 200 feet. Logs are distributed over the 200 feet, yarded, distributed over the next 200 feet, and the process continued until the unit boundary is reached. Substantial savings in computer time can be gained by this procedure but the number of logs per turn may bè underestimated. 5/ The underestimate arises when the yarding sequence approaches the boundary of an "outhaul block." Since logs beyond the block boundary have not yet been generated, all possible logs to build the load may not be considered. For the relatively short chokers used with slackpulling carriages (8 and 12 feet in this study) only a small error is introduced. For longer chokers, such as a simulation of clearcutting using a non-slackpulling carriage with 40-foot chokers, the error could be substantial and the outhaul blocks would have to be increased in length.

To test the sensitivity of the outhaul block length to load size a thinning of a 60-year old stand and the regeneration harvesting of a 100-year old stand were made and the results compared for different block lengths (Table 6). The difference between mean logs per turn for each set of simulations was compared and the differences were not significant at the 95 percent level of confidence in either case.

Some alternatives to the yarding procedures exist. A logical extension of this study would be to improve the sorting algorithm. The existing algorithm is the familiar "sinking" method of sorting

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5/ It can be shown that if the log sorting job is broken into k parts that the total job will take 1/k as long to sort as compared to sorting the entire job at once. See Appendix II.

by interchange of adjacent pairs. Considerable attention has been given to the development of efficient sorting routines to pre-process data in some optimal fashion. Examples of these routines are given by Hoare (1961) in the routine QUICKSORT, Scowen (1965) in the routine QUICKERSORT, and Singleton (1969) in ALGORITHM 347. A version of ALGORITHM 347 is available in the CYBER Library at the Oregon State Computer Center but was not used as a stand alone program was desired for flexibility of use on other computing machines.

TABLE 6. EFFECT OF OUTHAUL BLOCK LENGTH ON LOGS PER TURN AND PROCESSING TIME.

Thinning at Age 60 100 stems per acre cut	200 ft. block 1200 ft. skyline	1200 ft. block 1200 ft. skyline
Logs Yarded	538.000	528.000
Logs Per Turn	2.460	2.330
Standard Error of Logs Per Turn	0.087	0.083
Execution time, sec	1.102	3.691
Regeneration Harvest at Age 100 184 stems per acre cut		
Logs Yarded	1499.000	1492.000
Logs Per Turn	3.370	3.470
Standard Error of Logs Per Turn	0.074	0.071
Execution time, sec	6.064	9.610

Load Building

When using skylines, there are two primary log hooking strategies: the use of sliders and the use of the standard butthook. The standard butthook permits logs to be reached within a radius of approximately one choker length less the length of choker required to wrap the log. Sliders permit logs to be gathered in a band approximately two choker lengths in width. Figures 5 and 6 illustrate these concepts showing logs on the unit, the path of the skyline carriage, and the contact area for the two choker systems (dotted pattern). The particular choker system chosen for use depends on the log frequency relative to the payload and the number of residual trees. The primary advantage of the slider is that it permits a larger area to be covered increasing the probability of larger average log loads per cycle. A disadvantage of sliders, particularly in steep terrain, is that as the last log is being pulled toward the skyline corridor, collecting the other logs on the way, the chance of hangups and damage to the residual stand is increased. Little quantitative information is available relating severity of hangups to stand density. In this study the standard butthook was used. Logs are permitted to be hooked only on the end closest to the skyline corridor to reduce hangup potential.

To collect a turn of logs, the carriage is sent one choker length beyond the first unyarded log and all logs within choker reach are identified. Logs are added to the turn in the order of their relative distance from the hook until one of three conditions is met:

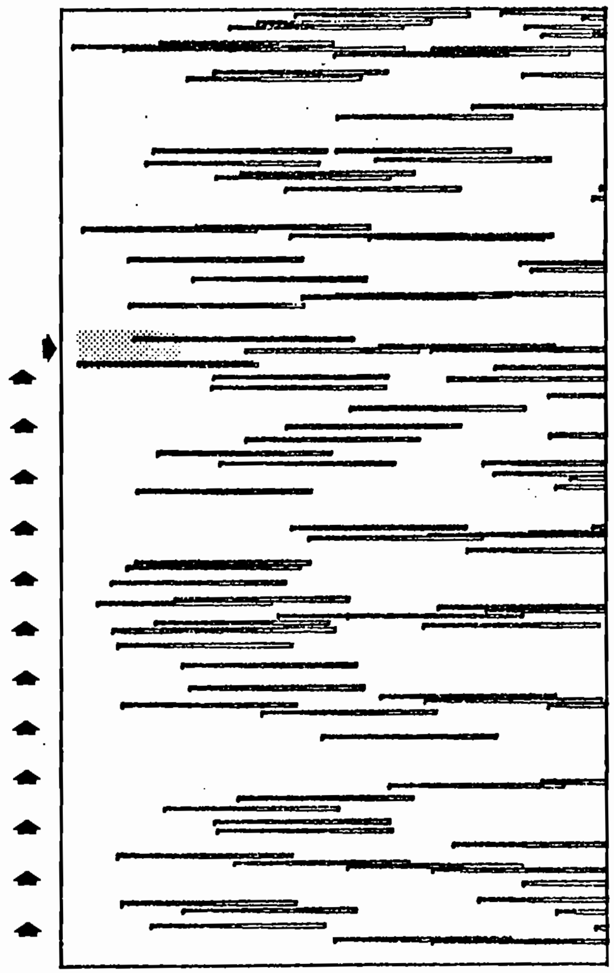


Figure 5. Generalized half-unit showing area of contact for use of the standard butthook.

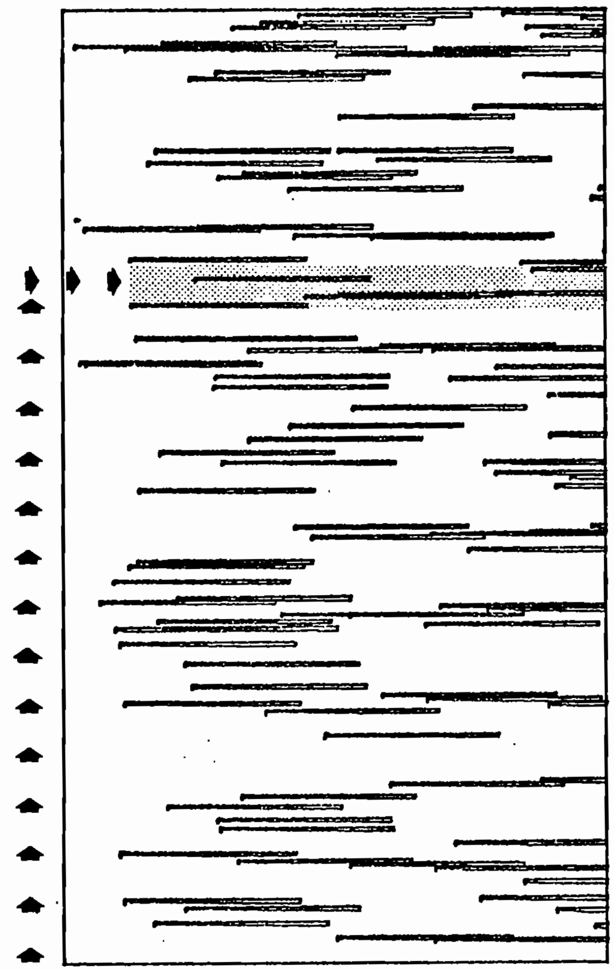


Figure 6. Generalized half-unit showing area of contact for use of sliding chokers.

(1) The maximum load is exceeded.

(2) There are no remaining free chokers.

(3) All logs within the pickup radius have been hooked.

Admittedly, this is a heuristic approach which does not assure load maximization. 6/ A choker setter might pick and choose from those logs within reach to increase log loads, but this is not an easy task. Hangup risk may be increased by leaving unyarded logs in the path of logs being yarded. Prior information must be adequate; the chokersetter may need to know not just where the next turn is coming from, but may require knowing several turns ahead which logs should go in the current turn.

Loading

Log loading in the harvesting simulation is performed in one of three modes.

(1) A log loader is stationed at the log landing full time and is used to keep both the landing clear and to load log trucks. This type of operation is referred to as "hot loading."

(2) A small rubber-tired skidder is used to swing the load from the landing to a storage area for later loading by self-loading trucks.

(3) Logs are decked at the landing without the use of a log

6/ It can be shown that for the linear cycle time model used in this study, maximizing the number of logs per turn is equivalent to minimizing logging cost. See Appendix III.

loader and are later loaded by a self-loading truck after yarding has been completed. This operation is referred to as "cold decking."

Hot loading of logs is performed when yarding production is high enough that a full time log loader is superior to a combination of swinging and later loading. Log loading from a cold deck provides the lowest loading cost, but requires either a sufficiently large landing to store the logs or an additional machine to swing the logs to a storage area for later rehandling. The method used depends upon the cost of landing construction, the cost of swinging, and the cost of log loading. Figure 7 illustrates relationships between the three variables.

In this simulation, all three loading methods are used. For thinning young second-growth by small skylines, Neilsen (1977) reports that log decks of up to 200 logs, approximately 2000 cf, could be decked in front of the yarder without creating unacceptable safety conditions. YARDALL uses this limit as the upper limit for storing logs on the landing without requiring removal to a storage area. When volumes in excess of 2000 cubic feet are to be brought to the landing by the small skyline, a small rubber-tired skidder is used to swing logs to storage areas for later loading. When the larger yarder is used, the production rate is high enough to justify a loader operating with the yarder continuously.

Loading times for self-loading trucks, were derived by Schneider (1978) for hydraulic boom self-loading trucks. Schneider expresses the total time to load a log truck as:

$$L_t = 505.75 + (35.1)(N_t)$$

where

L_t = Loading time per truck, seconds

N_t = Total number of logs in the load

The number of logs in the load is calculated from the allowable truck weight and the average log weight. Maximum net truck capacity is assumed to be 25 tons.

When the larger yarder is used, loading costs have been combined with the yarding cost since the loader is present continuously and the output is a joint function. For the small yarder, log loading cost is calculated separately.

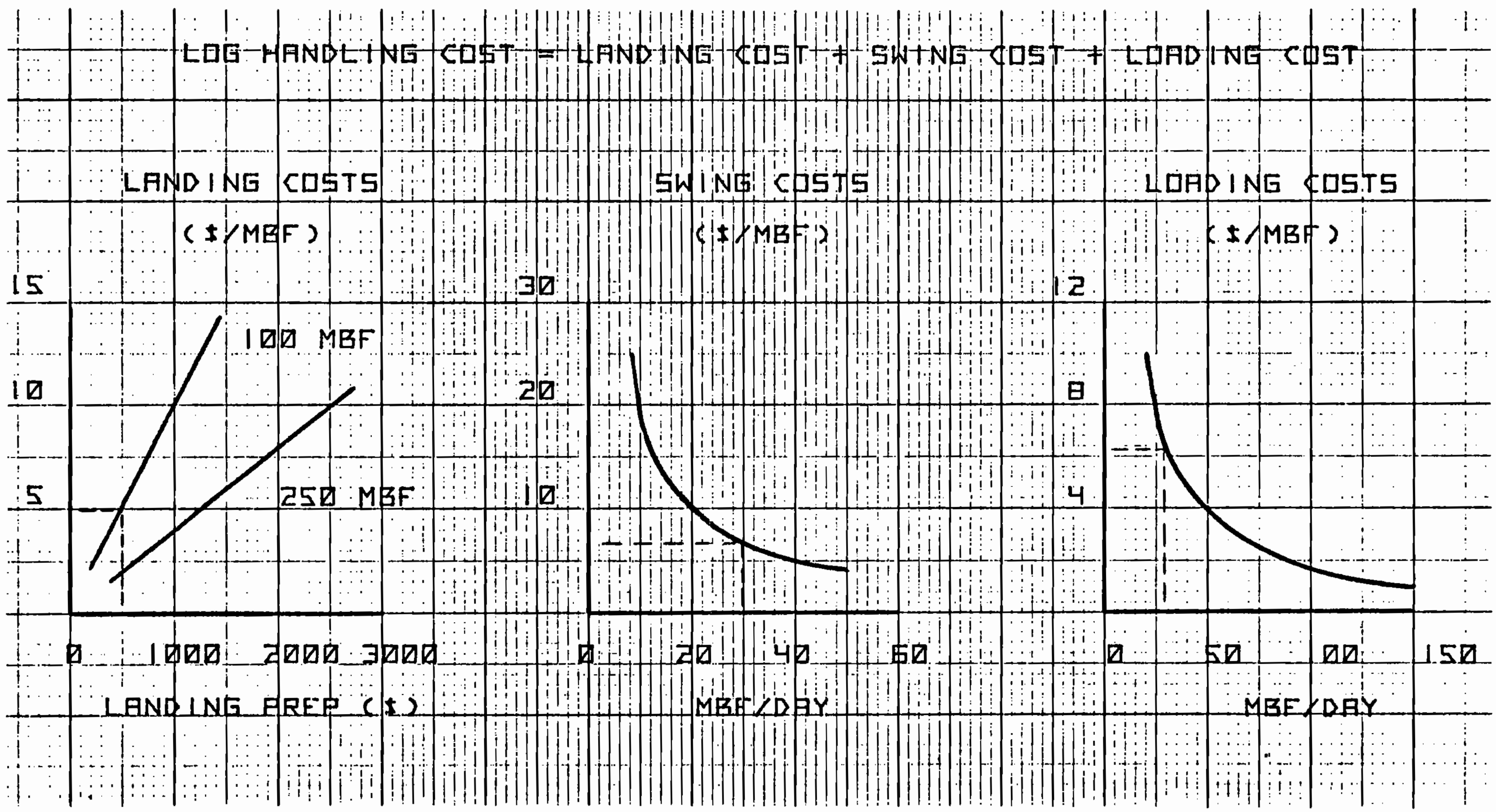


Figure 7. Log loading cost considerations.

Model Validation

Several comparisons were made between YARDALL predicted production and actual production from field studies.

Validation Test #1

Neilsen (1977) studied thinning of a stand of 35 to 40 year-old Douglas-fir and western hemlock in the University-owned Blodgett Tract Forest in Columbia County, Oregon. The stand sloped away from a spur road at slopes ranging from 10 to 70 percent. A convex break in the slope occurred 200 to 300 feet from the road, requiring the use of an intermediate support, and the maximum span length was 650 feet. Yarding was done with the Igland-Jones Trailer Alp. Average skyline height above the ground was 17 feet.

Neilsen sampled the stand before and after thinning and reported that 42 percent of the fir-hemlock stems and 37 percent of the volume was removed in an average of 96 stems per acre harvested. The percentages of stems removed by diameter class are shown in Table 7. Average stand height was 85 feet. The fallers were instructed to utilize each tree to a 5-inch top. Eight-foot chokers on a standard butthook were generally used although sliders were used occasionally.

Field conditions from the Neilsen study were simulated in YARDALL. To maintain accuracy during simulation, removals by diameter class were used rather than fitting the field data to a distribution. A bucking rule of maximum 40-foot lengths, 12-foot minimum, to a 5-inch top was used during simulation. The yarding of 211 trees, yielding 309 logs, was simulated. The results are summarized in the Table 8.

TABLE 7. PERCENTAGE OF STEMS REMOVED PER ACRE BY DIAMETER CLASS FROM NEILSEN (1977).

Midpoint of Diameter Class	Percentage of Stems
8	37%
10	17%
12	7%
14	14%
16	14%
18	8%
20	0%
22	2%
24	1%

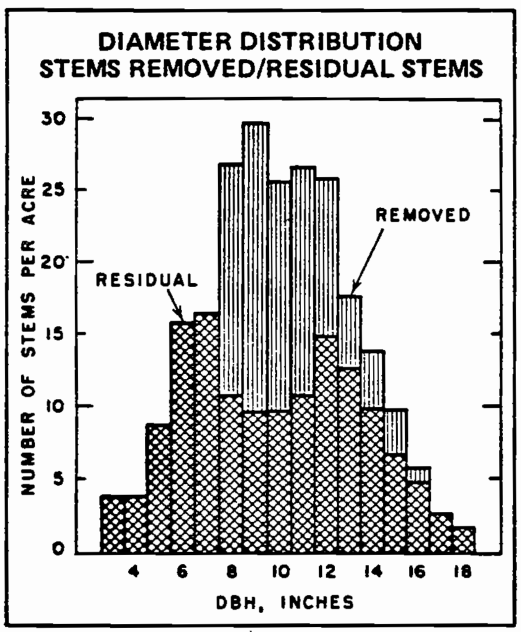
TABLE 8. COMPARISON OF YARDER PRODUCTION FROM NEILSEN (1977) AND YARDALL SIMULATION.

	Neilsen	YARDALL	Error
Volume Removed Per Acre	1850 cf	1966 cf	+6.3%
Logs Per Turn	1.62	1.60	-1.2%
Volume Per Turn	21.0 cf	22.45 cf	+6.9%

The standard error of the average pieces per turn from the simulation was 0.06. Part of the error in the volume per acre removed and the volume per turn might be related to deviations from the bucking rule in the field. Neilsen reports that although a 5-inch top was the goal, most bucking was closer to a 6-inch top.

Validation Test #2

Aulerich (1974) reports thinning results from a 35 to 40 year-old Douglas-fir stand on the Oregon State University McDonald Forest. Trees averaged 10 inches dbh and stand volume average 10,500 bf, Scribner, per acre. On the 95 acres that were thinned, 35 percent to 55 percent of the volume was removed. The diameter distribution from the study is shown in Figure 8.



Source: Aulerich, 1974

Figure 8. Diameter Distribution For Validation Test #2

A total of 8,800 trees were cut, an average of 93 trees per acre, producing 10,600 logs, or 112 logs per acre.

Yarding during the thinning was done by tractor and skyline. The skyline yarder was a modified Schield-Bantam. Spans averaged

600 feet and no intermediate supports were used. Chokers, 12-feet long, were used on sliders but travel of the sliders was limited to approximately five feet.

Bucking rules were to buck for poles and one-fifth of the volume extracted was in pole lengths of 28 to 45 feet. The remaining volume was predominantly in No. 3 and No. 4 Sawlogs.

Actual number of trees per diameter class were used in the YARDALL simulation. On a per acre basis, the percentages of trees removed by diameter class are shown in Table 9.

The results of the simulated yarding of 253 trees, producing 364 logs, are summarized in Table 10. Choker length during the simulation was assumed to be 17 feet. This value was used to approximate the modified slider arrangement used in the field. The standard error of the average logs per turn from the simulation was 0.094.

TABLE 9. PERCENTAGE OF STEMS REMOVED PER ACRE BY DIAMETER CLASS FROM AULERICH (1974).

Midpoint of Diameter Class	Percentage of Total Trees Removed
8	18%
9	22%
10	17%
11	17%
12	12%
13	6%
14	4%
15	3%
16	1%

TABLE 10. COMPARISON OF YARDER PRODUCTION FROM AULERICH (1974) AND YARDALL SIMULATION.

	Aulerich	YARDALL	Error
Volume removed per acre	1368 cf	1299 cf	-5.0%
Logs per turn	2.53	2.62	+3.6%
Volume per turn	31.1 cf	25.7 cf	-17.4%

IV. APPLICATION OF THE HARVESTING MODEL

Description of Equipment

Harvesting simulations were run for two sizes of skyline yarders: a medium size yarder, approximately 300 H.P., and a small yarder, approximately 70 H.P. The medium yarder is typical of common yarders thinning in the Douglas-fir region including the Madill 071 and the MAC Thunderbird. The small yarder, the Igland-Jones Trailer Alp, although not common in North America, is of a type common in plantations elsewhere. Both yarders generally operate as standing skylines, are able to yard up to 2000 feet slope distance, and can pass intermediate supports. Cycle time equations for the medium sized yarder, referred to as the "large yarder" were drawn from Dykstra's (1976a) analysis of a Skagit GT-3 from observations taken in Douglas-fir thinnings on the Mt. Hood National Forest. Although the GT-3 is a running skyline machine, it is similar in horsepower to the Madill 071 and MAC Thunderbird and uses a similar type of skyline carriage. The cycle time equation for the Trailer Alp, referred to as the "small" yarder, was drawn from Neilsen's (1977) analysis of data from thinnings by the Trailer Alp on the Oregon State University school forest.

Input data assumed typical for the large and small yarder operation in the Douglas-fir region are presented in Table 11. The number of chokers is larger than what is commonly observed in order to reflect the practice of "bonusing" or hooking more than one log with one choker if the opportunity exists. Choker lengths in Table 11 are effective lengths, that is, the total length of choker less the amount required to wrap the log.

TABLE 11. YARDER SPECIFICATIONS USED FOR SIMULATION

	Small Yarder	Large Yarder
Set-up time	1 hr/300 ft	1 hr/300 ft
Cost, $/hr	$39/$69.60	$143.25
Maximum Payload, lbs	3600	10,000
Crew Size	2/4	6
No. of Chokers	4	5
Choker Length	8	12

Longer effective choker lengths on the medium yarder reflect generally higher skyline heights permitting longer lengths while maintaining partial log suspension.

The set-up time includes time to rig and unrig a skyline corridor. Rigging time assumes that an intermediate support is required each 300 feet for the small yarder and each 600 feet for the larger yarder. All skyline roads are assumed to be parallel settings.

A detailed list of the owning and operating costs are in Appendix XI . The two cost per hour figures for the small yarder reflect the range in operating conditions which will occur in this

TABLE 12 . CYCLE TIME REGRESSION EQUATIONS USED FOR SIMULATION

Large Yarder (Dykstra, 1976a)

CT = 2.39219	+ 0.0019426	(CHORDSLOPE)
	- 0.11478	(RIGGERS)
	+ 0.00211976	(SYDIST)
	+ 0.0118565	(LDIST)
	+ 0.030463	(LOGS)
	+ 0.000863135	(BFVOL)
	- 0.000397724	(BFVOL/LOG)

Small Yarder (Neilsen, 1977)

CT = 1.6932	+ 0.005119	(SYDIST)
	+ 0.025653	(LDIST)
	+ 0.2783	(LOGS)

where:

CHORDSLOPE	=	chordslope of skyline, percent
RIGGERS	=	number of men in rigging crew
SYDIST	=	skyline distance, feet
LDIST	=	lateral distance, feet
LOGS	=	logs/turn
BFVOL 1/	=	gross board foot volume of log, Scribner

1/ For the cycle time estimates one board foot was assumed to equal 10 pounds.

study. For conditions when the average yarding distance is less than 150 feet 7/, a two-man crew is used as manual slackpulling forces are low and rigging effort will require at most one intermediate support adjacent to the landing. The short yarding distance will also satisfy the safety requirement that "no worker shall be put into a position such that he is so isolated that he is not within the visual or audible contact with another person." (Oregon Safety Code 1975) The three-man crew reflects general yarding conditions when volume per landing are less than 2000 cubic feet and a swing machine is not required. Four-man crews include the cost of an extra man with a small rubber tired skidder when log landing room at the yarder is insufficient and the logs must be swung to a storage area for later rehandling.

As discussed previously, bucking rules for the simulations were to buck to 40-foot lengths maximum, 12-foot minimum, and a 4-inch top. Cost per hour for felling and bucking was $14.60/hr. Loading costs have been discussed.

Total harvesting costs were calculated by summing the felling, bucking, yarding, and loading costs by the following formula:

$$TC = \frac{F_T * C_F}{V_R} + \frac{R_T * C_R}{V_R} + \frac{CT * (C_Y/60)}{(EH)(V_T)} + \frac{L_T * C_L}{V_R}$$

7/ Standard external yarding distance in this study was 1200-ft (600-ft average); shorter distances are also considered in Chapter VI.

where,

TC = Stump to Truck cost of harvesting, \$/Mcf

F_T = Total time to fell and buck trees to be removed, hr

C_F = Cost per hour to fell and buck trees, \$/hr

C_R = Owning and operating cost of the yarder during rigging, \$/hr 8/

R_T = Combined rigging and unrigging time for the skyline, hr

CT = Cycle time for the average yarding distance on the unit, min.

C_Y = Owning and operating cost of the yarder during yarding, \$/hr 8/

V_R = Volume removed from the unit, Mcf

V_T = Volume per turn, Mcf

EH = Effective hour for the yarding operation, decimal

L_T = Loading time for the unit, hr

C_L = Owning and operating cost of the loader, \$/hr

Data Analysis

Harvesting was simulated in natural unthinned stands of 7 inches to 22 inches mean stand diameter for the large yarder and the simulations repeated for mean stand diameters of 6 inches to 15 inches

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8/ In this study the average owning and operating cost for rigging and yarding are assumed to be the same.

for the small yarder for a rectangular skyline unit 1200-feet in length. The data were analyzed by standard regression analysis and a power curve model was chosen as the best overall fit. The power curve relationship is expresed as:

$$TC = A * V_R^{(B)}$$

where

TC = Stump to truck cost of harvest, \$/Mcf

V_R = Merchantable volume removed per acre, cf

A, B = Constants determined from least squares analysis

Coefficients for the harvesting cost relationships are listed in Tables 13-15 along with the number of sample points from the simulation and the R-squared values from the least squares analysis. A summary plot of harvest cost as a function of merchantable volume removed and mean stand diameter for the large yarder is shown in Figure 9. Harvest cost relationships for the small yarder as a function of diameter and volume for three and four-man crews are illustrated in Figure 10. Discontinuity in the cost curves occur when log storage area on the landing is exceeded and a rubber-tired skidder must be added. Plots of individual power curves showing the output data from simulation and best fit power curve by machine and mean stand diameter are in Appendix V and VI. The use of the power curve model implies that the ratio of the percentage change in harvesting cost divided by the percentage change in volume is constant for a given mean stand diameter over the range of simulation. 9/ Fitting the power curve to yarding and loading costs given by Conway (1976) yields R-squared values of 0.98 or better.

Pieces per turn were found to be a function of volume per acre removed for a given mean stand diameter and equipment characteristics. Predictive equations for pieces per turn as a function of log density and equipment capability were not formulated in this study since total harvest cost was the dependent variable of interest.

For the range of log size, spatial log densities, and topography in this study, skyline payload did not appear to be a serious constraint. Simulation of the final harvest of a 160-year old natural stand by the large yarder produced an average payload of 5100 pounds or 0.51 of the maximum loading with an average of 2.76 logs per load. Simulation of the final harvest of a 90-year old natural stand by the small yarder produced an average payload of 1900 pounds or 0.52 of the allowable payload with an average number of logs per load of 1.96. Sensitivity of cost to payload was not pursued in this analysis and further tradeoffs between rigging times and payload were not evaluated.

9/ The proof is as follows:

$$TC = A\ V^{(B)}\ ;\quad \frac{d\ TC}{dV} = A\ B\ V^{(B-1)}\ ;\quad \frac{V}{TC} \cdot \frac{d\ TC}{dV} = \frac{V}{TC} \cdot A\ B\ V^{(B-1)}$$

therefore $\frac{V}{TC} \cdot \frac{d\ TC}{dV} = B$; and rearranging, $\frac{d\ TC}{TC} = B \cdot \frac{dV}{V}$

Transformation of Data

All simulations assumed a rectangular unit, 1200 feet in length. Direct transformations of the results of the 1200-foot yarding simulations can be used to derive harvesting cost relationships for other yarding distances, operating costs, rigging times, or effective hours without repeating the simulations. This section will present the transformation equation used for converting the simulation results for the 1200-foot skyline to other skyline distances. Since the fixed cost of rigging, per unit removed, did not vary with skyline length, only changes in variable cost will be considered. The adjusted variable cost for an alternative yarding distance can be expressed as:

$$TC' = TC + \frac{(\Delta CT)\ (C/60)}{(EH)\ (V_T)} \cdot 100$$

where,

- TC' = Adjusted total harvesting cost from the 1200-ft base value, TC, \$/Mcf
- ΔCT = Change in cycle time from 1200-ft base value, min, dependent on changes in average yarding distance and the cycle time regression coefficients
- V_T = Volume per turn from simulation, cf.
- C = Cost per hour of yarding operation, \$/hr.
- EH = Effective hour, decimal.

The transformed cost data are then analyzed by least squares and new coefficients estimated.

If changes in skyline payload or log hooking strategies are made, direct transformations may not be accurate and the simulations may need to be repeated. Two indicators of the need to repeat the simulation for these situations are the magnitudes of:

(1) The ratio of the volume per turn divided by allowable skyline payload, and

(2) the ratio of the average pieces per turn divided by the available number of chokers.

The higher the value of the ratios, the more likely that these variables are constraining production. Relaxing the binding constraint will affect logs per turn, yarding production, and harvesting cost.

Comparison of Large and Small Yarder Costs

The larger yarder was found to be more efficient at larger volume removals and longer yarding distances due to its greater carrying capacity and higher line speeds. The small yarder was more efficient at short yarding distances, particularly when the volume per acre was sufficiently low that all material could be stored in the landing without use of a swing machine. With a 1200-foot skyline, the small yarder was relatively more efficient than the large yarder for removing less than 1000 cubic feet per acre from stands up to 15 inches mean diameter.

The elasticity of stump to truck harvesting cost with respect to volume removed is higher for the larger yarder than for the smaller

TABLE 13. LARGE YARDER POWER CURVE COEFFICIENTS FOR STUMP TO TRUCK HARVESTING COSTS AS A FUNCTION OF MERCHANTABLE VOLUME PER ACRE REMOVED FROM AN UNTHINNED NATURAL STAND WITH A 1200-FT SKYLINE.

$$TC\ (\$/MCF) = A * V^{(B)} \quad \underline{1}/$$

Mean Diameter	A	B	R^2	n 2/	Range 3/
7.63	16502.3	-.3789	0.98	11	295-4505
9.20	12022.7	-.3647	0.98	9	598-6466
10.90	9811.6	-.3640	0.99	7	883-7351
12.30	7987.0	-.3516	0.98	8	1264-8870
13.70	7288.8	-.3516	0.99	7	1381-10009
15.00	6785.2	-.3566	1.00	6	1700-11044
16.20	5911.4	-.3521	0.99	5	2437-12371
17.30	4337.7	-.3249	0.97	6	2921-13181
18.30	4980.8	-.3442	0.99	5	3285-13037
20.30	3913.1	-.3227	0.99	5	2325-14164
21.90	4670.5	-.3457	0.99	5	1485-16358

1/ V is merchantable cubic feet removed per acre.

2/ Number of simulations.

3/ Range in volume per acre removed during simulation, cubic feet.

TABLE 14. SMALL YARDER POWER CURVE COEFFICIENTS FOR STUMP TO TRUCK HARVESTING COSTS AS A FUNCTION OF MERCHANTABLE VOLUME PER ACRE FROM AN UNTHINNED NATURAL STAND WITH A FOUR-MAN CREW AND 1200-FT SKYLINE.

$$TC\ (\$/MCF) = A * V^{(B)} \quad 1/$$

Mean Diameter	A	B	R^2	n 2/	Range 3/
7.63	9490.1	-.2981	0.99	11	290-4394
9.20	8525.3	-.3135	0.99	10	562-6459
10.90	5975.4	-.2948	1.00	7	973-7687
12.30	4710.8	-.2766	0.99	8	1393-9252
13.70	3974.5	-.2651	0.98	7	1358-9454
15.00	3471.7	-.2577	0.98	7	1631-10913

1/ V is merchantable cubic feet removed per acre

2/ Number of simulations

3/ Range in volume per acre removed during simulation, cubic feet

TABLE 15. SMALL YARDER POWER CURVE COEFFICIENTS FOR STUMP TO TRUCK HARVESTING COSTS AS A FUNCTION OF MERCHANTABLE VOLUME PER ACRE FROM AN UNTHINNED NATURAL STAND WITH THREE-MAN CREW AND 1200-FT SKYLINE.

$$TC\ (\$/MCF) = A * V^{(B)} \quad 1/$$

Mean Diameter	A	B	R^2	n 2/	Range 3/
6.14	15456.5	-.3146	0.96	11	269-1601
7.63	5750.0	-.2628	0.97	7	55-1045
9.20	4461.4	-.2591	0.91	7	321-1089
10.90	2896.2	-.2327	0.98	4	745-2067
12.30	2411.3	-.2226	0.98	6	660-2140
13.70	2034.3	-.2091	0.97	5	557-1989
15.00	3103.6	-.2854	0.98	4	365-1995

1/ V is merchantable cubic feet removed per acre.

2/ Number of simulations.

3/ Range in volume per acre removed during simulation, cubic feet.

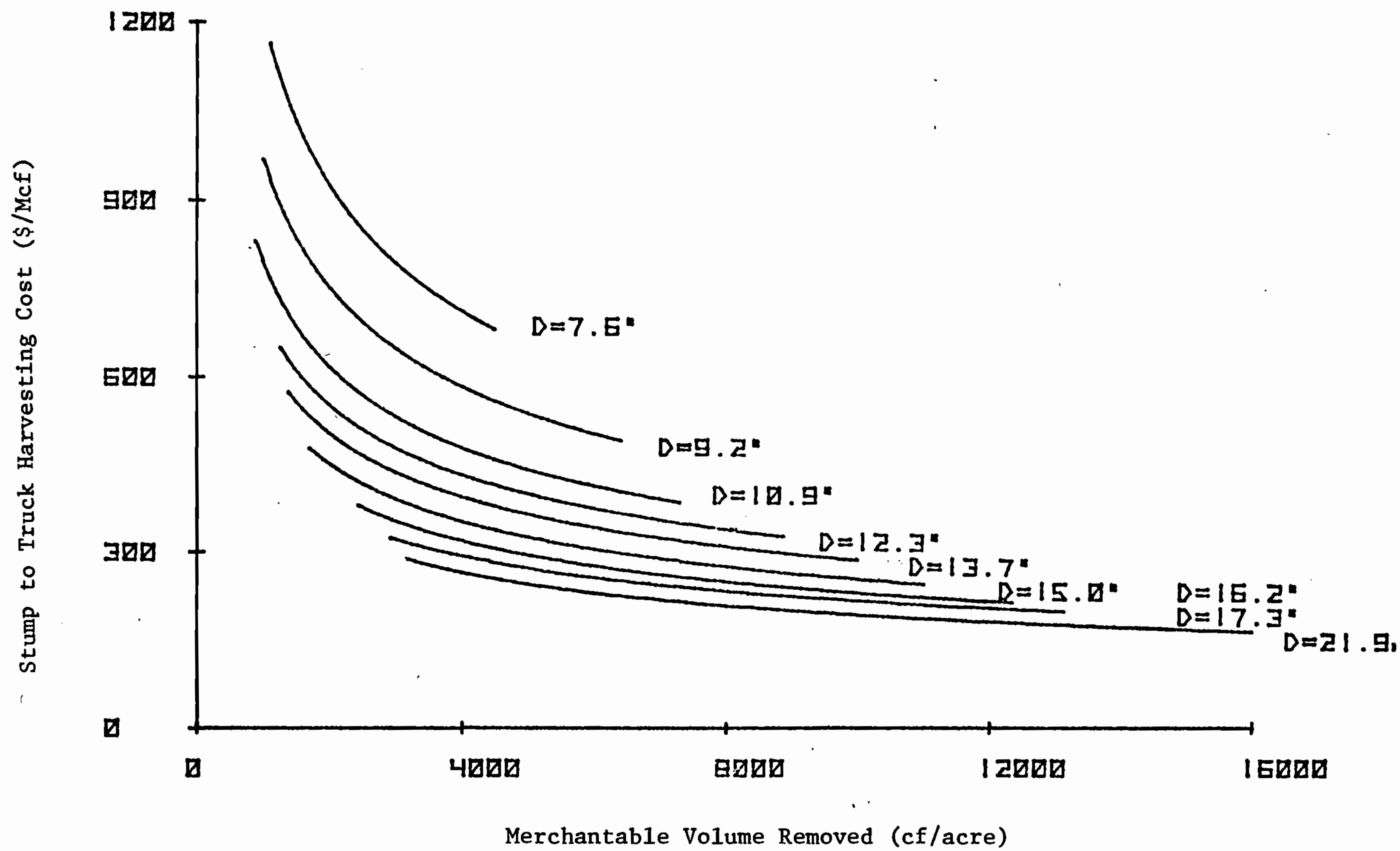


Figure 9. Summary of large yarder harvesting simulations.

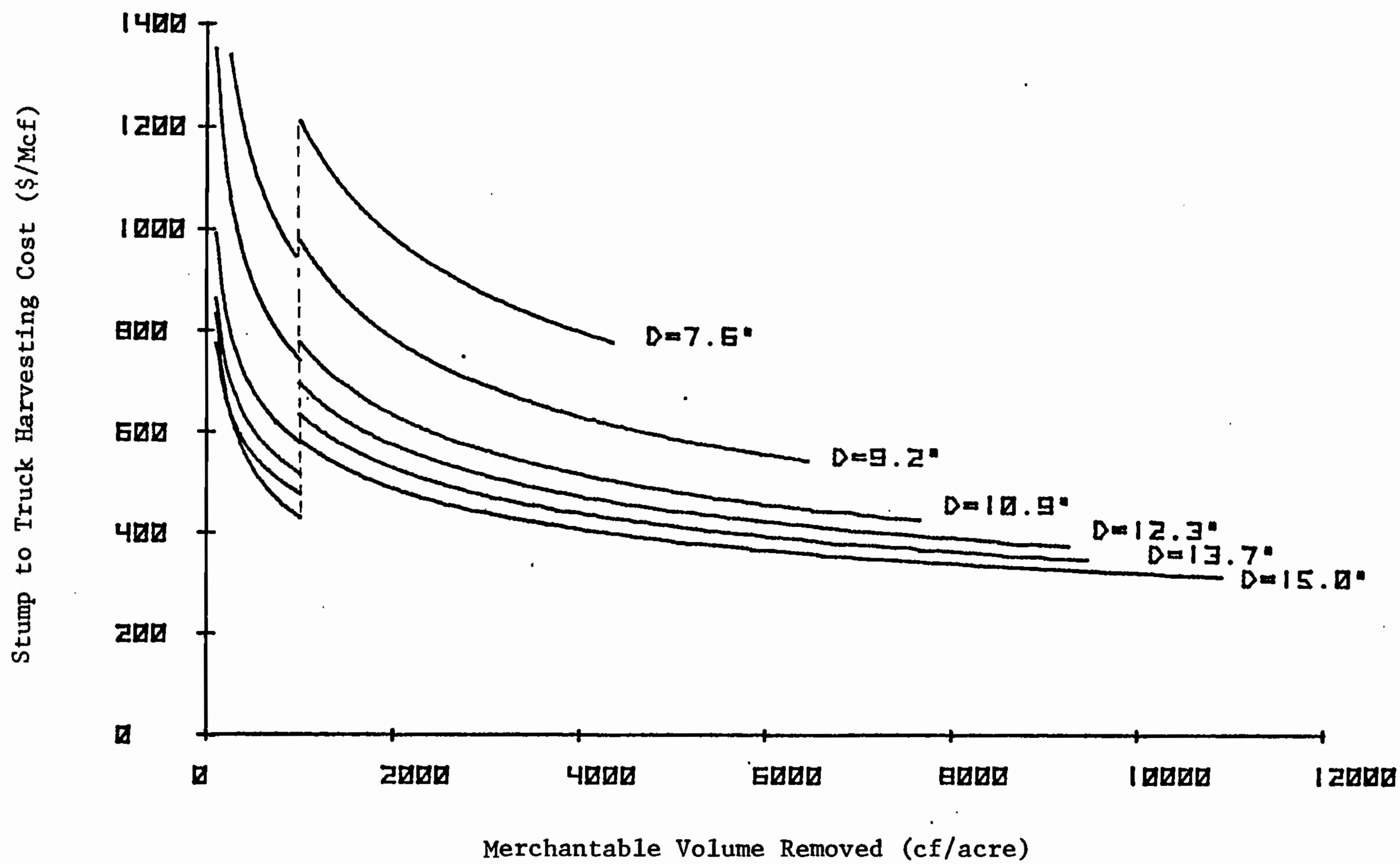


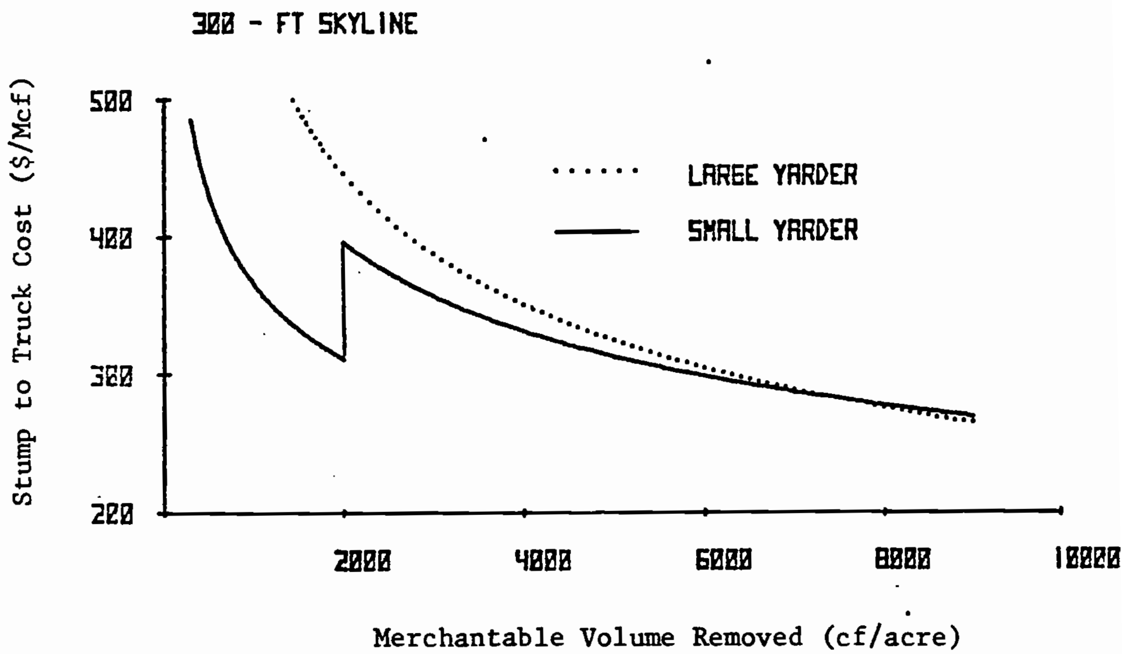
Figure 10. Summary of small yarder harvesting simulations.

yarder for all mean stand diameters under 15 inches due to higher fixed costs of operation. The elasticity is highest at the smaller diameters for both machines and declines as diameter increases.

The relative advantages of the two machines are shown graphically in Figure 11 for yarding in a stand of 12 inches mean diameter. At 1200 feet the breakeven point is about 1000 cubic feet per acre. At 300 feet the breakeven point is approximately 7500 cubic feet per acre. This diagram illustrates that it is not apparent that there is a single "best" machine for either a given diameter material or a given yarding distance. Neither machine dominates over the entire range of conditions which might occur from silvicultural activities.

Sensitivity of Harvest Cost to Variance of the Diameter Distribution

A basic assumption in the harvest model is that the variance of the diameter distribution is known. The relationship between variance and the diameter distribution was derived from analysis of stand tables from Bulletin 201 for natural fully stocked unthinned stands. To obtain an estimate of the sensitivity of harvest cost to changes in diameter variance, four alternative distributions were examined for an unthinned stand 65 years old. By Bulletin 201, the variance of the diameter distribution should be approximately 13 square inches. To bracket this expected value, two normal distributions with mean 11 inches and variances of 5 and 20 square inches were examined. In addition, an exponential distribution with mean



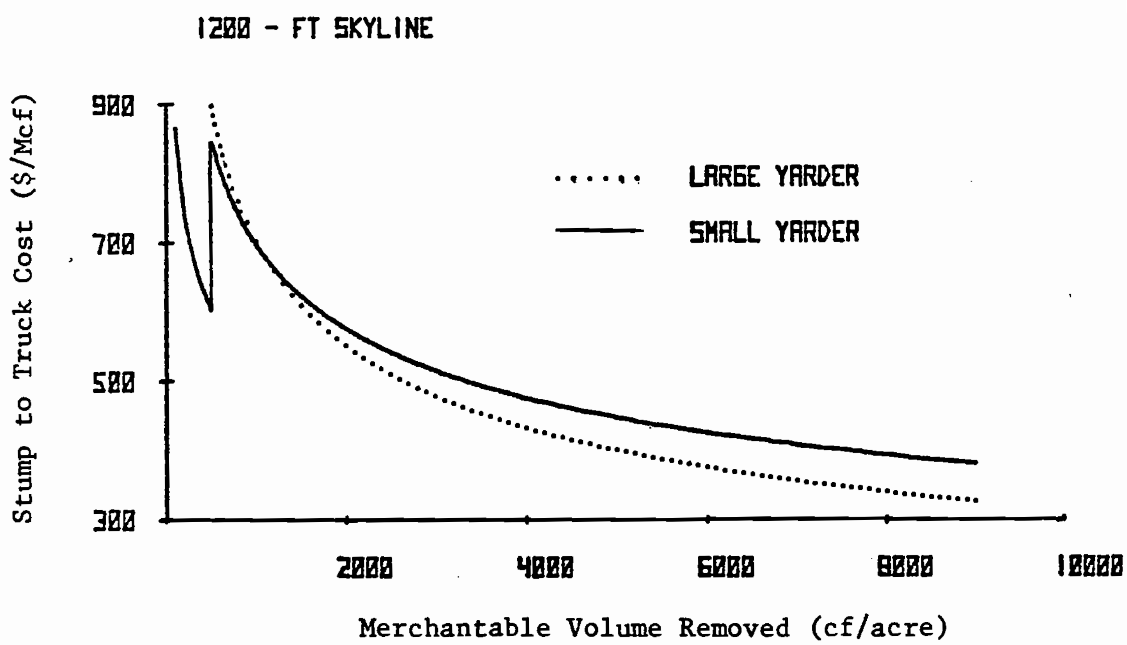


Figure 11. Comparison of breakeven points between yarders for skyline yarding distances of 300 feet and 1200 feet in an unthinned natural stand of 12 inches mean stand diameter.

11 inches and a uniform distribution were also examined. All the distributions were truncated with a minimum diameter of 3.5 inches and a maximum diameter of 19.5 inches.

The distributions are shown in Figure 12. The harvesting costs as a function of merchantable volume to a 5-inch top are shown in Figure 13. The uniform distribution (Figure 13, distribution 1) has the lowest cost per unit removed and the largest stand volume. The normal (11,5) has the highest cost per unit volume removed. The results are consistent with the density functions of Figure 12, as the uniform distribution has the highest proportion of large trees and the normal (11,5) has the lowest proportion.

The maximum difference between the expected distribution, normal (11,13), and the other distributions is approximately 10 percent. For this mean and variance, and the alternatives considered, it can be concluded that the linkage between stand variance and harvest cost may not be too strong. The observation may prove useful in making inferences for thinning regimes with thinning ratios which differ from 1.0.

Figure 14 shows cost relationships for three normal distributions of variance 5, 13, and 20. Maximum deviation of harvest cost from the expected cost for a variance of 13 was less than 6 percent. The apparent low sensitivity of harvest cost to changes in variance for normally distributed diameter distributions makes assumptions in this study concerning distribution variance less critical.

