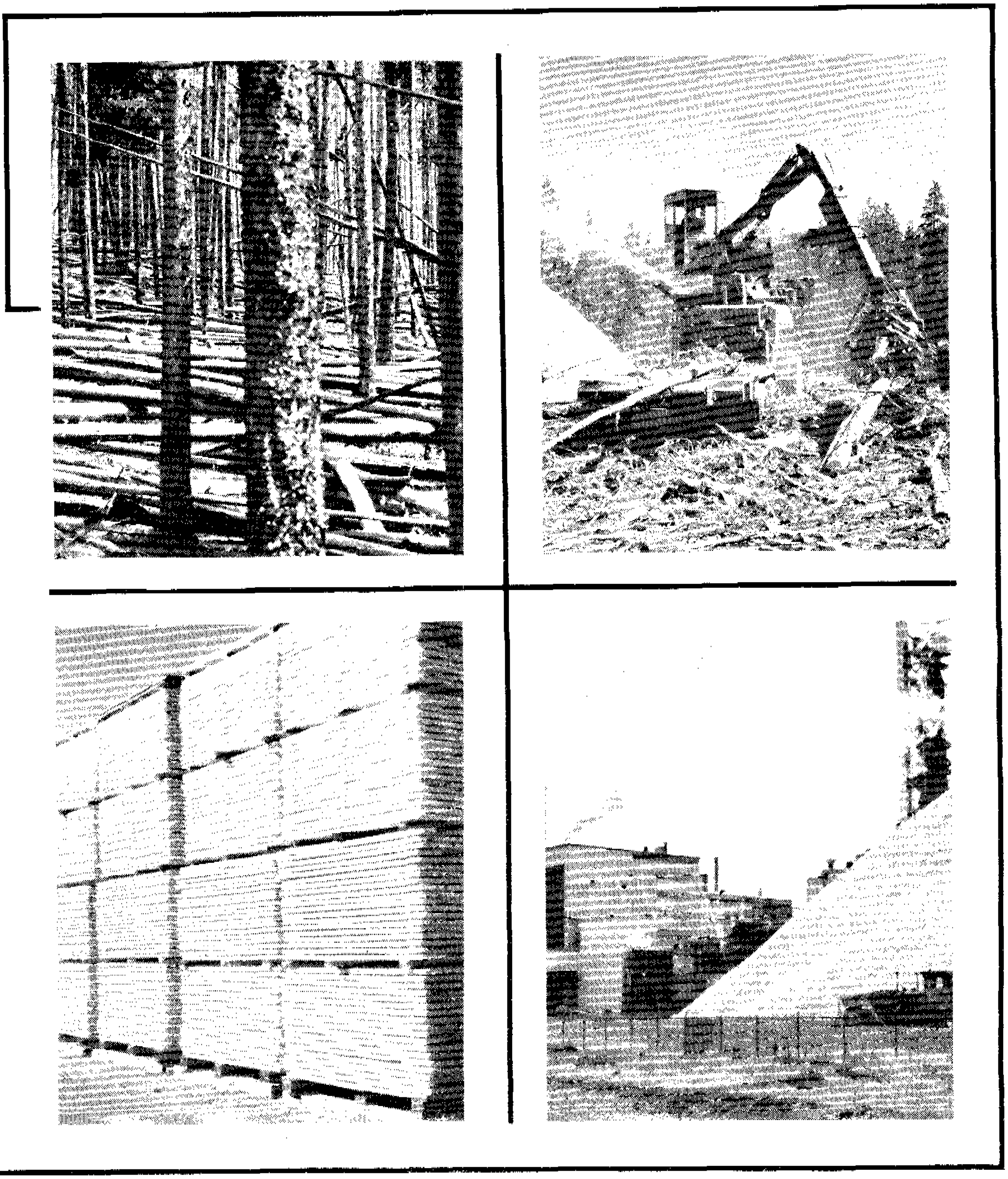
HARVESTING AND UTILIZATION OPPORTUNITIES FOR FOREST RESIDUES in the northern rocky mountains



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Forest Service
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OUTLOOK FOR NEW HARVESTING TECHNOLOGY

Michael J. Gonsior, Research Engineer
USDA Forest Service, Intermountain Forest and
Range Experiment Station

ABSTRACT

Because of increased emphasis on utilization of residues and smaller timber, rising energy and labor costs, and more severe environmental constraints pertaining to logging and road construction, the criteria for harvesting systems in the future will require both technological and institutional innovation.

This paper analyzes harvesting per se as well as its role in the total forest management picture. Models are presented for testing the sensitivity of total management cost and the harvesting components of cost to alternative silvicultural, utilization, and other forest management objectives. These models are used to discern opportunities for new harvesting technology.