The relatively low sensitivity of harvest cost to change in variance should not be confused with changing the mean diameter of

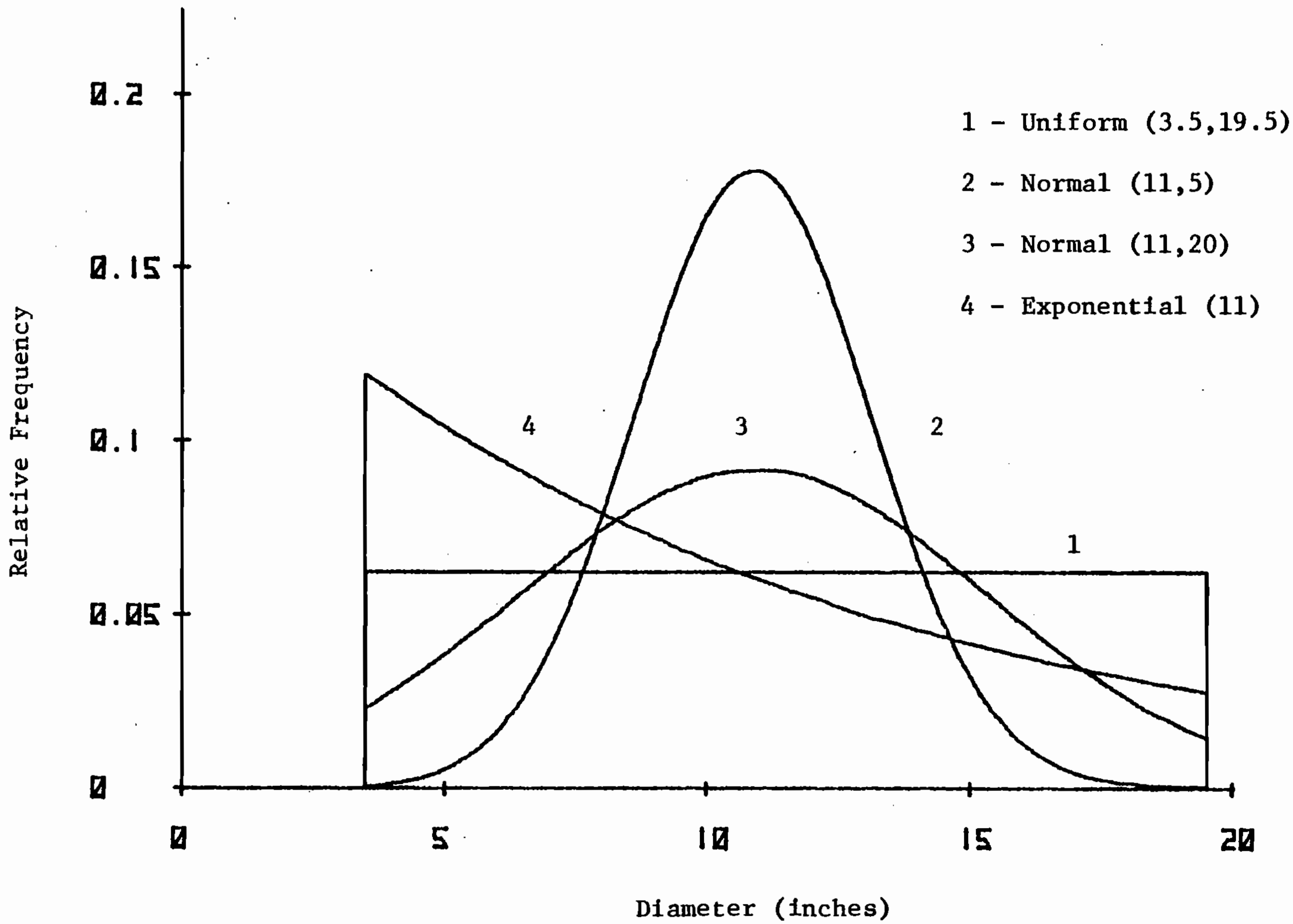


Figure 12. Relative frequencies for four distributions.

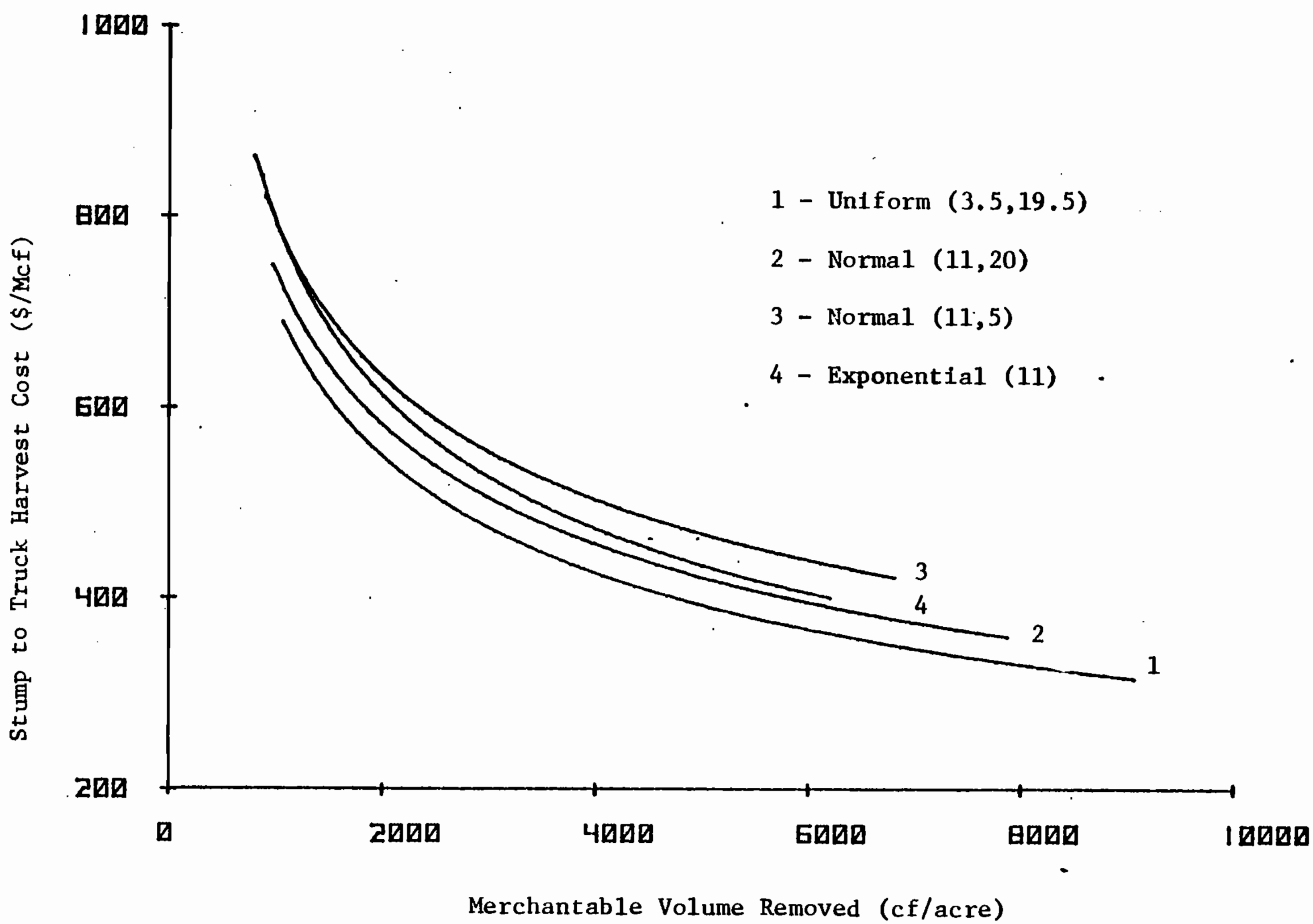


Figure 13. Small yarder harvesting cost as a function of volume per acre for uniform, normal, and exponential diameter distributions removed from a 65-year old unthinned natural stand.

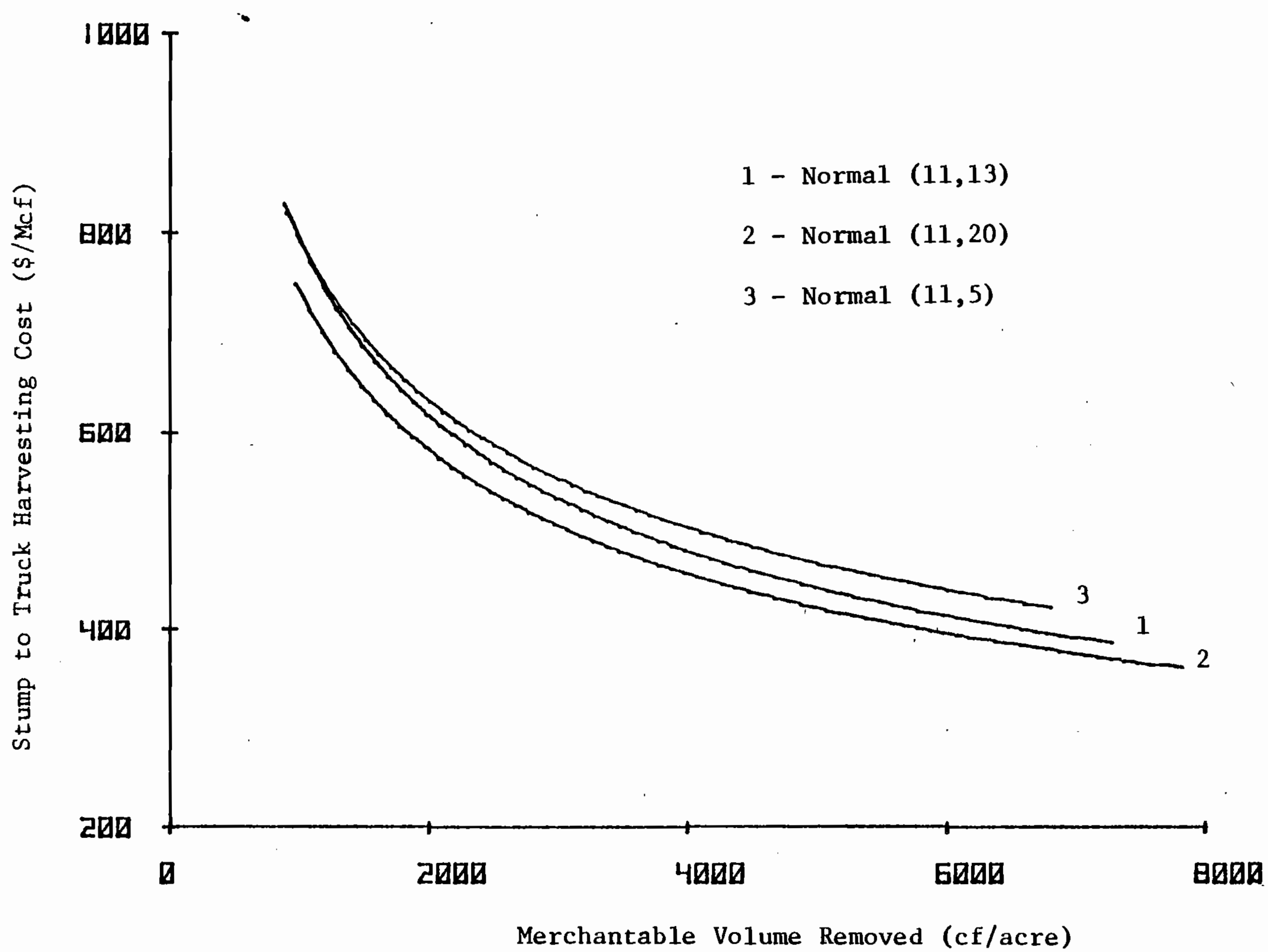


Figure 14. Small yarder harvesting cost as a function of volume per acre for three normal diameter distributions removed from a 65-year old unthinned natural stand.

the trees removed from the stand. Harvesting cost is _extremely_ sensitive to changes in _mean stand diameter_. Figure 15 illustrates harvesting cost changes for increasing the mean diameter of trees removed from natural unthinned stands. Although the variance is increasing as diameter increases from a variance of 5 for the 7-inch diameter to a variance of 20 for the 15-inch diameter, it has already been observed that only a small amount of the change in harvesting cost would be accounted for by this source.

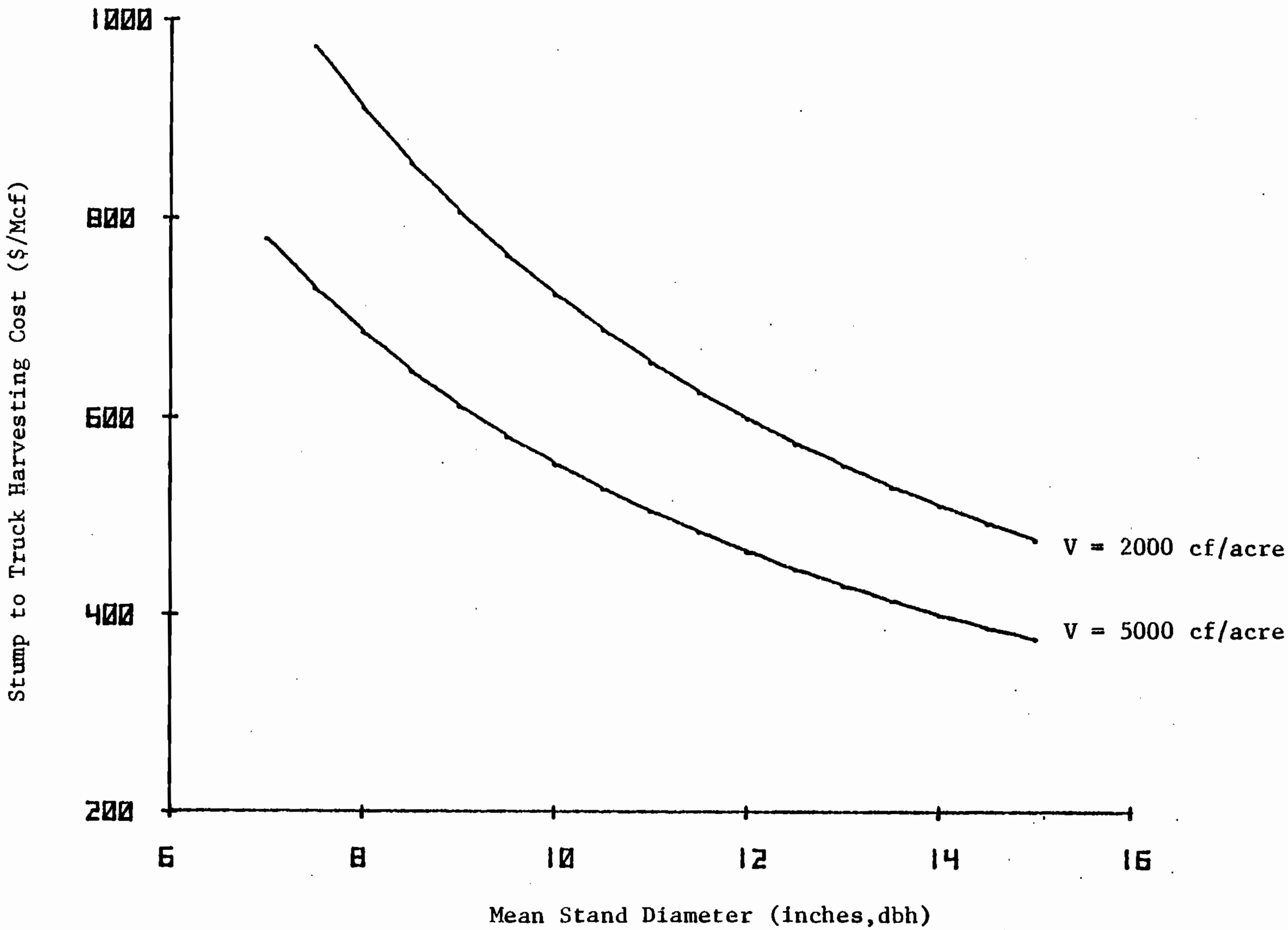


Figure 15. Small yarder harvesting cost as a function of mean stand diameter for volume removals of 2000 and 5000 cubic feet per acre from unthinned natural stands.

Bunch-and-Swing

System Description

An alternative to conventional yarding operations on steeper slopes, which has the potential for reducing yarding costs, is to prebunch logs prior to forwarding the logs to the landing. Logs would be yarded to the skyline corridor and decked along standing trees. The entire unit would be similarly treated and then either the same machine or a larger machine would forward the logs to the landing. Concepts and results from the harvesting simulations using conventional yarding can be used to model the bunch-and-swing operation.

Bunch-and-swing has several advantages over conventional yarding:

1. The lateral yarding element of the yarding cycle is eliminated.
2. Load factors per turn are increased.
3. A simpler machine can be used to forward the logs since slackpulling capability is not required.
4. Crew size for the swinging operation in some cases might be smaller than a regular crew required for slackpulling operations.
5. Since a large machine and crew are not tied up during the lateral yarding activity, it may be possible to laterally yard longer distances than otherwise, thus accumulating

greater volume in each corridor reducing rigging costs.

6. Residual stand damage may be reduced since a less powerful machine, pulling fewer pieces per turn, is being used.

Aulerich (1974) reports that in thinning 40-year old Douglas-fir, that 46 percent of the cycle time was spent in the lateral yarding activity. The disadvantage of prebunching, of course, is the prebunching cost. Using a mobile single drum yarder, Kellogg (1977) reports that prebunching reduced the total cost of the operation approximately 25 percent. In the Kellogg operation, the small single drum yarder was sled-mounted and winched itself along the skyline corridor inside the unit. Average production per hour for the one-man operation was 12 logs per hour for an average yarding distance of 76 feet. An alternative method of prebunching is to leave a small yarder at road side, rig a light skyline at a low height, and either pull slack manually or with a small slackpulling carriage, pull logs to the corridor.

The bunch-and-swing model in this study uses the latter approach. The small yarder is used to bunch the logs and the larger yarder is used to forward the logs after bunching has been completed. The cycle time equations for the small and large yarder in conventional yarding were used for the bunch-and-swing model with a zero outhaul distance for the small yarder and a zero lateral distance for the large yarder. A three-man crew was used for the prebunching operation and a six-man crew, including loader operator, was used for the forwarding operation.

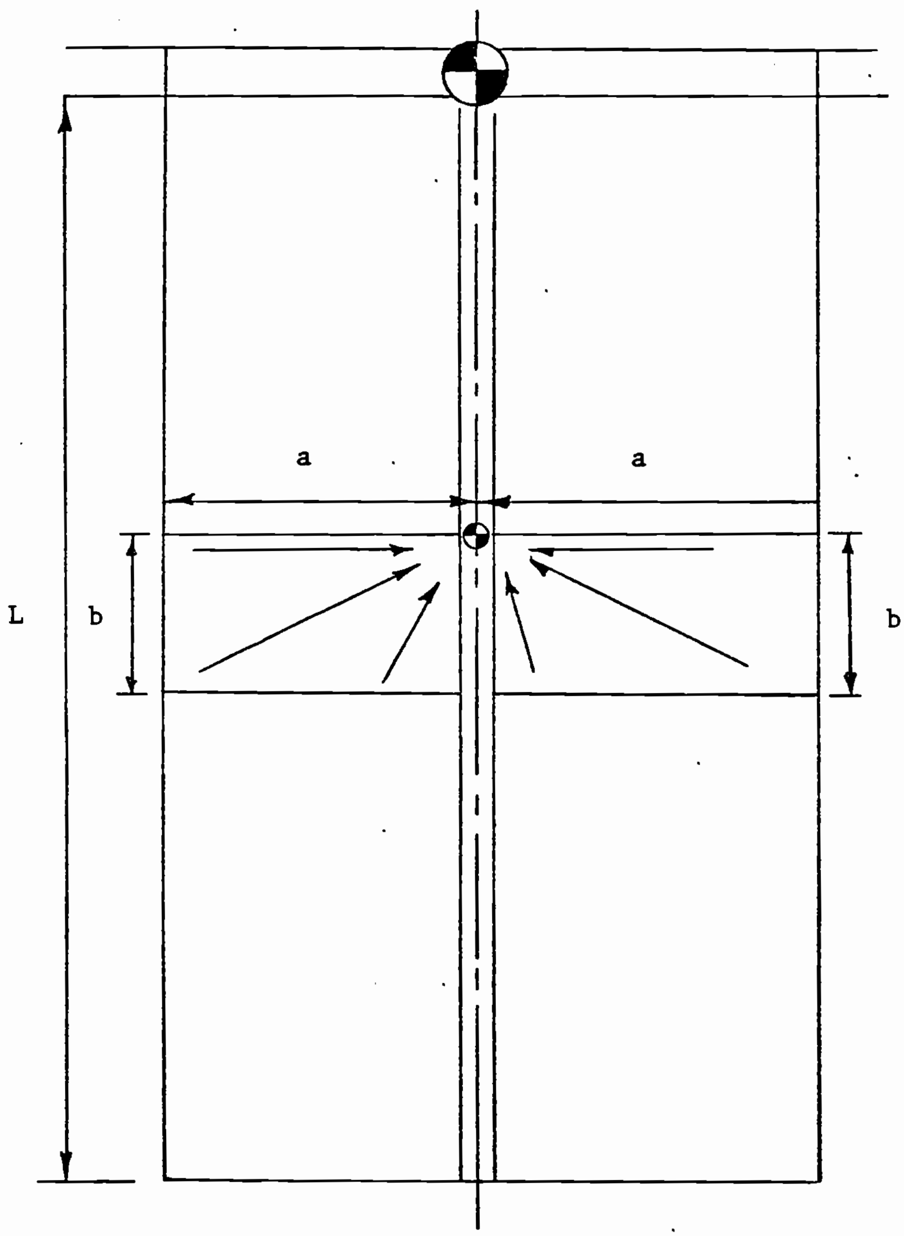


Figure 16. Typical rectangular prebunch setting.

Model Formulation

Information for average log size for the bunch-and-swing model was derived from the conventional small yarder simulation studies by regressing log size against mean stand diameter. A linear model was used to provide the following relationship,

$$\text{Average Log Size (cf)} = -10.23 + (2.092)(\text{Mean Stand Diameter,in})$$

with an R^2 of 0.92 with six observations. The average cost of pre-bunching is given by the relationship

$$\text{Bunching Cost (\$/Mcf)} = \frac{(C_1)(R_1)}{V_L} + \frac{(C_1)(R_2)}{V_S} + \frac{(CT_1)(C_1/60)}{(EH)(V_T)}$$

where,

C_1 = Owning and operating cost of the prebunching operation, \$/hr.

R_1 = Rigging time required to set up the prebunching yarder, hr.

R_2 = Rigging time required to change bunching locations, hr.

V_L = Volume per landing, Mcf.

V_S = Volume per prebunching setup.

CT_1 = Cycle time for prebunching, min.

EH = Effective hour, decimal.

V_T = Volume per turn, Mcf.

The cycle time equation is of the same general form as for the small yarder,

$$CT_1 = k_o + k_1 D_1 + k_2 D_2 + k_3 N$$

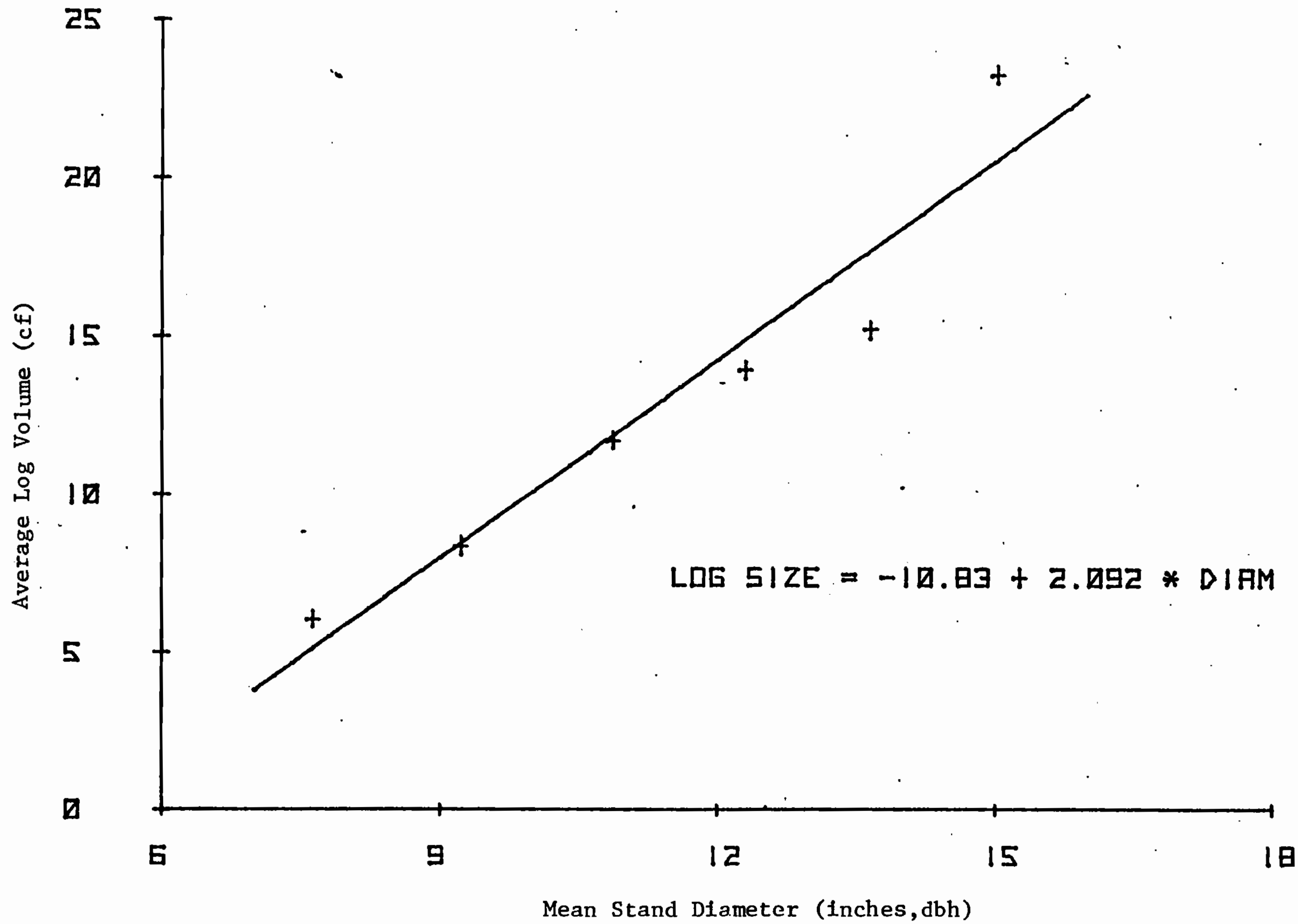


Figure 17. Log size as a function of mean stand diameter from the small yarder harvesting simulations.

where,

k_o = Unexplained variation from the least squares analysis.

k_1 = Marginal time per unit outhaul

k_2 = Marginal time per unit lateral distance.

k_3 = Marginal time per additional log.

The average outhaul distance, D_1, is set to zero and the average lateral distance, D_2, is calculated using the formulation by Peters (1978) and the geometry in Figure 16,

$$D_2 = 1/6\ \{2d + (a^2/b)\ \ln\ ((b+d)/a) + (b^2/a)\ \ln\ ((a+d)/b)\}$$

where, $d = (a^2 + b^2)^{\frac{1}{2}}$.

The total cost of the yarding operation becomes the <u>sum</u> of the bunching and the swinging costs,

$$C_{tot} = \underbrace{\frac{(C_o)(R_o)}{V_L} + \frac{(CT_o)(C_o/60)}{(EH_o)(V_{To})}}_{\text{Swinging}} + \underbrace{\frac{(C_1)(R_1)}{V_L} + \frac{(C_1)(R_2)}{V_S} + \frac{(CT_1)(C_1/60)}{(EH_1)(V_{T1})}}_{\text{Bunching}}$$

where, the variables are defined as previously. The volume per turn forwarded to the landing, V_{To}, is only indirectly related to the log density after felling and bucking. Prebunching setting dimensions (a,b) now determine the logs available for forwarding. Holding the setting width, a, constant at 100 feet to reduce hangup potential, the cost minimization problem to determine the optimum setting depth, b, can be expressed as

$$\text{Minimize } C_{tot}\ (b)$$

subject to

$$V_{To} \leq V_S$$

$$b \leq L$$

$$V_{To},\ b \geq 0$$

The total cost function is highly nonlinear. Since only one parameter, b, is variable in this simple formulation, visual inspection of a graph of the function is an efficient method for determining the setting depth which minimizes total yarding cost. Figure 18 shows a plot of the effect of setting depth on yarding cost for various logs per turn in the prebunching operation in an unthinned 60 year-old stand removing 2000 cubic feet per acre. From previous simulation results with the small yarder, 1.6 logs per turn would be expected. Minimum yarding cost occurs between 30 and 50 feet setting depth by inspection. The effect of removing other volumes per acre on optimum setting depth is shown in Figure 19. At lower volumes per acre the optimum setting depth is larger than at higher volumes as a larger area is necessary to gather the same volume of logs. The effect of skyline capacity for the forwarding operation is shown in Figure 20. Yarding cost decreases sharply until a capacity of 6000 pounds is reached. After this level costs decrease slowly. A similar relationship is shown between volume removed per acre and total yarding cost; cost decreases sharply until 3000 cubic feet per acre are removed, and then decreases slowly. Bunch-and-swing yarding costs are compared to conventional costs in a thinning a 60 year-old stand in Figure 22. In this example, bunch-and-swing costs are consistently lower than conventional costs.

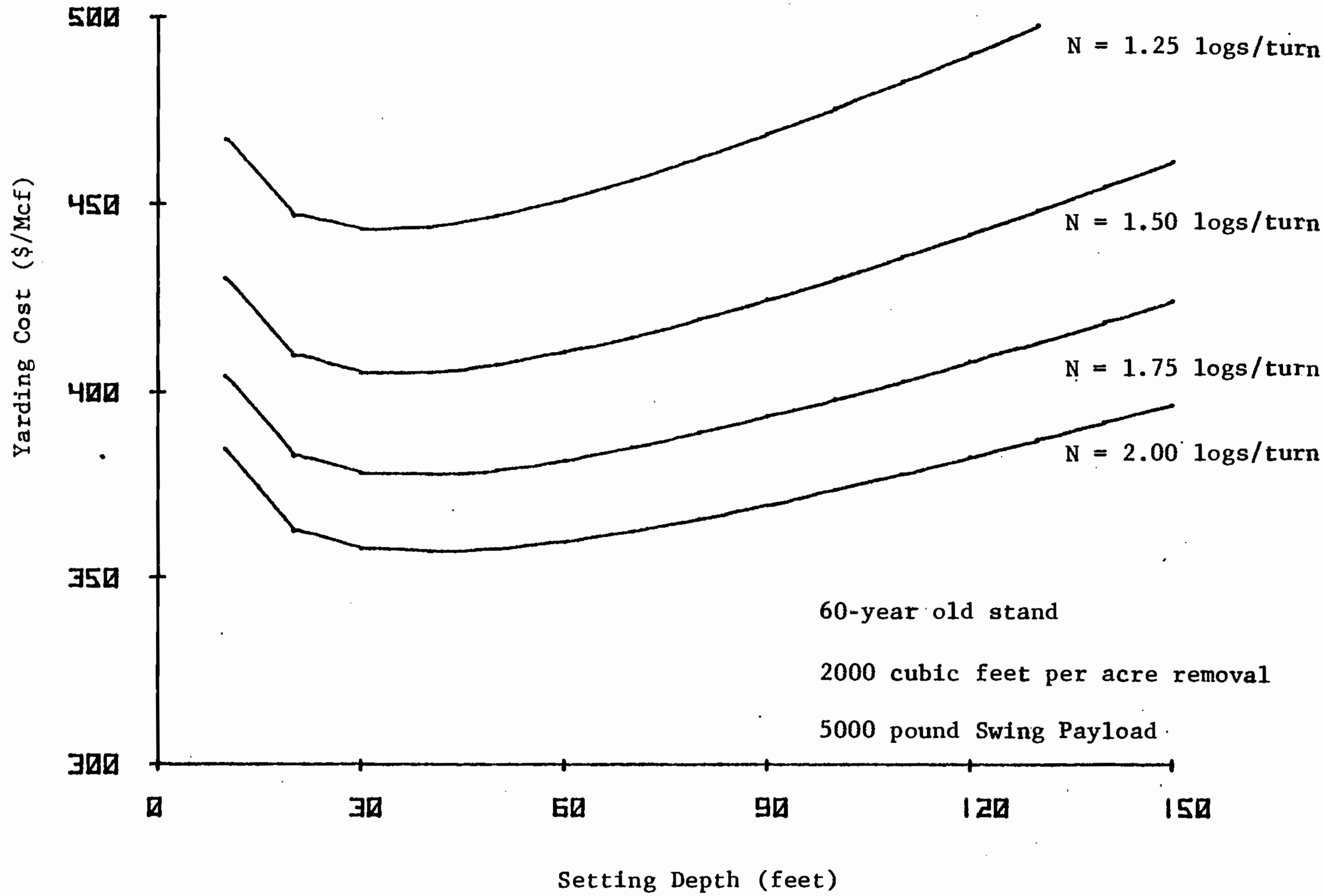


Figure 18. Bunch-and-swing yarding cost as a function of logs per turn and setting depth.

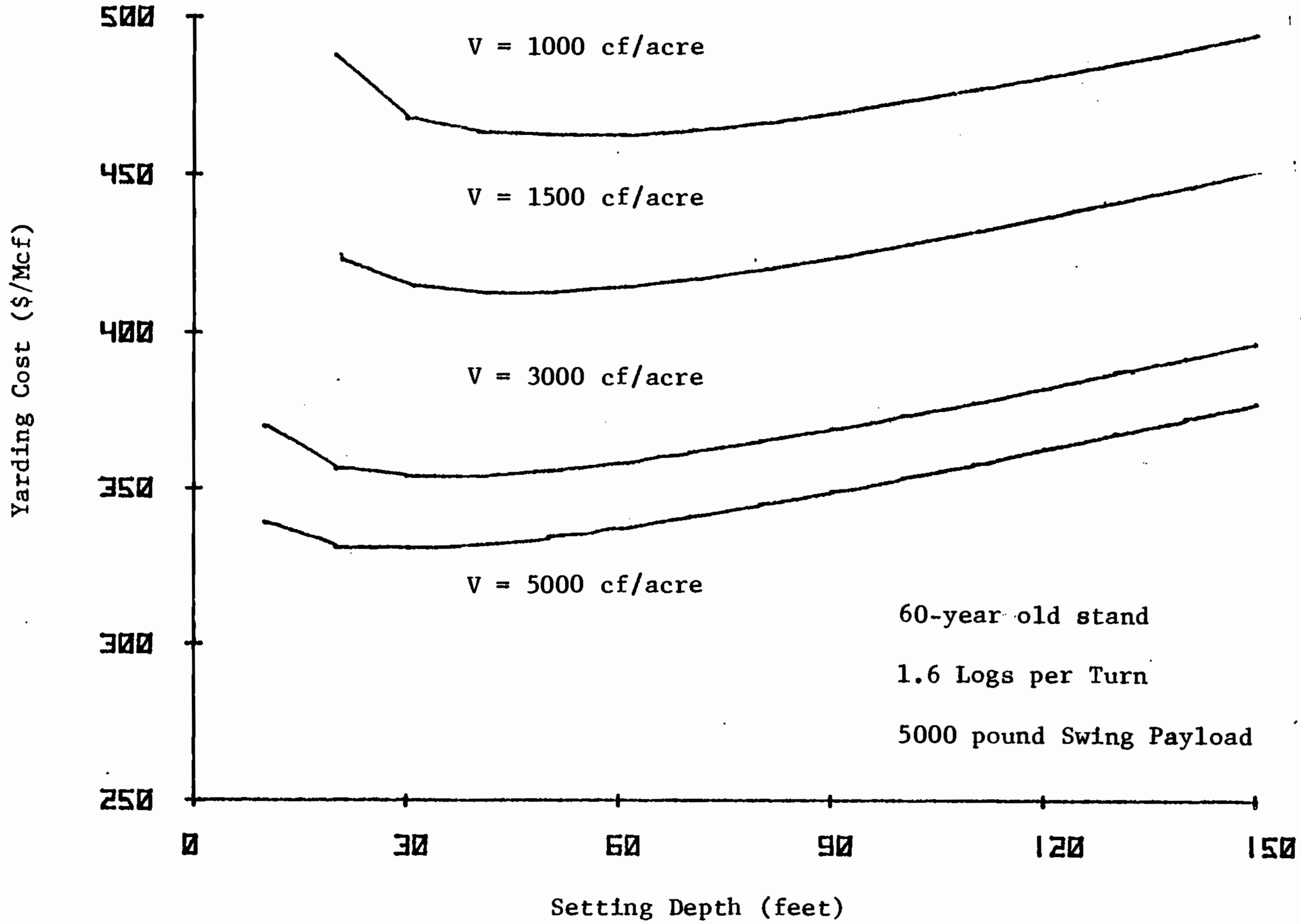


Figure 19. Bunch-and-swing cost as a function of volume per acre removed and setting depth.

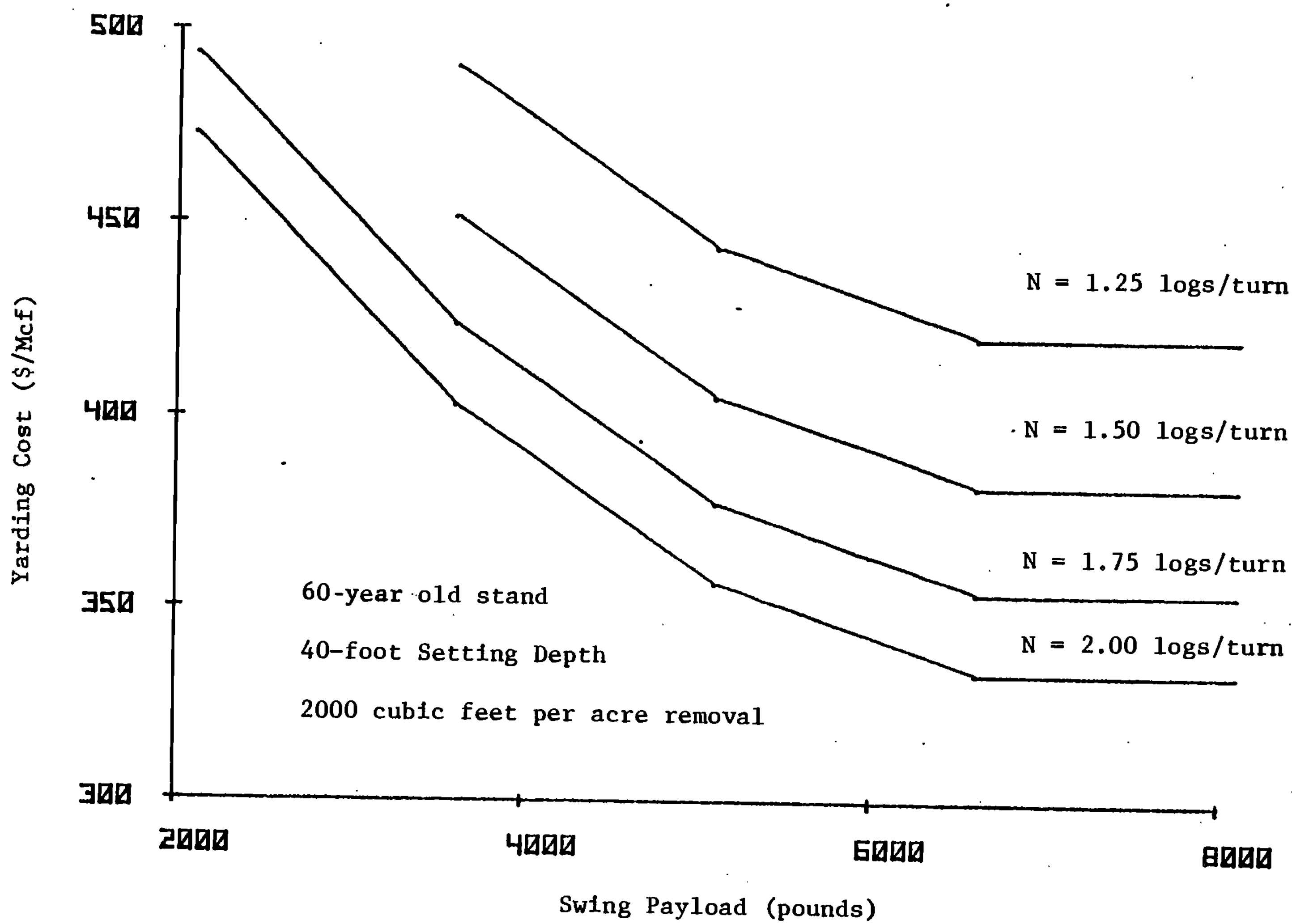


Figure 20. Bunch-and-swing yarding cost as a function of logs per turn and swing payload.

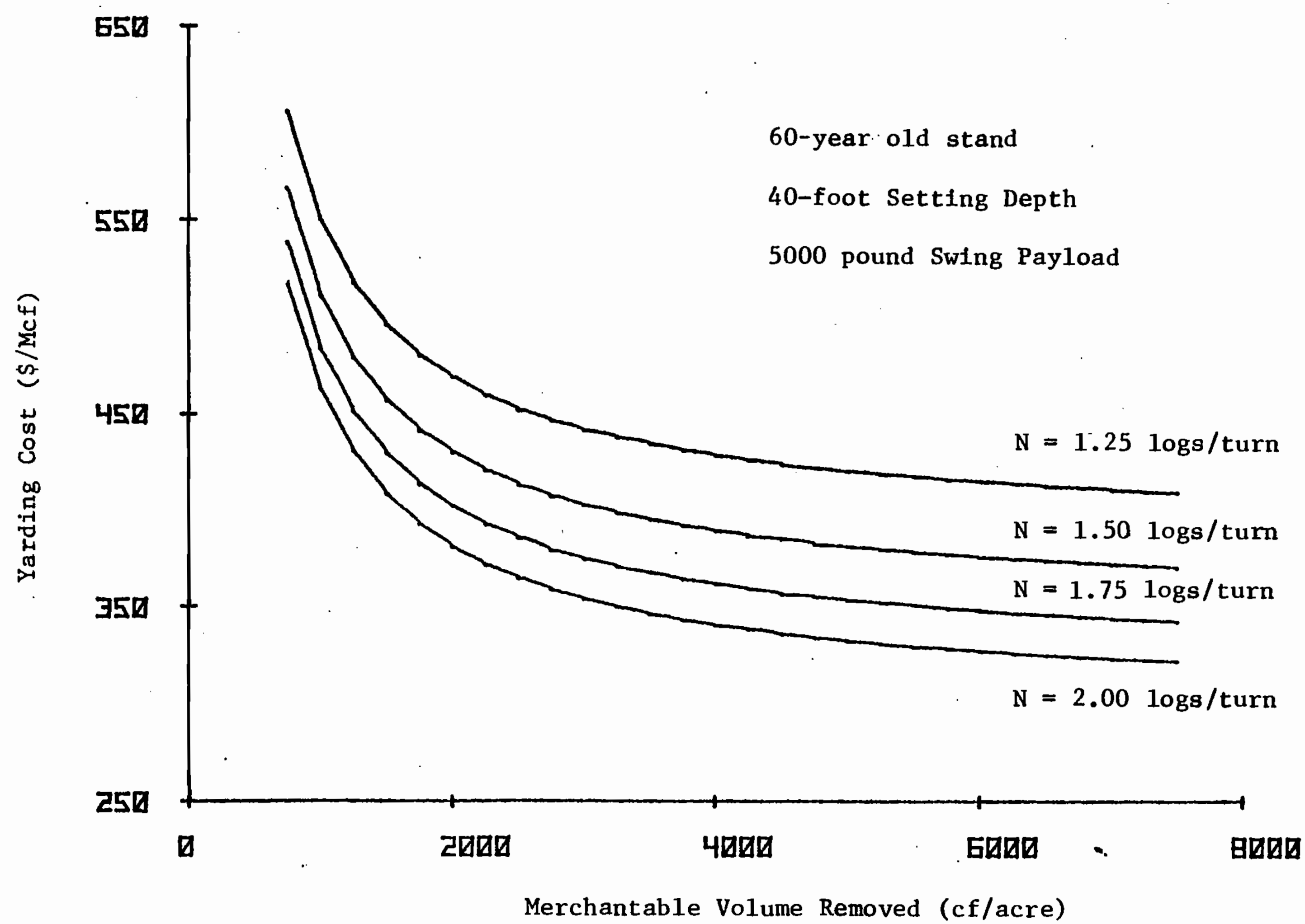


Figure 21. Bunch-and-swing yarding cost as a function of logs per turn and volume per acre removed.

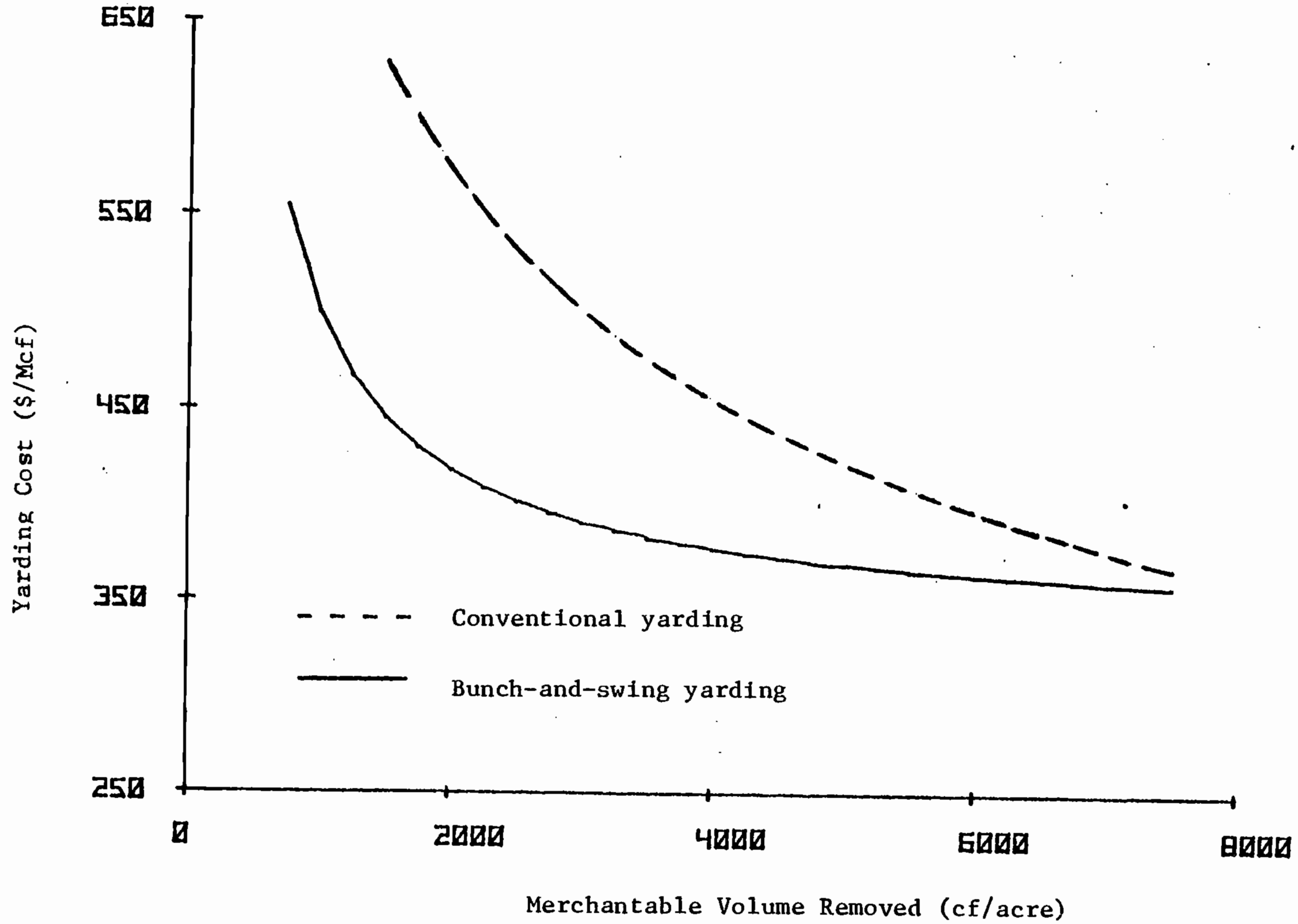


Figure 22. Bunch-and-Swing and small yarder conventional harvesting costs in a 60-year old unthinned natural stand.

The setting geometry for the bunch-and-swing model can be modified from the rectangular model, Figure 16, to a parallelogram, Figure 24, to more closely conform to field practice. Peters (1978) provides the generalized results for the average yarding distance, D_2, of a parallelogram by dividing it into two triangles (Figure 23) such that

$$D_2 = (d_1 A_1 + d_2 A_2)/(A_1 + A_2) = (d_1 + d_2)/2$$

where A_i is the area of triangle i, and

$$d_i = \left(\frac{r_1+r_2}{6r_3^2}\right) [r_3^2 + (r_1-r_2)^2] + \frac{[r_3^2 - (r_1-r_2)^2][(r_1+r_2)^2 - r_3^2]}{12\, r_3^3} \ln \left[\frac{r_1+r_2+r_3}{r_1+r_2-r_3}\right]$$

where, r_1 and r_2 are adjacent sides and r_3 is the opposite side.

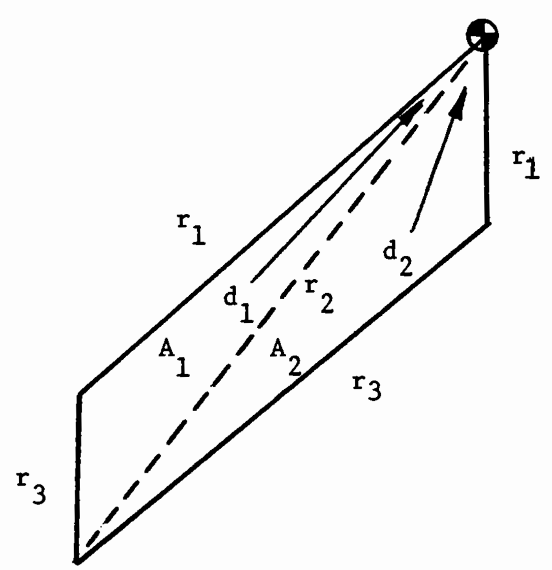


Figure 23. Nomenclature for parallelogram.

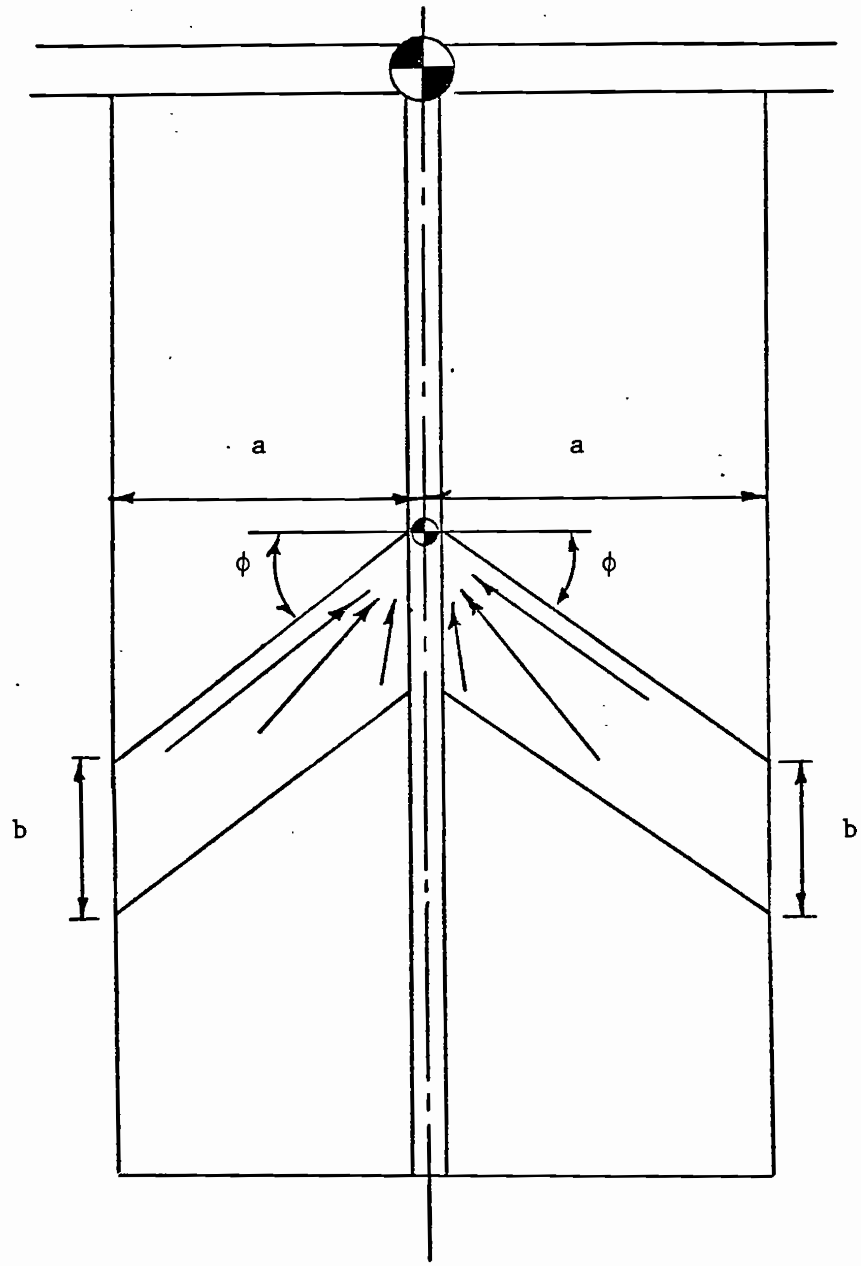


Figure 24. Typical non-rectangular prebunch setting.

The r_i can be expressed in terms of the setting geometry (a,b) of Figure 24 by the relationships for triangle A_1: $r_1=a/\cos\phi$ $r_2=[a^2+(b+a/\tan\phi)^2]^{\frac{1}{2}}$, $r_3=b$; and for triangle A_2: $r_1=b$, r_2 as before, $r_3=a/\cos\phi$.

Strategies combining both conventional yarding with bunch-and-swing exist but were not considered during optimization. Logs lying within the breakeven distance from road side could more economically be brought directly to the landing in a single operation rather than bunched and rehandled.

V. DETERMINATION OF OPTIMAL MANAGEMENT REGIME

Literature Review

Early approaches and some recent practitioners have used brute force trial and error methods or some form of complete enumeration to choose among management alternatives. Recent applications in this manner include work by Hardie (1977) and Reukema and Bruce (1977). Hardie presents thinning regimes derived from a complex biometric model. The optimization procedure was complete enumeration of a highly constrained set of alternatives. Reukema and Bruce present results for thinning Douglas-fir using the DFIT model by exhaustive simulation.

In the late 1950's and early 1960's researchers used marginal analysis including applications by Deurr (1960), USDA Forest Service (1963), Deurr and Christensen (1964) and Chappelle and Nelson (1964). Recent applications of marginal analysis in the Douglas-fir Region include Buongiorno and Teeguarden (1973).

In the 1960's interest in mathematical programming applications in forestry prompted a number of researchers to experiment with dynamic programming including Amidon and Akin (1968), Schreuder (1968, 1971), and Risvand (1969). Recently Brodie, Adams, and Kao (1978) and Brodie and Kao (1978) have used two and three descriptor dynamic programming models to consider optimal thinning regimes for Douglas-fir.

Other approaches have been attempted. Naslund (1969) formulated the thinning problem in a control theoretic framework using both continuous stocking and continuous time, but presented no solution. Later attempts at the control theoretic approach are reported by Schreuder (1971) and Anderson (1976). Pelz (1977) used inventory theory and duplicated the results of Chappelle and Nelson.

Selection of Optimization Method

Dynamic programming was chosen over other optimization methods for several reasons:

1. The dynamic programming algorithm can overcome deficiencies in marginal analysis such as the inability to easily account for precommercial opportunities and the interdependence of harvest costs and volume removals.
2. Dynamic programming uses a simple computation procedure, easily adaptable to highly nonlinear functions. Approaches such as the continuous state control theoretic formulation use complex mathematics for which solutions can be quite difficult.
3. Dynamic programming offers an efficient method of generating and evaluating the immense number of alternatives that exist within the feasible thinning-rotation set.
4. The recent work of Brodie and Kao (1978) using a three descriptor model presents a framework which with only minor revisions can be extended to choose among alternatives in mountainous terrain.

Forward Versus Backward Recursion

Dynamic programming formulations are generally characterized as being either forward or backward recursions. Both approaches have merits depending on the problem to be solved. The strength of the forward recursion is that the optimal paths from the initial state and stage to all stages are determined in a single pass through the network. In the backwards recursion, the optimal path from any state-stage combination to the final stage is determined by one pass through the network. A separate pass is required for each candidate terminal stage to determine the stage at which the objective function has the highest value. The strength of the backward recursion is that if one deviates from the optimal path, supplementary output from the backward solution automatically provides the new optimal path for all remaining state-stage combinations. The forward recursion requires restarting the algorithm at the current state-stage combination and continuing the calculations.

In terms of the problem at hand, the forward pass through the network advocated by Brodie, Adams, and Kao (1978) appears superior to the backwards recursion used by Amidon and Akin (1968) and Schreuder (1971). With the forward recursion the optimal path to each stage, or rotation age, is determined by one pass through the network. The rotation age with the highest present value is chosen as the optimal rotation age and the thinning regime is determined by stepping back along the optimal path. With the backward recursion a separate pass must be made for each candidate rotation age before the inter-age comparison can be made for the highest present value. Disadvantages of the forward recursion center about losses in flexibility in sensitivity analysis as discussed above.

Optimization Algorithm

The optimization algorithm is a three descriptor dynamic programming model combining forest growth, price, and harvest cost relationships. Forest growth is expressed in terms of total stand age, basal area, and the number of trees exceeding a specified merchantable limit as defined by the DFIT model (Reukema et al. 1977).

The dynamic programming problem to be solved is as follows. Defining the optimal value function as

$f_t(N,B)$ = the value of the maximum present worth "path" from regeneration to stand age t, number of trees, N, and basal area, B; which consists of revenues and regeneration costs. Then,

$$f_t(N,B) = \max_{\{s\}} \left[\frac{P_d V_t - C_{v,d} V_t}{(1+i)^t} + f_{t-10}(N,B) \right]$$

where,

P_d = unit revenue of material removed from a stand of mean diameter, d. Diameter premiums over time could change, but in this study the price-time relationship was held constant.

V_t = merchantable volume removed from the stand at age t.

$C_{v,d}$ = harvesting cost of removing volume V, of mean diameter, d.

i = discount rate

$\{s\}$ = set of all feasible tree-basal area combinations, (N,B) at age t-10 from which the current level of (N,B) can be reached.

and,

$f_{t-10}(N,B)$ = the value of the maximum present worth path from regeneration to stand age t-10 of the candidate node at the last stage being considered for the current stage. Note that the arguments (N,B) of f_t and f_{t-10} do not have the same values.

The $f_t(N,B)$ and optimal s are saved for each (N,B) combination physically obtainable at each stage. For any given t, the optimal single rotation terminal stocking is found by evaluating

$$f_t(0,0) = \max_{\{s\}} \left[\frac{P_d V_r - C_{r,d} V_r}{(1+i)^t} + f_{t-10}(N,B) \right]$$

where,

$f_t(0,0)$ = maximum present worth of cumulative thinnings plus final harvest over all feasible (N,B) combinations at age t-10 if regeneration harvested at age t.

V_r = merchantable regeneration harvest volume of mean diameter, d.

$C_{r,d}$ = harvesting cost of removing regeneration harvest volume, V_r, of mean diameter, d.

The optimal single rotation over the set {t} will be that age t such that

$$VAL_{pv} = \max_{\{t\}} [f_t(0,0)]$$

where,

VAL_{pv} = present value over the set {t} or the "optimum optimorum" of the present worths of the optimum stocking levels at each age, t.

The optimal infinite series rotation will then be at the age, t, such that

$$VAL_{se} = \max_{\{t\}} \left[\frac{f_t(0,0) \ (1+i)^t}{(1+i)^t - 1} \right]$$

where,

VAL_{se} = the infinite series present worth or so-called "soil expectation" rotation. (Duerr 1960).

The dynamic programming structure requires stratifying state and stage values into discrete intervals. Fixed intervals of 15 trees per acre, 4 square feet of basal area per acre, and 10-year periods were chosen as a compromise between computational burden and the desire to avoid constraining the thinning alternatives. To maintain the continuous nature of the DFIT growth model, however, the true number of trees and true basal area is carried throughout the calculations in the following way. Tree and basal area candidates within a neighborhood described by the tree interval and basal area interval are lumped together at each (N,B) combination and the largest f_t of the neighborhood becomes the f_t of the node. The following table contains sample data for a node (N=105, B=116) to demonstrate the the technique. The neighborhood is illustrated in Figure 25.

Table 16. SAMPLE CANDIDATES FOR THE CURRENT NETWORK NODE.

Candidate No.	N Trees.	B Ft^2/acre	f_t $/acre
1	103.5	115.2	107.23
2	101.2	114.7	106.42
3	105.0	116.4	112.22
4	93.2	117.5	114.23

Candidate No. 4 would be selected since

$$f_t(N,B) = f_t(105,116) = \max_{\{\text{neighborhood}\}} f_t$$

$$= 114.23.$$

The actual number of trees and basal area is carried through the calculations to the next stage. The geometry of the neighborhood has been selected to prevent half-interval tree counting problems at the zero-trees node.

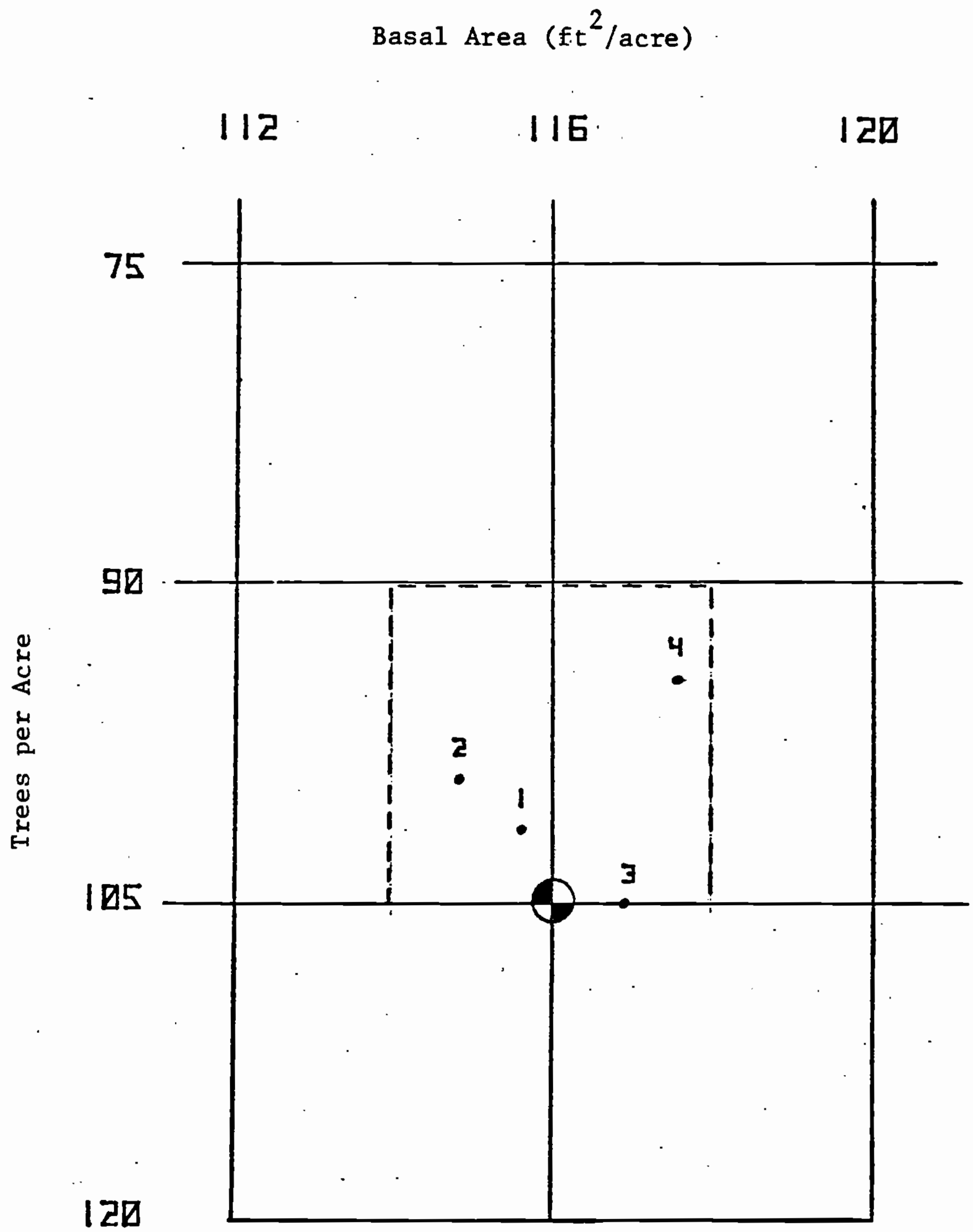


Figure 25. Node neighborhood.

The high rate of mortality in young natural stands suggest that computational efficiency might be improved by making the tree interval a function of the number of trees available for thinning in a natural stand. For example, if the tree interval was set equal to 1/30 of the number of trees in a natural stand at age (t) then for Site 140 Douglas-fir fully stocked, the initial tree interval declines from 30 to 6 trees at age 80. The use of a variable interval may approach the results obtained by a smaller fixed interval at less computational cost. This extension is only suggested and is not pursued in this study.

A flow chart of the optimization algorithm developed by Brodie and Kao (1978) is shown in Table 17.

Deviations From Bare Land Initial Conditions

If the initial starting condition is not bare land and/or the stand is not normally stocked, the optimal value function must be changed to reflect the possibility that the remaining path to regeneration harvest will not be repeated in future rotations.

The optimal value function becomes

$$f_t(N,B) = \max_{\{s\}} \left[\frac{P_d V_t - C_{v,d} V_t}{(1+i)^{t-t_o}} + f_{t-10}(N,B) \right]$$

where,

t_o = initial age of the stand at the beginning of the optimization.

The optimal rotation age for the first rotation will then be at that age, t, such that

$$VAL'_{se} = \max_{\{t\}} \left[f_t(0,0) + \frac{VAL_{se}}{(1+i)^{t-t_o}} \right]$$

where,

VAL_{se} = the maximum infinite series present worth for a normally stocked stand starting from bare land.

VAL'_{se} = the sum of the present worth of the first rotation plus an infinite series of rotations beginning with normally stocked stands.

All optimizations in this study were performed with normally stocked stands from bare land conditions.

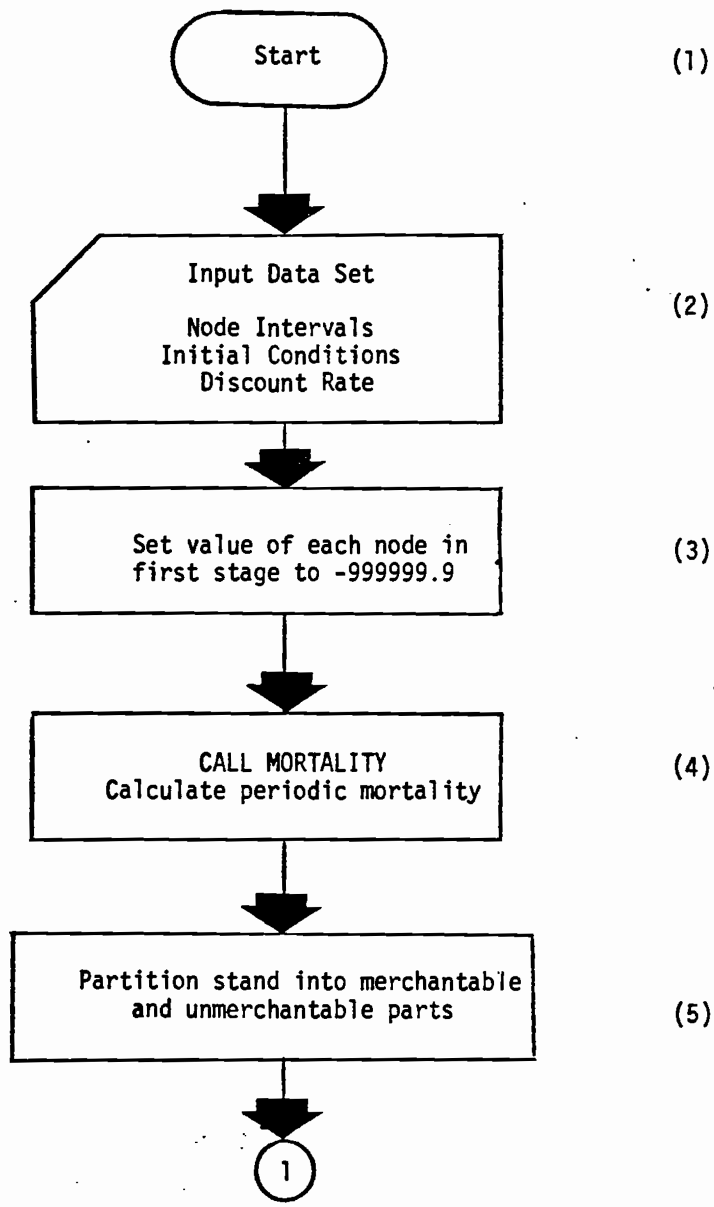
Noncommercial Thinning Constraint

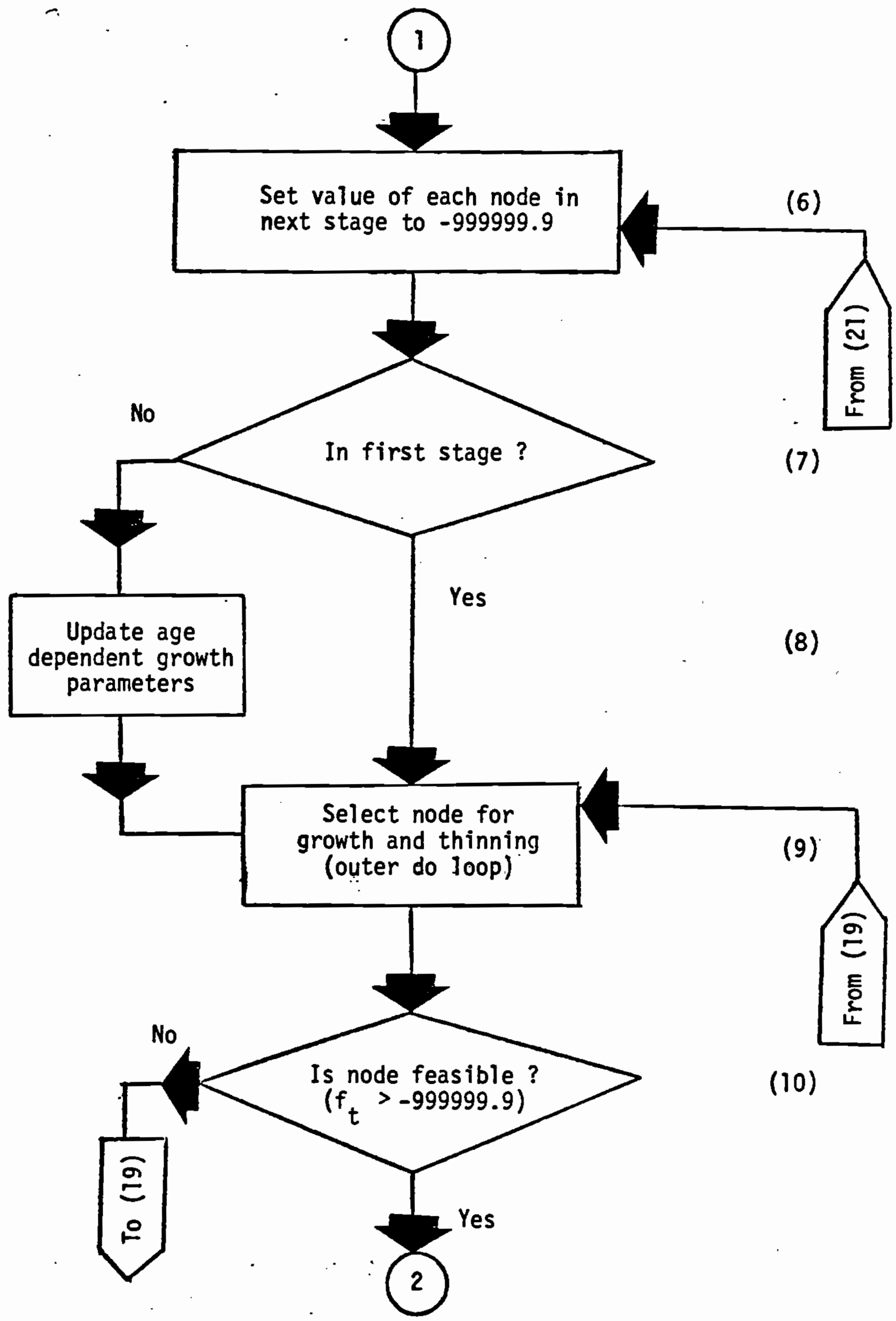
A noncommercial thinning is defined as a thinning which results in a negative contribution to cumulative net present worth. If desired, noncommercial thinnings can be eliminated from the optimal path with only minor changes in code. The procedure is as follows. For each candidate at a node the value of the planned thinning is calculated. If the revenue is negative, the <u>arc</u> is designated as infeasible by setting its cumulative net present value equal to a large negative number which eliminates it from future consideration. If all candidates for the node being considered have negative contributions to net present worth, the node becomes infeasible. If all arcs for all nodes are nonpositive because of high logging or entry cost, then the zero value arc and no-thinning node will be on the optimal path.

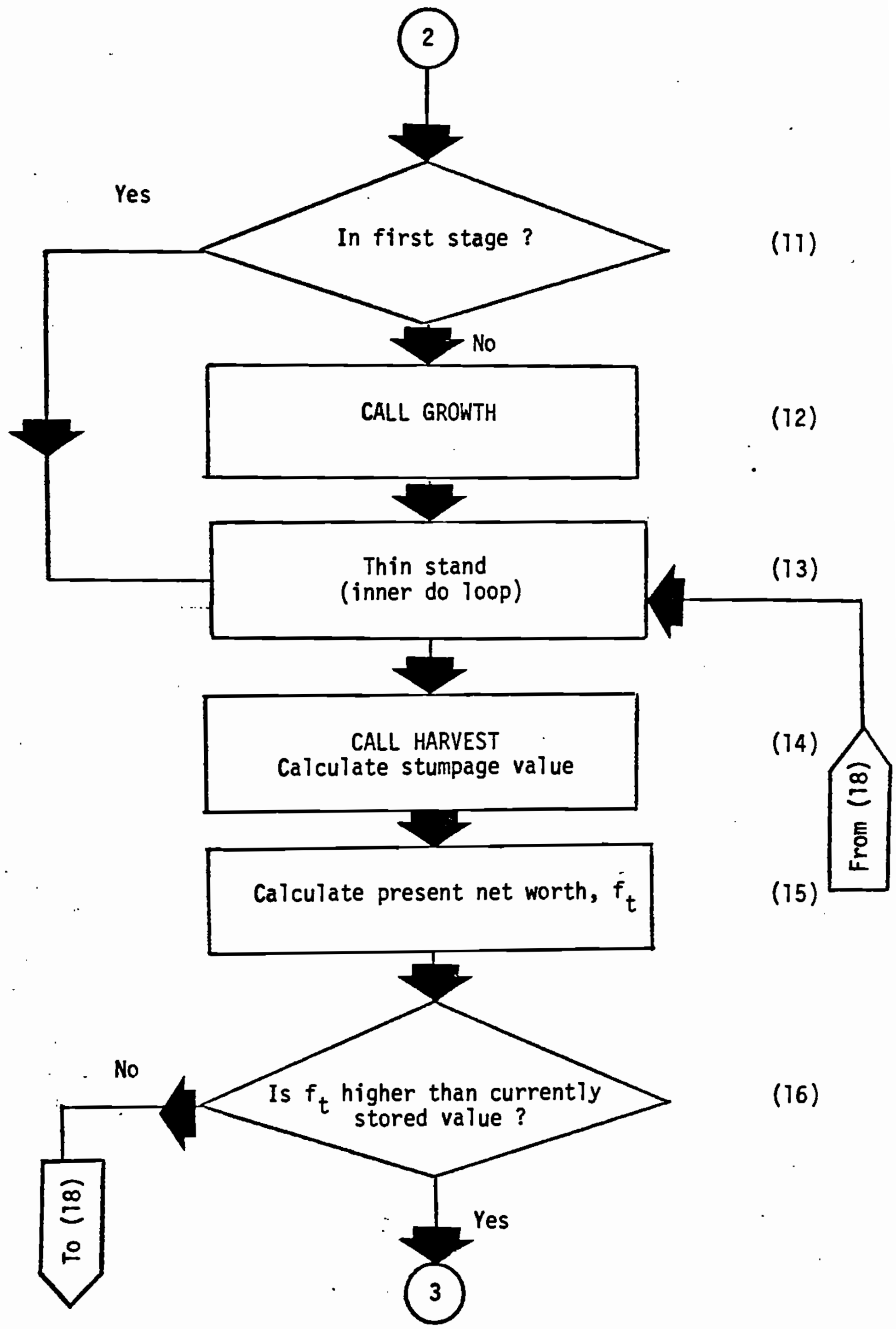
For the Site 140 Douglas-fir example (in mountainous terrain), inclusion of the noncommercial thinning constraint generally precludes thinning possibilities before age 50.

Present worth of thinning regimes with the thinning constraint will be equal to or less than the cumulative present worth of thinning regimes without the constraint. Examples comparing optimal paths with and without the constraint are presented in a later section.

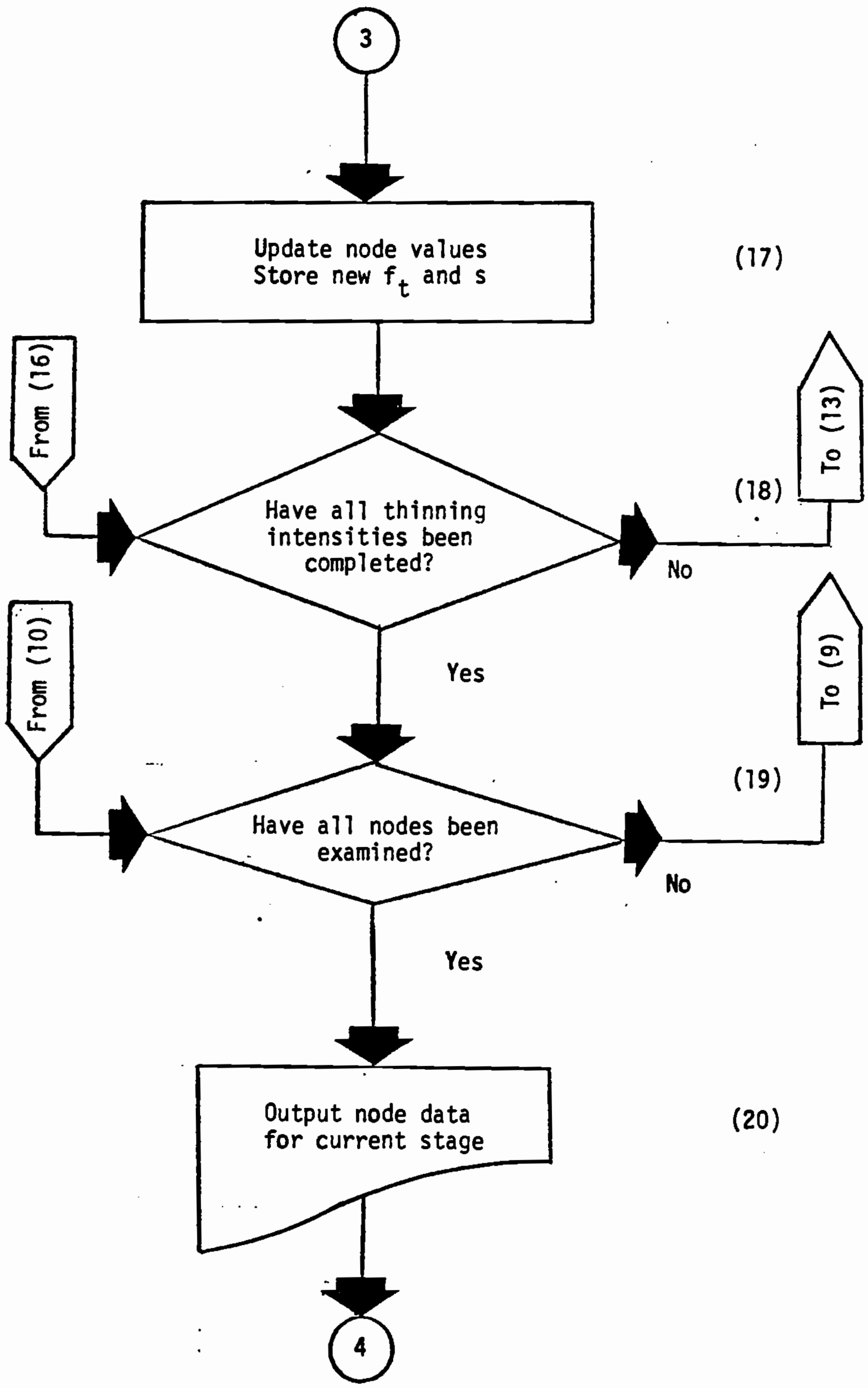
TABLE 17. FLOWCHART OF THE OPTIMIZATION ALGORITHM



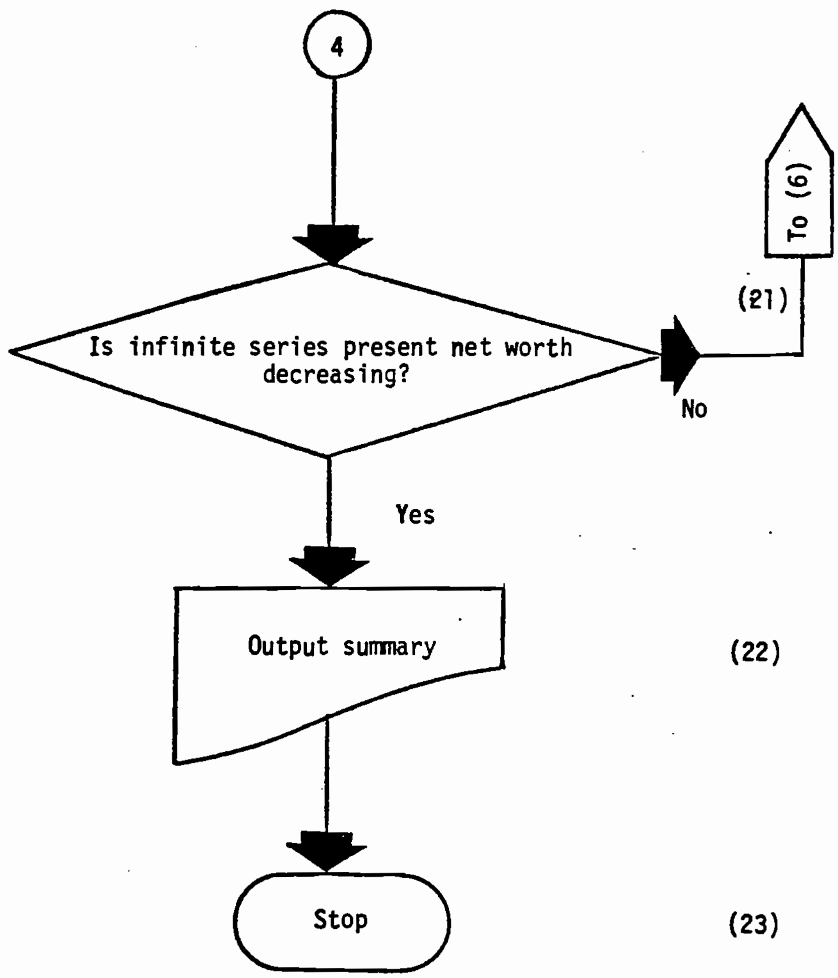

1
Set value of each node in next stage to -999999.9
(6)
From (21)
No
In first stage ?
(7)
Yes
Update age dependent growth parameters
(8)
Select node for growth and thinning (outer do loop)
(9)
From (19)
No
Is node feasible ? (f_t > -999999.9)
(10)
To (19)
Yes
2



2
Yes
In first stage ?
(11)
No
CALL GROWTH
(12)
Thin stand
(inner do loop)
(13)
CALL HARVEST
Calculate stumpage value
(14)
From (18)
Calculate present net worth, f_t
(15)
No
Is f_t higher than currently stored value ?
(16)
To (18)
Yes
3



3
Update node values
Store new f_t and s
(17)
From (16)
Have all thinning intensities been completed?
(18)
No
To (13)
Yes
From (10)
Have all nodes been examined?
(19)
No
To (9)
Yes
Output node data for current stage
(20)
4


4
Is infinite series present net worth decreasing?
No
To (6)
(21)
Yes
Output summary
(22)
Stop
(23)

Calculation of Stand Value

Revenue from either thinnings or regeneration harvest of the stand in the current period is determined from the equation.

Total Revenue = Average Unit Net Revenue x Merchantable Volume Cut

where,

Net Revenue = Pond Value - Stump to Truck Logging Cost - Haul Cost

Pond Value

Pond Value is defined as the value a mill would pay for logs received at the mill gate. Pond value was derived by taking a weighted average of logs recovered from thinning or regeneration harvesting a stand of known diameter distribution. Log values were assigned diameter premiums using values from the Oregon Department of Revenue, Timber Tax Division for January 1978 for Northwest Oregon. 10/

Logs from second-growth Douglas-fir are assumed to fall into one of five classes: 11/

No. 4 Mill Sawlogs - Less than 6 inches in diameter

No. 3 Mill Sawlogs - Less than 12 inches in diameter

No. 2 Mill Sawlogs - Less than 16 inches in diameter

10/ Specifically, the counties from the Columbia River to the southern end of Lane County and from the Cascade Divide to the coast.

11/ Log classes are from Official Log Scaling and Grading Rules for Columbia River Scaling Bureau; January 1, 1978.

Special Mill Grade - Less than 24 inches in diameter

No. 3 Peeler Logs - Over 24 inches in diameter.

Average log values for second-growth Douglas-fir as of January 1978 (Graham 1978) for Northwest Oregon are listed in Table 18.

TABLE 18. LOG VALUES FOR SECOND-GROWTH DOUGLAS-FIR IN NORTHWEST OREGON, 1978.

No. 4 Mill Sawlogs	215 $/Mbf
No. 3 Mill Sawlogs	230 $/Mbf
No. 2 Mill Sawlogs	265 $/Mbf
Special Mill Grade	300 $/Mbf
No. 3 Peeler Logs	330 $/Mbf

To derive the average unit revenue per thousand cubic feet of volume removed as a function of mean stand diameter, the following procedure was used to weight the various trees which would be removed in thinning or final harvests.

A. For a given diameter (dbh) distribution, the stand was divided into five intervals having equal probability.

B. The diameter of a tree corresponding to the midpoint of each interval was selected to model the interval.

C. Each of the five trees was scaled by the Girard and Bruce formula, V = 1.53 D**2 - 4*D - 8, which approximates the Columbia River Scaling Rule (Dilworth 1973).

D. Each log was multiplied by its corresponding value.

E. The cubic volume of each tree was calculated by assigning each tree a linear taper based on its diameter and the mean height of the stand.

F. The sum of the log values were then divided by the sum of the cubic volumes to give an estimate of the pond value of the stand per unit volume of the stand cut.

Values were computed for Site 140 Douglas-fir, ages 40 to 160, based on mean diameters from Bulletin 201.

TABLE 19. POND VALUE AS A FUNCTION OF MEAN STAND DIAMETER.

Mean Stand Dbh (inches)	Age (years)	Bf/Cf Ratio	Pond Value ($/mcf)
6.6	40	1.93	413.96
10.40	60	3.46	782.16
13.70	80	4.15	1002.50
16.20	100	4.58	1203.83
18.40	120	4.94	1351.88
20.20	140	5.11	1417.42
22.00	160	5.29	1509.37

A linear regression model was fitted to the data with an $R^2 = 0.99$ providing the following relationship between stand value and mean stand diameter,

Stand Value ($/Mcf) = 9.91 + 70.81 * Mean Stand Diameter (in)

This relationship is illustrated in Figure 26.

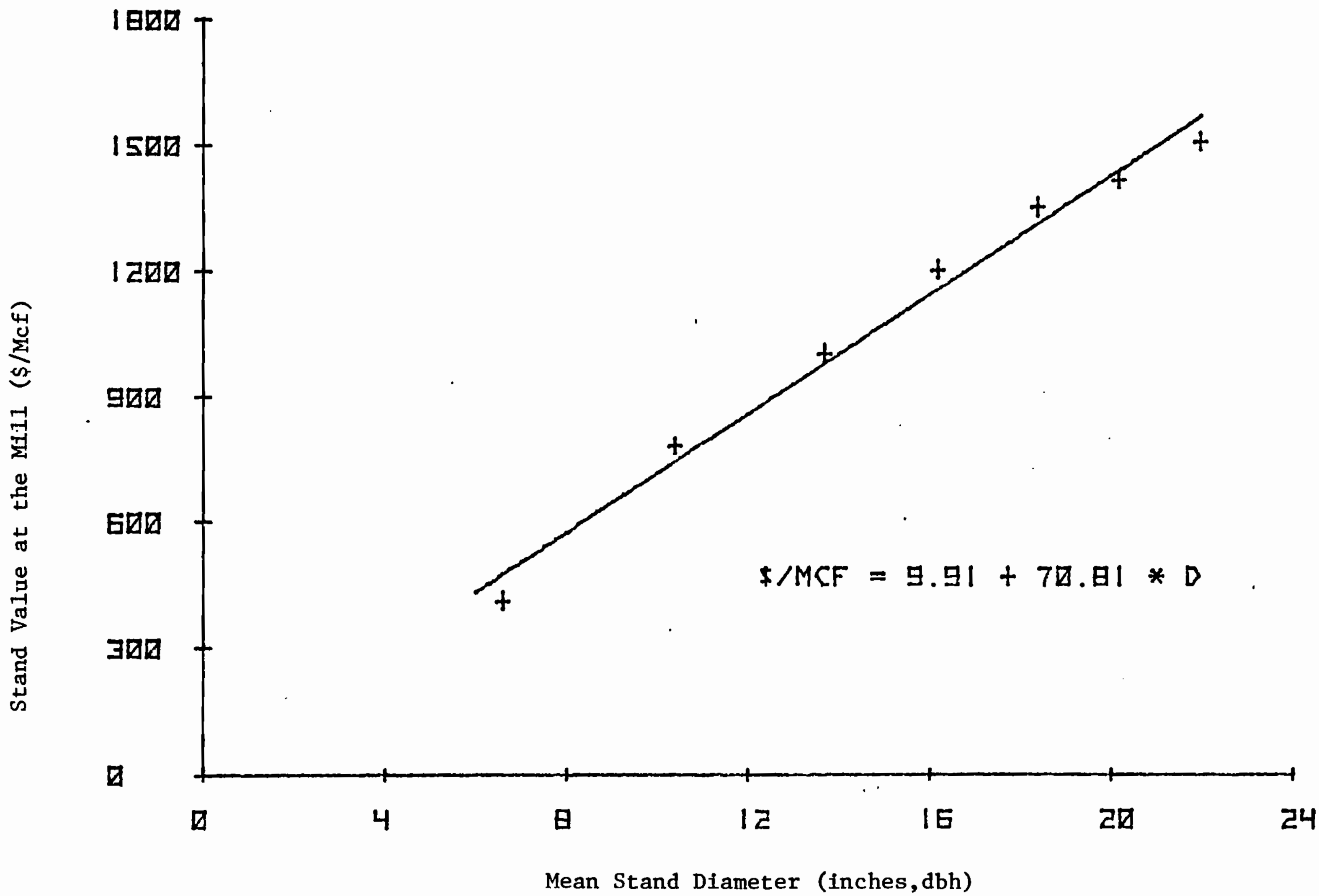


Figure 26. Stand value at the mill (pond value) as a function of mean stand diameter.

VI. APPLICATION OF THE OPTIMIZATION MODEL

This chapter presents the optimization results for Douglas-fir in mountainous terrain for a specific set of topographic and price conditions. The sensitivity of optimal management regime to changes in these "standard" conditions will be discussed with particular emphasis on sensitivity to changes in topographic variables of yarding direction and distance. The sensitivity of optimal regime to log gathering technique, haul cost, discount rate, and price changes will also be discussed.

Management Regime Under Standard Conditions

A set of standard conditions are assumed for the study of management regime in mountainous terrain. The conditions are:

1. Site 140 Douglas-fir, normally stocked at age 20.
2. Uphill yarding by skyline, 1200-ft horizontal span.
3. Cumulative net present worth of regeneration plus stand management costs of $200 per acre at age 20.
4. Constant truck haul cost of $150 per Mcf.
5. Real discount rate of 3 percent, constant prices and constant costs.

The optimization over trees per acre, basal area per acre, and time is constrained to node intervals of 15 trees per acre, 4 square feet of basal area per acre, and 10-year time periods as discussed in Chapter V. During optimization, harvesting costs are generated from a subroutine compiled from harvest simulator results for the large and small skyline as discussed in Chapter IV. All price and cost calculations are based on log volumes to a 4-inch top.

The management regime which maximized the infinite series present worth per acre required an initial heavy entry at age 80 and a final harvest at age 100. The single rotation present net worth was $299.60 per acre with a corresponding infinite series present worth of $316.02 per acre. Detailed data for the thinning regime which maximized the infinite series present worth are shown in Table 20 . Single rotation present worth values in the last column of Table 20 are cumulative values. The addition to present worth at each age is obtained by subtracting the value at the previous time period from the current time period. Table 21 presents a summary of the final harvest and present worth statistics for the thinning regime which maximizes the single rotation present worth for each rotation age and the corresponding infinite series present worth per acre. The optimal management regime which maximizes soil expectation is then the thinning regime for the rotation age at which the maximum infinite series present worth occurs, in this case, at age 100.

This management regime differs appreciably from results by Randall (1977). Randall's assumptions to (1) ignore diameter premium, (2) establish a constant ratio of net thinning stumpage to net final harvest stumpage of 0.75, and (3) to consider that thinnings are commercial when a mean stand diameter of 9 inches is reached resulted

TABLE 20. RUN #1 - THINNING SCHEDULE FOR CONVENTIONAL YARDING UNDER STANDARD CONDITIONS.

Age (Years)	Diameter 2/ (inch)	Volume Cut 3/ (Cubic Ft.)	Volume Left 4/ (Cubic Ft.)	Basal Area 5/ (Square Ft.)	Merchantable 6/ Trees Remaining	Cumulative 7/ Net Present Value ($/acre)
30	6.4	0	3157	126	560	-200
40	8.0	0	4993	163	468	-200
50	9.7	0	6543	185	358	-200
60	11.4	0	7872	203	286	-200
70	12.9	0	9025	217	239	-200
80	14.3	7719	2941	67	60	101.7
90	16.5	0	3576	79	53	101.7
100	18.6	4606	0	0	0	299.6

1/ Site 140 Douglas-fir, 1200-ft. skyline, 3 percent discount rate.
2/ Quadratic mean diameter of merchantable volume cut.
3/ Merchantable volume per acre including merchantable mortality.
4/ Merchantable volume per acre remaining after entry.
5/ Merchantable basal area per acre remaining after entry.
6/ Merchantable trees per acre remaining after entry.
7/ Cumulative single rotation net present value per acre after entry.