KEYWORDS: logging systems, timber harvesting, forest management, cost modeling, new technology

INTRODUCTION

This paper analyzes some of the major factors that influence logging and total on-site forest management costs, and assesses the opportunities for future harvesting technologies in light of assumed forest management objectives and constraints. Our principal focus will be on the problems associated with mountainous terrain.

While there may be alternatives to truck hauling as the final stage in timber harvesting, it seems unlikely that such alternatives will be used in the next few decades--at least on a widespread basis. Therefore, our analysis assumes a continued need for roads and trucks.

Similarly, while wood fiber in any form may eventually be usable for whatever products society needs, it seems likely that leaving wood in its largest natural states will still be preferable for the foreseeable future. Therefore, our analysis excludes consideration of chipping at the stump or similar breakdown of trees between stump and roadside.

Finally, while we acknowledge the economic advantages of ground skidding with tractors--even in relatively steep terrain, we will pay little attention to such methods here. This is not to deny the widespread importance of such methods; rather, we assume that environmental and safety considerations will preclude their general applicability in much of our mountainous terrain.

In short, we confine our analysis to the matter of stump-to-mill transport and handling of trees, logs, and sensibly large pieces or aggregations of wood in mountainous terrain, with full recognition of the potentials for roadside chipping of certain residues to facilitate disposal or subsequent transport by trucks.

ANALYSIS OF CURRENT TECHNOLOGY

Traditionally, timber harvesting has been treated as a distinct activity, separate from the remainder of forest management activities, in spite of its recognized influence on the remainder of management. With minor exceptions, management of virgin forests before entry for harvest has traditionally been limited to control of fire, insects, and disease. Then, based largely upon the capabilities and limitations of harvesting technology, roads are located and constructed to the stands. After harvesting is completed, slash disposal, planting, and subsequent cultural treatments are undertaken until the stand is again ready for harvest. The point is that until stands become ready for initial harvest entry, management is largely passive. Moreover, the nature of management after harvest is largely influenced by the roads that are built for harvesting; and the locations and types of roads are influenced largely by the types of harvesting technology used.

Through a combination of economic and political processes, road densities have been decreasing and yarding or skidding distances have been increasing. Both road and harvesting costs have been rising, but the rising prices of wood products have generally permitted a continuation of traditional ways of doing business.

As the harvesting industry has complied with pressures to increase yarding distances and avoid undesirable environmental impacts, so have the Forest Service and other forest management agencies continued to push for more restrictions and more demanding and costly road construction and harvesting requirements. Rightly or wrongly, in recent years there has been a shift toward using the harvesting process to accomplish a wider range of forest management objectives.

Thus, even though we are concerned here with harvesting technology, it is necessary to consider the totality of forest land management--with harvesting as but one component of the total management scheme--and to examine the effects of new harvesting requirements and technologies on total management costs. To do this, we will construct a generalized model to portray total management costs per acre, including harvesting costs.

General Cost Model

Consider a tract of forested land that is to be roaded, harvested, and placed under active management. The principal cost components include road design, construction and maintenance, inventory and planning, harvesting and subsequent post-harvest slash disposal, planting, and other cultural treatments. It is assumed here that costs of surveillance and control of fire, insects, and disease are unrelated to the characteristics of road systems. Similarly, our model ignores the costs incurred by recreationists, grazers, and other forest users.

ROAD COSTS

Appendix A shows how per acre road costs (RC) are derived. In general, these costs can be expressed

$$RC = K_R \frac{C_R}{S} \tag{1}$$

where RC is in dollars per acre; C_R is the cost for design, construction and maintenance of roads expressed in dollars per mile; S is the average maximum yarding distance or span expressed in feet; and K_R is a coefficient reflecting the acres served by the roads and over which road costs are distributed. K_R is expressed in units of ft.-mile per acre.

Figure 1 illustrates the general form of per acre road costs (RC) as a function of average maximum yarding distance or span (S).

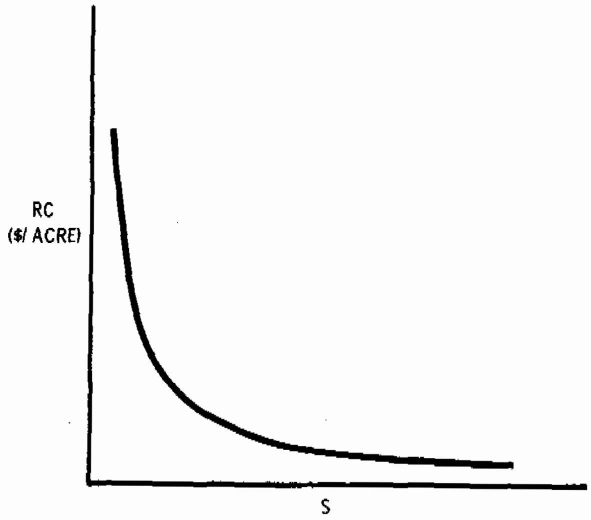

Figure 1.--General road cost (RC) versus span (S) relationship.