TABLE 21. RUN #1 - SUMMARY OF FINAL HARVEST AND PRESENT NET WORTH DATA FOR YARDING UNDER STANDARD CONDITIONS.1/

Rotation Age (Years)	Final Harvest Volume (Cubic Feet) 2/	Harvest Diameter (Inch) 3/	Harvest Basal Area (Square Feet) 4/	Present Net Worth ($/acre) 5/	Infinite Series Present Worth ($/acre) 6/
40	5718.24	7.97	162.46	-551.12	-794.76
50	5655.44	11.81	138.74	-288.41	-373.63
60	8570.24	11.39	202.76	21.73	26.17
70	9689.05	12.93	217.35	204.70	234.29
80	10659.59	14.34	229.81	272.64	300.91
90	11512.51	15.66	240.70	283.67	305.00
100	4606.00	18.61	89.02	299.58	316.02
110	4844.28	20.49	92.62	299.80	311.88
120	3960.49	22.31	74.69	293.17	301.87

1/ Site 140 Douglas-fir, 1200-foot skyline, 3 percent discount rate.
2/ Includes merchantable mortality at final harvest, does not include thinnings.
3/ Quadratic mean diameter of merchantable volume in final harvest.
4/ Basal area per acre of merchantable volume in final harvest.
5/ Single rotation present net worth for corresponding rotation age.
6/ Soil expectation or bare land value for corresponding rotation age.

in recommended regimes with entries each 10 years. Although Randall's results are not directly comparable to this study, it appears that his assumptions may not adequately consider the specific treatment costs and management opportunities in mountainous terrain.

Mean annual increment, average internal rate of return, and single rotation net present worth are shown in Figure 27 for alternative rotation lengths. Plotted values are calculated from the thinning regime to maximize single rotation net present worth for each alternative age. Due to diameter premiums and reduced harvest costs per unit for larger diameter material, the rotation age and thinning schedule which maximize net present worth do not maximize the mean annual increment. Internal rates of return assume zero land cost. For managers who lack the option of selling or not managing their lands, it is of interest that the average internal rate of return rises rapidly to 4 percent and remains constant over a wide range of alternative rotation lengths while mean annual increment declines.

Sensitivity Analysis

The primary value of the standard conditions is to establish a base line from which deviations can be measured. The remainder of this section will examine the effects upon optimal management regime caused by deviations from the standard conditions. Specifically, effects due to changes in yarding direction, yarding distance, haul cost, price-diameter relationships, discount rates and thinning constraints, will be examined.

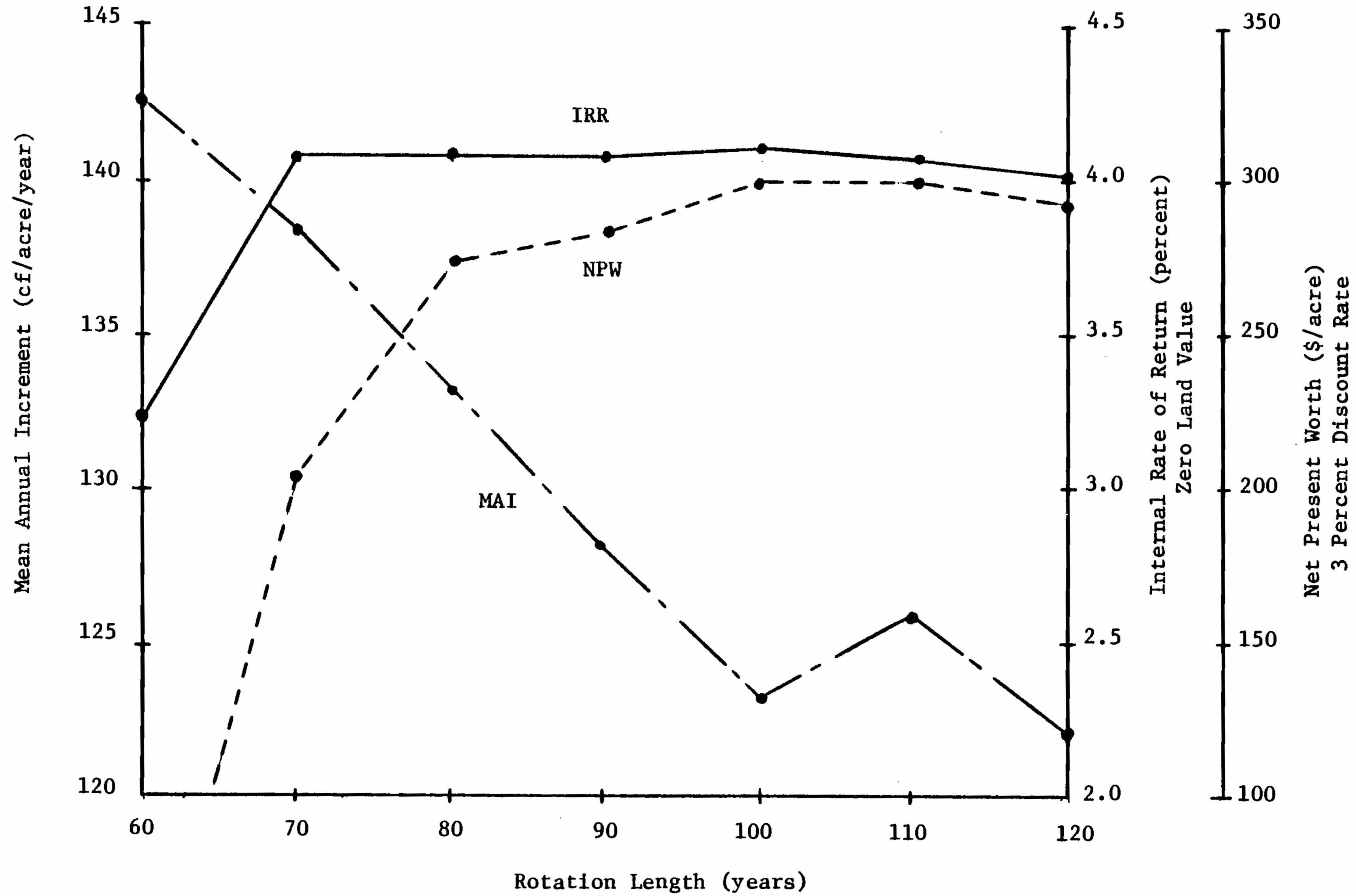


Figure 27. Mean annual increment, internal rate of return, and single rotation net present worth as a function of alternative rotation lengths for standard conditions.

Effect of Change in Yarding Direction

The standard conditions in this study are for uphill extraction. This section will briefly review cost differences due to yarding direction. If yarding direction influences yarding cost, it will affect the choice of thinning regime.

Sessions (1974) found, in thinning pine plantations, downhill yarding costs were 25 percent to 50 percent higher than uphill yarding costs. McGonagill (1975) reports that production decreases about one-third when a haulback is required for use on skylines. Conway (1976) reports that production of skylines using gravity return is 20 percent to 30 percent higher per day than slackline systems. And, in a memo to forests concerning appraisals for skyline yarding, the USDA-Forest Service, Northern Region (1976), recommended increasing uphill yarding costs 48 percent when planning downhill yarding in partial cuts and 27 percent in clearcuts.

The principal factors contributing to the higher costs for downhill yarding include slower outhaul times as compared to gravity outhaul systems, longer road change times due to the need to pack the rigging uphill, delays in cycle time due to safety considerations in bringing logs downhill over cutbanks on midslope roads, slower line speeds to keep the logs under control, increased hangups during lateral yarding particularly in trying to turn the logs into the skyline corridor, and reduced payloads if full suspension is required to protect soil and watershed values as well as the residual stand from bouncing logs during inhaul.

To test the sensitivity of thinning regime and rotation age to yarding direction in the Site 140 Douglas-fir example, harvesting costs were increased 25 percent for all diameter classes as a conservative estimate of the effect of change in yarding direction.

The optimal management regime for the 25 percent increase in harvesting cost was to final harvest at age 90 with no thinnings. Compared to the uphill yarding under standard conditions, this represented a 10 year reduction in rotation age. The infinite series present worth was $250.54 per acre or 21 percent lower than for uphill yarding. If the uphill yarding regime had been prescribed for the downhill harvest unit the infinite series present worth would have been $224.88 per acre or 10 percent lower than the optimal downhill strategy. These comparisons are summarized in Table 22. Detailed statistics for the downhill optimization are in Table 23 and Table 24.

TABLE 22. EFFECT OF YARDING DIRECTION ON MANAGEMENT REGIME.

	Optimal Uphill Thinning Regime	Optimal Downhill Thinning Regime	Optimal Uphill Regime Used on Downhill Unit
Thinning Age (years)	80	none	80
Final Harvest Age (years)	100	90	100
Single Rotation Present Worth ($/acre)	299.60	233.02	213.18
Infinite Series Present Worth ($/acre)	316.02	250.54	224.88

TABLE 23. RUN #2 - THINNING SCHEDULE FOR DOWNHILL YARDING. 1/

Age (Years)	Diameter 2/ (inch)	Volume Cut 3/ (Cubic Ft.)	Volume Left 4/ (Cubic Ft.)	Basal Area 5/ (Square Ft.)	Merchantable 6/ Trees Remaining	Cumulative 7/ Net Present Value ($/acre)
30	6.4	0	3157	126	560	-200
40	8.0	0	4993	163	468	-200
50	9.7	0	6543	185	358	-200
60	11.4	0	7872	203	286	-200
70	12.9	0	9025	217	239	-200
80	14.3	0	10037	230	205	-200
90	15.7	11512	0	0	0	233

1/ Site 140 Douglas-fir, 1200-ft. skyline, 3 percent discount rate.
2/ Quadratic mean diameter of merchantable volume cut.
3/ Merchantable volume per acre including merchantable mortality.
4/ Merchantable volume per acre remaining after entry.
5/ Merchantable basal area per acre remaining after entry.
6/ Merchantable trees per acre remaining after entry.
7/ Cumulative single rotation net present value per acre after entry.

TABLE 24. RUN #2 - SUMMARY OF FINAL HARVEST AND PRESENT NET WORTH DATA FOR DOWNHILL YARDING. 1/

Rotation Age (Years)	Final Harvest Volume (Cubic Feet) 2/	Harvest Diameter (Inch) 3/	Harvest Basal Area (Square Feet) 4/	Present Net Worth ($/acre) 5/	Infinite Series Present Worth ($/acre) 6/
40	5718.24	7.97	162.46	-787.10	-1135.05
50	7261.11	9.73	185.10	-518.92	- 672.27
60	8570.24	11.39	202.76	-119.46	- 143.88
70	9689.05	12.39	217.35	105.88	121.18
80	10659.50	14.34	229.81	201.12	221.98
90	11512.51	15.66	240.70	233.02	250.54
100	5585.22	18.40	108.82	224.35	236.66

1/ Site 140 Douglas-fir, 1200-foot skyline, 3 percent discount rate.
2/ Includes merchantable mortality at final harvest, does not include thinnings.
3/ Quadratic mean diameter of merchantable volume in final harvest.
4/ Basal area per acre of merchantable volume in final harvest.
5/ Single rotation present net worth for corresponding rotation age.
6/ Soil expectation or bare land value for corresponding rotation age.

Effect of Change in Yarding Distance

Road access options in mountainous terrain generally preclude the option of constructing parallel roads. As road spacing changes, the average yarding distance between roads changes. In this section the sensitivity of thinning regime to changes in yarding distance is discussed with examples shown for units of 300 feet and 600 feet in length.

Changing the yarding distance can áffect both the variable costs of yarding and the fixed cost of equipment move-in and setup. In this study the setup costs are assumed proportional to distance in such a way that fixed costs are constant regardless of skyline length. Variable cost, on the other hand, changes with the average distance yarded, the magnitude of the change depending on the coefficient of yarding distance. Table 25 summarizes the optimal thinning regimes for the three skyline spans.

Optimal rotation age for each yarding distance was approximately 100 years given the 10-year stages in this study. 12/ Single rotation present worth increased from $299.8 per acre to $401.5 per acre as skyline length decreased from 1200 feet to 300 feet. Because of lower line speeds for the small yarder, the reduction in yarding distance decreased small yarder costs proportionally more than for the large yarder. This reduced the relative cost of handling small wood as compared to larger wood favoring earlier entries. Comparing

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12/ The single payment present worth for the 1200-foot skyline was slightly higher at 110 years, but soil expectation was a maximum at age 100.

the thinning schedules for the 600-foot and 300-foot yarding distances there is an apparent anomaly as thinnings become lighter rather than heavier for the shorter yarding distance. Two possible explanations are suggested:

(1) The elasticity of stump to truck harvesting cost with respect to volume removed is lower for the 300-foot yarding distance than for the 600-foot yarding distance for mean stand diameters less than 15 inches. For example, for a mean stand diameter of 12 inches, the elasticity is approximately -0.26 for the 300-foot skyline and approximately -0.35 for the 600-foot skyline. Therefore, there is relatively less reward, in terms of reduced harvesting cost, for incremental additions of volume at the shorter yarding distance. This explanation would also rationalize the larger total yield for the 300-foot skyline. Since there is less incentive to increase volume cut to reduce harvest costs, a larger stock is left for future growth.

(2) The thinnings at age 80 and age 90 each remove 15 trees. As 15 trees is the smallest non-zero thinning permitted in this study, the grid interval may be too large. A finer grid, or use of the variable tree interval approach might yield a different solution.

Time and funding constraints prevented additional study to pursue these explanations.

TABLE 25. EFFECT OF YARDING DISTANCE ON MANAGEMENT REGIME.

Age (Years)	Run #1 1200-ft skyline Volume Cut (cf/acre)	Run #3 600-ft skyline Volume Cut (cf/acre)	Run #4 300-ft skyline Volume Cut (cf/acre)
30	0	0	0
40	0	0	0
50	0	0	0
60	0	0	0
70	0	6851	6284
80	7719	774	700
90	0	1053	973
100	4606	4425	5631
	12325	13103	13588

TABLE 26. RUN #3 - THINNING SCHEDULE FOR 600-FT. SKYLINE

Age (Years)	Diameter (inch) 2/	Volume Cut (Cubic Ft.) 3/	Volume Left (Cubic Ft.) 4/	Basal Area (Square Ft.) 5/	Merchantable Trees Remaining 6/	Cumulative Net Present Value ($/acre) 7/
30	6.4	0	3157	126	560	-200
40	8.0	0	4993	163	468	-200
50	9.7	0	6543	185	358	-200
60	11.4	0	7872	203	286	-200
70	12.9	6851	2838	68	75	67.3
80	15.3	774	3354	77	60	85.6
90	17.6	1053	3445	76	45	128.3
100	19.7	4425	0	0	0	345.7

1/ Site 140 Douglas-fir, 3 percent discount rate.
2/ Quadratic mean diameter of merchantable volume cut.
3/ Merchantable volume per acre including merchantable mortality.
4/ Merchantable volume per acre remaining after entry.
5/ Merchantable basal area per acre remaining after entry.
6/ Merchantable trees per acre remaining after entry.
7/ Cumulative single rotation net present value per acre after entry.

TABLE 27. RUN #3 - SUMMARY OF FINAL HARVEST AND PRESENT WORTH DATA FOR 600-FT. SKYLINE [1/]

Rotation Age (Years)	Final Harvest Volume (Cubic Feet) [2/]	Harvest Diameter (Inch) [3/]	Harvest Basal Area (Square Feet) [4/]	Present Net Worth ($/acre) [5/]	Infinite Series Present Worth ($/acre) [6/]
40	5368.32	8.16	150.59	-878.69	-878.69
50	7261.11	9.73	185.10	-214.21	-277.51
60	8570.24	11.39	202.76	92.30	111.17
70	9689.05	12.93	217.35	254.01	290.73
80	10659.50	14.34	229.81	308.21	340.17
90	5445.51	17.34	108.07	330.85	355.72
100	4424.79	19.74	85.57	345.71	364.68
110	5293.81	21.37	101.61	342.13	355.91

1/ Site 140 Douglas-fir, 3 percent discount rate.
2/ Includes merchantable mortality at final harvest, does not include thinnings.
3/ Quadratic mean diameter of merchantable volume in final harvest.
4/ Basal area per acre of merchantable volume in final harvest.
5/ Single rotation present net worth for corresponding rotation age.
6/ Soil expectation or bare land value for corresponding rotation age.

TABLE 28. RUN #4 - THINNING SCHEDULE FOR 300-FT. SKYLINE

Age (Years)	Diameter 2/ (inch)	Volume Cut 3/ (Cubic Ft.)	Volume Left 4/ (Cubic Ft.)	Basal Area 5/ (Square Ft.)	Merchantable 6/ Trees Remaining	Cumulative 7/ Net Present Value ($/acre)
30	6.4	0	3157	126	560	-200
40	8.0	0	4993	163	468	-200
50	9.7	0	6543	185	358	-200
60	11.4	0	7872	203	286	-200
70	12.9	6284	3406	82	90	56.6
80	15.2	700	4134	95	75	84.0
90	17.3	973	4472	98	60	120.3
100	19.4	5631	0	0	0	401.5

1/ Site 140 Douglas-fir, 3 percent discount rate.
2/ Quadratic mean diameter of merchantable volume cut.
3/ Merchantable volume per acre including merchantable mortality.
4/ Merchantable volume per acre remaining after entry.
5/ Merchantable basal area per acre remaining after entry.
6/ Merchantable trees per acre remaining after entry.
7/ Cumulative single rotation net present value per acre after entry.

TABLE 29. RUN #4 - SUMMARY OF FINAL HARVEST AND PRESENT WORTH DATA FOR 300-FT. SKYLINE 1/

Rotation Age (Years)	Final Harvest Volume (Cubic Feet) 2/	Harvest Diameter (Inch) 3/	Harvest Basal Area (Square Feet) 4/	Present Net Worth ($/acre) 5/	Infinite Series Present Worth ($/acre) 6/
40	5718.24	7.97	162.46	-494.62	-713.27
50	4495.67	12.41	106.03	-169.19	-219.19
60	8570.24	11.39	202.76	128.21	154.42
70	9689.05	12.93	217.35	273.78	313.35
80	4835.12	15.21	97.49	321.32	354.65
90	5445.51	17.34	108.07	380.61	409.23
100	5631.35	19.38	109.88	401.50	423.54
110	3590.14	21.46	68.34	397.66	413.67

1/ Site 140 Douglas-fir, 3 percent discount rate.
2/ Includes merchantable mortality at final harvest, does not include thinnings.
3/ Quadratic mean diameter of merchantable volume in final harvest.
4/ Basal area per acre of merchantable volume in final harvest.
5/ Single rotation present net worth for corresponding rotation age.
6/ Soil expectation or bare land value for corresponding rotation age.

Effect of Change in Haul Cost

Haul costs in the harvesting simulation are treated as exogenous. All costs falling into the category of truck transport are grouped into the category of haul costs including, primarily, truck haul and road maintenance costs. A cost of $150 per Mcf was assumed as the standard haul cost. If haul costs are reduced, it would be expected that the net present value of the harvests would increase by the present worth of the haul cost reduction. The optimal management regime may also change. To test this assumption, the haul cost was reduced to zero for the 1200-foot skyline and the example rerun.

The detailed run summaries are in Tables 31 and 32. The optimal single rotation present worth is $446.4 per acre for a zero haul cost as compared to $299.8 per acre for a haul cost of $150 per Mcf. The difference between the alternatives is $166.6 per acre. This difference can be divided between the reduction in haul cost, and $21.9 per acre due to a change in management regime. The change in optimal management regime can be rationalized by considering the candidates for an arbitrary node in the dynamic programming network. Recalling that the value function, f_t, is

$$f_t = \max_{\{s\}} \left[\frac{P_t V_t - C_{v,d} V_t}{(1+i)^t} + f_{t-10}(s) \right]$$

the stump to mill cost, $C_{v,d}$, is partitioned into two components such that

$$C_{v,d} = C'_{v,d} + H$$

where

$$C'_{v,d} = \text{stump to truck cost, \$/Mcf}$$
$$H = \text{haul cost, \$/Mcf}$$

the value function becomes

$$f_t = \max_{\{s\}} \left[\frac{P_t V_t - C'_{v,d} V_t - H V_t}{(1+i)^t} + f_{t-10}(s) \right]$$

It is now clear that the candidate most severely penalized by the haul cost, H, is the candidate with the largest volume harvested in the current period, t. When H is reduced, in this case to zero, the candidate with the largest V_t will gain the most. Since the same phenomenon occurs at all nodes for a given age, the result will be a shifting forward of the harvesting schedule, or at a minimum, no change. In this example the harvest shifted forward 10 years as shown in Table 30.

TABLE 30. EFFECT OF HAUL COST CHANGE ON MANAGEMENT REGIME.

Age (years)	Haul = 0.0 \$/Mcf Volume Cut (cf/acre)	Haul = 0.0 \$/Mcf Cumulative NPW (\$/acre)	Haul = 150.0 \$/Mcf Volume Cut (cf/acre)	Haul = 150.0 \$/Mcf Cumulative NPW (\$/acre)
30	0	-200	0	-200
40	0	-200	0	-200
50	0	-200	0	-200
60	0	-200	0	-200
70	6851	151.3	0	-200
80	774	174.0	7719	101.7
90	1073	22.9	0	101.7
100	4425	466.4	4606	299.6
	13123		12325	

TABLE 31. RUN #5 - THINNING SCHEDULE FOR ZERO HAUL COST

Age (Years)	Diameter 2/ (inch)	Volume Cut 3/ (Cubic Ft.)	Volume Left 4/ (Cubic Ft.)	Basal Area 5/ (Square Ft.)	Merchantable 6/ Trees Remaining	Cumulative 7/ Net Present Value ($/acre)
30	6.4	0	3157	126	560	-200
40	8.0	0	4993	163	468	-200
50	9.7	0	6543	185	358	-200
60	11.4	0	7872	203	286	-200
70	12.9	6851	2838	68	75	151.3
80	15.3	774	3354	77	60	174.0
90	17.6	1073	3445	76	45	222.9
100	19.7	4425	0	0	0	466.4

1/ Site 140 Douglas-fir, 1200-ft. skyline, 3 percent discount rate.
2/ Quadratic mean diameter of merchantable volume cut.
3/ Merchantable volume per acre including merchantable mortality.
4/ Merchantable volume per acre remaining after entry.
5/ Merchantable basal area per acre remaining after entry.
6/ Merchantable trees per acre remaining after entry.
7/ Cumulative single rotation net present value per acre after entry.

TABLE 32. RUN #5 - SUMMARY OF FINAL HARVEST AND PRESENT WORTH DATA FOR ZERO HAUL COST 1/

Rotation Age (Years)	Final Harvest Volume (Cubic Feet) 2/	Harvest Diameter (Inch) 3/	Harvest Basal Area (Square Feet) 4/	Present Net Worth ($/acre) 5/	Infinite Series Present Worth ($/acre) 6/
40	5718.24	7.97	162.46	-319.86	-461.27
50	5655.44	11.81	138.74	- 29.81	- 38.62
60	7066.21	13.97	163.44	228.89	275.68
70	9689.05	12.93	217.35	380.75	435.79
80	10659.50	14.34	229.81	417.94	461.30
90	4517.66	17.57	88.78	453.81	487.93
100	4424.79	19.74	85.57	466.45	492.65
110	1854.68	21.80	35.27	458.27	476.73

1/ Site 140 Douglas-fir, 1200-ft. skyline, 3 percent discount rate.
2/ Includes merchantable mortality at final harvest, does not include thinnings.
3/ Quadratic mean diameter of merchantable volume in final harvest.
4/ Basal area per acre of merchantable volume in final harvest.
5/ Single rotation present net worth for corresponding rotation age.
6/ Soil expectation or bare land value for corresponding rotation age.

Effect of Change in Price-Diameter Relationship

Two types of changes in price diameter relationships are examined; increases in the price intercept and increases in the price slope. From these two changes inferences concerning variations or combinations of these changes can be made.

Changes in Price Intercept

Increasing the price intercept will have the same effect as lowering the haul cost discussed in the previous section. Recalling that the haul cost in this study is treated as a constant, the analogy between an increase in price intercept and reduction in haul cost becomes obvious upon examination of the net revenue function.

Net Revenue ($/Mcf) = Price ($/Mcf) - Haul Cost ($/Mcf) -
All Other Costs ($/Mcf)

The previous conclusion that lowering the haul cost increased the present value of the harvest and shifted the cutting schedule forward with earlier thinnings applies similarly. Raising the price intercept will increase the present value of the harvest and shift the cutting schedule forward. Lowering the price intercept will postpone thinnings as well as lowering the cumulative present value of the harvests.

Changes in Slope of Price Function

Increasing the slope of the price function increases the diameter premium making larger diameter material even more valuable relative to smaller diameter material. Although one might intuitively think this would extend rotation to permit growing larger trees or thin less so trees are left to grow larger, the result for this example is to shift the cutting schedule forward in order to stimulate the concentration of growth on fewer, larger trees.

Changing the price function for the 1200-ft skyline, conventional yarding from P = 9.91 + (70.81)(D) to P = 9.91 + (100)(D) produced the thinning schedules in Table 33.

TABLE 33. EFFECT OF INCREASE IN PRICE SLOPE ON MANAGEMENT REGIME.

	Run #1 P = 9.91 + (70.81)(D)		Run #6 P = 9.91 + (100)(D)	
Age (years)	Diameter (inches)	Volume Cut (cf/acre)	Diameter (inches)	Volume Cut (cf/acre)
30	6.4	0	6.4	1464
40	8.0	0	9.7	0
50	9.7	0	11.6	0
60	11.4	0	14.0	3346
70	12.9	0	16.7	1595
80	14.3	7719	19.5	1151
90	16.5	0	22.0	1646
100	18.6	4606	24.6	4546
		12,325		13,748

The rotation age remained the same but cutting began at year 30 rather than at year 80. The cumulative present value of the harvests for Run #1 was $299.6 per acre and for Run #6 the cumulative present value of the harvests was $831.0 per acre. The initial entry at year 30 for Run #6 was noncommercial, contributing a negative addition to net present worth of $-203.0 per acre. The investment was required to stimulate diameter growth to produce the final cumulative net present value of $831.0 per acre. The accelerated cutting schedule from Run #6 also resulted in a larger total yield due to salvage of mortality. Run #1 provided 12,325 cubic feet in cumulative harvests while Run #6 yielded 13,748 cubic feet or an increase of 12 percent. Detailed statistics for Run #6 can be found in Tables 34 and 35.

TABLE 34. RUN #6 - THINNING SCHEDULE FOR CHANGE IN PRICE-DIAMETER RELATIONSHIP 1/

Age (Years)	Diameter 2/ (inch)	Volume Cut 3/ (Cubic Ft.)	Volume Left 4/ (Cubic Ft.)	Basal Area 5/ (Square Ft.)	Merchantable 6/ Trees Remaining	Cumulative 7/ Net Present Value ($/acre)
30	6.4	1464	1692	67	300	-403.0
40	9.7	0	3466	112.6	251	-403.0
50	11.6	0	5014	142	192	-403
60	14.0	3346	3720	96	90	- 90.1
70	16.74	1595	3808	92	60	74.1
80	19.5	1151	4061	93	45	196.6
90	22.0	1646	3621	80	30	371.1
100	24.6	4546	0	0	0	831.0

1/ Site 140 Douglas-fir, 1200-ft. skyline, 3 percent discount rate.
2/ Quadratic mean diameter of merchantable volume cut.
3/ Merchantable volume per acre including merchantable mortality.
4/ Merchantable volume per acre remaining after entry.
5/ Merchantable basal area per acre remaining after entry.
6/ Merchantable trees per acre remaining after entry.
7/ Cumulative single rotation net present value per acre after entry.

TABLE 35. RUN #6 - SUMMARY OF FINAL HARVEST AND PRESENT WORTH DATA FOR CHANGE IN PRICE-DIAMETER RELATIONSHIP 1/

Rotation Age (Years)	Final Harvest 2/ Volume (Cubic Feet)	Harvest 3/ Diameter (Inch)	Harvest Basal 4/ Area (Square Feet)	Present Net 5/ Worth ($/acre)	Infinite Series 6/ Present Worth ($/acre)
40	5718.24	7.97	162.46	-217.73	-313.99
50	5655.44	11.81	138.74	182.00	235.78
60	7066.21	13.97	163.44	497.94	599.73
70	4652.44	16.90	97.31	666.51	762.86
80	5212.74	19.46	106.04	771.07	851.05
90	5266.94	22.07	105.00	822.12	883.93
100	4546.02	24.16	88.65	830.96	876.57
110	2667.93	26.25	51.12	803.76	836.13

1/ Site 140 Douglas-fir, 1200-ft. skyline, 3 percent discount rate.
2/ Includes merchantable mortality at final harvest, does not include thinnings.
3/ Quadratic mean diameter of merchantable volume in final harvest.
4/ Basal area per acre of merchantable volume in final harvest.
5/ Single rotation present net worth for corresponding rotation age.
6/ Soil expectation or bare land value for corresponding rotation age.

<u>Effect of Noncommercial Thinning Constraint</u>

Some forest managers, due to cash flow or other management constraints, are interested in the optimal management regime when all thinnings "must pay for themselves" or, in other words, yield a positive addition to cumulative net present worth. This can be accomplished within the optimization algorithm with minor changes in code discussed in Chapter V. The result of introducing an additonal constraint will be a thinning regime which will have a net present worth equal or less than the unconstrained problem. To illustrate this, consider the thinning regime under the price-diameter relationship P=9.91+100*D of the previous section. A noncommercial thinning was on the optimal path at age 30 and added a negative contribution to net present worth of -$203 per acre. The cumulative present net worth of this strategy for a single rotation was $831 per acre. If noncommercial thinnings are not permitted for the same example, entry into the stand is delayed until year 70 and the cumulative single rotation present worth is $750 per acre or a reduction in present worth of 10 percent. The thinning regimes with and without the noncommerical thinning constraint are compared in Table 36. The delayed entries in the constrained thinning example produced a total yield of 13,123 cubic feet per acre over the rotation compared to 13,748 cubic feet from the unconstrained example, or a reduction of 5 percent due to mortality loss. Detailed statistics for the constrained thinning example are provided in Tables 37 and 38.

TABLE 36. EFFECT OF NONCOMMERCIAL THINNING CONSTRAINT.

	Run #6 No Thinning Constraint		Run #7 Thinning Constraint	
Age (years)	Diameter (inches)	Volume Cut (cf/acre)	Diameter (inches)	Volume Cut (cf/acre)
30	6.4	1464	6.4	0
40	9.7	0	8.0	0
50	11.6	0	9.7	0
60	14.0	3346	11.4	0
70	16.7	1595	12.9	6851
80	19.5	1151	15.3	774
90	22.0	1646	17.6	1073
100	24.6	4546	19.7	4425
		13,748		13,123

TABLE 37. RUN #7 - THINNING SCHEDULE WITHOUT NONCOMMERCIAL THINNINGS 1/

Age (Years)	Diameter 2/ (inch)	Volume Cut 3/ (Cubic Ft.)	Volume Left 4/ (Cubic Ft.)	Basal Area 5/ (Square Ft.)	Merchantable 6/ Trees Remaining	Cumulative 7/ Net Present Value ($/acre)
30	6.4	0	3157	126	560	-200
40	8.0	0	4993	163	468	-200
50	9.7	0	6543	185	358	-200
60	11.4	0	7872	203	286	-200
70	12.9	6851	2838	68	75	301.1
80	15.3	774	3354	77	60	342.3
90	17.6	1073	3445	76	45	415.2
100	19.7	4425	0	0	0	749.8

1/ Site 140 Douglas-fir, 1200-ft. skyline, 3 percent discount rate.
2/ Quadratic mean diameter of merchantable volume cut.
3/ Merchantable volume per acre including merchantable mortality.
4/ Merchantable volume per acre remaining after entry.
5/ Merchantable basal area per acre remaining after entry.
6/ Merchantable trees per acre remaining after entry.
7/ Cumulative single rotation net present value per acre after entry.

TABLE 38. RUN #7 - SUMMARY OF FINAL HARVEST AND PRESENT WORTH DATA WITHOUT NONCOMMERCIAL THINNINGS 1/

Rotation Age (Years)	Final Harvest Volume (Cubic Feet) 2/	Harvest Diameter (Inch) 3/	Harvest Basal Area (Square Feet) 4/	Present Net Worth ($/acre) 5/	Infinite Series Present Worth ($/acre) 6/
40	5718.24	7.97	162.46	-217.73	-313.99
50	7261.11	9.73	185.10	59.38	76.92
60	8570.24	11.39	202.76	425.34	512.29
70	9689.05	12.35	217.35	602.26	689.32
80	4835.12	15.21	97.49	661.77	730.41
90	4517.66	17.57	88.78	727.29	781.97
100	4424.79	19.74	85.57	749.82	790.98
110	3632.76	21.59	69.18	745.06	775.06

1/ Site 140 Douglas-fir, 1200-ft. skyline, 3 percent discount rate.
2/ Includes merchantable mortality at final harvest, does not include thinnings.
3/ Quadratic mean diameter of merchantable volume in final harvest.
4/ Basal area per acre of merchantable volume in final harvest.
5/ Single rotation present net worth for corresponding rotation age.
6/ Soil expectation or bare land value for corresponding rotation age.

Effect of Change in Discount Rate

Raising the discount rate shortens the rotation and reduces bare land values as later returns become progressively less valuable than earlier returns. Increasing the discount rate from 3 percent to 5 percent for the 1200-foot skyline with conventional yarding reduced rotation length approximately 30 years with a final harvest at year 70. No thinning is on the optimal path for the 70-year rotation and single rotation present worth is negative with an average internal rate of return of 4.0 percent. An alternative rotation age at year 80 has a slightly lower present worth. The thinning regime for final harvest at year 80 scheduled a heavy thinning at year 70 reducing carrying costs for the remainder of the rotation. Detailed thinning and final harvest statistics are in Tables 39 and 40.

TABLE 39. RUN #8 - THINNING SCHEDULE FOR INCREASE IN DISCOUNT RATE 1/

Age (Years)	Diameter 2/ (inch)	Volume Cut 3/ (Cubic Ft.)	Volume Left 4/ (Cubic Ft.)	Basal Area 5/ (Square Ft.)	Merchantable 6/ Trees Remaining	Cumulative 7/ Net Present Value ($/acre)
30	6.4	0	3157	126	560	-200
40	8.0	0	4993	162	468	-200
50	9.7	0	6543	185	358	-200
60	11.4	0	7872	203	286	-200
70	12.9	9689	0	0	0	- 94.7

1/ Site 140 Douglas-fir, 1200-ft. skyline, 5 percent discount rate.
2/ Quadratic mean diameter of merchantable volume cut.
3/ Merchantable volume per acre including merchantable mortality.
4/ Merchantable volume per acre remaining after entry.
5/ Merchantable basal area per acre remaining after entry.
6/ Merchantable trees per acre remaining after entry.
7/ Cumulative single rotation net present value per acre after entry.

TABLE 40. RUN #8 - SUMMARY OF FINAL HARVEST AND PRESENT WORTH DATA FOR INCREASE IN DISCOUNT RATE 1/

Rotation Age (Years)	Final Harvest 2/ Volume (Cubic Feet)	Harvest 3/ Diameter (Inch)	Harvest Basal 4/ Area (Square Feet)	Present Net 5/ Worth ($/acre)	Infinite Series 6/ Present Worth ($/acre)
40	5718.24	7.97	162.46	-362.70	-422.74
50	7261.11	9.73	185.10	-244.25	-267.58
60	8570.24	11.39	202.76	-130.06	-137.42
70	9689.05	12.93	217.35	- 94.69	- 97.90
80	3371.66	15.39	66.59	- 97.60	- 99.61

1/ Site 140 Douglas-fir, 1200-ft. skyline, 5 percent discount rate.
2/ Includes merchantable mortality at final harvest, does not include thinnings.
3/ Quadratic mean diameter of merchantable volume in final harvest.
4/ Basal area per acre of merchantable volume in final harvest.
5/ Single rotation present net worth for corresponding rotation age.
6/ Soil expectation or bare land value for corresponding rotation age.

Management Regime Under Bunch-and-Swing Yarding Systems

In Chapter IV, bunch-and-swing was shown to have cost advantages over conventional yarding for handling small pieces and low volumes per acre. The small yarder was used to prebunch logs along the skyline corridor for the large yarder to forward up the corridor to the landing. The primary advantages were the reduction in operating costs associated with log gathering and a larger number of logs per turn during inhaul. To test the sensitivity of management regime to this log gathering technique, the bunch-and-swing model was added to the harvest subroutine. The optimization algorithm was provided the option of using either the bunch-and-swing yarding method or the conventional yarding method for removals in stands less than 15 inches in diameter. In stands over 15 inches in diameter, the conventional yarder was more competitive. Setting depth for prebunching alternatives was held constant at 50 feet and a rectangular prebunch setting was assumed. Swing payloads were limited to the lessor of 10 logs or 7500 pounds. With these assumptions the optimal thinning regime with the bunch-and-swing option provided a single rotation present worth of $366.7 per acre, or 22 percent greater than yarding a similar unit by conventional yarding systems exclusively. The initial stand entry was at year 70 with final harvest at year 100. A comparison of thinning regimes with conventional versus the bunch-and-swing system/conventional system is shown in Table 41. The earlier entry in the bunch-and-swing alternative provided a larger yield over the rotation, primarily from capture of mortality.

TABLE 41. EFFECT ON MANAGEMENT REGIME BY ADDITION OF THE BUNCH-AND-SWING ALTERNATIVE.

	Run #1		Run #9	
	Conventional Yarding		Bunch-and-Swing/Conventional	
Age (years)	Diameter (inches)	Volume Cut (cf/acre)	Diameter (inches)	Volume Cut (cf/acre)
30	6.4	0	6.4	0
40	8.0	0	8.0	0
50	9.7	0	9.7	0
60	11.4	0	11.4	0
70	12.9	0	12.9	6284
80	14.3	7719	15.2	700
90	16.5	0	17.3	974
100	18.6	4606	19.4	5631
		12,325		13,589

TABLE 42. RUN #9 - THINNING SCHEDULE WHEN BUNCH AND SWING IS PERMITTED 1/

Age (Years)	Diameter 2/ (inch)	Volume Cut 3/ (Cubic Ft.)	Volume Left 4/ (Cubic Ft.)	Basal Area 5/ (Square Ft.)	Merchantable 6/ Trees Remaining	Cumulative 7/ Net Present Value ($/acre)
30	6.4	0	3157	126	560	-200
40	8.0	0	4993	163	468	-200
50	9.7	0	6543	185	358	-200
60	11.4	0	7872	203	286	-200
70	12.9	6284	3406	82	90	61.3
80	15.2	700	4135	95	75	77.7
90	17.3	974	4472	98	60	104.1
100	19.4	5631	0	0	0	366.7

1/ Site 140 Douglas-fir, 1200-ft. skyline, 3 percent discount rate.
2/ Quadratic mean diameter of merchantable volume cut.
3/ Merchantable volume per acre including merchantable mortality.
4/ Merchantable volume per acre remaining after entry.
5/ Merchantable basal area per acre remaining after entry.
6/ Merchantable trees per acre remaining after entry.
7/ Cumulative single rotation net present value per acre after entry.

TABLE 43. RUN #9 - SUMMARY OF FINAL HARVEST AND PRESENT WORTH DATA WHEN BUNCH AND SWING IS PERMITTED 1/

Rotation Age (Years)	Final Harvest 2/ Volume (Cubic Feet)	Harvest 3/ Diameter (Inch)	Harvest Basal 4/ Area (Square Feet)	Present Net 5/ Worth ($/acre)	Infinite Series 6/ Present Worth ($/acre)
40	4116.08	9.16	109.24	-488.17	-703.97
50	5655.44	11.81	138.74	-165.81	-214.81
60	8570.24	11.39	202.76	121.79	146.68
70	9689.05	12.93	217.35	318.33	318.33
80	4835.12	15.21	97.49	326.84	360.74
90	5445.51	17.34	108.07	354.88	381.56
100	5631.35	19.38	109.88	366.74	386.87

1/ Site 140 Douglas-fir, 1200-ft. skyline, 3 percent discount rate.
2/ Includes merchantable mortality at final harvest, does not include thinnings.
3/ Quadratic mean diameter of merchantable volume in final harvest.
4/ Basal area per acre of merchantable volume in final harvest.
5/ Single rotation present net worth for corresponding rotation age.
6/ Soil expectation or bare land value for corresponding rotation age.

Multiple Regimes Under A Common Skyline

The optimization algorithm, DOPT, implicitly assumes that all acres under the skyline are treated equally. There is no reason to believe, a priori, that this assumption assures present worth maximization. Due to increases in yarding cost as a function of yarding distance, alternative strategies which vary management intensity along the skyline may be superior to the equal treatment strategy. This section will examine two alternative strategies and compare the present worth of these alternative regimes with the single regime return. A general formulation will be presented.

Mixed Strategies

To test the sensitivity of present worth to changes in yarding distance, two alternative strategies are formulated for the 1200-ft skyline:

(1) Treat the first 600 feet as a separate 600-foot skyline for thinning regime, and let the remaining 600 feet grow as a natural unthinned stand which would be harvested at the same age the final harvest for the first 600 feet was prescribed.

(2) Treat the first 300 feet as a separate 300-foot skyline for thinning regime, and let the remaining 300 feet grow as a natural unthinned stand which would be harvested at the same age the final harvest for the first 300 feet was prescribed.

Comparison With Single Regime Returns

For Alternative (1), the equal treatment strategy was superior to the mixed strategy of intensively managing the first 600 feet and letting the last 600 feet grow naturally. The single rotation present worth for all rotation ages with the equal treatment exceeded the alternative strategy except at a rotation age of 90 years as shown in Figure 28.

For Alternative (2), the equal treatment strategy was inferior to the mixed strategy of intensively managing the first 300 feet and letting the remaining 900 feet grow naturally. Single rotation present worth for rotation ages from 70 to 100 years with the mixed strategy exceeded the equal treatment strategy. At age 90, the weighted net present worth per acre for the mixed strategy was $338.88 per acre or 13 percent higher than for the equal treatment strategy as shown in Figure 29. The thinning regime for Alternative (2) requires a noncommercial entry at age 30 to stimulate diameter growth. By age 40, returns from thinnings are positive. Volume removals during the early decades do not exceed 2000 cubic feet per acre, taking advantage of economies afforded by both the smaller crew [13/] and the ability to store the entire volume on the landing.

The present worth of the mixed treatment alternatives peak more rapidly than the equal treatment alternative. This follows statements by Duerr (1960) concerning the ability to carry a stand longer by reducing stocking through thinning. Should a manager

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13/ Neilsen (1977) observes that only one man was required to pull slack manually at distances up to 500 feet on steep slopes.

implement Alternative (2), delaying the rotation past 90 years rapidly reduces net present worth.

General Formulation

The choice of mixed strategies has been arbitrary. No claim is made that Alternative (2) is optimal, only that it is superior to the equal treatment strategy for the conditions of this example. To find the mixed strategy which maximizes net present worth requires incorporation of the skyline partition variable, ℓ, into the optimal value function of the dynamic programming problem. Using the terminology from Chapter V, the rotation age t and skyline partition ℓ which maximize single rotation present worth, V_{se}, is that combination of (t,ℓ) which satisfies the relationship

$$V_{pv} = \max_{\{t,\ell\}} [f_t(0,0)_\ell + f_{tn}(0,0)_{L-\ell}]$$

where,

$f_t(0,0)_\ell$ = maximum present worth of cumulative thinnings plus final harvests over all feasible (N,B) combinations at age t-10 if regeneration harvested at age t over skyline span ℓ.

$f_{tn}(0,0)_{L-\ell}$ = present worth of final harvest of an unthinned natural stand of age t for the remainder of the skyline span, $L-\ell$.

The rotation age and skyline partition which maximize the infinite series present worth, V_{se}, is that combination of (t,ℓ) which satisfies the relationship

$$V_{se} = \max_{\{t,\ell\}} \left| [f_t(0,0) + f_{tn}(0,0)_{L-\ell}][\frac{(1+i)^t}{(1+i)^t-1}] \right|$$

where the variables are defined as previously. This study does not pursue mixed strategies beyond the two examples previously discussed.

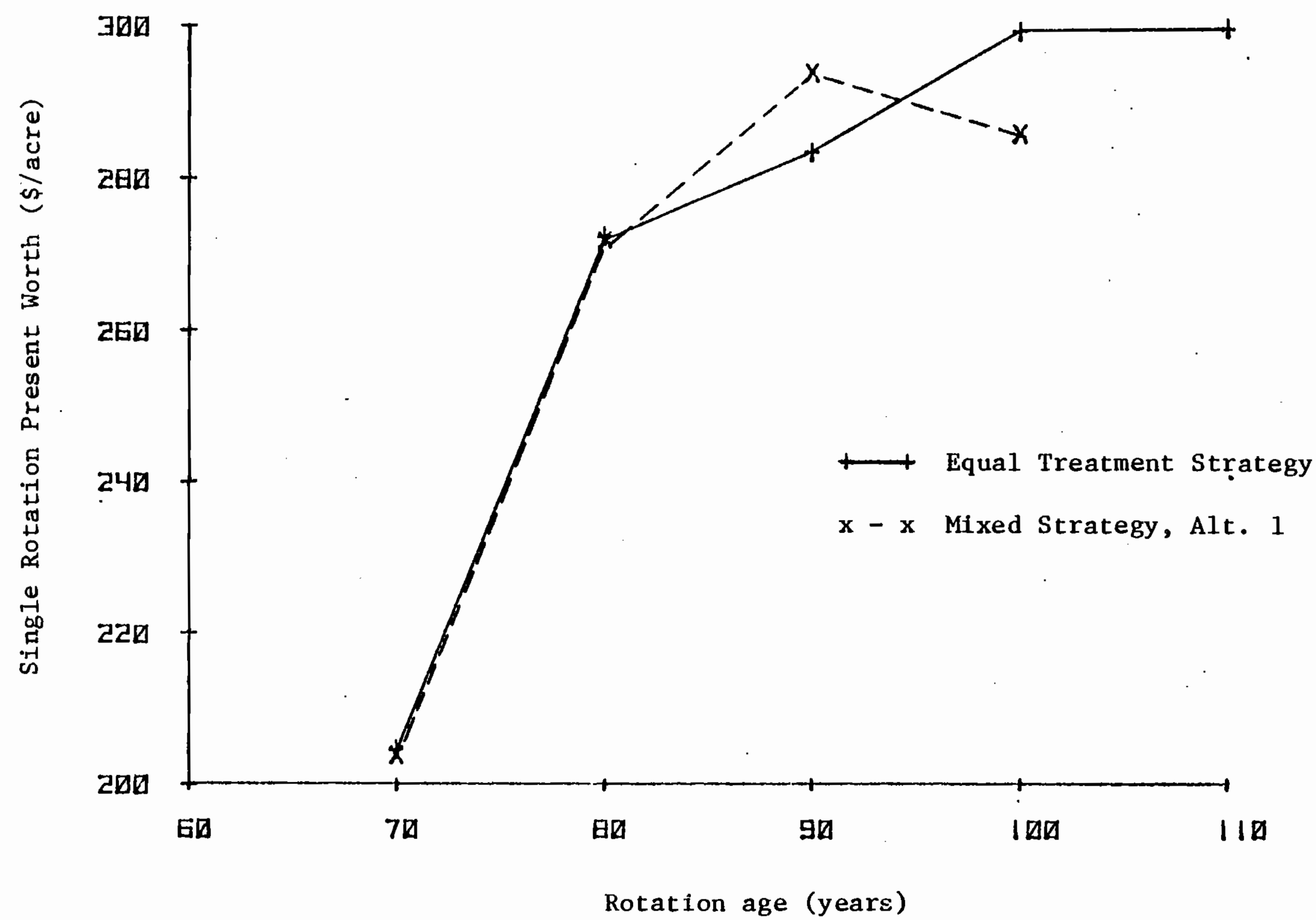

Figure 28. Single rotation present worth for mixed strategy Alternative 1 and the equal treatment strategy.

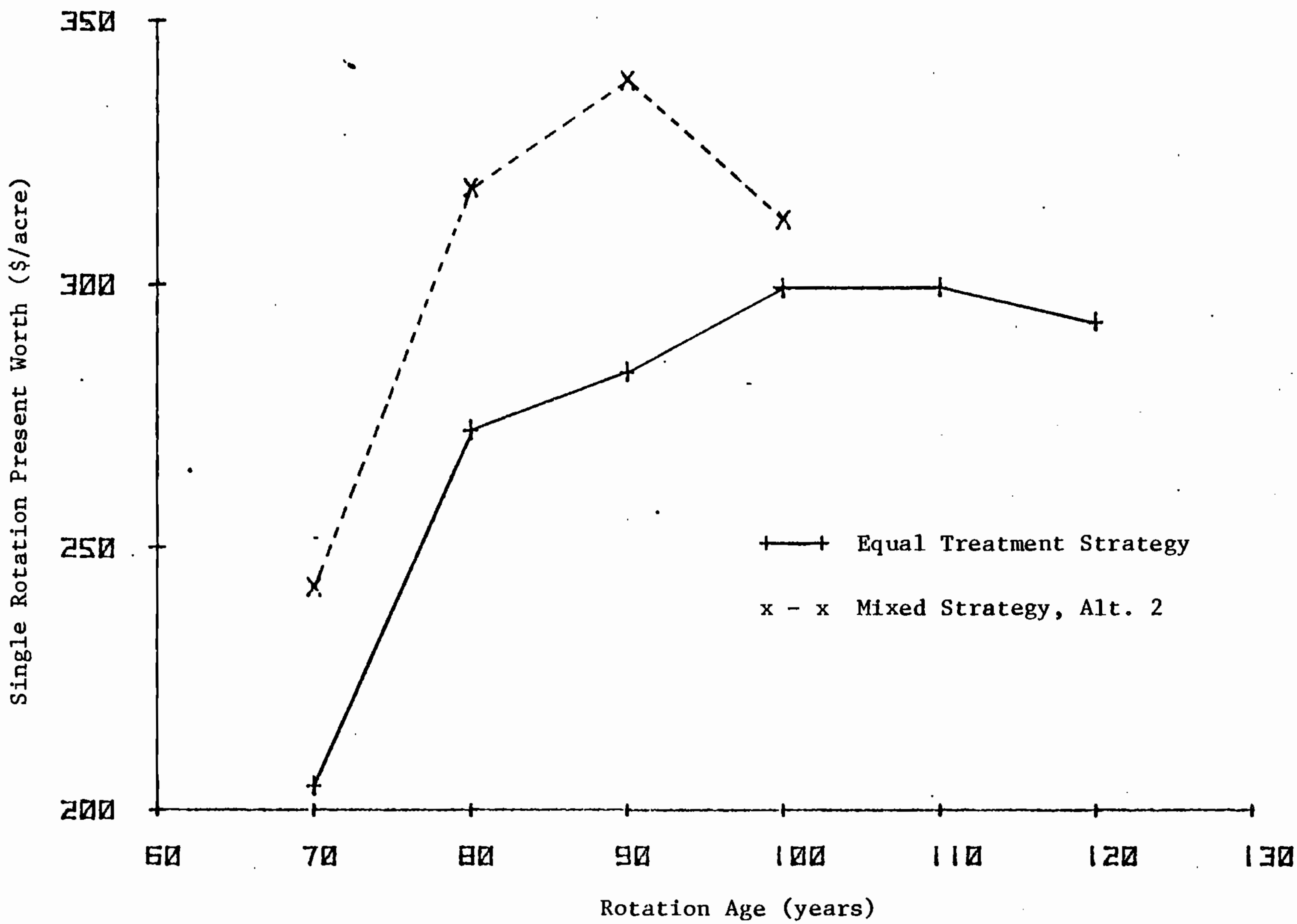

Figure 29. Single rotation present worth for mixed strategy Alternative 2 and the equal treatment strategy.

TABLE 44. SINGLE ROTATION PRESENT NET WORTHS FOR THE EQUAL TREATMENT STRATEGY FOR A 1200-FT. SKYLINE VERSUS TREATING THE FIRST 600 FEET INTENSIVELY AND LETTING THE REMAINING 600 FEET GROW UNTHINNED.

Age (years)	Thin 1st 600 Feet Single Rotation NPW ($/acre)	Do Not Thin 2nd 600 Feet Single Rotation NPW ($/acre)	Weighted Average Single Rotation NPW ($/acre)	Equal Treatment Single Rotation NPW ($/acre)
70	254.01	154.06	204.04	204.70
80	308.21	236.09	272.15	272.64
90	330.85	257.37	294.11	283.67
100	345.71	226.78	286.25	299.58
110	--	--	--	299.80
120	--	--	--	293.17

TABLE 45. SINGLE ROTATION PRESENT NET WORTHS FOR THE EQUAL TREATMENT STRATEGY FOR A 1200-FT. SKYLINE VERSUS TREATING THE FIRST 300 FEET INTENSIVELY AND LETTING THE REMAINING 900 FEET GROW UNTHINNED.

Age (years)	Thin 1st 300 Feet Single Rotation NPW ($/acre)	Do Not Thin Last 900 Feet Single Rotation NPW ($/acre)	Weighted Average Single Rotation NPW ($/acre)	Equal Treatment Single Rotation NPW ($/acre)
70	434.66	178.58	242.60	204.70
80	512.37	253.80	318.44	272.64
90	545.60	269.97	338.88	283.67
100	544.17	235.54	312.70	299.58
110	--	--	--	299.80
120	--	--	--	293.17

TABLE 46. RUN #10 - THINNING SCHEDULE FOR 300-FT. SKYLINE USING A TWO-MAN YARDING CREW 1/

Age (Years)	Diameter 2/ (inch)	Volume Cut 3/ (Cubic Ft.)	Volume Left 4/ (Cubic Ft.)	Basal Area 5/ (Square Ft.)	Merchantable 6/ Trees Remaining	Cumulative 7/ Net Present Value ($/acre)
30	6.4	1549	1608	64	285	-422.5
40	9.2	1579	2538	82	180	-369.4
50	12.3	1697	3056	86	105	-267.7
60	15.4	1904	3034	78	60	- 83.1
70	18.6	976	3542	85	45	0.0
80	21.6	1491	3350	77	30	140.5
90	24.6	4361	0	0	0	545.6

1/ Site 140 Douglas-fir, 3 percent discount rate.
2/ Quadratic mean diameter of merchantable volume cut.
3/ Merchantable volume per acre including merchantable mortality.
4/ Merchantable volume per acre remaining after entry.
5/ Merchantable basal area per acre remaining after entry.
6/ Merchantable trees per acre remaining after entry.
7/ Cumulative single rotation net present value per acre after entry.

TABLE 47. RUN #10 - SUMMARY OF FINAL HARVEST AND PRESENT WORTH DATA FOR 300-FT. SKYLINE USING A TWO-MAN YARDING CREW 1/

Rotation Age (Years)	Final Harvest 2/ Volume (Cubic Feet)	Harvest 3/ Diameter (Inch)	Harvest Basal 4/ Area (Square Feet)	Present Net 5/ Worth ($/acre)	Infinite Series 6/ Present Worth ($/acre)
40	4116.08	9.16	109.24	-331.08	-477.44
50	4495.67	12.41	106.03	9.65	12.50
60	4454.60	15.76	97.46	262.69	316.39
70	4517.40	18.63	94.62	434.66	497.49
80	4840.47	21.64	98.73	512.37	565.51
90	4360.74	24.55	86.68	545.60	586.62
100	2804.56	27.33	54.64	544.17	574.04

1/ Site 140 Douglas-fir, 3 percent discount rate.
2/ Includes merchantable mortality at final harvest, does not include thinnings.
3/ Quadratic mean diameter of merchantable volume in final harvest.
4/ Basal area per acre of merchantable volume in final harvest.
5/ Single rotation present net worth for corresponding rotation age.
6/ Soil expectation or bare land value for corresponding rotation age.

VII. SUMMARY AND CONCLUSIONS

This study has introduced a unified theory of harvesting in mountainous terrain which brings together silvicultural method, harvesting technology, product yield, and product price to identify the optimal stocking regime for the maximization of net present worth. In the absence of suitable techniques for predicting harvesting costs as a function of the specific diameter distribution to be removed from the stand, the first part of the research has concentrated upon model development of a harvesting simulator for mountainous terrain. Considerable detail has been devoted to discussion of the validity of model assumptions concerning log distributions, heuristic rules for log gathering, and the cost sensitivity with respect to the shape of the diameter distribution.

The procedure used to generate the harvest costs represents an initial attempt to explicitly incorporate equipment characteristics, topography, and silvicultural method directly into the harvest cost model for simulation of harvesting in mountainous terrain. Other attempts consider these relationships implicitly resulting in model formulations which do not relate variables of interest including log load, diameter distribution of the cut, and volume per acre. A discussion of the experimental design leading to these "implicit" model structures has been discussed in Chapter III.

Given the specifics of topography, stand structure, and thinning density, the harvesting simulator provides a consistent set of cost curves expressing harvest costs as a function of mean stand diameter and volume per acre. Harvesting cost has been shown to be more sensitive to the mean stand diameter of the trees to be removed than to the particular shape of the diameter distribution.

The harvesting simulator was tested against two time studies of Douglas-fir thinning in mountainous terrain and was found to compare favorably with field observations.

To develop the relative harvesting costs for illustration in the stocking level analysis, two skyline yarders typical of the range expected to be operating in second growth Douglas-fir were evaluated using the simulator. The results from simulating harvest activities of the two yarders suggest that single best yarding machine may not exist. The larger yarder was relatively more efficient over longer distances and greater volumes per acre due to its higher line speeds and greater payload capability. The small yarder was more efficient at short distances and low volumes per acre due to its lower owning and operating cost. The resulting locus of points defining the minimum cost envelope was shown to be highly nonlinear. Analysis of the harvesting cost results indicate that over the range of values analyzed, the elasticity of harvest cost with respect to volume removed is constant for a given mean diameter of material removed. The power curve model was found to fit individual segments of the cost curves with the lowest R-squared value being 0.91.

Costs from the harvest simulator were combined with a Douglas-fir growth model in a three descriptor dynamic programming structure. The potential effects of diameter growth acceleration were modeled through biometric relationships between the three descriptors; stand age, trees per acre, and basal area per acre.

The optimal thinning regime and optimal rotation age were determined simultaneously for a medium site Douglas-fir example under a predetermined set of average conditions. The sensitivity of optimal stocking level to harvest technology variables of yarding direction, yarding distance, truck transport cost, and log gathering strategies was examined. Under assumed cost differentials between uphill and downhill yarding, bare land values for downhill yarding are lower than for uphill yarding and the optimal management intensity is lower with less frequent, heavier entries.

Increases in yarding cost with distance indicate that optimal stocking levels not only depend on traditional concepts of prices and costs, but that management intensity is also spatially oriented. The three descriptor dynamic programming model permitted alternative generation over the number of trees, basal area, and stand age. The implicit assumption of this model structure is that variations in the three parameters cover the full set of important solutions to the stocking problem. Other options were shown to exist including varying management intensity along the skyline. It was demonstrated that due to the technical production functions involved, managing the stand more intensively at shorter yarding distances than at longer yarding distances markedly incresed cumulative net present worth over the equal treatment strategy.

Haul costs are exogenous to the harvesting cost simulation. However, reductions in haul cost increase bare land values by at least the magnitude of the present value of the haul cost decrease and may increase the optimal level of management intensity.

The sensitivity of stocking regime to log gathering technique is examined by formulating a prebunch model which stratifies the log handling activity into two components. Logs are first gathered into bunches along the skyline corridor, and then the bunches are forwarded up the corridor to roadside. Results from the small yarder simulation are used as the basis for the prebunching production estimates and the large yarder production relationships are used to generate costs for the forwarding activities. Prebunching and forwarding under the model assumptions is found not only to increase bare land values but in some circumstances to reduce the cost of handling early thinnings sufficiently to justify noncommercial entries to accelerate diameter growth.

Changes in price, due to increased price intercept or increased slope resulted in raising the relative value of diameter growth acceleration and thinning schedules would be moved forward in time. Increasing the discount rate increased the relative weight of earlier returns the optimal management regime predictably shortened the rotation, as well in this example, driving land values negative.

Increasing the diameter premium produced a thinning regime which yielded early thinnings with negative contribution to net present worth in order to promote future diameter growth. Although such actions, often referred to as noncommercial thinnings, are not common on either private or public lands in the Douglas-fir region, under appropriate conditions noncommercial thinning can substantially increase cumulative net present worth.

One must conclude that the determination of optimal stocking levels in mountainous terrain can be extremely sensitive to the topographic variables of yarding direction, yarding distance, and skyline payload capacity and the stand variables of diameter and volume per acre. Casual advice to forest managers concerning the timing and magnitude of stand removals can lead to poor estimates of the optimal stocking regime without detailed information concerning local production functions. Such generalizations as thinning stumpage can be valued as a constant fraction of final harvest stumpage, that capture of mortality is necessary, and that all thinnings must pay can lead to substantial reductions in bare land values if present worth maximization is the manager's objective.

Suggestions for Additional Research

During the development and testing of the methodologies considered in this study, several areas were identified in which additional research might increase understanding of forest management-harvest operation interactions. These include:

1. Additional analysis of log distributions resulting from silvicultural operations. This study assumed logs were randomly distributed over the unit without regard to the specific trees from which they originated. Increased log density along the skyline corridor from trees removed to permit carriage passage

was ignored. Incorporation of nonrandom log distributions into the model requires only minor changes in code and would facilitate simulation of harvest units where a change of site or stocking is known to exist along the skyline in either a longitudinal or lateral direction. Approaches to individual tree modeling similar to that used by Buongiorno and Teeguarden (1973) might prove useful for addressing in more depth the edge effects of trees falling into and out of the harvest unit.

2. Generalization of the model to fan-shaped units. This study was limited to rectangular units. Direct transformation of the simulation results to account for changes in fixed and variable costs could easily be done. An alternative to direct transformation would be the introduction of triangular log density distributions during simulation.

3. The bunch-and-swing model was a first attempt. Joint optimization over the setting depth, setting width, and setting angle variables should improve realism of the model as well as incorporation of results from current studies being conducted by Keller (1978).

4. The computer program for the harvesting simulator should be considered experimental. Improvements in the sorting algorithms could substantially reduce computing time.

5. The optimization algorithm restricted alternative generation to three descriptors. All alternatives evaluated assumed mean stand diameter before and after thinning to be equal or a

thinning ratio of 1.00. To vary the thinning ratio would require adding a fourth descriptor to the optimization model. This would require development and research in three areas:

A. Additional harvest simulations for different thinning ratios. This is straight forward providing the diameter distribution of the trees to be removed from the stand is known.

B. Extension of the harvest subroutine of the optimization algorithm to include the thinning density variable. The present harvest cost subroutine requires two descriptors; mean stand diameter and volume per acre to be removed. Extension of the harvest cost subroutine would require three descriptors with the most likely candidates being thinning ratio, mean stand diameter after thinning, and volume per acre. Preliminary examination of the relationships of harvest cost sensitivity to stand variance indicates that relatively rough representation of harvest cost as a function of thinning ratio will be sufficiently accurate.

C. Addition of the fourth descriptor to the optimization algorithm requires only minor changes in code. The major problem is storage of node values during computation. At present all node values for the current stage and the previous stage are being stored in core. The present tree interval of 15 trees and 4 square feet of basal area requires the full core capacity of the computer system employed.[14/] Incorporation of a fourth descriptor would require changing to either a coarser grid or changing the structure of the data handling to the use of tape operations.

6. This study has used only fixed intervals for the number of trees removed during optimization. Investigation of the variable interval approach discussed in Chapter V may lead to savings in computation time for a given level of accuracy as well as reduced core requirements.

Concluding Remarks

The methodology which has been developed in this study provides the forest manager with insights into the relationship between harvesting technology and the planning of thinning regime and rotation age in mountainous terrain. It should be emphasized that the procedure is general, and the results of the Douglas-fir example should not be considered an inflexible rule. Rather, it should be remembered that harvesting costs are strongly related to stand composition, silvicultural method, and topography; and, that thinning regime is strongly dependent on harvesting costs.

The model formulated, like all models, is an abstraction of reality. This model integrates harvesting technology directly into the

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14/ A CYBER 70, CDC 6400 computer with an in-core memory of approximately 130 K words.

decision making process, thereby exposing the many alternatives available. It is not considered a final product, but rather a beginning. Gaps in basic data and roughness of the formulation have been cited and provide areas where the model can be extended and improved.

It is recognized that the abstraction of the forest considered in this study is the individual harvest unit, the so-called "basic building block" of forest operations. Although the sum of the harvest units is the forest, the sum of the block strategies is not the forest strategy. Forests are not homogeneous entities operating in isolation. Constraints exogenous to the forest often strongly influence forest strategy. It is not suggested that the optimal thinning regime and rotation age determined by use of this optimization procedure be adopted as a forest-wide policy. The primary value of applications of this methodology should be to establish the basic opportunities for management of individual harvest units. Large scale resource allocation models, particularly of the structure implemented by Navon (1972) readily accept the optimal and near-optimal strategies generated by these procedures to schedule activities over the entire forest.

In conclusion, <u>if</u> this study contributes to clarifying relationships between harvesting technology and silvicultural prescriptions in mountainous terrain, it will have made a contribution to one of the fundamental activities of the forest manager.

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APPENDICES

APPENDIX I.

QUADRATIC DIAMETER - MEAN DIAMETER RELATIONSHIPS

The DFIT model expresses diameter as the mean quadratic diameter. The mean quadratic diameter of a stand is defined as the diameter of the tree of mean basal area. The mean quadratic diameter is a biased estimator of the true mean diameter of a diameter distribution. It is of interest to know the relationship between the quadratic mean diameter and the unbiased mean diameter. The derivation follows:

Let D_N = unbiased mean diameter

D_Q = quadratic mean diameter

A_N = unbiased mean basal area

f_i = relative frequency of diameter class i, D_i

N = number of trees in stand

then,

$$A_N = \frac{\Sigma A_i}{N} = \frac{\Sigma \frac{\pi D_i^2}{4}}{N} = \frac{\pi}{4N} \Sigma D_i^2 \qquad \text{Eq. 1}$$

$$D_Q = \left(\frac{4 A_N}{\pi} \right) = \left(\frac{\Sigma D_i^2}{N} \right) = \left(\frac{\Sigma f_i D_i^2}{\Sigma f_i} \right) \qquad \text{Eq. 2}$$

$$\frac{D_Q}{D_N} = \left(\frac{\Sigma f_i D_i^2}{\Sigma f_i} \right) \bigg/ \frac{\Sigma f_i D_i}{\Sigma f_i} = \left(\Sigma f_i \cdot \frac{\Sigma f_i D_i^2}{(\Sigma f\ D_i)^2} \right) \qquad \text{Eq. 3}$$

Eq. 6 holds for any distribution with a finite mean.

The derivation can be carried several steps furthur to derive a useful relationship between the D_Q/D_N ratio and the stand variance as follows:

$$\left(\frac{D_Q}{D_N}\right)^2 = \Sigma f_i \frac{\Sigma f_i D_i}{(\Sigma f_i D_i)^2} \qquad \text{Eq. 4}$$

If D_i represents the distance from the origin to a mass f_i, then the product $D_i f_i$ represents the first moment about the origin. Similarly, $D_i^2 f_i$ is the second moment about the origin. A useful mathematical property is that the sum of the second moments about the origin can be partioned into two components (Timoshenko, 1972) as follows:

Σ second moments about the origin	=	Σ second moments about center of mass	+	product of mass times distance squared between the origin and the center of mass

If, the center of mass is located at a distance u from the origin, then

$$\Sigma f_i D_i^2 = \Sigma f_i (D_i - u)^2 + (\Sigma f_i)(u^2) \qquad \text{Eq. 5}$$

Substituting into Eq. 4 and noting that $\Sigma f_i = 1$ yields

$$\left(\frac{D_Q}{D_N}\right)^2 = \frac{\Sigma f_i (D_i - u)^2 + u^2}{u^2} \qquad \text{Eq. 6}$$

Since $\Sigma f_i (D_i - u)^2$ is the definition of the variance, σ^2, then Eq. 6 simplifies to

$$\frac{D_Q}{D_N} = \left(\frac{\sigma^2 + u^2}{u^2}\right) \qquad \text{Eq. 7}$$

Eq. 7 holds for any distribution with finite mean. Since D_N by definition is equal to u, then given the quadratic mean, D_Q, the true mean diameter can be calculated by

$$D_N = (D_Q^2 - \sigma^2)^{\frac{1}{2}} \qquad \text{Eq. 8}$$

Since variance is always positive, the bias is always positive, with D_Q larger than D_N.15/

15/ Derived with generous assistance from E. Schneider, Logging Systems Training Program, Oregon State University, Corvallis, Oregon.

APPENDIX II.

SOME ASPECTS OF LOG SORTING

It can be shown that the sum of n integers is (Kmenta 1975)

$$\sum_{i=1}^{n} i = \frac{1}{2} (n) (n + 1) \qquad \text{Eq. 1}$$

For just one outhaul equal in length, L, to the entire skyline unit then the average number of sorts expected will be 1/2 of Eq. (1) or

$$N = \frac{1}{2} \cdot \frac{(n) (n + 1)}{2} \qquad \text{Eq. 2}$$

For k outhaul blocks where each outhaul block is equal to L/k in length then N_k, the expected number of sorts per outhaul block will be

$$N_k = \frac{1}{2} \cdot \frac{\left(\frac{n}{k}\right)\left(\frac{n}{k} + 1\right)}{2} \qquad \text{Eq. 3}$$

and the expected total number of sorts per skyline length L, over all outhaul blocks will be

$$\bar{N}_k = \frac{k}{2} \cdot \frac{\left(\frac{n}{k}\right)\left(\frac{n}{k} + 1\right)}{2} \qquad \text{Eq. 4}$$

If we look at the ratio of $N_O/\bar{N}_k$, that is, the ratio of the total number of sorts expected for an outhaul block divided by the total time required to sort k blocks of length, L/k, we have

$$R = \frac{N_O}{\bar{N}_k} = \frac{n + 1}{\frac{n}{k} + 1} \qquad \text{Eq. 5}$$

for large n and small k, R tends to the limit

$$\lim R_{n \to \infty} = k \qquad \text{Eq. 6}$$

To test this derivation, two examples were run on the Cyber CDC 6400.

TABLE 48. SORT TIMES AS A FUNCTION OF LOGS AND BLOCK LENGTH.

Example #1	Run 1	Run 2
Number of Logs Sorted	538	528
Total Execution Time, sec.	1.102	3.691
Skyline Length, L	1200	1200
Outhaul Block Length	200	1200
Example #2		
Number of Logs Sorted	1499	1492
Total Execution Time, sec.	6.064	9.610
Skyline Length, L, ft.	1200	1200
Outhaul Block Length, L/k, ft.	200	400

If the total execution time is partitioned into two components, a constant not associated with the sorting routines, and a coefficient related to the number of outhaul blocks; the relationship can be expressed as

$$T = A + B\ (1/k) \qquad \text{Eq. 7}$$

where

T = total execution time

A = Constant not associated with sorting time

B = A coefficient related to the sort time as a function of the variable (1/k).

k = The number of outhaul blocks per skyline length.

Solving for coefficients A and B using the data from Example #1 and Example #2 gives

$$T = 0.584 + 3.108 * (1/k) \qquad \text{(Example \#1)}$$

$$T = 2.518 + 21.276 * (1/k) \qquad \text{(Example \#2)}$$

From Eq. 6, Example #1 should take six times the amount of time to run with k = 1 compared to k = 6. Subtracting the non-sort time from Example #1 and taking the ratio of sorting times yields,

$$R_{actual} = \frac{3.107}{0.518} = 5.998$$

Similarly, for Example #2 the ratio of the time required for the 400-foot outhaul block should take twice the time to yard the 1200-foot span with the 200-foot block. Subtracting the coefficient for nonsort time of 2.518 seconds,

$$R_{actual} = \frac{7.092}{3.546} = 2.000$$

The relationship between sort time and the number of outhaul blocks appears consistent with observed run times.

APPENDIX III.

OPTIMUM NUMBER OF LOGS PER TURN

The heuristic for load building each turn is to build the largest turn possible subject to the number of chokers, choker length, spatial distribution of the logs, and the maximum permissable load on the skyline. For the linear cycle time model used in this study, it can be shown that, in general, maximizing the number of logs per turn minimizes logging cost. The following derivation will assume all logs are the same size.

The cost per unit volume yarded can be expressed as,

$$\text{Cost} = \frac{(C_o)(T_o)}{V_L} + \frac{(CT)(C_1/60)}{(EH)(V_T)} \qquad \text{Eq. 1}$$

where,

Cost = Cost per unit volume, \$/cf

C_o = Cost per hour of rigging, \$/hr

C_1 = Cost per hour of yarding, \$/hr

T_o = Time required for rigging, hr

EH = Effective hour for yarding, decimal

V_L = Volume per landing, cf

V_T = Volume per turn, cf

N = Logs per turn

The first order conditions for cost minimization are, The first order conditions for cost minimization are,

$$\frac{d\ (\text{Cost})}{dN} = 0 = \frac{1}{V_T} \cdot \frac{d\ (CT)}{dN} + (CT) \cdot \frac{d\ (1/V_T)}{dN} \qquad \text{Eq. 2}$$

Defining $V_T = N \cdot V_L$, where V_L is the average volume per log, and substituting into Eq. 2 yields,

$$\frac{d\ (CT)}{dN} = \frac{CT}{N} \qquad \text{Eq. 3}$$

This infers that the necessary condition for cost minimization occurs when the average time per log equals the marginal time per log. Average time is defined as the total cycle time divided by the total number of logs per turn. The marginal time per log is the extra cycle time required by the addition of one more log to the load.

Considering a specific case, the cycle time equation for the small yarder is of the form

$$CT = k_o + k_1 D_1 + k_2 D_2 + k_3 N \qquad \text{Eq. 4}$$

where,

k_o = Constant associated with unexplained variation

k_1 = Marginal cycle time per unit roundtrip distance

k_2 = Marginal cycle time per unit roundtrip lateral yarding distance

D_1 = Roundtrip distance units for outhaul

D_2 = Rountrip distance units for lateral yarding

k_3 = Marginal cycle time per additional log

N = Logs per turn

Substituting the expression for cycle time into Eq. 3 and differentiating results in,

$$0 = k_o + k_1 D_1 + k_2 D_2$$

which means that average cost continues to decline as the number of logs increases. The cycle time for the large yarder is also linear and so leads to the same result. Of course, the cycle time equations derived from the least squares estimates are valid only over the limits of the sample observations. Hangups during inhaul may yield a nonlinear relationship. If logs enter the cycle time equation in a nonlinear manner, a finite upper limit on the number of logs per turn may exist to minimize costs. For example, if the cycle time equation was of the form

$$CT = k_o + k_1 D_1 + k_2 D_2 + k_3 N^2 \qquad \text{Eq. 5}$$

the necessary condition for cost minimization becomes

$$N = \left(\frac{k_o + k_1 D_1 + k_2 D_2}{k_3} \right)^{\frac{1}{2}}$$

Cost relationships for the linear and nonlinear cycle time models are plotted in Figure 30 for values of the regression coefficients for the small yarder, a 1200-ft skyline, and removals of 2000 cubic feet per acre from a previously unthinned natural stand.

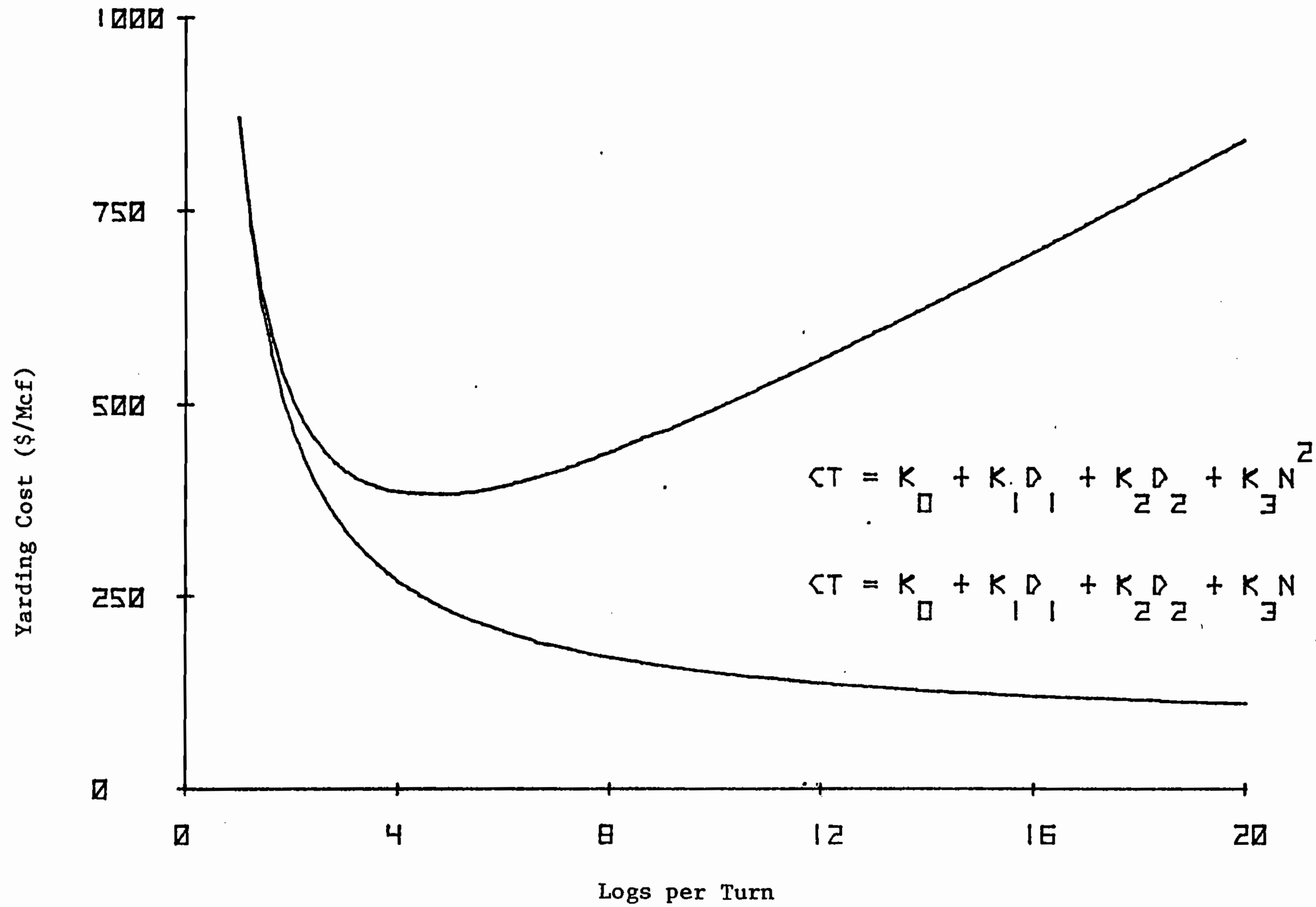


Figure 30. Yarding cost as a function of logs per turn for two cycle time models.

APPENDIX IV.

HISTOGRAMS OF NORMAL STAND DISTRIBUTIONS

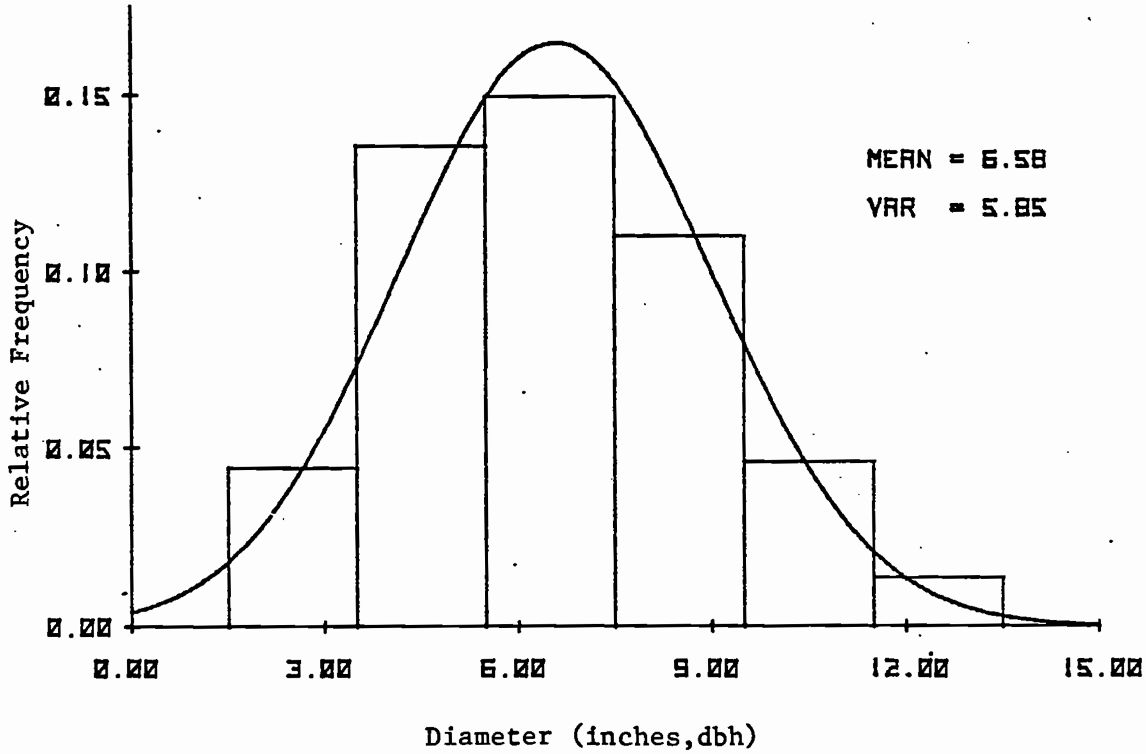


Figure 31. Histogram for Douglas-fir Site 140, Age 40.

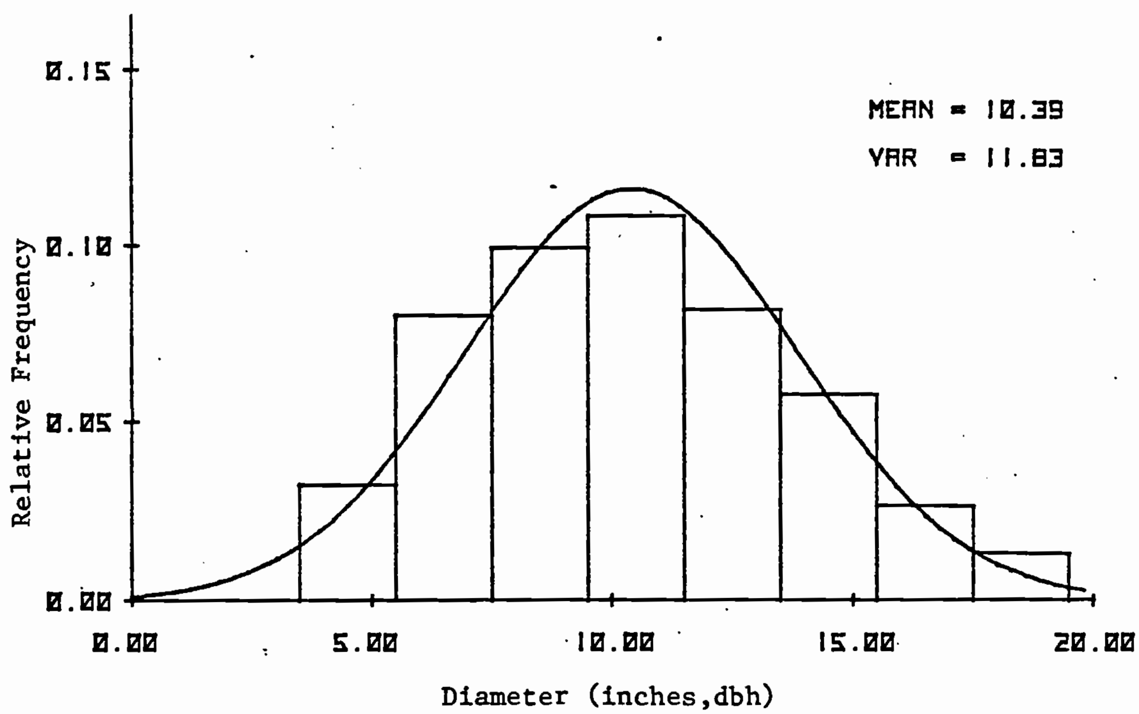


Figure 32. Histogram for Douglas-fir Site 140, Age 60.

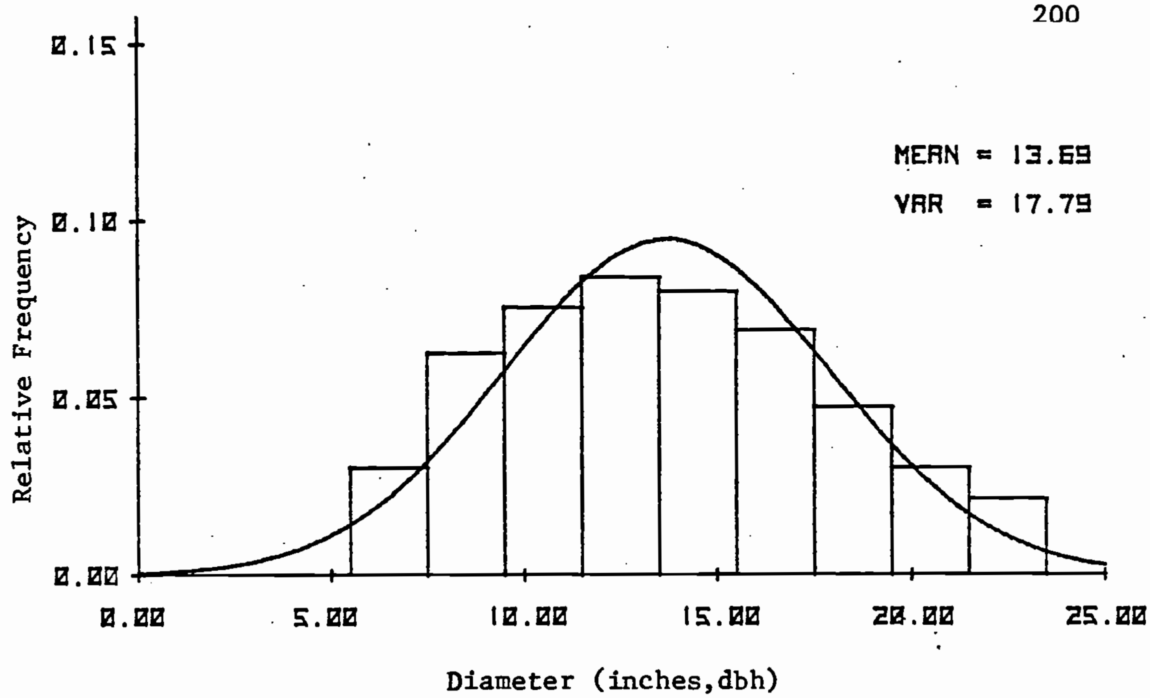


Figure 33. Histogram for Douglas-fir Site 140, Age 80.

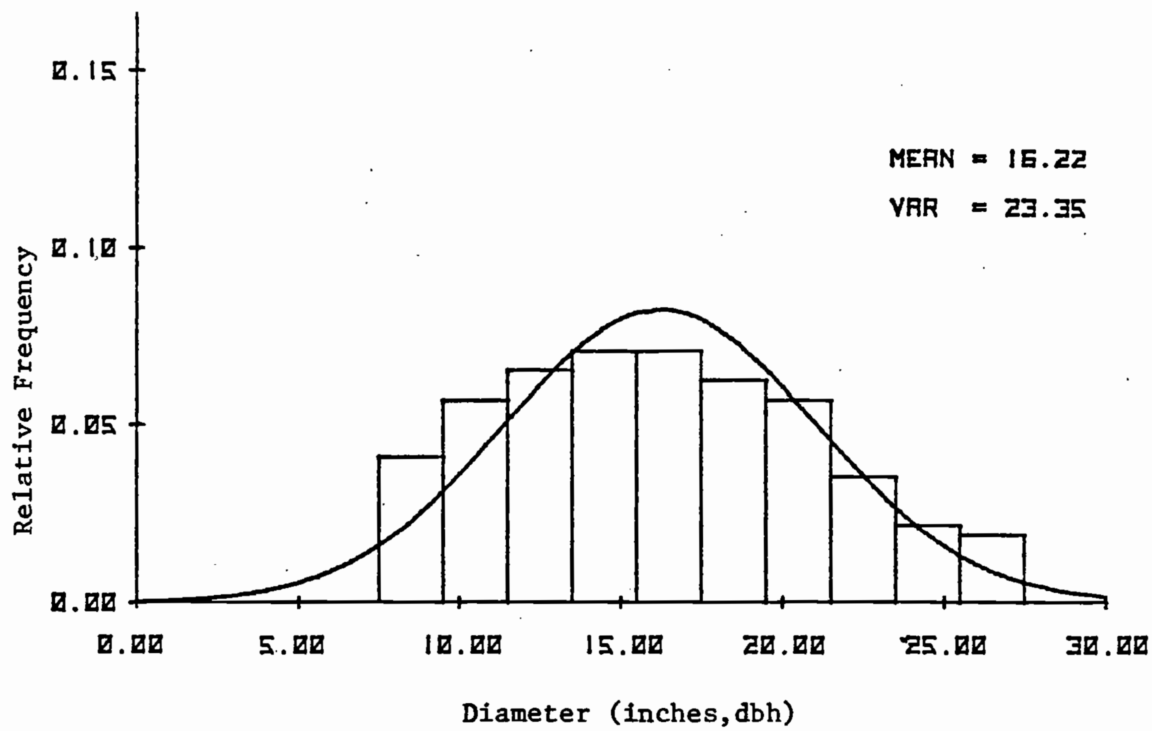


Figure 34. Histogram for Douglas-fir Site 140, Age 100.

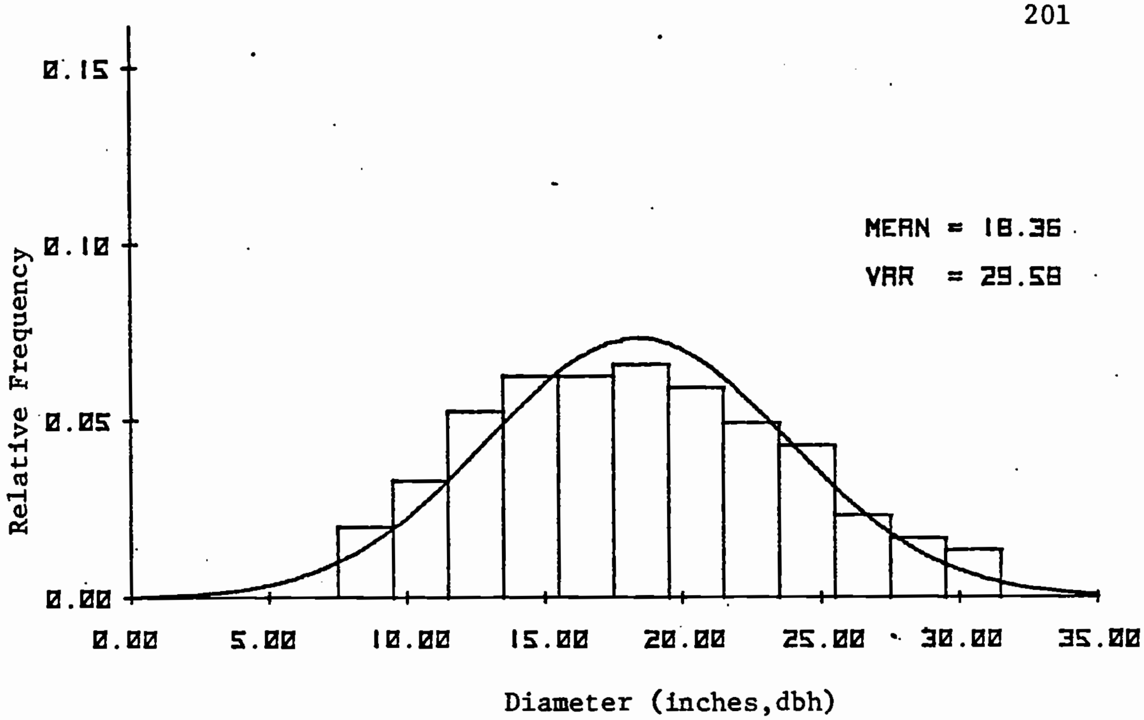


Figure 35. Histogram for Douglas-fir Site 140, Age 120.

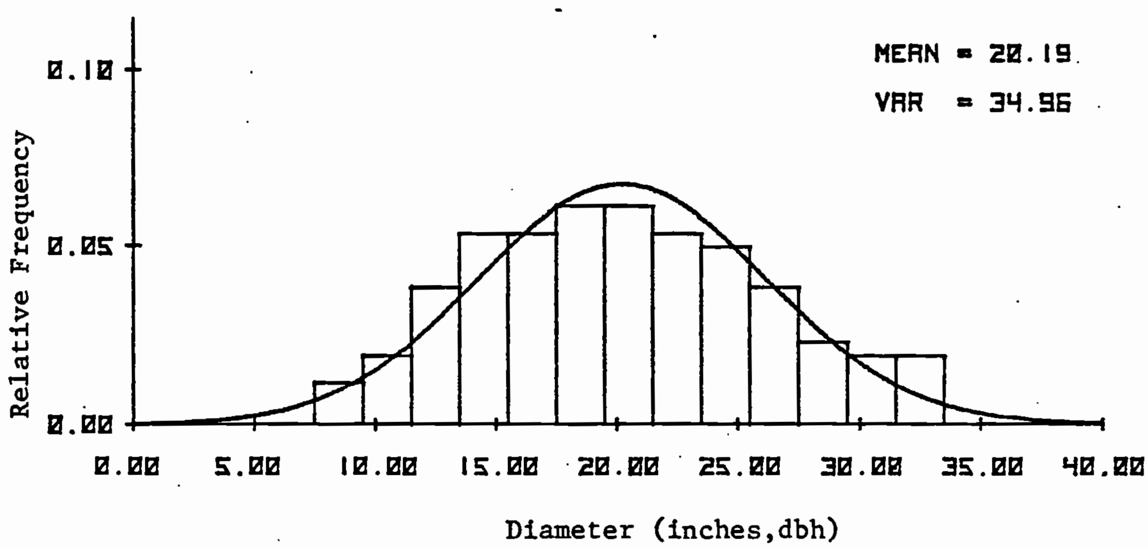


Figure 36. Histogram for Douglas-fir Site 140, Age 140.