LABOR INTENSIVE COSTS

Appendix A contains a discussion of the types of pre- and post-harvest activities or treatments that are considered herein to be labor intensive, and for which the costs are affected by yarding distance or road spacing. The cumulative per acre costs (LIC) for such activities or treatments are derived in appendix A, and are shown to be

$$LIC = \sum_{i=1}^{m} \frac{C_i}{P_i T_i} \left(\frac{1}{1-K_i S}\right) \qquad (2)$$

where C_i is the daily cost for the i^{th} system; P_i is the basic production rate for the i^{th} system in acres per hour; and T_i is the available number of hours in the workday for the i^{th} system, exclusive of vehicle travel to and from the woods. S is as defined previously, and K_i is a coefficient reflecting walking speed between the roadside and work site, length of workday, and type of yarding system.

Figure 2 illustrates the general form of per acre labor intensive costs (LIC) as a function of average maximum yarding distance or span (S).

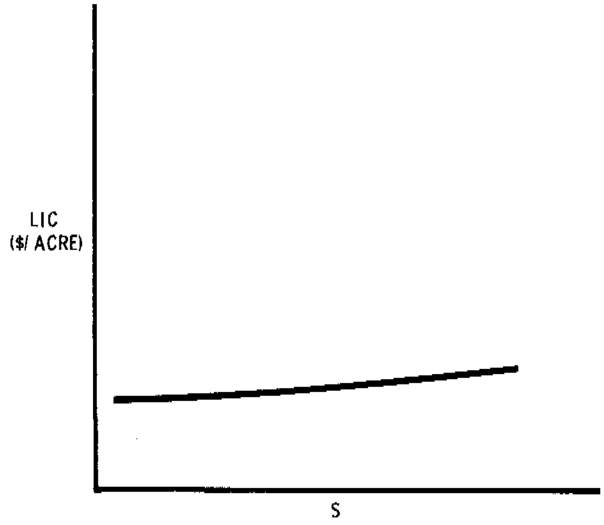

Figure 2.--Generalized relationship between labor intensive (LIC) and span (S).

LOGGING COSTS

It is convenient to consider logging as three separate operations: (1) falling (including in-woods processing); (2) yarding; and (3) hauling. Sometimes roadside processing, handling, and decking or loading accompany the yarding operation, in which case the definition of the yarding system would be broadened to include ancillary labor and machinery. At other times, roadside processing, sorting and loading might accompany the hauling operation, in which case the definition of the hauling system would be broadened accordingly.

Appendix A shows the derivation of expressions for per acre falling costs (FC), yarding costs (YC) and hauling costs (HC). Respectively, these expressions are

$$FC = \frac{C_f \overline{V}}{P_f T_f} \left(\frac{1}{1-K_f S} \right) \tag{3}$$

$$YC = \frac{C_y}{60T_y} \left[\frac{43560}{b} \left(\frac{R_0}{S} + R_1 \right) + \frac{(\overline{V} + V_R)}{v} \left(Y_0 + Y_1 S + Y_2 b + Y_3 n \right) \right] \tag{4}$$

and

$$HC = C_h \, (\overline{V} + V_R) \tag{5}$$

where C_f and C_y are the daily costs for the falling and yarding systems, respectively; $\overline{V}$ and V_R are the per acre volumes to be extracted of merchantable timber and residues, respectively; T_f and T_y are the available hours in the work day for the falling and yarding systems, respectively; P_f is the falling system production rate, in units of volume per hour; K_f is a coefficient reflecting walking speed between roadside and work site, length of workday, and type of yarding system; b is the average spacing between yarding corridors, in feet; v is the average volume per yarding cycle, expressed in units compatible with $\overline{V}$ and V_R; C_h is the hauling system cost per unit volume (where volume is expressed in units compatible with $\overline{V}$ and V_R; R_0 and R_1 are coefficients reflecting yarding system rigging time; Y_0, Y_1, Y_2 and Y_3 are coefficients reflecting yarding cycle time; n is the average number of pieces (or piece equivalents) per yarding cycle; and S is as previously defined.

Figure 3 illustrates the general form of FC, YC and HC as well as total logging cost (LC) versus S, where

$$LC = FC + YC + HC. \tag{6}$$

Note that there is an optimum span at which total logging cost is minimized, and beyond which per acre costs rise approximately at the rate at which per acre yarding costs increase.