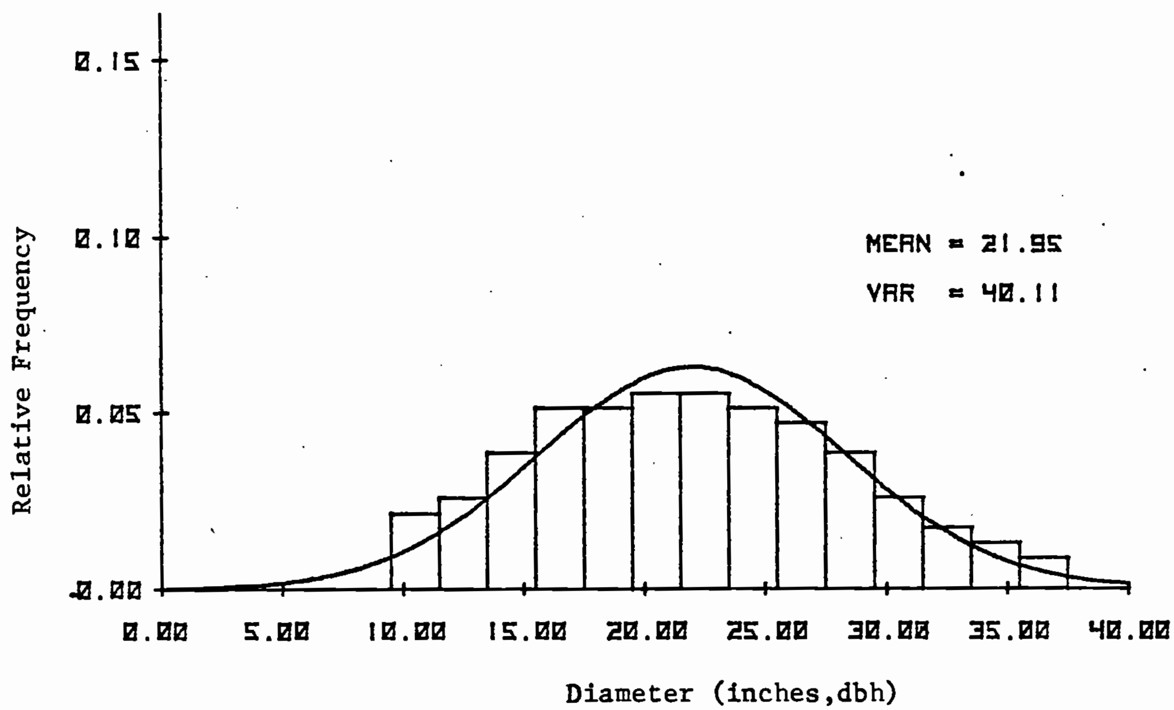


Figure 37. Histogram for Douglas-fir Site 140, Age 160.

APPENDIX V.

POWER CURVES FROM LARGE YARDER SIMULATIONS

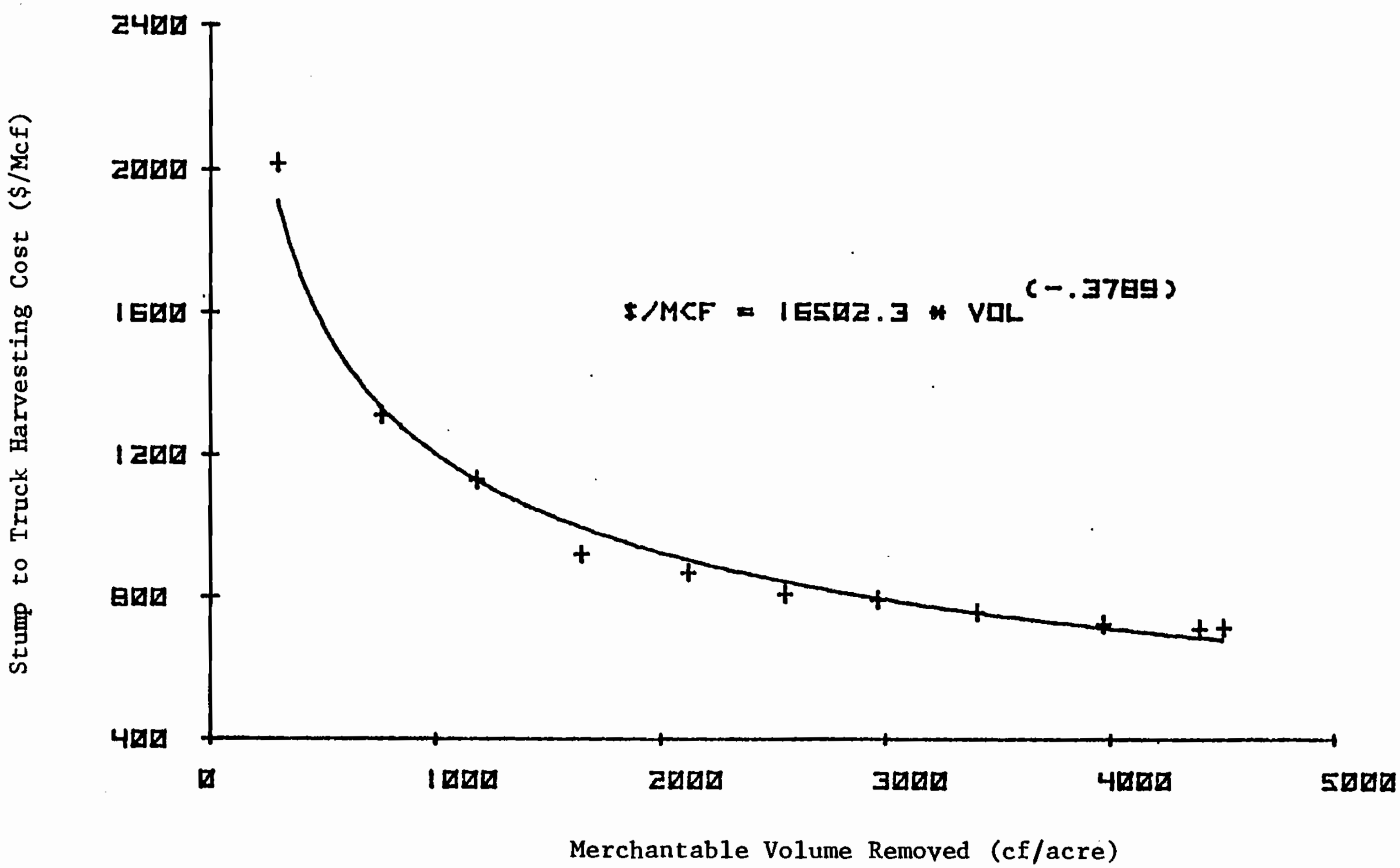


Figure 38. Simulation results for the large yarder operating in an unthinned natural stand, 7.6 inch mean stand diameter.

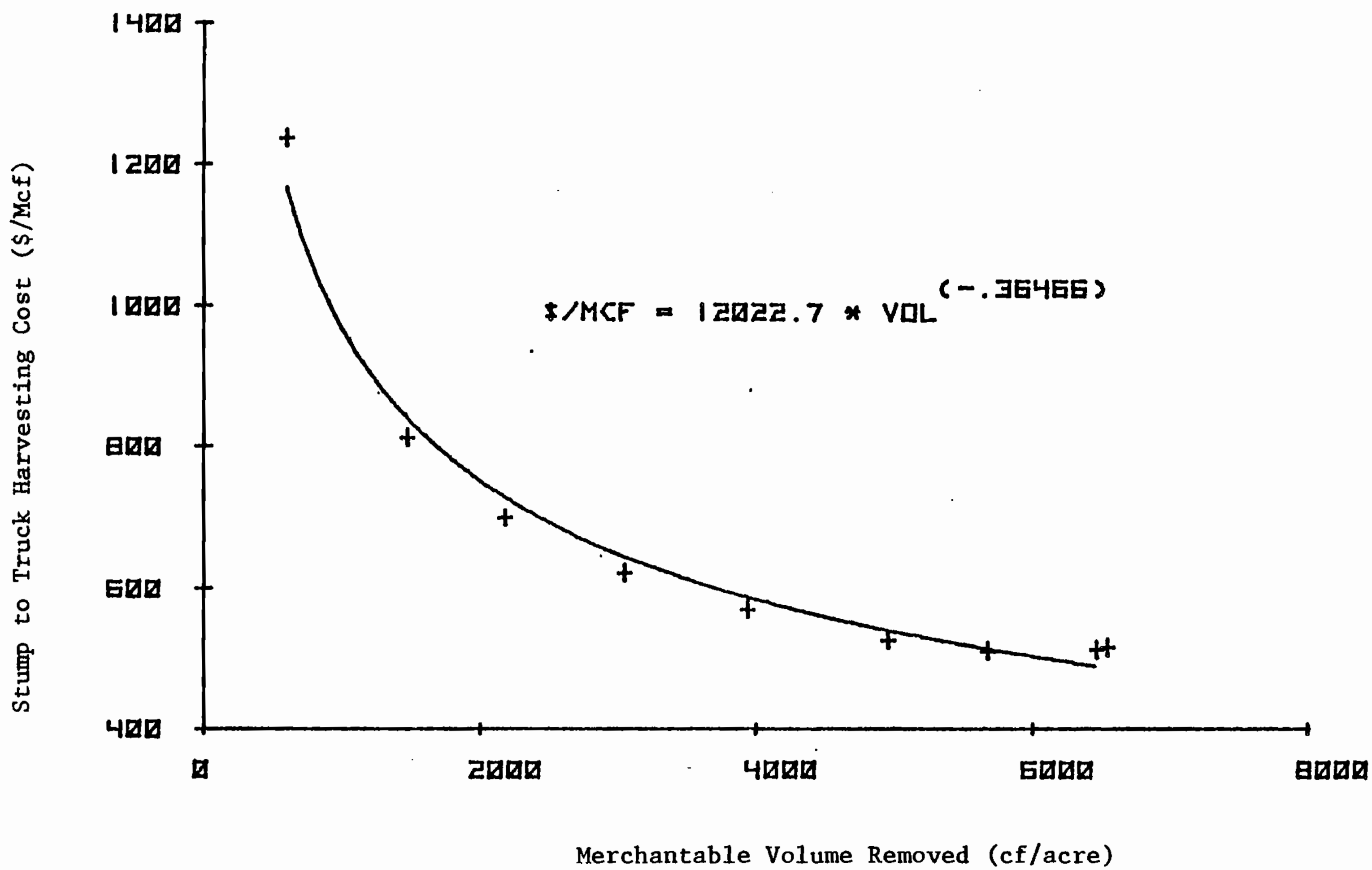


Figure 39. Simulation results for the large yarder operating in an unthinned natural stand, 9.2 inch mean stand diameter.

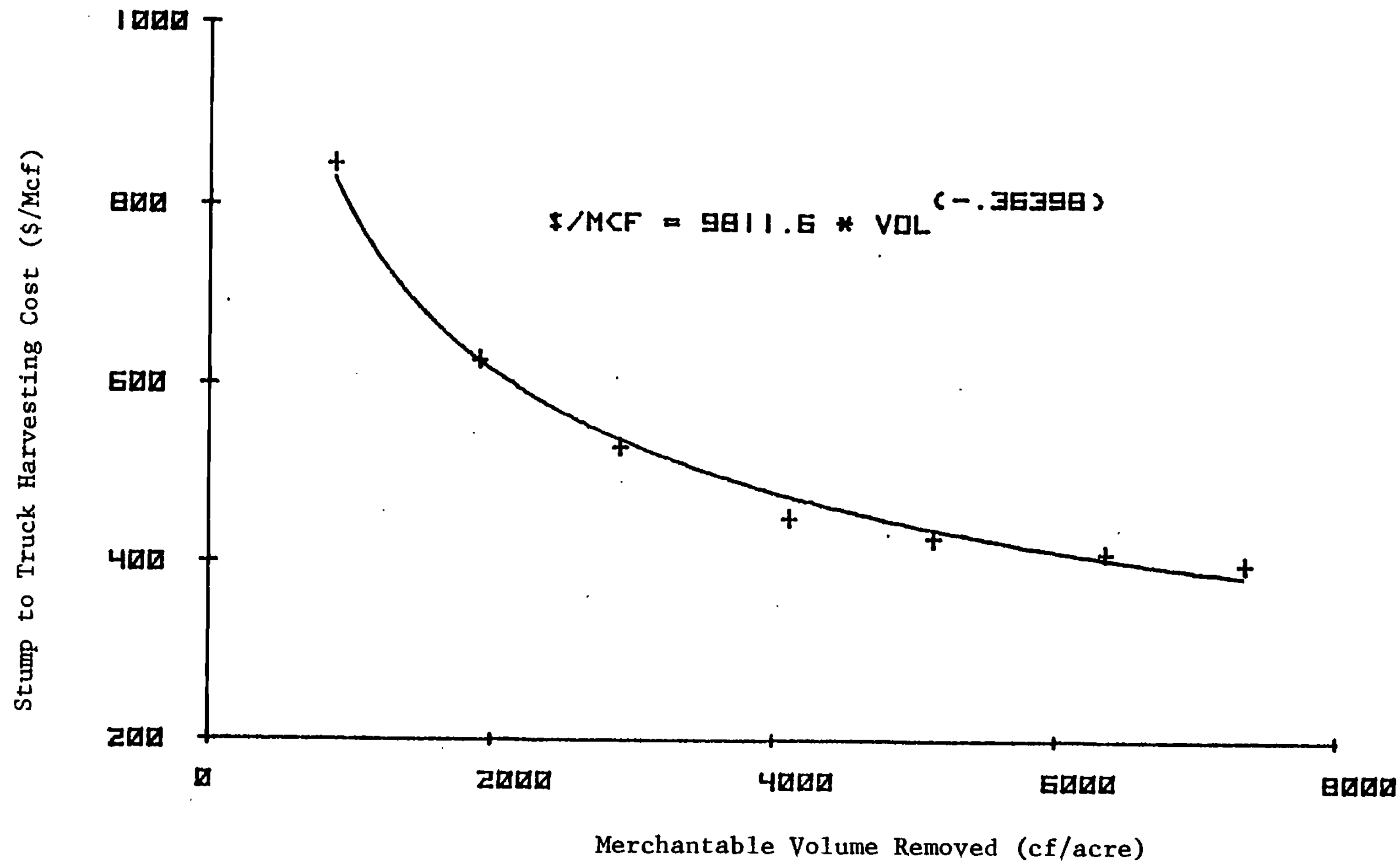


Figure 40. Simulation results for the large yarder operating in an unthinned natural stand, 10.9 inch mean stand diameter.

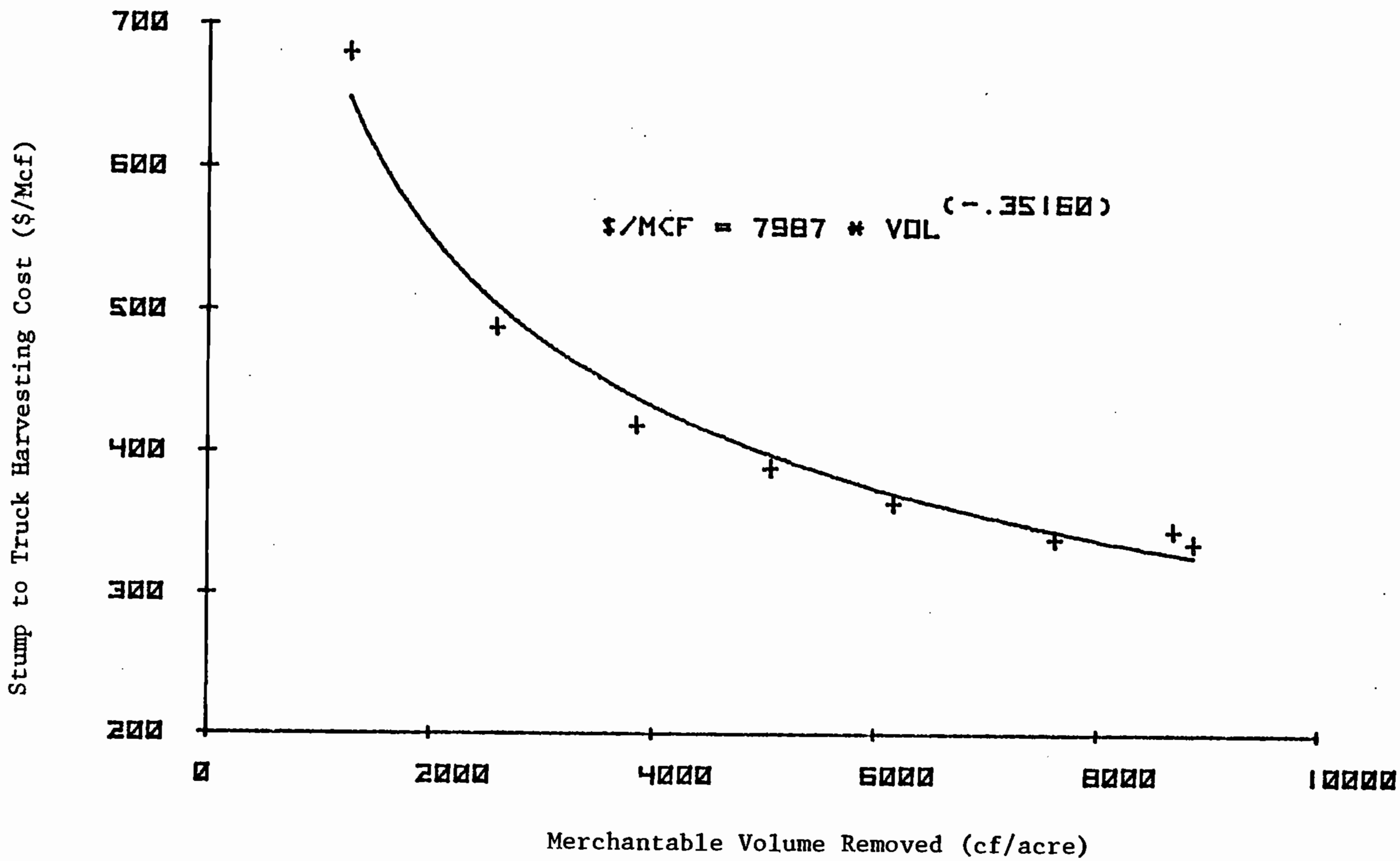


Figure 41. Simulation results for the large yarder operating in an unthinned natural stand, 12.3 inch mean stand diameter.

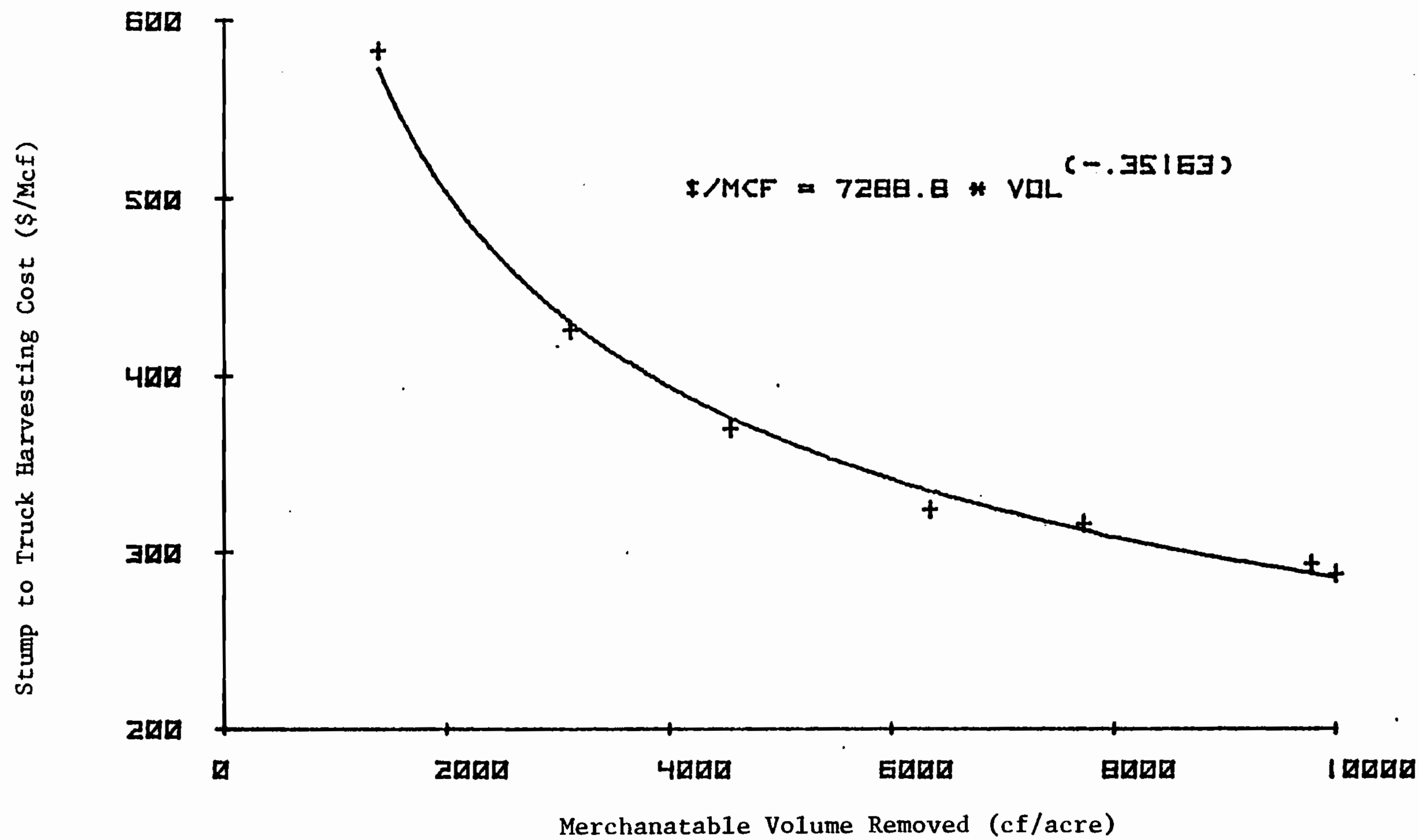


Figure 42. Simulation results for the large yarder operating in an unthinned natural stand, 13.7 inch mean stand diameter.

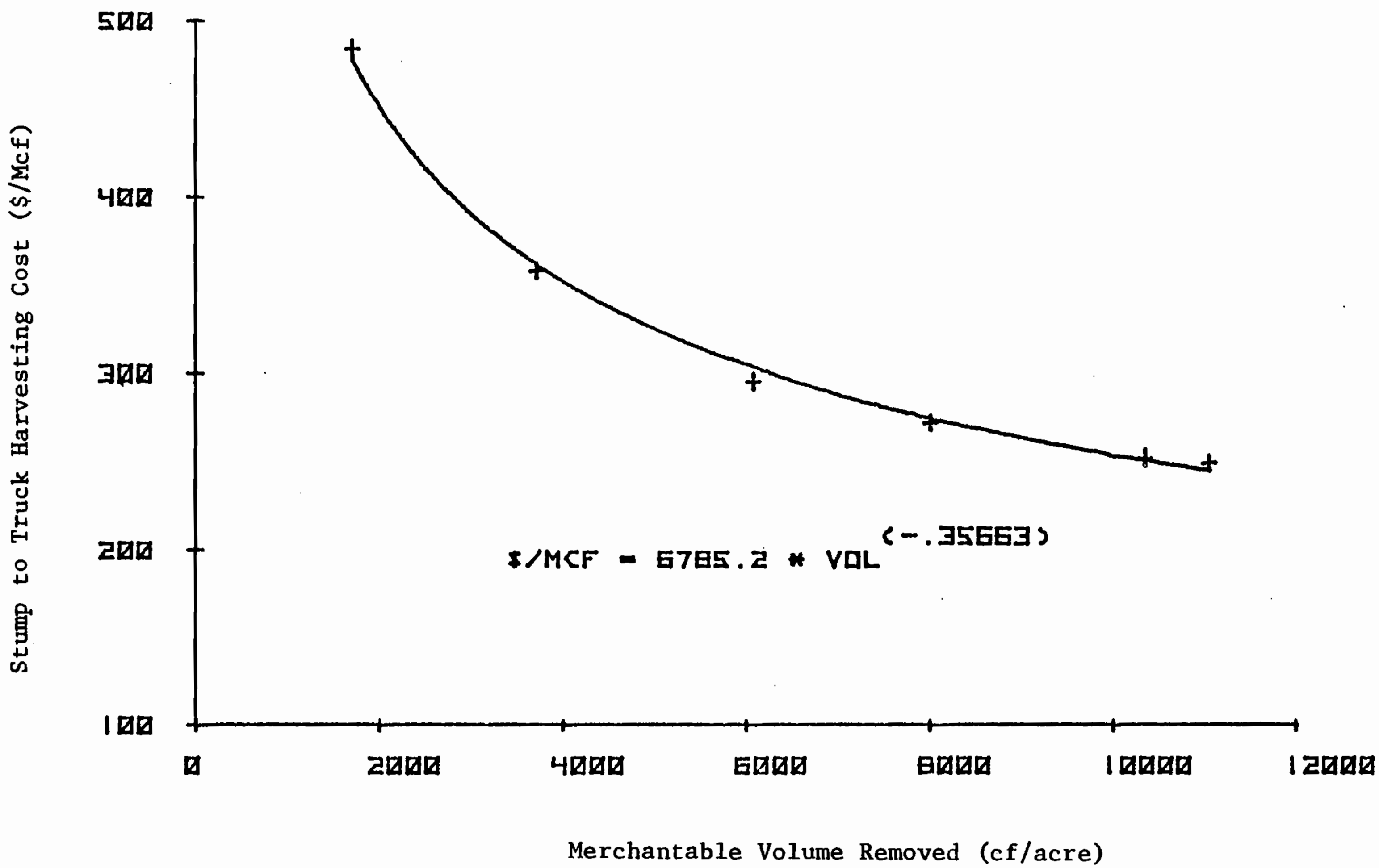


Figure 43. Simulation results for the large yarder operating in an unthinned natural stand, 15.0 inch mean stand diameter.

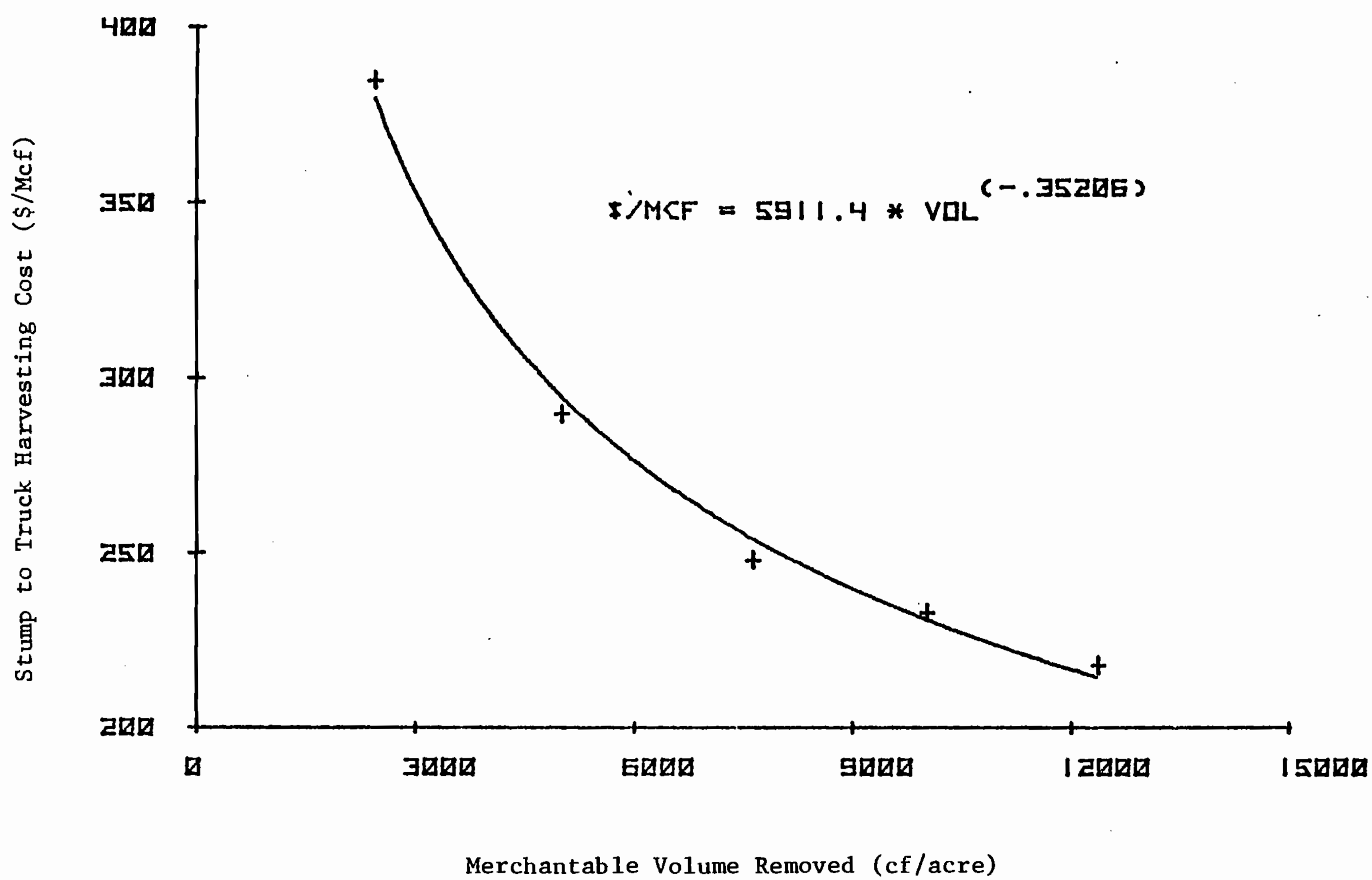


Figure 44. Simulation results for the large yarder operating in an unthinned natural stand, 16.2 inch mean stand diameter.

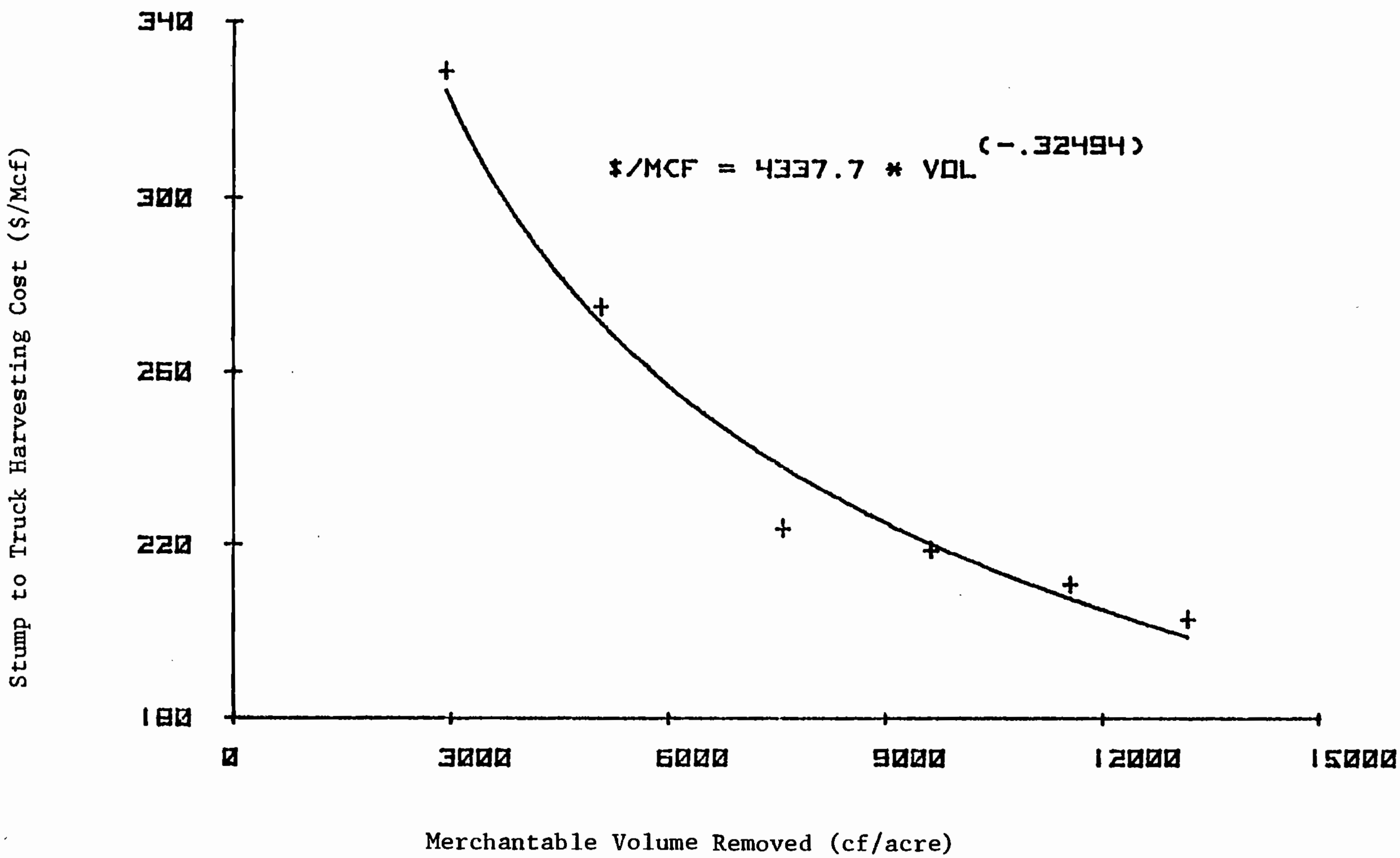


Figure 45. Simulation results for the large yarder operating in an unthinned natural stand, 17.3 inch mean stand diameter.

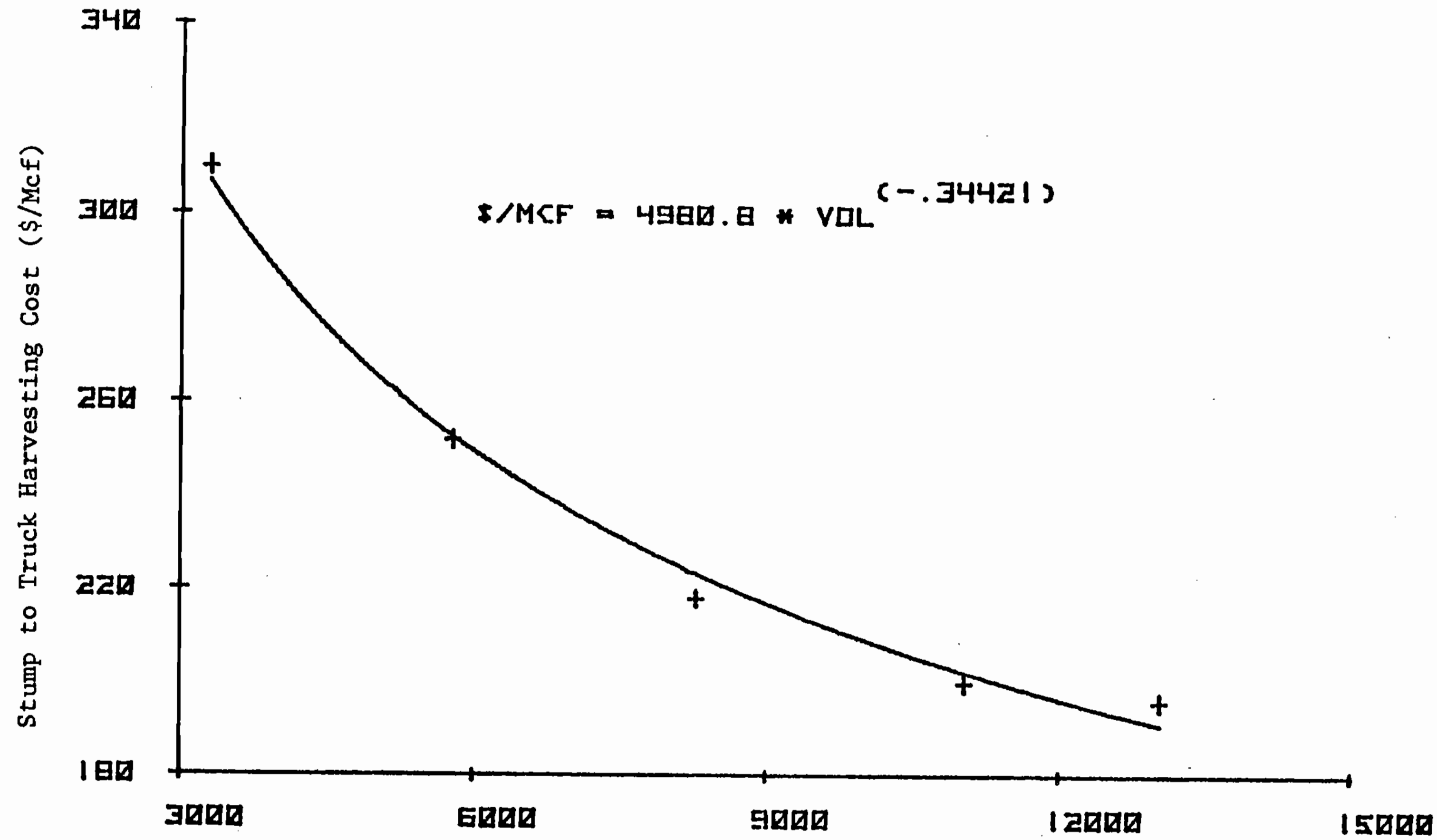


Figure 46. Simulation results for the large yarder operating in an unthinned natural stand, 18.3 inch mean stand diameter.

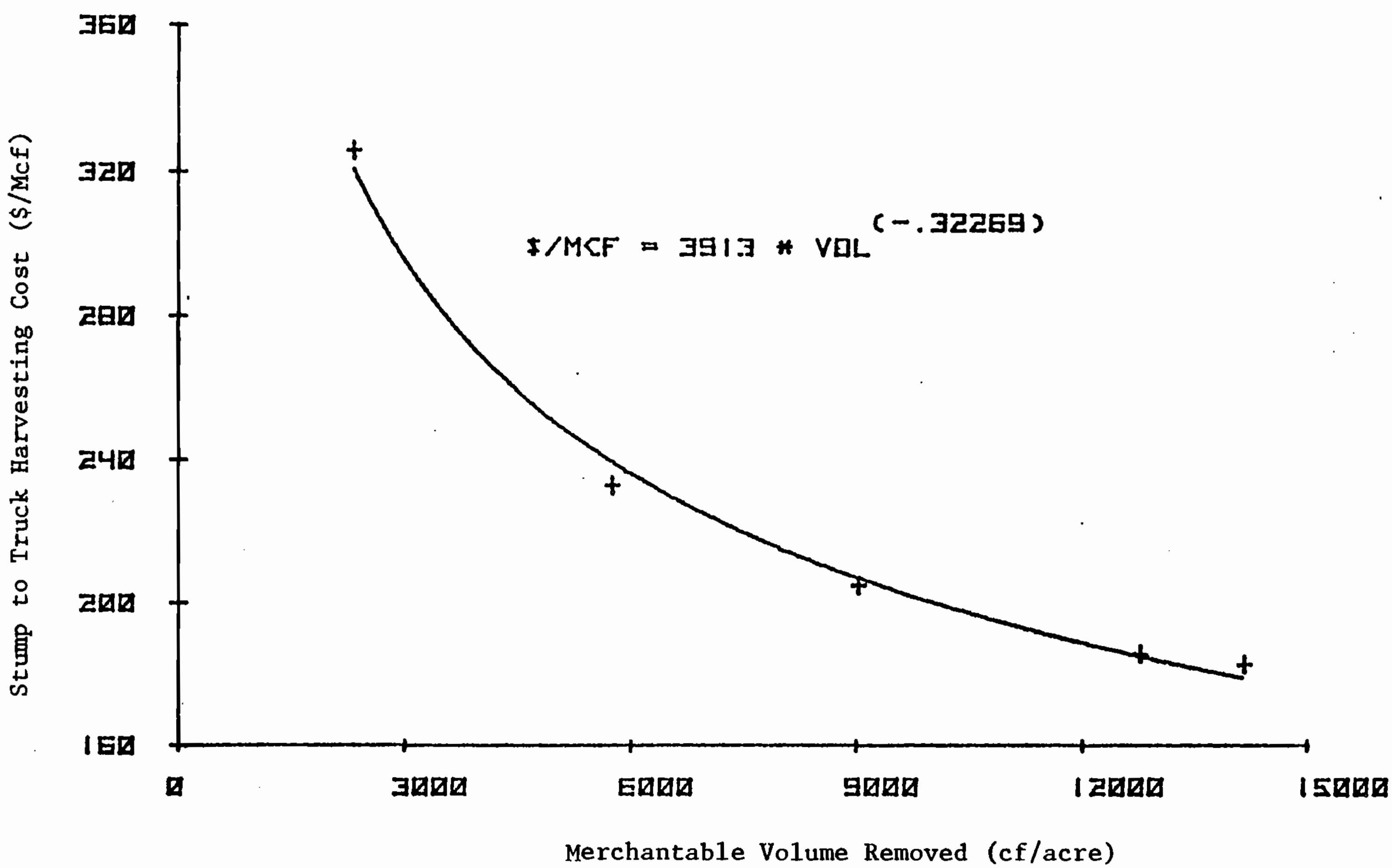


Figure 47. Simulation results for the large yarder operating in an unthinned natural stand, 20.3 inch mean stand diameter.

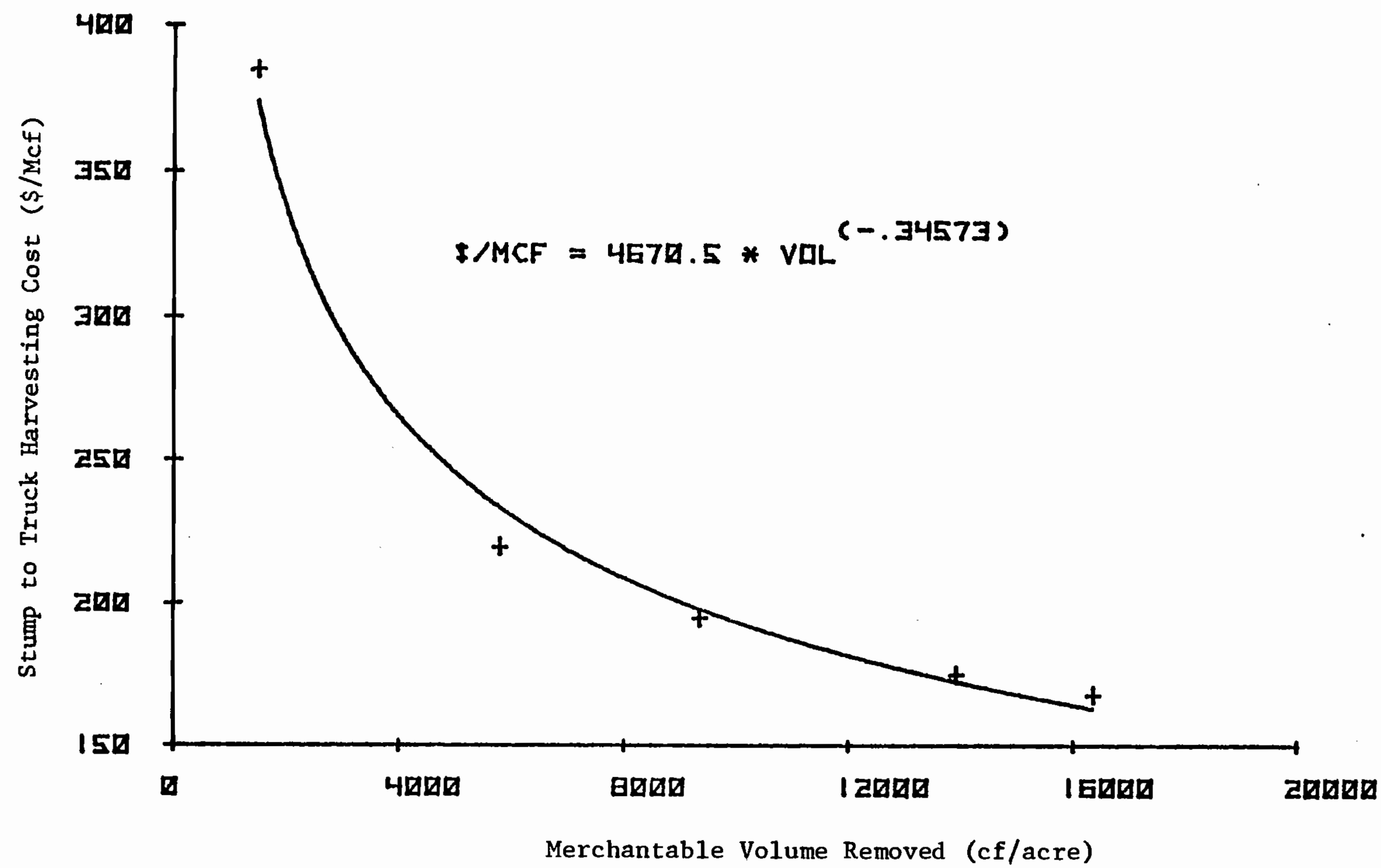


Figure 48. Simulation results for the large yarder operating in an unthinned natural stand, 21.9 inch mean stand diameter.

APPENDIX VI.

POWER CURVES FROM SMALL YARDER SIMULATIONS

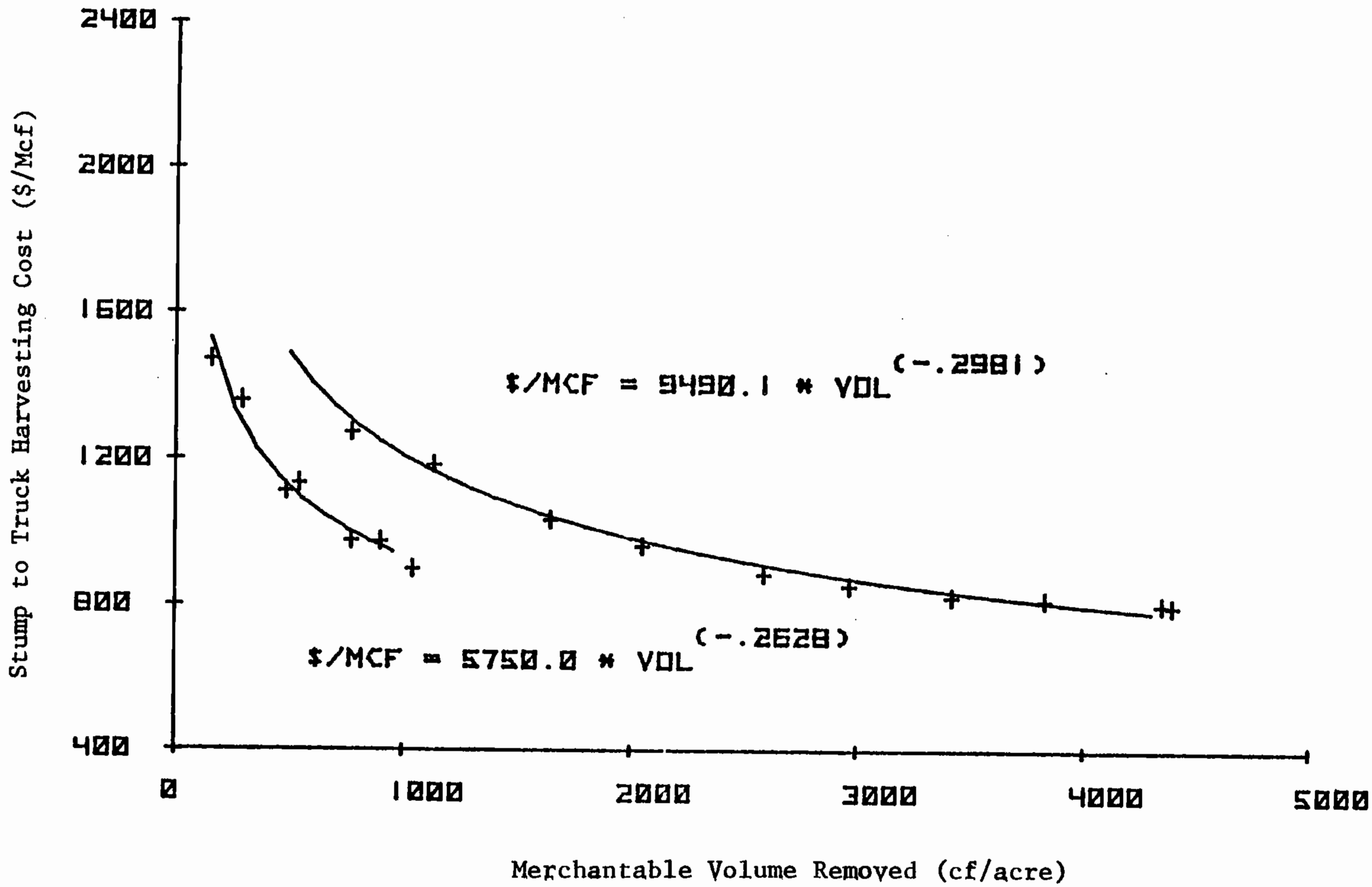


Figure 49. Simulation results for the small yarder operating in an unthinned natural stand, 7.6 inch mean stand diameter.