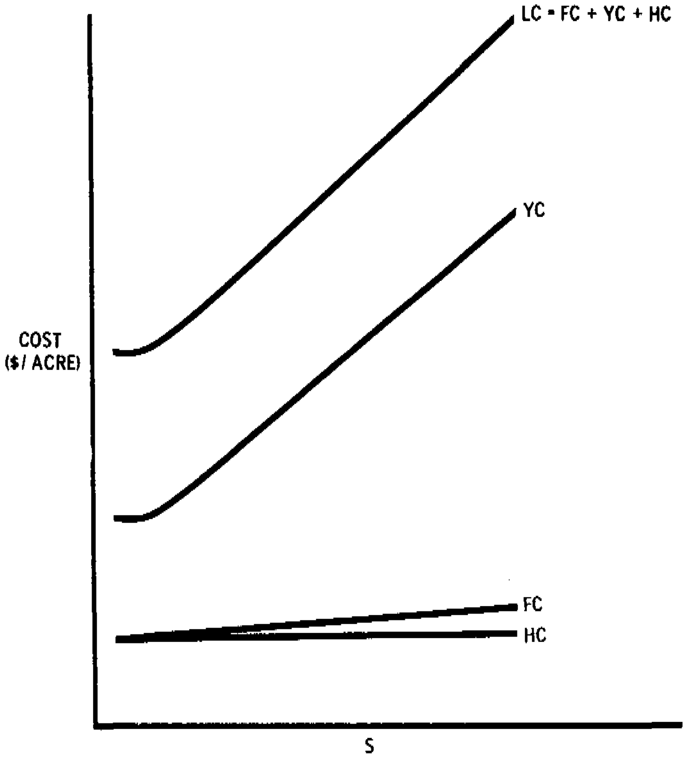

Figure 3.--General relationship between logging costs and span (S), where total logging cost (LC) is the sum of falling cost (FC), yarding cost (YC) and hauling cost (HC).

AGGREGATION OF COSTS

Assuming the period of consideration is sufficiently short that only one harvesting entry needs to be considered, and ignoring the time spread of investments during this period, then the total investment per acre (C) may be estimated as

$$C = RC + LIC + LC$$

or

$$C = K_R \frac{C_R}{S} + \sum_{i=1}^{m} \frac{C_i}{P_i T_i} \left(\frac{1}{1-K_i S}\right) + \frac{C_f \overline{V}}{P_f T_f} \left(\frac{1}{1-K_f S}\right)$$

$$+ \frac{C_y}{60T_y} \left[\frac{43560}{b} \left(\frac{R_0}{S} + R_1\right) + \frac{(\overline{V} + V_R)}{v} \left(Y_0 + Y_1 S + Y_2 b + Y_3 n\right)\right]$$

$$+ C_h (\overline{V} + V_R) \ . \qquad (7)$$

Use of equation 7 requires numerous assumptions relative to the stand and terrain conditions, the harvesting system to be used, and the nature of pre-and post-harvest activities. Our purpose here is to show how such a model can be used and to analyze the general effects of selected changes in conditions on per acre management cost.

First, we assume that management constraints do not preclude operation of the yarding systems at other than optimal corridor spacing. To determine this optimum, we differentiate equation 7 with respect to b and equate the resulting expression to zero to find

$$b_{opt} = \sqrt{\frac{43560\ (v)\left(\frac{R_0}{S} + R_1\right)}{Y_2\ (\bar{V} + V_R)}} \qquad (8)$$

when we substitute equation 8 for b in equation 7, we obtain

$$C = K_R\ \frac{C_R}{S} + \sum_{i=1}^{m} \frac{C_i}{P_i T_i} \left(\frac{1}{1-K_i S}\right) + \frac{C_f \bar{V}}{P_f T_f} \left(\frac{1}{1-K_f S}\right)$$

$$+ \frac{C_y}{60T_y} \left[2\sqrt{\frac{43560\ Y_2\ (\bar{V} + V_R)\left(\frac{R_0}{S} + R_1\right)}{v}} + \frac{(\bar{V} + V_R)}{v} \left(Y_0 + Y_1 S + Y_3 n\right)\right]$$

$$+ C_h\ (\bar{V} + V_R) \qquad (9)$$

Note that yarding cost is now

$$YC = \frac{C_y}{60T_y} \left[2\sqrt{\frac{43560\ Y_2\ (\bar{V} + V_R)\left(\frac{R_0}{S} + R_1\right)}{v}} + \frac{\bar{V} + V_R}{v} \left(Y_0 + Y_1 S + Y_3 n\right)\right] \qquad (10)$$

Effects of Road Spacing or Span

Based on the example in appendix B, figure 4 illustrates the relationships of road costs, labor intensive costs, logging costs, and total managment costs versus span.

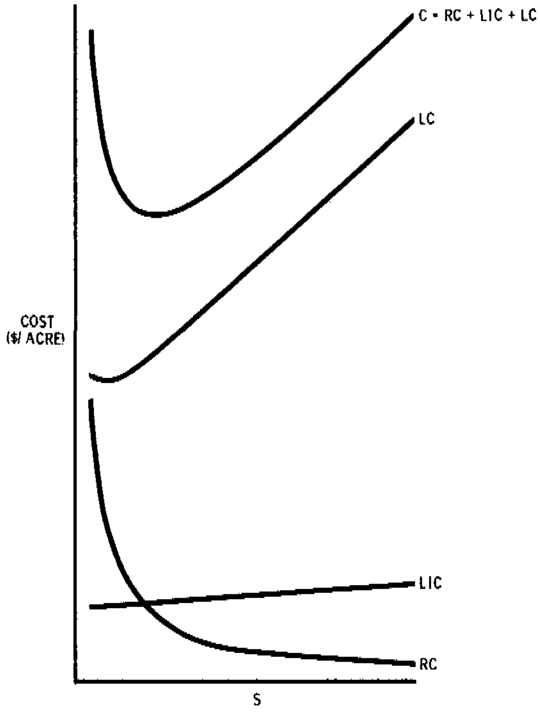

Figure 4.--General form of total management cost (C) versus span (S), where total management cost is the sum of road cost (RC), labor intensive cost (LIC) and logging cost (LC).

The major point to be made here is that the optimum span with respect to total management costs is significantly greater than the optimum span with respect to logging costs alone--nearly three-fold in this example, chiefly because of the influence of road costs.

A second point to be made from figure 4 is that, for spans greater than the optimum, the economic penalties increase at approximately the same rate as logging costs; as previously noted, logging cost increases are chiefly due to yarding cost increases.

The foregoing ignores any constraints on rigging, yarding, or road construction imposed by terrain or other factors. Indeed, as cable yarding distance is increased in mountainous terrain, multi-span capability often becomes necessary; and, correspondingly, rigging cost may rise dramatically. Obversely, as distances between roads increase, road costs per mile may decrease if road locations become less critical. Consequently, we believe that equations 7 and 9 above are generally both reasonable and useful with respect to a broad range of road spacings, even in difficult terrain.

Effects of Increasing Road Costs

Per acre road costs increase when per mile costs (C_R) increase or if the coefficient K_R increases. Figure 5 illustrates the effects of doubled per mile road costs on both per acre road costs and total management costs. The same effects would occur if per mile road costs remained unchanged and the acreage allocation coefficient K_A were to be halved. The implication of figure 5 is that as inflation or environmental constraints increase road costs, or as the proportions of accessed areas not managed or incapable of management increase, optimum yarding spans also increase. This implication alone makes increasing yarding distance capabilities a desirable goal for future logging technology.

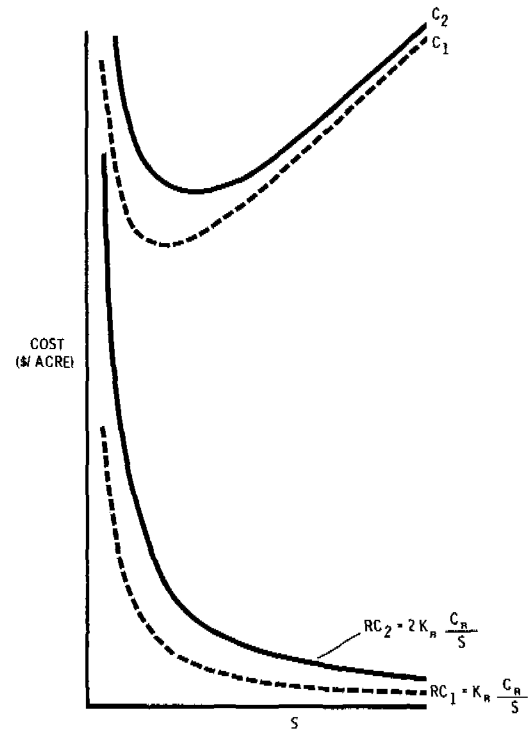

Figure 5.--Effect of doubled road cost on per acre road cost (RC) and total management cost (C) versus span (S). (RC_1 and C_1 represent the per acre road and total management cost of figure 4; and RC_2 and C_2 represent the per acre road and total management cost if per mile road costs are doubled.)