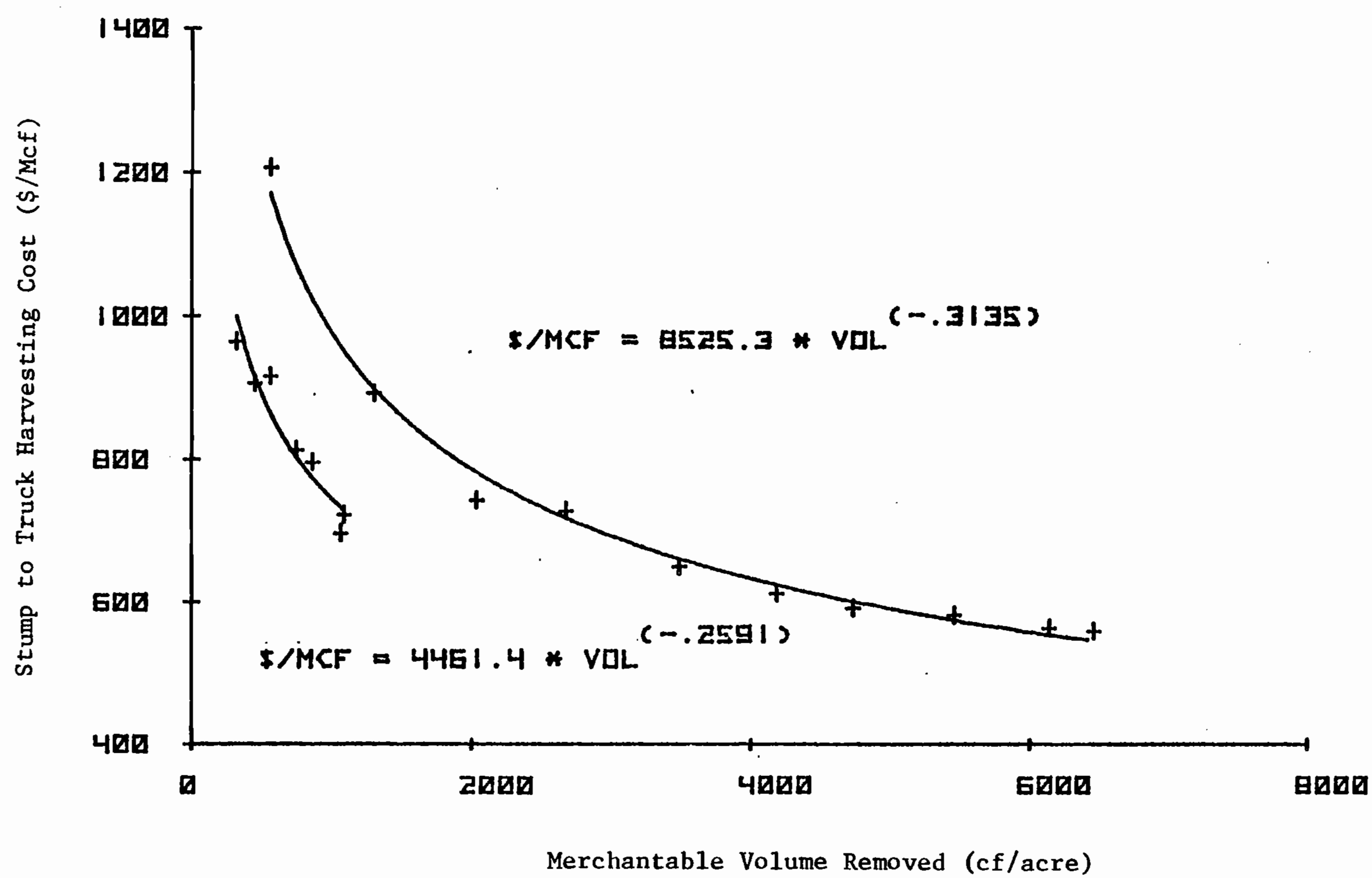


Figure 50. Simulation results for the small yarder operating in an unthinned natural stand, 9.2 inch mean stand diameter.

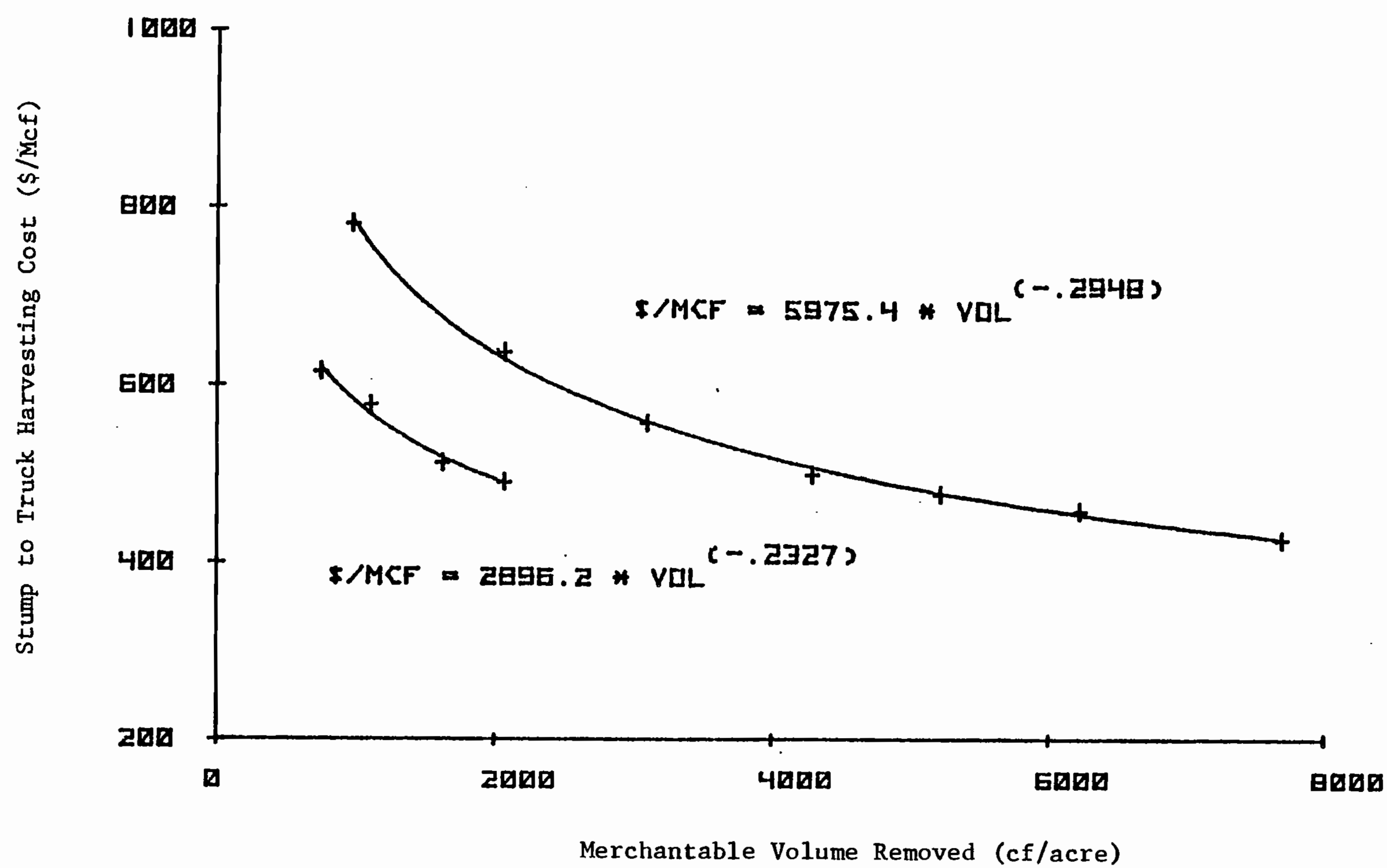


Figure 51. Simulation results for the small yarder operating in an unthinned natural stand, 10.9 inch mean stand diameter.

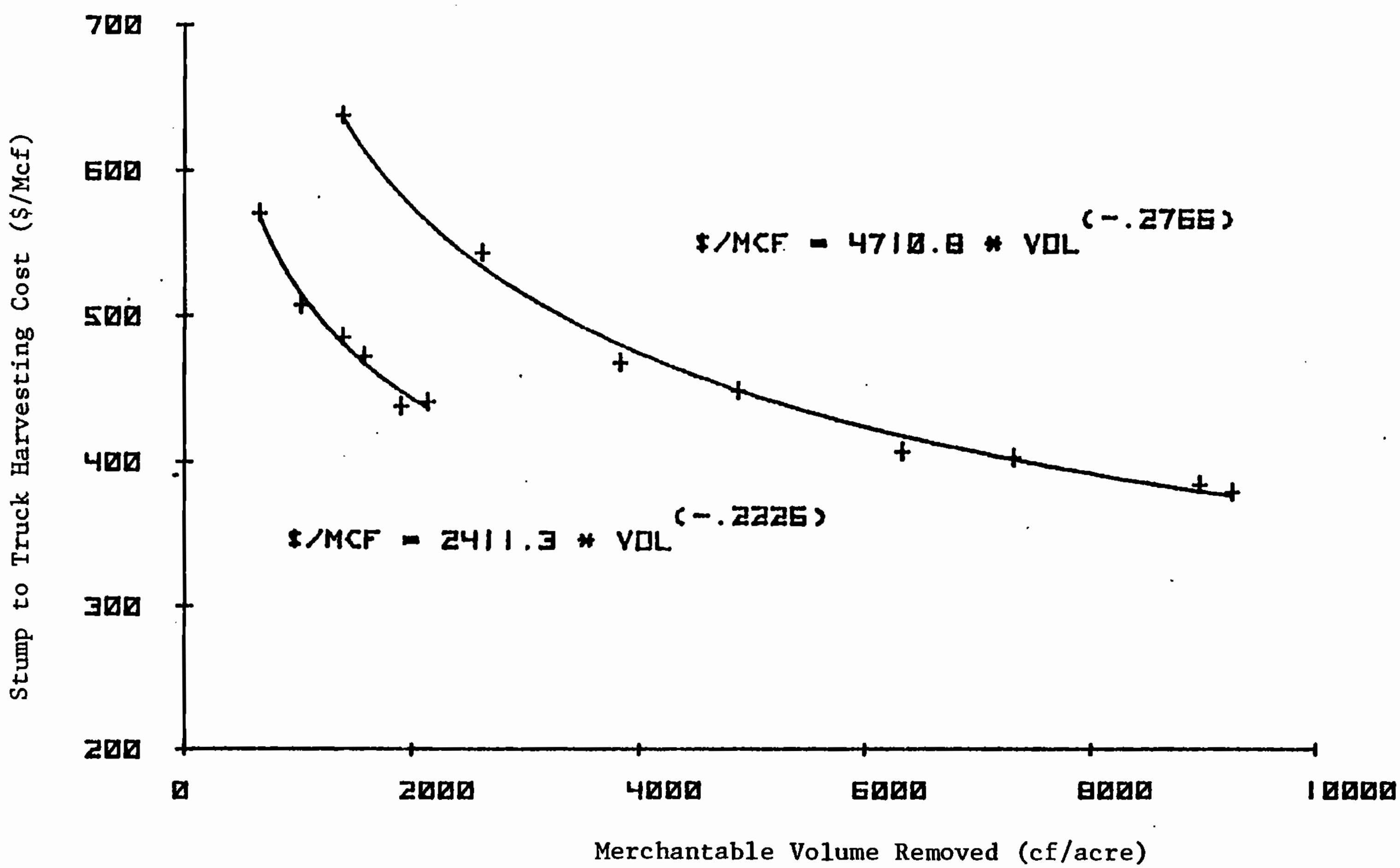


Figure 52. Simulation results for the small yarder operating in an unthinned natural stand, 12.3 inch mean stand diameter.

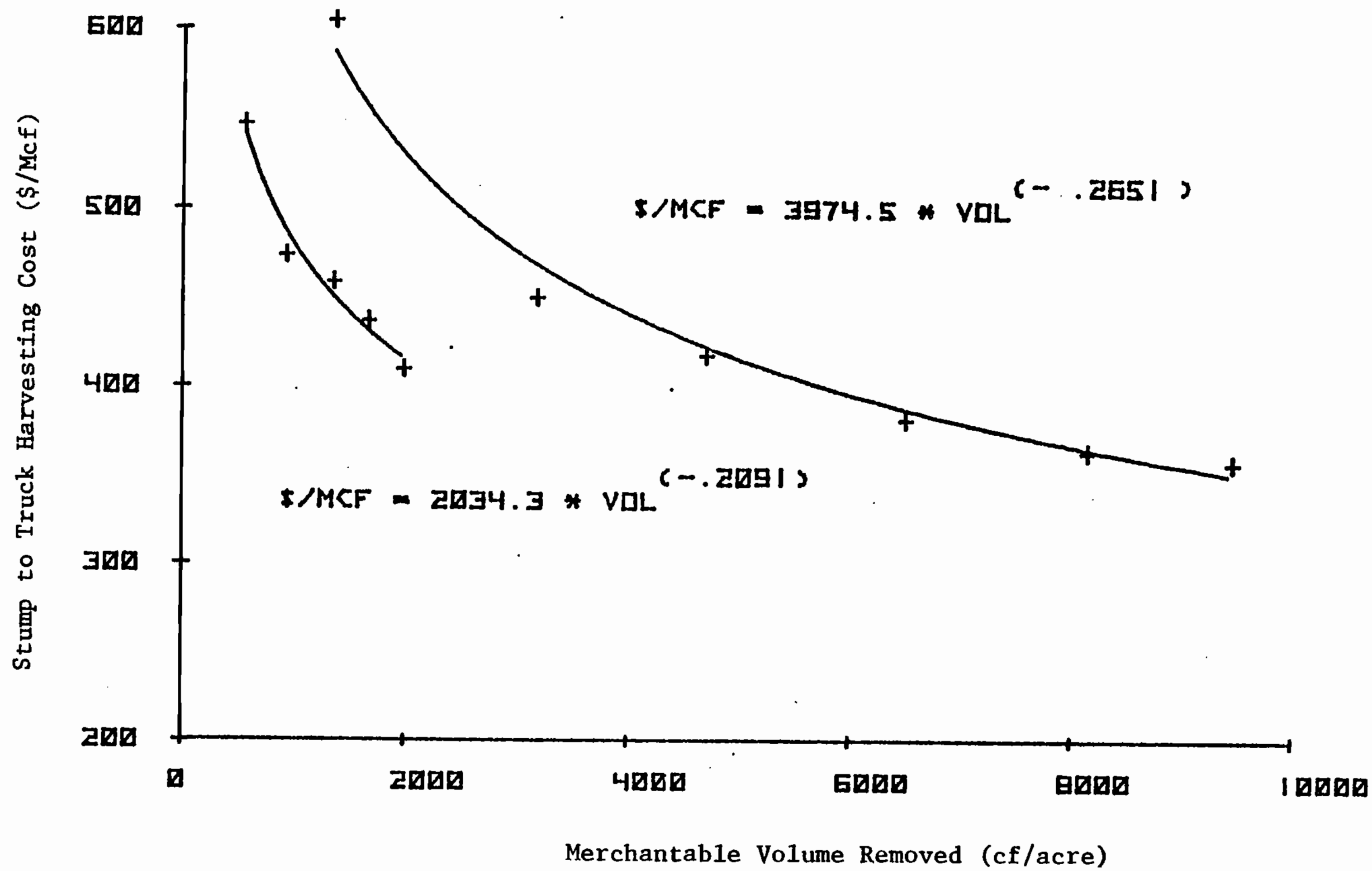


Figure 53. Simulation results for the small yarder operating in an unthinned natural stand, 13.7 inch mean stand diameter.

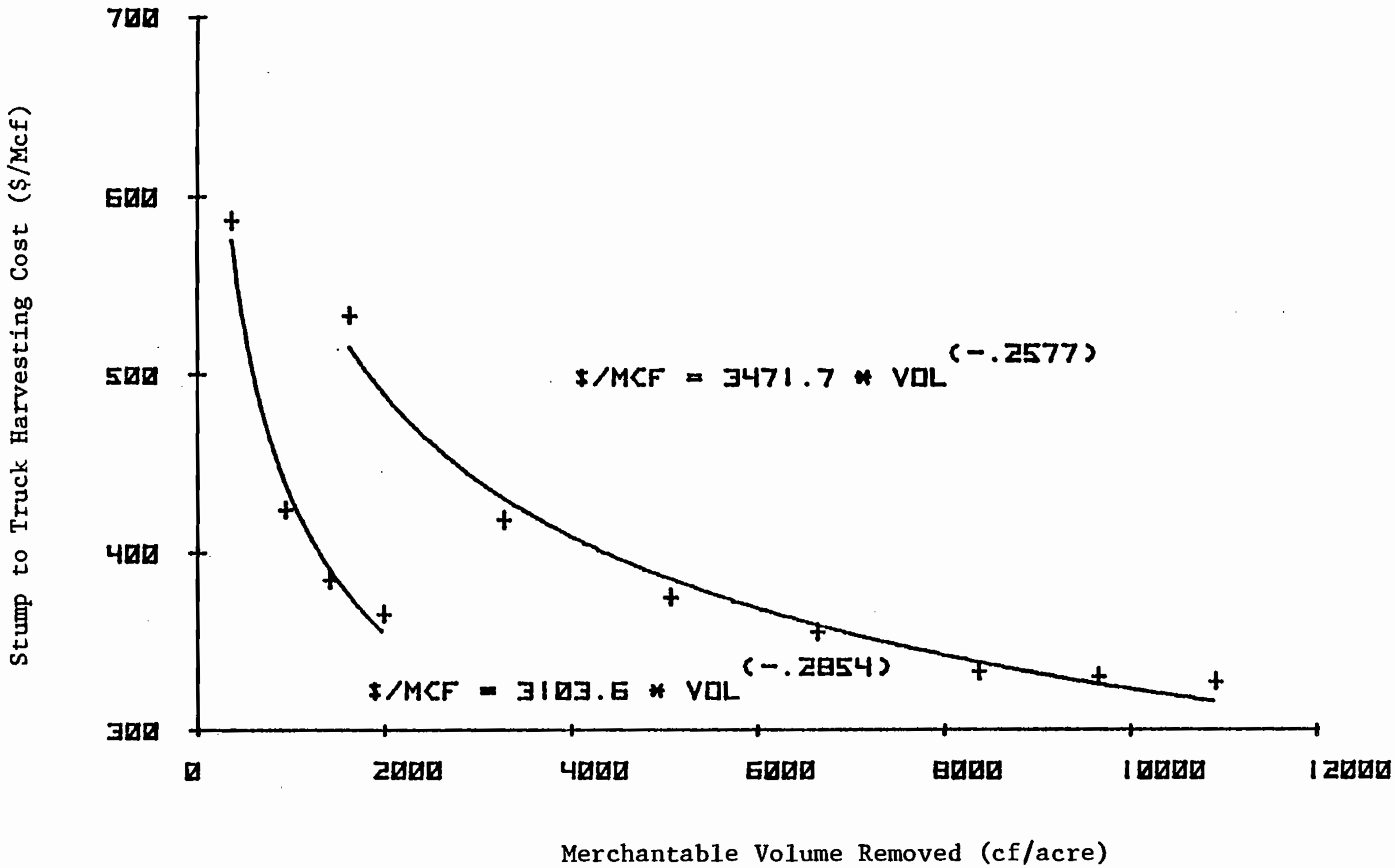


Figure 54. Simulation results for the small yarder operating in an unthinned natural stand, 15.0 inch mean stand diameter.

APPENDIX VII.

LISTING OF THE HARVEST SIMULATION PROGRAM

```
      PROGRAM YARDALL(INPUT,OUTPUT,TAPE60=INPUT,TAPE61=OUTPUT)
C
      DIMENSION G(500),H(500),R(10),S(10),V(100),W(500),A(100)
      DIMENSION STOR0(25),STOR1(25),STOR2(25),STOR3(25),STOR4(25)
      DIMENSION STOR5(25),STOR6(25),D(100),L(100)
      REAL I3,LC,N1,N2,N3,N4,N5,I2,L0,L1,L2,L3, L8,L9
      REAL N0,N9,L,L10
      INTEGER OUT
      IN=60
      OUT=61
      DELTA=0.0
    1 READ(IN,10) A0,A1
      IF(EOF(IN)) 5000,2
    2 CONTINUE
      READ(IN,10) P2,D7,D8,D9,VAR
      READ(IN,10) D6,L1,L2,W0,HT
      READ(IN,10) R1,A8,LC,P3
      READ(IN,10) P,P1,DELTA
      READ(IN,10) L8,L9,L10
   10 FORMAT (10F5.0)
      NK=0
      XX1=XX2=YY1=YY2=PCOR=0.
      D66=D6
      D6=1.1*D6
      TL8=L8
      A1MAX=A0
      DO 2450 K=1,15
      IF(A1 .GT. A1MAX) A1=A1MAX
      NK=NK+1
      L8=TL8
      L0=L8
      T6=T7=T8=T9=0.
      Z0=Z1=Y3=0.
      I2=I3=0.
      N0=N1=N2=N4=N5=0.
      N3=N8=IP=NSUB=0
      CALL RANSET (X)
C
C     SEPARATE OUTHAUL DISTANCE INTO 200-FT BLOCKS
C
      IF (L8 .LT. 200.) GO TO 745
  743 L0=L0-200.
      L8=200.
  745 N9=(A1*L8*L9/43560.)+.5
C
```

```
C     GENERATE TREE DBH AND LOG WEIGHTS
C
      IF(P.EQ.0.0) GO TO 760
      WRITE(OUT,750)
  750 FORMAT("0    LOG LIST (D,L,W)",/)
  760 IF(NO.GT.N9) GO TO 1040
  770 U=RANF(X)
C
C     UNIFORM, EXPONENTIAL, OR NORMAL DBH DISTRIBUTION
C
      IF (P2) 775,780,805
  775 D4=D9*U
      GO TO 800
  780 D4=-D8*ALOG(U)
      IF (D4 .GT. D9) GO TO 770
  800 IF (D4 .LT. D7) GO TO 770
      GO TO 880
  805 IF(IP.EQ.1) GO TO 820
  810 U1=RANF(X)
      U2=RANF(X)
      IF(U1.EQ.0. .OR. U2.EQ.0.) GO TO 810
      D4=D8+SQRT(-2.*VAR*ALOG(U1))*COS(6.28319*U2)
      IP=1
      IF (D4 .LE. D9 .AND. D4 .GE. D7) GO TO 880
  820 D4=D8+SQRT(-2.*VAR*ALOG(U1))*SIN(6.28319*U2)
      IP=0
      IF (D4 .GT. D9 .OR. D4 .LT. D7) GO TO 810
C
C     FELL AND BUCK LOGS
C
  880 TAPER=HT/D4
      DBHMIN=D6+L2/TAPER
      IF(D4.GE.DBHMIN) GO TO 885
      NSUB=NSUB+1
      NO=NO+1
      JJ=1
      Y2=0.2*D4
      GO TO 1035
  885 NO=NO+1
      L3=L1
      D(1)=D4
      DO 1000 J=2,20
      D(J)=D(J-1)-L3/TAPER
      IF(D(J) .GE. D6) GO TO 930
      L(J)=(D(J-1)-D6)*TAPER
```

```
      IF(J .GT. 2) GO TO 900
      JJ=J
      D(J)=D6
      L(J)=(D4-D6)*TAPER
      V(J)=0.00545415*L(J)*(D4-L(J)/(2.*TAPER))**2*W0*1.14
      GO TO 950
  900 L(J-1)=(L(J-1)+L(J) )/2.
      D(J-1)=D(J-2)-L(J-1)/TAPER
      V(J-1)=0.00545415*L(J-1)*(D(J-2)-L(J-1)/(2.*TAPER))**2*W0*1.14
      W(N8)=V(J-1)
      Z0=Z0+D(J-1)
      D(J)=D6
      L(J)=L(J-1)
      V(J)=0.00545415*L(J)*(D(J-1)-L(J)/(2.*TAPER))**2*W0*1.14
      JJ=J
      GO TO 950
  930 L(J)=L3
  940 V(J)=0.00545415*L(J)*(D(J-1)-L(J)/(2.*TAPER))**2*W0*1.14
  950 IF(V(J) .LE. R1) GO TO 990
      L(J)=L(J)-2.
      D(J)=D(J)+2./TAPER
      GO TO 940
  990 N8=N8+1
      W(N8)=V(J)
      Z0=Z0+D(J)
      IF (D(J) .EQ. D6) GO TO 1010
 1000 CONTINUE
 1010 IF (P .EQ. 0. ) GO TO 1030
      DO 1020 JJJ=2,JJ
      WRITE(OUT,1015) D(JJJ),L(JJJ),V(JJJ)
 1015 FORMAT (3F10.1)
 1020 CONTINUE
C
C     COMPUTE FELLING AND BUCKING TIME/TREE AND SUM
C
 1030 Y2=2.0+0.01134*D4*D4+1.179*(J-1)
 1035 Y3=Y3+Y2
      GO TO 760
C
C     GENERATE XOM LOG DISTRIBUTION
C
 1040 DO 1110 I=1,N8
      U=RANF(X)
      G(I)=L9*U
      IF (G(I) .GT. 0. ) GO TO 1090
```

```
      G(I)=1.
 1090 U=RANF(X)
      H(I)=LB*U+Z1
 1110 CONTINUE
C
C     SORT OUTHAUL DISTANCE
C
      NBT=NB-1
      DO 1330 I= 1,NBT
      I1=I+1
      DO 1320 J= I1,NB
      IF ((H(I)-H(J)) .LE. 0.) GO TO 1320
      T=H(I)
      H(I)=H(J)
      H(J)=T
      T=G(I)
      G(I)=G(J)
      G(J)=T
      T=W(I)
      W(I)=W(J)
      W(J)=T
      T=W(I)
 1320 CONTINUE
 1330 CONTINUE
      IF(P.EQ.0.0) GO TO 1650
      WRITE (OUT,1336)
 1336 FORMAT ("     LOG LIST (OUT,LAT,W)",/)
      DO 1370 I=1,NB
      WRITE (OUT,1340) H(I),G(I),W(I)
 1340 FORMAT ("     ", 3F10.1)
 1370 CONTINUE
      IF (P1 .EQ. 0.0) GO TO 1650
      WRITE (OUT,1630)
 1630 FORMAT ("0    TURN STATISTICS",/)
 1650 N=0
      N1=0.
      WSUM=0.
C
C     AUTO REACH SELECTION
C
 1710 DO 1760 I=1,NB
      IF (G(I).EQ. 0.0) GO TO 1760
      D1=H(I)+LC
      D2=G(I)
      GO TO 1770
```

```
 1760 CONTINUE
 1770 N=0
      DO 1840 I=1,N8
      IF (G(I).EQ.0.0) GO TO 1840
      IF(H(I).GT.(D1+LC)) GO TO 1850
      N=N+1
      A(N)=I
      D(N)=(G(I)-D2)**2 + (H(I)-D1)**2
 1840 CONTINUE
 1850 IF (N .EQ. 0) GO TO 2292
      IF (N.EQ. 1) GO TO 2010
C
C     SORT LOGS WITHIN REACH
C
      NT=N-1
      DO 1990 I=1,NT
      I1=I+1
      DO 1980 J=I1,N
      IF((D(I)-D(J)).LE. 0.0) GO TO 1980
      T=D(I)
      D(I)=D(J)
      D(J)=T
      T=A(I)
      A(I)=A(J)
      A(J)=T
 1980 CONTINUE
 1990 CONTINUE
C
C     BUILD TURN
C
 2010 W9=R1
      DO 2180 I=1,N
      IF(P3.GT.0.0) GO TO 2080
      IF (D(I).GT.(LC*LC)) GO TO 2200
 2080 IF ((N1+1.).GT. A8) GO TO 2200
      KAT=A(I)
      IF (WSUM+W(KAT).GT.W9) GO TO 2205
      N1=N1+1.
      WSUM=WSUM+W(KAT)
      G(KAT)=0.
 2180 CONTINUE
C
C     TURN STATISTICS
C
 2200 C1=1.97+.00212*D1+0.0119*D2+.030463*N1
```

```
     *       +.000863*(WSUM/10.)-.000398*(WSUM/10.)/N1
 2205 IF(P1.EQ.0.0) GO TO 2212
      WRITE (OUT,2210) D1,D2,N1,WSUM,C1
 2210 FORMAT(5F10.2)
 2212 T6=T6+D1
      T7=T7+D2
      T8=T8+N1
      T9=T9+N1*N1
      N2=N2+1.
      N3=N3+N1
      N4=N4+WSUM
      N5=N5+C1/60.
      N1=0.
      N=0
      WSUM=0.
      IF (N3 .EQ.N8) GO TO 2292
      GO TO 1710
C
C     INITIALIZE FOR NEXT OUTHAUL BLOCK
C
 2292 IF(L0.EQ.0.0) GO TO 2310
      IF (L0 .GT. 200.) GO TO 2298
      L8=L0
      N8=0
      N0=0.
      N3=0
      L0=0.
      Z1=Z1+200.
      GO TO 745
 2298 Z1=Z1+200.
      N8=0
      N0=0.
      N3=0
      GO TO 743
C
C     SUMMARY STATISTICS
C
 2310 WRITE(OUT,2311)
 2311 FORMAT("1INPUT DATA **",/)
      WRITE(OUT,2312) A0,A1
 2312 FORMAT("0     TREES PER ACRE BEFORE CUT",4X,F6.0,/,
     *       "      TREES PER ACRE CUT",11X,F6.0)
      WRITE(OUT,2313)P2,D7,D8,D9,VAR
 2313 FORMAT("      DBH DISTRIBUTION PARAMETER",3X,F6.0,/,
     *       "      MINIMUM DBH",18X,F6.2,/,
```

```
     *        "     AVERAGE DBH",18X,F6.2,/,
     *        "     MAXIMUM DBH",18X,F6.2,/,
     *         "     VARIANCE (NORMAL DIST ONLY)",2X,F6.2)
      WRITE(OUT,2314) D66,L1,L2,W0
 2314 FORMAT("     MINIMUM DIAMETER I.B.",8X,F6.0,/,
     *        "     MAXIMUM LOG LENGTH   ",8X,F6.0,/,
     *        "     MINIMUM LOG LENGTH   ",8X,F6.0,/,
     *        "     LOG DENSITY (LB/CF)  ",8X,F6.0,/)
      WRITE (OUT,2315)R1,A8,LC,P3
 2315 FORMAT("     NET PAYLOAD (LB)",13X,F6.0,/,
     *         "     NUMBER OF CHOKERS",12X,F6.0,/,
     *        "     CHOKER LENGTH    ",12X,F6.0,/,
     *        "     HOOK PARAMETER   ",12X,F6.0,/,)
      WRITE(OUT,2316)TL8,L9,L10
 2316 FORMAT("     MAXIMUM OUTHAUL DIST",9X,F6.0,/,
     *         "     MAXIMUM LATERAL DIST",9X,F6.0,/,
     *         "     MAX OUTHAUL DIST (CT CALC)",3X,F6.0)
      WRITE(OUT,2320)
 2320 FORMAT("0SUMMARY STATISTICS**",/)
      Y3=Y3/60.
      WRITE (OUT,2350) Y3
 2350 FORMAT("0    TOTAL F AND B (HR)",11X,F6.2)
      WRITE (OUT,2352) N2
 2352 FORMAT ("     TOTAL TURNS YARDED",11X,F6.0)
      WRITE (OUT,2354) T8
 2354 FORMAT("     TOTAL PIECES YARDED",10X,F6.0)
C      CONVERT TO NET CUBIC FEET REMOVED
      BR=.85
      IF(D8 .GT. 9.23) BR=0.81
      N4=BR*N4/W0
      WRITE (OUT,2356) N4
 2356 FORMAT ("     TOTAL VOLUME YARDED (CF)",5X,F6.0)
      WRITE (OUT,2358) N5
 2358 FORMAT ("     TOTAL TIME YARDING (HR)",6X,F6.2)
      ACRES=TL8*L9/43560.
      NSUB=NSUB/ACRES+.5
      AVT=N4/N2
      APT=T8/N2
      ACT=N5*60./N2
      WRITE (OUT,2360)AVT
 2360 FORMAT ("0    AVE VOLUME/TURN (CF)",9X,F6.2)
      WRITE (OUT,2362)APT
 2362 FORMAT("     AVE PIECES/TURN",14X,F6.2)
      WRITE (OUT,2364)ACT
 2364 FORMAT("     AVE CYCLE TIME (MIN)",9X,F6.2)
```

```
      Z0=Z0/T8
      VOLAC=N4/ACRES
      WRITE (OUT,2366)Z0,VOLAC,NSUB
      VOLAC=N4/ACRES
 2366 FORMAT("     AVE DIAM PIECE (IN)",10X,F6.2,/,
     *       "     AVE VOL/ACRE REMOVED (CF)",4X,F6.0,
     *    /, "     AVE SUBMERCH TREES CUT/ACRE",2X,I6)
      VAR1=(T9-((T8**2)/N2))/(N2-1.)
      SE =(VAR1/N2)**.5
      WRITE (OUT,2370)SE
 2370 FORMAT("     STD ERROR PIECES/TURN",8X,F6.2)
      T6=T6/N2
      WRITE (OUT,2375) T6
 2375 FORMAT ("0    AVE OUTHAUL DIST",9X,F10.0)
      T7=T7/N2
      WRITE (OUT,2380)T7
 2380 FORMAT ("     AVE LATERAL DIST", 9X,F10.0)
C
C     LOADING TIME
C
      WBAR=W0*N4/(BR*T8)
      N1=50000./WBAR
      T=(505.75+35.1*N1)/3600.
      WRITE (OUT,2390)T
 2390 FORMAT("0    AVE LOAD TIME (HR)",11X,F6.2)
      WRITE (OUT,2395)N1
 2395 FORMAT("     AVE PIECES/TRUCK",13X,F6.0)
      Z2=1000.*14.6*Y3/N4
      IF(L10 .GT. 0.0) GO TO 2397
      Z3=1000.*(4.*143.25/ (2.*N4)+(143.25*N5)/(.75*N4))
      GO TO 2398
 2397 CT=1.97+.00212*(L10/2.)+.0119*(L9/2.)+.030463*APT
     *       + .000863*AVT*5.-.000398*(AVT/APT)
      N4=N4*(L10/TL8)
      Z3=1000.*((4.*143.25)/(2.*N4)+(CT*143.25)/(45.*AVT))
 2398 Z4=1000.*28.0*T/(50000./45.)
      WRITE (OUT,2400) Z2
 2400 FORMAT("0    AVE F AND B COST ($/MCF)",8X,F10.0)
      WRITE (OUT,2410)Z3
 2410 FORMAT("     AVE YARDING COST ($/MCF)",8X,F10.0)
C     HOT LOADING COST COMBINED WITH YARDING COST
      Z4=0
      WRITE (OUT,2420) Z4
 2420 FORMAT("     AVE LOADING COST ($/MCF)",8X,F10.0)
      Z1=Z2+Z3+Z4
```

```
      WRITE (OUT,2430)Z1
 2430 FORMAT("     AVE TOTAL   COST ($/MCF)",8X,F10.0)
      STOR0(K)=A1
      STOR1(K)=VOLAC
      STOR2(K)=Z3
      STOR3(K)=Z1
      STOR4(K)=AVT
      STOR5(K)=APT
      STOR6(K)=SE
      XX1=XX1+ALOG(VOLAC)
      XX2=XX2+(ALOG(VOLAC))**2
      YY1=YY1+ALOG(Z1)
      YY2=YY2+(ALOG(Z1))**2
      PCOR=PCOR+ALOG(VOLAC)*ALOG(Z1)
      IF(DELTA .EQ. 0.) GO TO 5000
      IF(A1 .GE. A1MAX) GO TO 2500
      IF(A1 .LT. A1MAX) A1=A1+DELTA
 2450 CONTINUE
 2500 WRITE(OUT,2600)
 2600 FORMAT(1H1)
      WRITE(OUT,2610)
 2610 FORMAT(" TREES/ACRE    VOL/ACRE CUT    YC($/MCF)   TC($/MCF)",
     *3X,"V/T   P/T   SE")
      DO 2700 K=1,NK
      WRITE(OUT,2620) STOR0(K),STOR1(K),STOR2(K),STOR3(K),STOR4(K),
     *STOR5(K),STOR6(K)
 2620 FORMAT(F7.0,12X,F6.0,10X,F4.0,4X,F8.0,4X,F5.1,F5.2,F6.3)
 2700 CONTINUE
C       CALCULATE POWER CURVE COEFFICIENTS
      B=(PCOR-(XX1*YY1/NK))/(XX2-(XX1**2/NK))
      AA=2.71828**((YY1/NK)-B*(XX1/NK))
      RSQ=(PCOR-YY1*XX1/NK)**2/((XX2-XX1**2/NK)*(YY2-YY1**2/NK))
      WRITE(OUT,2740) AA,B,RSQ
 2740 FORMAT("0 POWER CURVE COEFFICIENTS (Y=A*X**B)  A=",
     *F9.3,10X,"B=",F8.5,10X,"R-SQ=",F7.3)
      GO TO 1
 5000 CALL EXIT
      END
```

APPENDIX VIII.

USER'S GUIDE TO THE HARVEST SIMULATION PROGRAM

Data for the harvest simulation consist of six lines. Format and symbol definition for each line are as follows.

Line 1

The format for Line 1 is shown below with symbol codes and format type.

AØ	A1
(F5.0)	(F5.0)
__________,	__________

The explanation for the entries in Line 1 is as follows:

AØ -- Number of trees per acre before cutting.

A1 -- The lowest thinning intensity to be simulated, expressed as trees per acre. If the only thinning intensity desired is to final harvest, set A1 equal to AØ. Increments in thinning intensity will be controlled by the variable DELTA.

Line 2

The format for Line 2 is shown below with symbol codes and format type.

P2	D7	D8	D9	VAR
(F5.0)	(F5.0)	(F5.0)	(F5.0)	(F5.0)
__________,	__________,	__________,	__________,	__________

The explanation for the entries in Line 2 is as follows:

P2 -- A code used to define the diameter distribution of the trees to be removed from the stand.

P2 = 0 Negative exponential distribution.
P2 = 1 Normal distribution.
P2 =-1 Uniform distribution.

D7 -- Lower diameter limit (dbh) in the distribution defined by P2, expressed in inches.

D8 -- Mean diameter (dbh) in the distribution, expressed in inches.

D9 -- The upper limit of the diameter distribution specified by P2, expressed in inches.

VAR -- The variance of the diameter distribution expressed in square inches, required only if a normal distribution is specified.

Line 3

The format for Line 3 is shown below with symbol codes and format type.

D6	L1	L2	WØ	HT
(F5.0)	(F5.0)	(F5.0)	(F5.0)	(F5.0)

________,________,________,________,________

The explanation of the entries in Line 3 is as follows:

D6 -- The minimum diameter inside bark permitted for any log produced in the bucking process, expressed in inches. For weight calculations, an average bark thickness of D6/10 is assumed.

L1 -- The maximum log length permitted to be generated during the bucking process, expressed in feet.

L2 -- The minimum log length permitted to be generated during the bucking process, expressed in feet. Zero trim is assumed.

WØ -- The weight per cubic foot including bark, expressed in pounds per cubic foot.

HT -- The average height of trees being removed from the stand, expressed in feet.

Line 4

The format for Line 4 is shown below with symbol codes and format type.

R1	A8	LC	P3
(F5.0)	(F5.0)	(F5.0)	(F5.0)

________,________,________,________

The explanations for the entries in Line 4 is as follows:

R1 -- The maximum allowable log weight permitted to be yarded to the landing, expressed in pounds.

A8 -- The number of chokers available for building each load.

LC -- The effective choker length after subtracting sufficient length to wrap the average log.

P3 -- A code which specifies whether a standard butthook is to be used or if sliding chokers are permissable.

P3 = Ø Standard butthook.
P3 = 1 Sliding chokers.

Line 5

The format for Line 5 is shown below with symbol codes and format type.

P	P1	DELTA
(F5.0)	(F5.0)	(F5.0)

_________, ________, _________

The explanation for the entries in Line 5 is as follows:

P -- A code controlling supplementary listing of the logs generated during the bucking process. Output includes log length, small end log diameter, and log weight.

P = Ø Suppress output.
P = 1 Provide log list.

P1 -- A code controlling supplementary listing of the turn statistics during simulation. Output includes outhaul distance, lateral distance, logs per turn, log load weight, and cycle time.

P1 = Ø Suppress output.
P1 = 1 Provide turn statistics.

DELTA -- The increment in thinning intensity, expressed in trees per acre.

Line 6

The format for Line 6 is shown below with symbol codes and format type.

L8	L9	L10
(F5.0)	(F5.0)	(F5.0)

_________, _________, _________

The explanation for the entries in Line 6 is as follows:

L8 -- The maximum slope yarding distance expressed in feet.

L9 -- The maximum lateral yarding distance, expressed in feet.

L10 -- A variable which controls the yarding distance used for yarding cost calculations. If L10 is zero then the average yarding distance is derived directly from the simulation results. If L10 is not zero, then L10/2 is used for the average yarding distance. L10 is expressed in feet.

Cycle time equations and machine costs -- The cycle time equations are located in statement numbers 2200 and 2397. Machine and crew costs are located between statement 2395 and 2398.

APPENDIX IX.