Effects of Reduced Cutting Intensity

If environmental considerations produce a preference for more selective logging and less clearcutting, the effect would be to reduce the extracted volumes per acre. With $\overline{V}_1$ representing the merchantable volume per acre to be removed on first entry into a stand, where

$$\overline{V}_1 = K\overline{V} \quad , \quad K < 1$$

(and $\bar{V}$, as before, is the total merchantable volume per acre in the stand), figure 6 shows the effect of selective logging on total per acre management cost and on cost per unit of merchantable volume removed versus span, S. (Figure 6 is based on calculations in appendix C, wherein K = 0.5.)

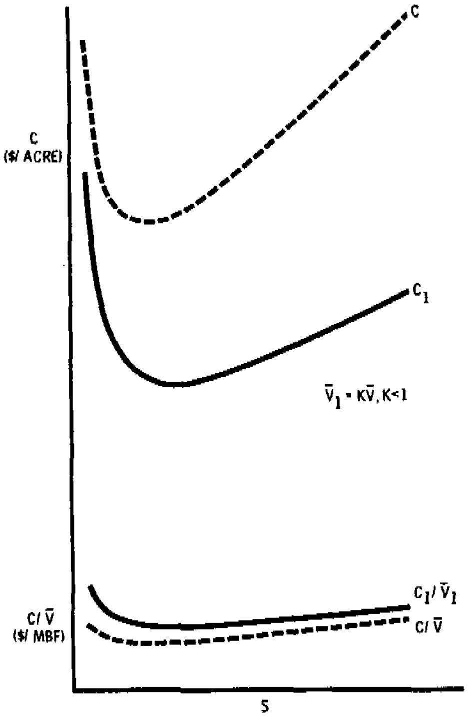

Figure 6.—Effect of partial cutting on total management costs per acre (C) and per unit volume ($C/\bar{V}$) versus span (S). (C and $C/\bar{V}$ correspond to figure 4; C and C_1/V_1 correspond to the example of appendix C.)

Figure 6 shows that optimum spans are increased, based on total management costs incurred on first entry alone, and that economic penalties for increasing spans beyond the optimum are reduced in comparison with removal of the entire merchantable volume, $\bar{V}$. Of course, costs per unit volume also are increased, as shown in the bottom part of figure 6. Therefore, we conclude that selective logging increases the need for or the desirability of extended yarding spans and wider road spacings, at least on the basis of initial entry considerations alone.

If the economic planning horizon extends to later entries, however, then optimum spans would not be appreciably different from what they would be if all the merchantable volume were removed on first entry (fig. 7). That is, assuming the costs incurred on second entry are the same as those incurred on first entry (except for road costs), the sum of first and second entry per acre costs ($C_1 + C_2$) versus span, S, will be of about the same form as the C vs. S relationship shown in figure 4, although higher. Correspondingly, the total cost per unit volume will also be higher, or

$$\frac{C_1 + C_2}{\bar{V}} > \frac{C}{\bar{V}}$$

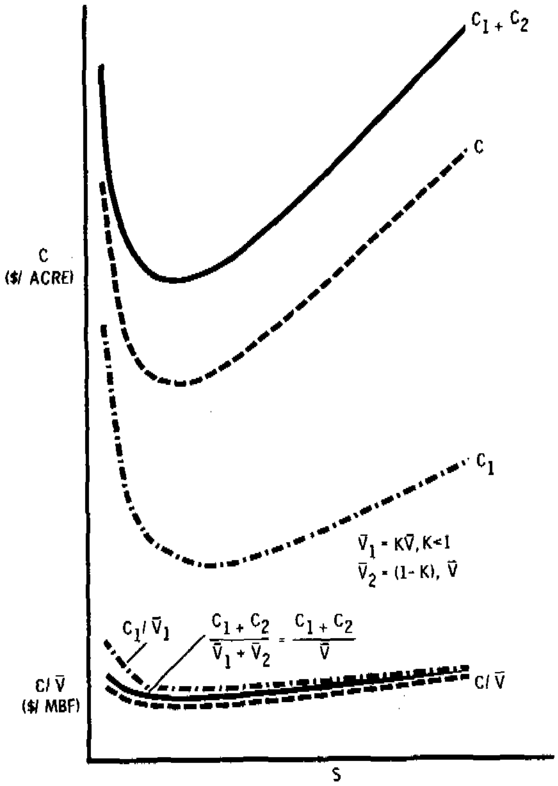

Figure 7.--Cumulative first and second entry management cost per acre $(C_1 + \underline{C_2})$ *and per unit volume* $((C_1 + C_2)/\bar{V})$ *versus span (S).* *(C,* $C/\bar{V}$*, C and C /*$\bar{V}$ *are from figure 5;* C_2 *and* $\bar{V}_2$ *are the additional costs incurred and volumes removed per acre, respectively, during second entry.)*

Thus, based on considering all entries, from initial selective removal to final harvest cutting, there would appear to be no need for increasing yarding span capabilities; rather, the principal objective for new harvesting technology would appear to be a combination of lower costs and lower economic penalties for yarding beyond optimum spans.