LISTING OF THE OPTIMIZATION PROGRAM

```
      PROGRAM DOPT(INPUT,OUTPUT,TAPE60=INPUT,TAPE61=OUTPUT)
      DIMENSION VAL(39,72,2),VLM(39,72,2),TRUEBA(39,72,2),TRUET(39,72,2)
      DIMENSION VCUT(39,72),DMEAN(39,72),OPOLVR(39,72),OPOLHR(39,72)
      DIMENSION HRVSTD(16),HRVSTB(16),HRVSTP(16),HRVSTS(16),HRVSTC(16)
      DIMENSION NN(100),TNORM(16),GNORM(16),VNORM(16),Z(16)
      COMMON TAGE,TBASE,DM,SITE,TRATIO,GRATIO,VGRATIO
      COMMON PMORTN(25),PMORTG(25),PMORTV(25),YMORTN(200),YMORTG(200)
      COMMON TNONMER(25),GNONMER(25),VNONMER(25)
      INTEGER OPOLVR,OPOLHR
      N=1
      READ(60,5) MAXVR,MAXHR,INTVR,INTHR,TBASE,SITE,R,TEST,VAL1
    5 FORMAT(4I3,2F4.0,F4.2,2F5.0)
      TAGE=TBASE
***   SET THE VALUE OF EACH NODE TO -999999.9
      DO 10 I=1,MAXVR
      DO 10 J=1,MAXHR
   10 VAL(I,J,1)=-999999.99
***   CALCULATE NATURAL STAND AT THE CURRENT AGE
      BHAGE=TAGE-13.22+0.033*SITE
      DNATURE=10**(0.1097-3.4857/BHAGE**0.25+1.0531*ALOG10(SITE))
      TNATURE=10**(3.9108+5.2306/BHAGE**0.25-1.5803*ALOG10(SITE))
      GNATURE=10**(1.8669-1.7408/BHAGE**0.25+0.5259*ALOG10(SITE))
      HT=10**(0.1567-15.673/TAGE+ALOG10(SITE))
      VG=VGRATIO=10**(-0.0282+0.7917*ALOG10(HT))
      VNATURE=GNATURE*VGRATIO
      TRATIO=GRATIO=1.
      IF(TEST.EQ.0.) GOTO 13
***   FOR NON-NATURAL STAND READ IN NUMBER OF TREES AND BASAL AREA.
      READ(60,12) STREE,SBA
   12 FORMAT(2F4.0)
      TRATIO=STREE/TNATURE
      GRATIO=SBA/GNATURE
***   CALCULATE MERCHANTABLE PART AND MORTALITY LATER PART
   13 DIAM=DF=DNATURE/0.875
      DM=DF*0.75
      CALL SUBMORT(DNATURE)
      GMERCH=10**(1.6958+0.4994*ALOG10(DF))
      TMERCH=GMERCH/(0.005454154*DF**2)
      DL=0.698*DNATURE
      TNONMER(1)=(TNATURE-TMERCH)*TRATIO
      GNONMER(1)=TNONMER(1)/TRATIO*0.005454154*DL**2*GRATIO
      VNONMER(1)=VGRATIO*TARIF(DNATURE)/TARIF(DL)*GNONMER(1)
      VMERCH=VNATURE-VNONMER(1)/GRATIO
      I=TMERCH*TRATIO/INTVR+1
      J=(GMERCH*GRATIO+INTHR/2.)/INTHR+1
```

```
      TRUET(I,J,1)=TMERCH*TRATIO
      TRUEBA(I,J,1)=GMERCH*GRATIO
      VLM(I,J,1)=VMERCH*GRATIO
      VAL(I,J,1)=VAL1
      NS=TRUET(I,J,1)/(2.*INTVR)+2.
      ENTRYC=5.
***   CALCULATE NATURAL STAND AND MERCHANTABLE TREES.
      DO 14 I=1,14
      AB=TBASE+10*(I-1)
      B=AB-13.22+0.033*SITE
      TNORM(I)=10**(3.9108+5.2306/B**0.25-1.5803*ALOG10(SITE))
      GNORM(I)=10**(1.8669-1.7408/B**0.25+.5259*ALOG10(SITE))
      VNORM(I)=10**(1.9628-12.4083/AB-1.7408/B**.25+1.3176*ALOG10(SITE))
   14 Z(I)=TNORM(I)-TNONMER(I)
***   SET THE INITIAL VALUES OF EVERY NODE IN NEXT STAGE TO -999999.9
   15 DO 20 I=1,MAXVR
      DO 20 J=1,MAXHR
      VAL(I,J,2)=VLM(I,J,2)=TRUEBA(I,J,2)=TRUET(I,J,2)=-999999.9
   20 OPOLVR(I,J)=OPOLHR(I,J)=VCUT(I,J)=DMEAN(I,J)=-999999.9
      IF(N.EQ.1) GOTO 25
      NS=1
      HT=10**(0.1567-15.673/(TAGE-10.)+ALOG10(SITE))
      VG=10**(-0.0282+0.7917*ALOG10(HT))
   25 KJ=TAGE/10.
      GBOUND=0.
      DO 55 I=2,MAXVR
      DO 50 J=1,MAXHR
***   IF THE VALUE OF THE NODE IS -999999.9 THEN IT IS INFEASIBLE
      IF(VAL(I,J,1).LE.-999999.9) GOTO 50
***   IN THE FIRST STAGE WE THIN FIRST THEN GROW
      IF(N.EQ.1) GOTO 30
      ENTRYC=2.5
      VOL=VLM(I,J,1)+VNONMER(N)
      CALL GROWTH(TRUET(I,J,1),VOL,VMER,VMORT1,GMER,GMORT1,N)
      VLM(I,J,1)=VMER
      TRUEBA(I,J,1)=GMER
      PNORM=TRUET(I,J,1)/Z(N-1)
      TMORT1=(Z(N-1)-Z(N))*PNORM
      TRUET(I,J,1)=TRUET(I,J,1)-TMORT1
      DIAM=SQRT(TRUEBA(I,J,1)/(0.005454154*TRUET(I,J,1)))
   30 NT=TRUET(I,J,1)/INTVR+2.
***   WITH I TREES THERE ARE I+1 KINDS OF THINNING.
***   THIN PROPORTIONALLY TO THE DISTRIBUTION OF DIAMETER SO
      DO 40 K=NS,NT                                       DMEAN IS UNCHANGED.
      IF(K.NE.NT) GOTO 32
```

```
      TMPBA=TRUEBA(I,J,1)
      TMPVLM=VLM(I,J,1)
      CUT=REVNOW=0.
      GOTO 35
   32 TMPBA=TRUEBA(I,J,1)*(K-1)*INTVR/TRUET(I,J,1)
      TMPVLM=VLM(I,J,1)*(K-1)*INTVR/TRUET(I,J,1)
      CUT=VLM(I,J,1)-TMPVLM+VMORT1
      DIAM1=SQRT((TRUEBA(I,J,1)-TMPBA+GMORT1)/(.005454154*(TRUET(I,J,1)-
     $(K-1)*INTVR+TMORT1)))
      CALL HARVEST(DIAM1,CUT,TRUET(I,J,1),PRICE,REVNOW)
   35 TMPVAL=REVNOW/((1+R)**TAGE)+VAL(I,J,1)
      KK=IFIX((TMPBA+INTHR/2.)/INTHR)+1
      IF(TMPVAL.LE.VAL(K,KK,2)) GOTO 40
      DMEAN(K,KK)=DIAM
      VAL(K,KK,2)=TMPVAL
      OPOLVR(K,KK)=(I-1)*INTVR
      OPOLHR(K,KK)=(J-1)*INTHR
      TRUEBA(K,KK,2)=TMPBA
      IF(TMPBA.GT.GBOUND) GBOUND=TMPBA
      TRUET(K,KK,2)=(K-1)*INTVR
      IF(K.EQ.NT) TRUET(K,KK,2)=TRUET(I,J,1)
      IF(K.EQ.1) HRVSTB(KJ)=TRUEBA(I,J,1)
      VLM(K,KK,2)=TMPVLM
      VCUT(K,KK)=CUT
   40 CONTINUE
   50 CONTINUE
   55 CONTINUE
***   OUTPUT
      WRITE(61,60) TAGE
   60 FORMAT("1AGE=",F5.1/" 1=MEAN DIAMETER (INCH)"/" 2=VOLUME (CUBIC FE
     $ET)"/" 3=VOLUME CUT IN THIS STAGE (CUBIC FEET)"/" 4=TRUE BASAL ARE
     $A (SQUARE FEET)"/" 5=TRUE NUMBER OF TREES"/" 6=CUMULATIVE VALUE FR
     $OM THINNING ($PNW)"/" 7=WHERE IT COMES FROM( TREES,BA)")
      WRITE(61,61) TNONMER(N),TNORM(N)
   61 FORMAT(" NONMERCHANTABLE TREES=",F5.1/" TOTAL TREES =",F7.1/)
      DO 62 I=1,72
   62 NN(I)=(I-1)*INTHR
      IS=-11
      DO 75 IJ=1,6
      IS=IS+12
      IE=IS+11
      WRITE(61,64) TAGE,(NN(I),I=IS,IE)
   64 FORMAT(" AGE=",F5.1/" TREES*BA ",12(I3,7X))
      NI=Z(N)/INTVR+2.
      DO 70 I=1,NI
```

```
      II=(I-1)*INTVR
      WRITE(61,65) II,(DMEAN(I,J),J=IS,IE)
   65 FORMAT(3X,I3,12(3X,F7.1))
      WRITE(61,66) (VLM(I,J,2),J=IS,IE)
      WRITE(61,66) (VCUT(I,J),J=IS,IE)
      WRITE(61,66) (TRUEBA(I,J,2),J=IS,IE)
      WRITE(61,66) (TRUET(I,J,2),J=IS,IE)
      WRITE(61,66) (VAL(I,J,2),J=IS,IE)
   66 FORMAT(6X,12(3X,F7.1))
      WRITE(61,68) (OPOLVR(I,J),OPOLHR(I,J),J=IS,IE)
   68 FORMAT(7X,12("(",I3,",",I3,")",1X))
   70 CONTINUE
      IF(IE.GE.IFIX((GBOUND+INTHR/2.)/INTHR)+1) GOTO 80
      WRITE(61,72)
   72 FORMAT("1")
   75 CONTINUE
   80 HRVSTD(KJ)=DMEAN(1,1)
      HRVSTP(KJ)=VAL(1,1,2)
      HRVSTS(KJ)=VAL(1,1,2)*(1+R)**TAGE/((1+R)**TAGE-1)
      HRVSTC(KJ)=VCUT(1,1)
      IF(VAL(1,1,2).LE.VAL(1,1,1).OR.N.GE.3) GOTO 95
      N=N+1
      TAGE=TAGE+10.
      DO 90 I=1,MAXVR
      DO 90 J=1,MAXHR
      VAL(I,J,1)=VAL(I,J,2)
      VLM(I,J,1)=VLM(I,J,2)
      TRUET(I,J,1)=TRUET(I,J,2)
   90 TRUEBA(I,J,1)=TRUEBA(I,J,2)
      GOTO 15
   95 WRITE(61,96)
   96 FORMAT(/"1ROTATION AGE   HARVEST VOLUME   DIAMETER   HARVEST BA
     $  PNW       SE")
      KI=TBASE/10.
      DO 98 L=KI,KJ
      LL=L*10
   98 WRITE(61,99) LL,HRVSTC(L),HRVSTD(L),HRVSTB(L),HRVSTP(L),HRVSTS(L)
   99 FORMAT(1X,I7,10X,F9.2,5X,F7.2,4X,F9.2,5X,F7.2,F9.2)
      END
      SUBROUTINE SUBMORT(DD)
      COMMON TAGE,TBASE,DM,SITE,TRATIO,GRATIO,VGRATIO
      COMMON PMORTN(25),PMORTG(25),PMORTV(25),YMORTN(200),YMORTG(200)
      COMMON TNONMER(25),GNONMER(25),VNONMER(25)
***   CALCULATE PERIODIC MORTALITY STARTS FROM THE AGE OF FIRST THINNING
      TNONMER(1)=YMORTN(1)=10**(3.8622+3.1994*ALOG10(DM)-4.7*ALOG10(DD))
```

```
     $*TRATIO
      GNONMER(1)=YMORTG(1)=10**(1.4034+4.9394*ALOG10(DM)-4.44*ALOG10(DD)
     $)*GRATIO
      DO 10 JJ=1,18
      AGE=TBASE+JJ*10.
      BHAGE=AGE-13.22+0.033*SITE
      D=10**(0.1097-3.4857/BHAGE**0.25+1.0531*ALOG10(SITE))
      TNONMER(JJ+1)=10**(3.8622+3.1994*ALOG10(DM)-4.7*ALOG10(D))*TRATIO
      GNONMER(JJ+1)=10**(1.4034+4.9394*ALOG10(DM)-4.44*ALOG10(D))*GRATIO
      DMORTL=SQRT((GNONMER(JJ+1)/TNONMER(JJ+1))/0.005454154)
      HT=10**(0.1567-15.673/AGE+ALOG10(SITE))
      VG=10**(-0.0282+0.7917*ALOG10(HT))
      TAVE=(VG*TARIF(D)+VGRATIO*TARIF(DD))/2.
      VNONMER(JJ+1)=TAVE/TARIF(DMORTL)*GNONMER(JJ+1)
      PMORTN(JJ)=(TNONMER(JJ)-TNONMER(JJ+1))
      PMORTG(JJ)=(GNONMER(JJ)-GNONMER(JJ+1))
      DMORT=SQRT((PMORTG(JJ)/PMORTN(JJ))/0.005454154)
      PMORTV(JJ)=TAVE/TARIF(DMORT)*PMORTG(JJ)
   10 CONTINUE
***   CALCULATE YEARLY MORTALITY STARTS FROM THE AGE OF FIRST THINNING
      DO 20 II=1,180
      AGE=TBASE+II
      BHAGE=AGE-13.22+0.033*SITE
      D=10**(0.1097-3.4857/BHAGE**0.25+1.0531*ALOG10(SITE))
      YMORTN(II+1)=10**(3.8622+3.1994*ALOG10(DM)-4.7*ALOG10(D))
      YMORTG(II+1)=10**(1.4034+4.9394*ALOG10(DM)-4.44*ALOG10(D))
      YMORTN(II)=(YMORTN(II)-YMORTN(II+1))*TRATIO
      YMORTG(II)=(YMORTG(II)-YMORTG(II+1))*GRATIO
   20 CONTINUE
      RETURN
      END
      SUBROUTINE GROWTH(TREE,V,VMER,VMORT1,GMER,GMORT1,N)
      COMMON TAGE,TBASE,DM,SITE,TRATIO,GRATIO,VGRATIO
      COMMON PMORTN(25),PMORTG(25),PMORTV(25),YMORTN(200),YMORTG(200)
      COMMON TNONMER(25),GNONMER(25),VNONMER(25)
      VGROW=VGROW1=0.
***   ASSUME FIRST CT AT FIRST STAGE
      ADJ1=(405.-TBASE)/400.
      GLIMIT=10**(3.3446-0.3328*ALOG10(TREE))
      HT=10**(0.1567-15.673/(TAGE-10)+ALOG10(SITE))
      TMPAGE=TAGE-10.
      DO 10 I=1,10
      NN=TMPAGE-TBASE+2.
      BHAGE=TMPAGE-13.22+0.033*SITE
      DHT=10**(1.7141+ALOG10(SITE)-15.673/TMPAGE-2.*ALOG10(TMPAGE))
```

```
      HT=HT+DHT
      VG=10**(-0.0282+0.7917*ALOG10(HT))
      DVA=1.12+0.0105*TMPAGE-0.00005*TMPAGE**2
      IF(TMPAGE.GT.105.) DVA=10**0.22304
      DVOL=10**(ALOG10(2.3026)+ALOG10(12.4083/TMPAGE**2+.4352/BHAGE**
     $1.25)+ALOG10(DVA)+1.9628-12.4083/TMPAGE-1.7408/BHAGE**0.25+
     $1.3176*ALOG10(SITE))
      DVOL=DVOL*ADJ1
      TMPVOL=VGROW+DVOL+V
      G=TMPVOL/VG
      GMERCH=G-YMORTG(NN)
      CR=GMERCH/GLIMIT
      ADJ2=1.-16.*(CR-0.5)**4
      DVOL=DVOL*ADJ2
      VGROW=VGROW+DVOL
      DVOL1=10**(ALOG10(2.3026)+ALOG10(12.4083/TMPAGE**2+.4352/BHAGE**
     $1.25)+1.9628-12.4083/TMPAGE-1.7408/BHAGE**.25+1.3176*ALOG10(SITE))
      DVOL1=DVOL1*ADJ1
      TMPVOL1=VGROW1+DVOL1+V
      G1=TMPVOL1/VG
      GMERCH1=G1-YMORTG(NN)
      CR1=GMERCH1/GLIMIT
      ADJ21=1.-16.*(CR1-0.5)**4
      DVOL1=DVOL1*ADJ21
      VGROW1=VGROW1+DVOL1
      TMPAGE=TMPAGE+1
   10 CONTINUE
***   CALCULATE MERCHANTABLE MORTALITY AND MERCHANTABLE LIVE TREES.
      VMORT1=VGROW-VGROW1
      VMER=V+VGROW1-VNONMER(N+1)
      GMORT1=(V+VGROW)/VG-(V+VGROW1)/VG
      GMER=(V+VGROW)/VG-GMORT1-GNONMER(N+1)
      RETURN
      END
      FUNCTION TARIF(DIAM)
      TARIF=(0.00497819*DIAM**2)/(0.005454154*(DIAM**2+16.)*(1.0378+
     $1.4967*(0.0134**(DIAM/10.)))-0.174532)
      RETURN
      END
      SUBROUTINE HARVEST (DQ,CUT,TREE,UNITREV,REVNOW)
C
      COMMON TAGE,TBASE,DM,SITE,TRATIO,GRATIO,VGRATIO
      COMMON PMORTN(25),PMORTG(25),PMORTV(25),YMORTN(200),YMORTG(200)
      COMMON TNONMER(25),GNONMER(25),VNONMER(25)
C
```

SUBROUTINE HARVEST (1200-ft)

```
      SUBROUTINE HARVEST (DQ,CUT,TREE,UNITREV,REVNOW)
C
      COMMON TAGE,TBASE,DM,SITE,TRATIO,GRATIO,VGRATIO
      COMMON PMORTN(25),PMORTG(25),PMORTV(25),YMORTN(200),YMORTG(200)
      COMMON TNONMER(25),GNONMER(25),VNONMER(25)
C
C     CALCULATE CUBIC VOLUME REMOVED TO A 4-INCH TOP
C
      HD=10.**(.1567-15.673/TAGE+ALOG10(SITE))
      N1=(TAGE-TBASE)/10.+1
      ALLTREE=TREE+TNONMER(N1)
      HM=HD*(3040.-ALLTREE)/3000.
      IF (HM.GT.HD) HM=HD
      CU=.8758+.001049*HM-.000002824*HM**2+0.3221/DQ-45.647/DQ**3
      VOL=CU*CUT
C
C     DETERMINE VARIANCE OF STAND DIAMETER DISTRIBUTION
C
      VAR=-5.367+0.287*TAGE
C
C     DETERMINE UNBIASED MEAN STAND DIAMETER
C
      D=SQRT(DQ**2 - VAR)
C
C     CALCULATE STUMP TO TRUCK LOGGING COST
C
C
      IF (D.GT.7.63) GO TO 10
      COST=5750.0*VOL**(-.2628)
      GO TO 150
C
   10 IF (D.GT.9.23) GO TO 20
      IF (VOL.GT.500.) GO TO 15
      C1=5750.0*VOL**(-.2628)
      C2=4461.4*VOL**(-.2591)
      DELTA=(C1-C2)/(9.23-7.63)
      COST=C1-DELTA*(D-7.63)
      GO TO 150
C
   15 C1=16502.3*VOL**(-.37893)
      C2=12022.7*VOL**(-.36466)
      DELTA=(C1-C2)/(9.23-7.63)
      COST=C1-DELTA*(D-7.63)
      GO TO 150
C
```

```
   20 IF (D.GT.10.87) GO TO 30
      C1=12022.7*VOL**(-.36466)
      C2= 9811.6*VOL**(-.36398)
      DELTA=(C1-C2)/(10.87-9.23)
      COST=C1-DELTA*(D-9.23)
      GO TO 150
C
   30 IF (D.GT.12.31) GO TO 40
      C1=9811.6 *VOL**(-.36398)
      C2=7987.0*VOL**(-.35160)
      DELTA=(C1-C2)/(12.31-10.87)
      COST=C1-DELTA*(D-10.87)
      GO TO 150
C
   40 IF (D.GT.13.66) GO TO 50
      C1=7987.0*VOL**(-.35160)
      C2=7288.8*VOL**(-.35163)
      DELTA=(C1-C2)/(13.66-12.31)
      COST=C1-DELTA*(D-12.31)
      GO TO 150
C
   50 IF(D.GT.15.03) GO TO 60
      C1=7288.8*VOL**(-.35163)
      C2=6785.2*VOL**(-.35663)
      DELTA=(C1-C2)/(15.03-13.66)
      COST=C1-DELTA*(D-13.66)
      GO TO 150
C
   60 IF (D.GT.16.19) GO TO 70
      C1=6785.2*VOL**(-.35663)
      C2=5911.4*VOL**(-.35206)
      DELTA=(C1-C2)/(16.19-15.03)
      COST=C1-DELTA*(D-15.03)
      GO TO 150
C
   70 IF (D.GT.17.26) GO TO 80
      C1=5911.4*VOL**(-.35206)
      C2=4337.7*VOL**(-.32494)
      DELTA=(C1-C2)/(17.26-16.19)
      COST=C1-DELTA*(D-16.19)
      GO TO 150
C
   80 IF (D.GT.18.31) GO TO 90
      C1=4337.7*VOL**(-.32494)
      C2=4980.8*VOL**(-.34421)
```

```
      DELTA=(C1-C2)/(18.31-17.26)
      COST=C1-DELTA*(D-17.26)
      GO TO 150
C
   90 IF (D.GT.20.25) GO TO 100
      C1=4980.8*VOL**(-.34421)
      C2=3913.1*VOL**(-.32269)
      DELTA=(C1-C2)/(20.25-18.31)
      COST=C1-DELTA*(D-18.31)
      GO TO 150
C
  100 IF (D.GT.21.90) GO TO 110
C
      C1=3913.1*VOL**(-.32269)
      C2=4670.5*VOL**(-.34573)
      DELTA=(C1-C2)/(21.9-20.25)
      COST=C1-DELTA*(D-20.25)
      GO TO 150
C
  110 COST=4670.5*VOL**(-.34573)
C     CALCULATE CURRENT REVENUE
C
  150 PONDVAL=9.91+70.81*D
      HAUL=150.
      UNITREV=(PONDVAL-COST-HAUL)*.001
      REVNOW=VOL*UNITREV
      RETURN
      END
```

SUBROUTINE HARVEST (600-ft)

```
      SUBROUTINE HARVEST (DQ,CUT,TREE,UNITREV,REVNOW)
C
      COMMON TAGE,TBASE,DM,SITE,TRATIO,GRATIO,VGRATIO
      COMMON PMORTN(25),PMORTG(25),PMORTV(25),YMORTN(200),YMORTG(200)
      COMMON TNONMER(25),GNONMER(25),VNONMER(25)
C
C     CALCULATE CUBIC VOLUME REMOVED TO A 4-INCH TOP
C
      HD=10.**(.1567-15.673/TAGE+ALOG10(SITE))
      N1=(TAGE-TBASE)/10.+1
      ALLTREE=TREE+TNONMER(N1)
      HM=HD*(3040.-ALLTREE)/3000.
      IF (HM.GT.HD) HM=HD
      CU=.8758+.001049*HM-.000002824*HM**2+0.3221/DQ-45.647/DQ**3
      VOL=CU*CUT
C
C     DETERMINE VARIANCE OF STAND DIAMETER DISTRIBUTION
C
      VAR=-5.367+0.287*TAGE
C
C     DETERMINE UNBIASED MEAN STAND DIAMETER
C
      D=SQRT(DQ**2 - VAR)
C
C     CALCULATE STUMP TO TRUCK LOGGING COST
C
      IF(D.GT.6.05) GO TO 5
      COST=7790.9*VOL**(-.2834)
      GO TO 150
C
    5 IF(D.GT.7.63) GO TO 10
      IF(VOL.GT.1000.)GO TO 7
      C1=7790.9*VOL**(-.2834)
      C2=4954.7*VOL**(-.2726)
      DELTA=(C1-C2)/(7.63-6.05)
      COST=C1-DELTA*(D-6.05)
      GO TO 150
C
    7 C1=7800.8*VOL**(-.2539)
      C2=7187.5*VOL**(-.2891)
      DELTA=(C1-C2)/(7.63-6.05)
      COST=C1-DELTA*(D-6.05)
      GO TO 150
C
   10 IF (D.GT.9.23) GO TO 20
```

```
      IF(VOL.GT.1000.) GO TO 15
      C1=4954.7*VOL**(-.2726)
      C2=3768.0*VOL**(-.2662)
      DELTA=(C1-C2)/(9.23-7.63)
      COST=C1-DELTA*(D-7.63)
      GO TO 150
C
   15 IF(VOL.GT.2000.) GO TO 18
      C1=7187.5*VOL**(-.2891)
      C2=6254.8*VOL**(-.3013)
      DELTA=(C1-C2)/(9.23-7.63)
      COST=C1-DELTA*(D-7.63)
      GO TO 150
C
   18 C1=14353.0*VOL**(-.3782)
      C2=10336.6*VOL**(-.3627)
      DELTA=(C1-C2)/(9.23-7.63)
      COST=C1-DELTA*(D-7.63)
      GO TO 150
C
   20 IF (D.GT.10.87) GO TO 30
      IF(VOL.GT.1000.) GO TO 25
      C1=3768.0*VOL**(-.2662)
      C2=4375.0*VOL**(-.2833)
      DELTA=(C1-C2)/(10.87-9.23)
      COST=C1-DELTA*(D-9.23)
      GO TO 150
C
   25 IF(VOL.GT.2000.) GO TO 28
      C1=6524.8*VOL**(-.3013)
      C2=4375.0*VOL**(-.2833)
      DELTA=(C1-C2)/(10.87-9.23)
      COST=C1-DELTA*(D-9.23)
      GO TO 150
C
   28 C1=10336.6*VOL**(-.3627)
      C2=8479.6*VOL**(-.3626)
      DELTA=(C1-C2)/(10.87-9.23)
      COST=C1-DELTA*(D-9.23)
      GO TO 150
   30 IF (D.GT.12.31) GO TO 40
      C1=8479.6*VOL**(-.3626)
      C2=6839.5*VOL**(-.3492)
      DELTA=(C1-C2)/(12.31-10.87)
      COST=C1-DELTA*(D-10.87)
```

```
      GO TO 150
C
   40 IF (D.GT.13.66) GO TO 50
      C1=6839.5*VOL**(-.3492)
      C2=6276.4*VOL**(-.3498)
      DELTA=(C1-C2)/(13.66-12.31)
      COST=C1-DELTA*(D-12.31)
      GO TO 150
C
   50 IF(D.GT.15.03) GO TO 60
      C1=6276.4*VOL**(-.3498)
      C2=5848.5*VOL**(-.3548)
      DELTA=(C1-C2)/(15.03-13.66)
      COST=C1-DELTA*(D-13.66)
      GO TO 150
C
   60 IF (D.GT.16.19) GO TO 70
      C1=5848.5*VOL**(-.3548)
      C2=4980.1*VOL**(-.3475)
      DELTA=(C1-C2)/(16.19-15.03)
      COST=C1-DELTA*(D-15.03)
      GO TO 150
C
   70 IF (D.GT.17.26) GO TO 80
      C1=4980.1*VOL**(-.3475)
      C2=3765.6*VOL**(-.3238)
      DELTA=(C1-C2)/(17.26-16.19)
      COST=C1-DELTA*(D-16.19)
      GO TO 150
C
   80 IF (D.GT.18.31) GO TO 90
      C1=3765.6*VOL**(-.3238)
      C2=4215.0*VOL**(-.3402)
      DELTA=(C1-C2)/(18.31-17.26)
      COST=C1-DELTA*(D-17.26)
      GO TO 150
C
   90 IF (D.GT.20.25) GO TO 100
      C1=4215.0*VOL**(-.3402)
      C2=3377.5*VOL**(-.3207)
      DELTA=(C1-C2)/(20.25-18.31)
      COST=C1-DELTA*(D-18.31)
      GO TO 150
C
  100 IF (D.GT.21.90) GO TO 110
```

```
      C1=3377.5*VOL**(-.3207)
      C2=4209.5*VOL**(-.3488)
      DELTA=(C1-C2)/(21.9-20.25)
      COST=C1-DELTA*(D-20.25)
      GO TO 150
C
  110 COST=4209.5*VOL**(-.3488)
C
C     CALCULATE CURRENT REVENUE
C
  150 PONDVAL=9.91+70.81*D
      HAUL=150.
      UNITREV=(PONDVAL-COST-HAUL)*.001
      REVNOW=VOL*UNITREV
      RETURN
      END
```

SUBROUTINE HARVEST (300-ft)

```
      SUBROUTINE HARVEST (DQ,CUT,TREE,UNITREV,REVNOW)
C
      COMMON TAGE,TBASE,DM,SITE,TRATIO,GRATIO,VGRATIO
      COMMON PMORTN(25),PMORTG(25),PMORTV(25),YMORTN(200),YMORTG(200)
      COMMON TNONMER(25),GNONMER(25),VNONMER(25)
C
C     CALCULATE CUBIC VOLUME REMOVED TO A 4-INCH TOP
C
      HD=10.**(.1567-15.673/TAGE+ALOG10(SITE))
      N1=(TAGE-TBASE)/10.+1
      ALLTREE=TREE+TNONMER(N1)
      HM=HD*(3040.-ALLTREE)/3000.
      IF (HM.GT.HD) HM=HD
      CU=.8758+.001049*HM-.000002824*HM**2+0.3221/DQ-45.647/DQ**3
      VOL=CU*CUT
C
C     DETERMINE VARIANCE OF STAND DIAMETER DISTRIBUTION
C
      VAR=-5.367+0.287*TAGE
C
C     DETERMINE UNBIASED MEAN STAND DIAMETER
C
      D=SQRT(DQ**2 - VAR)
C
C     CALCULATE STUMP TO TRUCK LOGGING COST
      IF(D.GT.6.05) GO TO 5
      COST=6507.3*VOL**(-.2737)
      GO TO 150
C
    5 IF (D.GT.7.63) GO TO 10
      IF(VOL.GT.2000.) GO TO 7
      C1=6507.3*VOL**(-.2737)
      C2=4536.8*VOL**(-.2794)
      DELTA=(C1-C2)/(7.63-6.05)
      COST=C1-DELTA*(D-6.05)
      GO TO 150
    7 C1=7319.2*VOL**(-.2603)
      C2=5994.0*VOL**(-.2825)
      DELTA=(C1-C2)/(7.63-6.05)
      COST=C1-DELTA*(D-6.05)
      GO TO 150
C
   10 IF (D.GT.9.23) GO TO 20
      IF(VOL.GT.2000.) GO TO 15
      C1=4536.8*VOL**(-.2794)
```

```
      C2=3405.5*VOL**(-.2712)
      DELTA=(C1-C2)/(9.23-7.63)
      COST=C1-DELTA*(D-7.63)
      GO TO 150
C
   15 C1=5994.2*VOL**(-.2825)
      C2=5114.0*VOL**(-.2928)
      DELTA=(C1-C2)/(9.23-7.63)
      COST=C1-DELTA*(D-7.63)
      GO TO 150
C
   20 IF (D.GT.10.87) GO TO 30
      IF(VOL.GT.2000.) GO TO 25
      C1=3405.5*VOL**(-.2712)
      C2=2075.7*VOL**(-.2349)
      DELTA=(C1-C2)/(10.87-9.23)
      COST=C1-DELTA*(D-9.23)
      GO TO 150
C
   25 C1=5114.0*VOL**(-.2928)
      C2=3561.6*VOL**(-.2747)
      DELTA=(C1-C2)/(10.87-9.23)
      COST=C1-DELTA*(D-9.23)
      GO TO 150
C
   30 IF (D.GT.12.31) GO TO 40
      IF (VOL.GT.2000.) GO TO 35
      C1=2075.7*VOL**(-.2349)
      C2=1834.5*VOL**(-.2334)
      DELTA=(C1-C2)/(12.31-10.87)
      COST=C1-DELTA*(D-10.87)
      GO TO 150
C
   35 C1=3561.6*VOL**(-.2747)
      C2=2790.6*VOL**(-.2569)
      DELTA=(C1-C2)/(12.31-10.87)
      COST=C1-DELTA*(D-10.87)
      GO TO 150
C
   40 IF (D.GT.13.66) GO TO 50
      IF(VOL.GT.2000.) GO TO 45
      C1=1834.5*VOL**(-.2334)
      C2=1634.8*VOL**(-.2281)
      DELTA=(C1-C2)/(13.66-12.31)
      COST=C1-DELTA*(D-12.31)
```

```
      GO TO 150
C
   45 C1=2790.6*VOL**(-.2569)
      C2=2448.2*VOL**(-.2510)
      DELTA=(C1-C2)/(13.66-12.31)
      COST=C1-DELTA*(D-12.31)
      GO TO 150
C
   50 IF(D.GT.15.03) GO TO 60
      IF (VOL.GT.2000.) GO TO 55
      C1=1634.8*VOL**(-.2281)
      C2=2767.3*VOL**(-.3182)
      DELTA=(C1-C2)/(15.03-13.66)
      COST=C1-DELTA*(D-13.66)
      GO TO 150
C
   55 IF (VOL.GT.5000.) GO TO 57
      C1=2448.2*VOL**(-.2510)
      C2=2207.3*VOL**(-.2482)
      DELTA=(C1-C2)/(15.03-13.66)
      COST=C1-DELTA*(D-13.66)
      GO TO 150
C
   57 C1=5771.8*VOL**(-.3486)
      C2=5377.6*VOL**(-.3535)
      DELTA=(C1-C2)/(15.03-13.66)
      COST=C1-DELTA*(D-13.66)
      GO TO 150
C
   60 IF (D.GT.16.19) GO TO 70
      IF(VOL.GT.5000.) GO TO 65
      C1=2207.3*VOL**(-.2482)
      C2=4550.8*VOL**(-.3455)
      DELTA=(C1-C2)/(16.19-15.03)
      COST=C1-DELTA*(D-15.03)
      GO TO 150
C
   65 C1=5377.6*VOL**(-.3535)
      C2=4550.8*VOL**(-.3455)
      DELTA=(C1-C2)/(16.19-15.03)
      COST=C1-DELTA*(D-15.03)
      GO TO 150
C
   70 IF (D.GT.17.26) GO TO 80
      C1=4550.8*VOL**(-.3455)
```

```
      C2=3455.2*VOL**(-.3222)
      DELTA=(C1-C2)/(17.26-16.19)
      COST=C1-DELTA*(D-16.19)
      GO TO 150
C
   80 IF (D.GT.18.31) GO TO 90
      C1=3455.2*VOL**(-.3222)
      C2=3481.1*VOL**(-.3379)
      DELTA=(C1-C2)/(18.31-17.26)
      COST=C1-DELTA*(D-17.26)
      GO TO 150
C
   90 IF (D.GT.20.25) GO TO 100
      C1=3481.1*VOL**(-.3379)
      C2=3135.3*VOL**(-.3204)
      DELTA=(C1-C2)/(20.25-18.31)
      COST=C1-DELTA*(D-18.31)
      GO TO 150
C
  100 IF (D.GT.21.90) GO TO 110
      C1=3135.3*VOL**(-.3204)
      C2=3964.2*VOL**(-.3500)
      DELTA=(C1-C2)/(21.9-20.25)
      COST=C1-DELTA*(D-20.25)
      GO TO 150
C
  110 COST=3964.2*VOL**(-.3500)
C
C     CALCULATE CURRENT REVENUE
C
  150 PONDVAL=9.91+70.81*D
      HAUL=150.
      UNITREV=(PONDVAL-COST-HAUL)*.001
      REVNOW=VOL*UNITREV
      RETURN
      END
```

SUBROUTINE HARVEST (Bunch-and-Swing)

```
      SUBROUTINE HARVEST (DQ,CUT,TREE,UNITREV,REVNOW)
C
      COMMON TAGE,TBASE,DM,SITE,TRATIO,GRATIO,VGRATIO
      COMMON PMORTN(25),PMORTG(25),PMORTV(25),YMORTN(200),YMORTG(200)
      COMMON TNONMER(25),GNONMER(25),VNONMER(25)
C
C     CALCULATE CUBIC VOLUME REMOVED TO A 4-INCH TOP
C
      HD=10.**(.1567-15.673/TAGE+ALOG10(SITE))
      N1=(TAGE-TBASE)/10.+1
      ALLTREE=TREE+TNONMER(N1)
      HM=HD*(3040.-ALLTREE)/3000.
      IF (HM.GT.HD) HM=HD
      CU=.8758+.001049*HM-.000002824*HM**2+0.3221/DQ-45.647/DQ**3
      VOL=CU*CUT
C
C     DETERMINE VARIANCE OF STAND DIAMETER DISTRIBUTION
C
      VAR=-5.367+0.287*TAGE
C
C     DETERMINE UNBIASED MEAN STAND DIAMETER
C
      D=SQRT(DQ**2 - VAR)
C
C     CALCULATE STUMP TO TRUCK LOGGING COST
C
C
      IF (D.GT.7.63) GO TO 10
      COST=5750.0*VOL**(-.2628)
      GO TO 150
C
   10 IF (D.GT.9.23) GO TO 20
      IF (VOL.GT.500.) GO TO 15
      C1=5750.0*VOL**(-.2628)
      C2=4461.4*VOL**(-.2591)
      DELTA=(C1-C2)/(9.23-7.63)
      COST=C1-DELTA*(D-7.63)
      GO TO 150
C
   15 C1=16502.3*VOL**(-.37893)
      C2=12022.7*VOL**(-.36466)
      DELTA=(C1-C2)/(9.23-7.63)
      COST=C1-DELTA*(D-7.63)
      GO TO 150
C
```

```
   20 IF (D.GT.10.87) GO TO 30
      C1=12022.7*VOL**(-.36466)
      C2= 9811.6*VOL**(-.36398)
      DELTA=(C1-C2)/(10.87-9.23)
      COST=C1-DELTA*(D-9.23)
      GO TO 150
C
   30 IF (D.GT.12.31) GO TO 40
      C1=9811.6 *VOL**(-.36398)
      C2=7987.0*VOL**(-.35160)
      DELTA=(C1-C2)/(12.31-10.87)
      COST=C1-DELTA*(D-10.87)
      GO TO 150
C
   40 IF (D.GT.13.66) GO TO 50
      C1=7987.0*VOL**(-.35160)
      C2=7288.8*VOL**(-.35163)
      DELTA=(C1-C2)/(13.66-12.31)
      COST=C1-DELTA*(D-12.31)
      GO TO 150
C
   50 IF(D.GT.15.03) GO TO 60
      C1=7288.8*VOL**(-.35163)
      C2=6785.2*VOL**(-.35663)
      DELTA=(C1-C2)/(15.03-13.66)
      COST=C1-DELTA*(D-13.66)
      GO TO 150
C
   60 IF (D.GT.16.19) GO TO 70
      C1=6785.2*VOL**(-.35663)
      C2=5911.4*VOL**(-.35206)
      DELTA=(C1-C2)/(16.19-15.03)
      COST=C1-DELTA*(D-15.03)
      GO TO 150
C
   70 IF (D.GT.17.26) GO TO 80
      C1=5911.4*VOL**(-.35206)
      C2=4337.7*VOL**(-.32494)
      DELTA=(C1-C2)/(17.26-16.19)
      COST=C1-DELTA*(D-16.19)
      GO TO 150
C
   80 IF (D.GT.18.31) GO TO 90
      C1=4337.7*VOL**(-.32494)
      C2=4980.8*VOL**(-.34421)
```

```
      DELTA=(C1-C2)/(18.31-17.26)
      COST=C1-DELTA*(D-17.26)
      GO TO 150
C
   90 IF (D.GT.20.25) GO TO 100
      C1=4980.8*VOL**(-.34421)
      C2=3913.1*VOL**(-.32269)
      DELTA=(C1-C2)/(20.25-18.31)
      COST=C1-DELTA*(D-18.31)
      GO TO 150
C
  100 IF (D.GT.21.90) GO TO 110
C
      C1=3913.1*VOL**(-.32269)
      C2=4670.5*VOL**(-.34573)
      DELTA=(C1-C2)/(21.9-20.25)
      COST=C1-DELTA*(D-20.25)
      GO TO 150
C
  110 COST=4670.5*VOL**(-.34573)
  150 IF (D.GT.15.0) GO TO 350
C     BUNCH AND SWING ALTERNATIVE
C
      IF (D.GT.7.63) GO TO 160
      BUNCH=3889.6*VOL**(-.2616)
      GO TO 250
C
  160 IF (D.GT.9.23) GO TO 170
      C1=4069.4*VOL**(-.2795)
      C2=3440.6*VOL**(-.2889)
      DELTA=(C1-C2)/(9.23-7.63)
      BUNCH=C1-DELTA*(D-7.63)
      GO TO 250
C
  170 IF (D.GT.10.87) GO TO 180
      C1=3440.6*VOL**(-.2889)
      C2=2391.2*VOL**(-.2709)
      DELTA=(C1-C2)/(10.87-9.23)
      BUNCH=C1-DELTA*(D-9.23)
      GO TO 250
C
  180 IF (D.GT.12.31) GO TO 190
      C1=2391.2*VOL**(-.2709)
      C2=1870.1*VOL**(-.2530)
      DELTA=(C1-C2)/(12.31-10.87)
```

```
      BUNCH=C1-DELTA*(D-10.87)
      GO TO 250
C
  190 IF (D.GT.13.66) GO TO 200
      C1=1870.1*VOL**(-.2530)
      C2=1653.1*VOL**(-.2482)
      DELTA=(C1-C2)/(13.66-12.31)
      BUNCH=C1-DELTA*(D-12.31)
      GO TO 250
C
  200 C1=1653.1*VOL**(-.2482)
      C2=1500.4*VOL**(-.2464)
      DELTA=(C1-C2)/(15.03-13.66)
      BUNCH=C1-DELTA*(D-13.66)
C
C     COMPUTE SWING MACHINE COST
      IF(D.EQ.0.0 .OR. VOL.EQ.0.0) GO TO 350
  250 AVELOG=-10.83+2.092*D
      VSET=(10000./43560.)*VOL
      ITURN=(VSET*51.3)/7500. +0.5
      IF (ITURN.EQ.0) ITURN=1
      VWCT=VSET/ITURN
      VMAX=10.*AVELOG
      IF (VWCT.GT.VMAX) VWCT=VMAX
      TLOGS=VWCT/AVELOG
      CT=3.67+.030463*TLOGS-.199/TLOGS
      SWING=4.*143.25/(5.51*VOL)+(143.25*CT)/(45.*VWCT)
C     SUM BUNCH AND SWING COST ($/MCF)
      ALTCOST=BUNCH+1000.*SWING
C     ADJUST FOR LOAD COST SO NOT DOUBLE COUNTED
      N1=50000./(45.*AVELOG)
      T=(505.75+35.1*N1)/3600.
      Z4=1000.*28.*T/(50000./45.)
      ALTCOST=ALTCOST-Z4
      IF(COST.GT.ALTCOST) COST=ALTCOST
C     CALCULATE CURRENT REVENUE
C
  350 PONDVAL=9.91+70.81*D
      HAUL=150.
      UNITREV=(PONDVAL-COST-HAUL)*.001
      REVNOW=VOL*UNITREV
      RETURN
      END
```

APPENDIX X.

USER'S GUIDE TO THE OPTIMIZATION PROGRAM

The input data required for the optimization program consists of two lines, Line 1 (not optional) and Line 2 (optional). Line 1 specifies the node intervals, initial conditions, discount rate, and regeneration cost. Line 1 assumes a normally stocked stand. Line 2 permits data entries for stands which are not normally stocked. Internal adjustments are made for approach to normality.

The format for Line 1 is shown below with symbol names and format type.

Line 1 (not optional)

MAXVR	MAXHR	INTVR	INTHR	TBASE	SITE	R	TEST	VAL1
(I3)	(I3)	(I3)	(I3)	(F4.0)	(F4.0)	(F4.2)	(F5.0)	(F5.0)

________,_______,_______,_______,________,_______,________,_______,_________

The explanation for the entries for Line 1 is as follows:

MAXVR -- Maximum number of tree intervals. MAXVR should be not less than the maximum possible number of trees divided by the tree interval, INTVR. MAXVR is presently dimensioned for a maximum of 39 intervals.

MAXHR -- Maximum number of basal area intervals. MAXHR should not be less than the maximum basal area per acre divided by the basal area interval. MAXHR is presently dimensioned for a maximum of 72 intervals.

INTVR -- Tree interval. INTVR defines the vertical dimension between nodes. (Figure 55).

INTHR -- Basal area interval. INTHR defines the horizontal dimension between nodes. (Figure 55).

TBASE -- The earliest age at which the first possible thinning could occur.

SITE -- The Douglas-fir site index, 100 year basis.

R -- The discount rate expressed as a decimal.

TEST -- A code to indicate stand stocking.

Code 0 = normally stocked
Code 1 = not normally stocked

VAL1 -- Present worth of all regeneration costs and management costs prior to age TBASE.

The format for Line 2 is shown below with symbol names and format type.

Line 2 (optional)

STREE	SBA
(F4.0)	(F4.0)

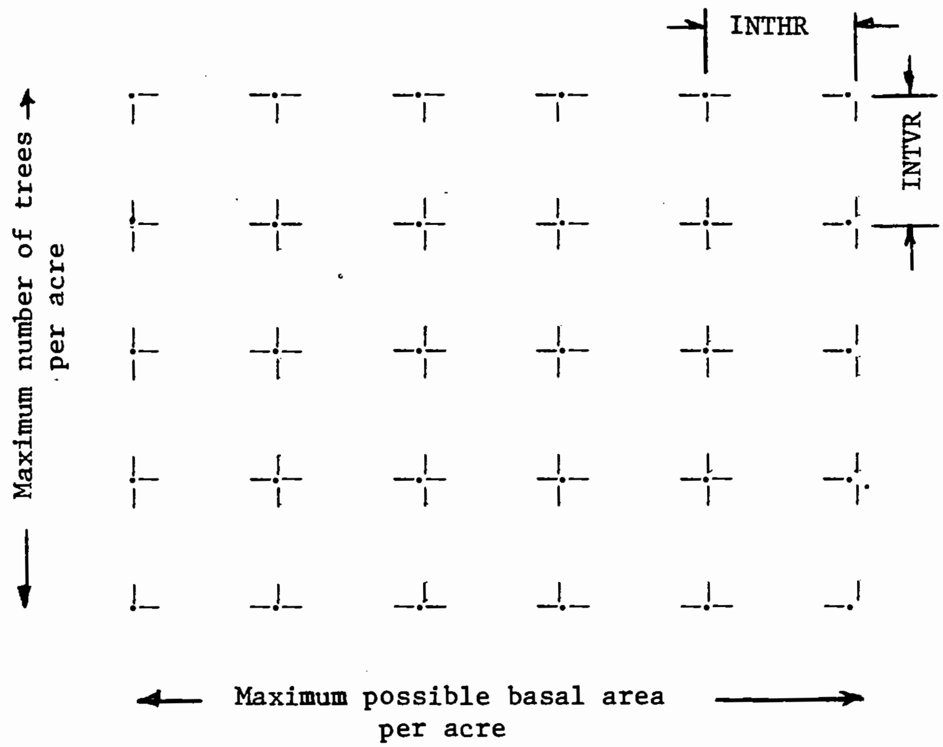
_________,_________

The explanation for the entries for Line 2 is as follows:

STREE -- The number of trees per acre for a stand which is not normally stocked.

SBA -- The corresponding basal area, square feet per acre.

Upper limit on thinning intensity -- Due to silvicultural considerations, the first possible thinning at age TBASE is limited to removing no more than 50 percent of the stand. This constraint is controlled by the variable 'NS' on line 50 of the main program. This constraint can be applied to all thinnings by replacing line 66 by line 50.



Suggested values:

MAXVR = INT [maximum number of trees/INTVR + 1]
MAXHR = INT [maximum basal area per acre/INTHR + 1]

Figure 55. Range limits for network nodes.

APPENDIX XI.

EQUIPMENT OWNING AND OPERATING COSTS

References

Costs and methodology used in computing the equipment, labor, and wire rope cost estimates in this Appendix have been taken from the following sources:

Bureau of Land Management, USDI. 1977. Timber production costs, schedule 20. Portland, USDI Bureau of Land Management, Oregon State Office. Various paging.

Forest Service, USDA. 1977. Cost guide for empirical appraisals. Revision 6. Portland, USDA Forest Service, Region 6, Timber Management. 72 p.

Forest Service, USDA. 1978. Timber appraisal handbook (Chapter 415.81b Siuslaw Supplement No. 83). Corvallis, USDA Forest Service, Region 6, Siuslaw National Forest. 36 p.

Estimated Hourly Yarding System Costs

Equipment Item	Hourly Cost Dollars
MADILL 071 WEST COAST TOWER -- Large Skyline	
Depreciation	
Yarder-tower ($195,000 initial cost, depreciated to 20% salvage value, estimated useful life 12,800 hrs.)	12.19
Carriage (Danebo S-30 with intermediate support equip., $10,000, 20%, 6400 hour life)	1.25
Loader ($119,000, 20%, 12,800 hour life)	7.44
Landing tractor ($14,000, 10%, 8000 hour life)	1.58
Radios ($3921, 10%, 6400 hour life)	0.55
Wire rope ($1.50/Mbf @ 30 Mbf/day)	5.63
Guylines ($1343, no salvage, 12,800 hour life)	0.10
Tail and corner rigging ($3000, 10%, 6400 hour life)	0.42
Miscellaneous equipment ($10,000, no salvage, 6400 hr)	1.56
Subtotal	30.72
Maintenance and repair costs	
Yarder, loader, and carriage (50% of depreciation)	10.44
Radios (60% of depreciation)	0.33
Tractor (10% of depreciation, used 20% of time)	0.16
Subtotal	10.93
Fuel and lubricants	6.48
Total equipment costs	$48.13
Labor	
Hooktender	13.84
Yarder operator	12.02
Loader operator	13.25
Rigging slinger	11.18
Chaser	10.23
Choker setter	9.98
Total labor costs	$70.50
Total labor and equipment cost	118.63
Overhead (5%, insurance, taxes, interest, accountant)	5.93
Profit and Risk (15% of labor, equip., and overhead)	18.69
TOTAL ESTIMATED HOURLY COSTS	$143.25

Estimated Hourly Yarding System Costs

Equipment Item	Hourly Cost Dollars
IGLAND-JONES TRAILER ALP -- Small Skyline	
Depreciation	
Yarder ($40,000 initial cost, depreciated to 20% salvage, estimated useful life 10,000 hours) ..	3.20
Tractor ($10,000, 20%, 10,000 hours life) ..	0.80
Radios ($3921, 10%, 6400 hour life) ..	0.55
Carriages (Maki and Igland-Jones,$4000, 20%, 6400 hr) ..	0.50
Wire rope and guylines ..	1.88
Tail and corner rigging ($2000, 10%, 6400 hours life) ..	0.28
Miscellaneous equipment ($3000, no salvage, 6400 hrs) ..	0.47
Subtotal	7.68
Maintenance and repair costs	
Yarder and carriages (50% of depreciation) ..	1.85
Tractor (150% of depreciation) ..	1.20
Radios (60% of depreciation) ..	0.33
Subtotal	3.38
Fuel and lubricants ..	1.00
Total equipment costs	$12.06
Labor	
Yarder operator ..	10.23
Choker setter ..	9.98
Choker setter ..	9.98
Total labor	$30.19
Total labor and equipment cost	42.25
Overhead (5%, insurance, taxes, interest, accountant)	2.11
Profit and risk (15% of labor, equip., and overhead)	6.65
TOTAL ESTIMATED HOURLY COSTS (three-man crew)	$51.01
TOTAL ESTIMATED HOURLY COSTS (two-man crew)	$38.96
SMALL FOUR WHEEL DRIVE TRACTOR with operator including depreciation, maintenance, fuel, overhead, profit and risk	$18.59