Effects of Residues Removal

One may consider two basic classes of logging residues: (1) those that are similar in character to the merchantable logs (i.e., of comparable weight, length, and diameter), and (2) those that are small or irregular (e.g., limbs, tops, broken chunks, and small trees). The effect on cost of removing residues of the first type is not appreciably different from that of increasing per acre volumes to be removed. The upper part of figure 8 illustrates that total per acre management costs are increased, and that optimum spans are decreased, as per acre volumes of the first class of residues to be removed increase. (Figure 8 is based on data generated in appendix D.)

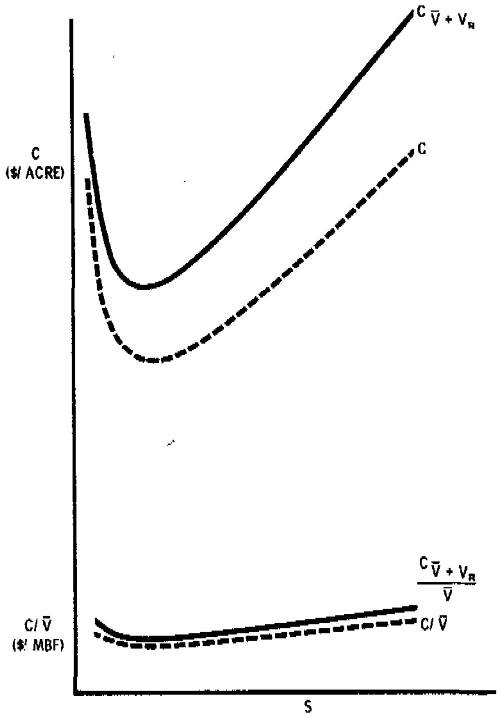

Figure 8.--Effect of residue removal on per acre management cost ($C_{\overline{V}+\overline{V}_R}$) *and cost per unit of merchantable volume* ($C_{\overline{V}+V_R}/\overline{V}$) *versus span (S). (C and C/*$\overline{V}$ *are from figure 4.)*

The lower part of figure 8 shows the effects of residue removal on cost per unit of merchantable volume; as would be expected, costs per unit volume in this situation are higher than for the case where $V_R = 0$.

If by removing the larger class of residues there would be no reduction in need for slash disposal or other labor intensive work (as was assumed in appendix D), then it would be of interest to determine what value these residues would need to possess in order to produce no economic penalty for their removal. If ρV_R were to represent the equivalent net merchantable volume in the residues, where $0 \leq \rho \leq 1$, then avoiding economic penalty would require that

$$\frac{C_{\overline{V}+V_R}}{\overline{V}+\rho V_R} \leq \frac{C}{\overline{V}}$$

or that

$$\rho \geq \frac{\overline{V}}{V_R}\left(\frac{C_{\overline{V}+V_R}}{C} - 1\right) \qquad (11)$$

where $C_{\overline{V}+V_R}$ is the total per acre management cost incurred when both merchantable timber and residues are removed. (C, as before, would represent the total per acre management cost incurred when only merchantable timber is removed.)

Figure 9 (again based on an example outlined in appendix D) illustrates the relationship between ρ and S, and shows that the net merchantable volume (or equivalent thereof) must increase as yarding distances or road spacings increase.

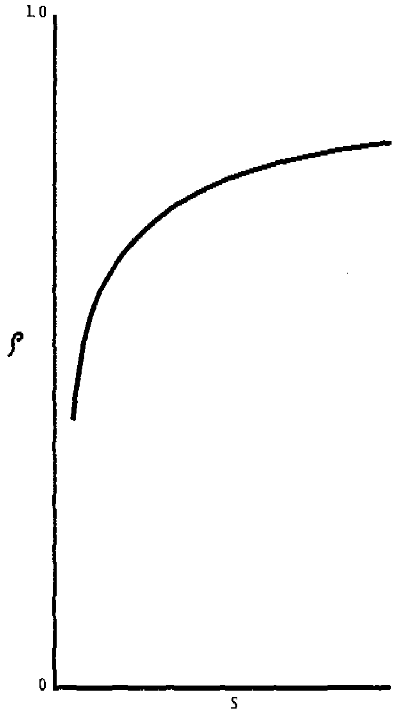

Figure 9.--Minimum net merchantability of residues (ρ) versus span (S) to avoid economic penalty for removal. (ρV_R is that function of gross residues volume, V_R, that is equivalent in value to the merchantable volume $\bar{V}$.)

Obviously, for residues of the second class (i.e., those containing no merchantable volumes), there can be no economic justification for removal except insofar as other on-site treatment costs can be reduced.

INTERIM CONCLUSIONS

It seems clear from the foregoing that if road costs continue to increase and selective logging is prescribed with greater frequency, then road spacings and yarding distance capabilities will likewise be required to increase if economic penalties for operating below optimum spans are to be avoided. Correspondingly, the outlook for greater utilization of residues would be discouraging unless major reductions in yarding cost can be achieved.

As major goals for future harvesting technology, we see the following:

(1) Reduce total per acre management cost by providing the capability to yard at or beyond optimum spans.

(2) Reduce economic penalties associated with yarding distances or road spacings greater than the optimum.

We conclude that improved logging systems would offer the greatest opportunities for meeting these goals. In particular, yarding or stump-to-roadside operations would require the most improvement.

ANALYSIS OF PROSPECTS

We will now examine some possibilities for improving the stump-to-roadside transport situation. Our analysis assumes that little can be done to alter or reduce the cost of timber falling in steep terrain, at least in the near future, and that current labor intensive falling methods will continue indefinitely. The major opportunities for reducing the difficulties and costs of falling appear to be in reducing or eliminating the need for limbing and bucking in the woods through whole tree extraction and roadside processing.

We will consider opportunities for technological innovation in three areas:

(1) Aerial systems

(2) Cable yarding systems

(3) Combination yarding and forwarding systems

Aerial Systems

Three classes of aerial systems are analyzed in appendix E: (1) "small" helicopters, (2) "large" helicopters, and (3) "giant" airships. Based on these analyses, figure 10 shows an apparent potential for larger capacity helicopters or airships to achieve the desired goals of lower costs and reduced economic penalties for operating beyond optimum road spacings. However, as shown in the bottom portion of the figure, this potential can only be realized when production rates are in the order of 25 to 50 times those of "conventional" technology. Unless we can solve the logistical problems associated with falling and concentrating loads of logs or stems at rates sufficient to match the yarding production capacity of large aerial systems, it seems unlikely that the potential cost savings shown in figure 10 will be realized.

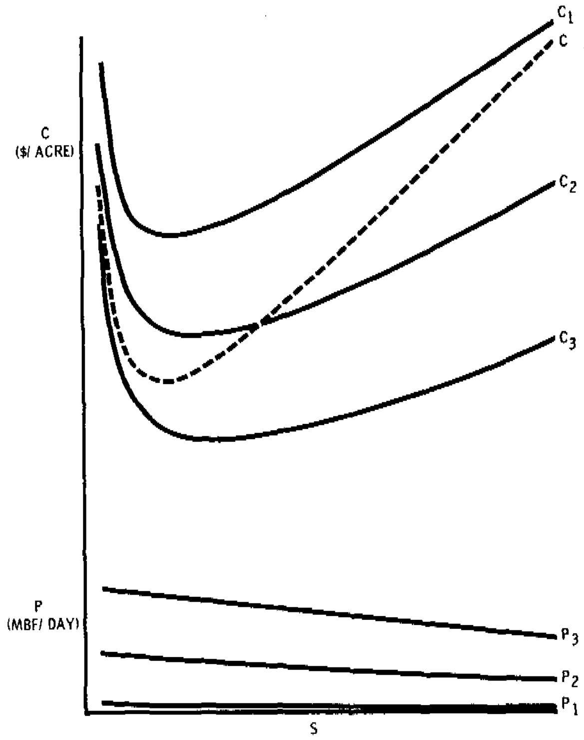

Figure 10.--Total per acre management costs (C) and daily production rates (P) versus span (S) with three classes of aerial systems. (C and P represent small helicopters, C_2 and P_2 represent large helicopters, C_3 and P_3 represent giant airships, and C is from figure 4.)

Cable Yarding Systems

With cable yarding systems, it would seem that opportunities for meeting our improvement objectives would be as follows:

(1) Increase load capacity

(2) Increase speed

(3) Reduce system cost

Increasing load capacity implies increasing either cable tensions or deflections. Given the prospects for harvesting smaller timber in the future, the difficulties associated with anchoring to resist higher cable tensions must be carefully considered. Increasing cable deflections--either through use of intermediate supports or by extending spans to take advantage of mountainous topography would be more likely to be acceptable.

Increasing the load capacity of yarding systems is likely to require some type of pre-bunching or load concentration in advance of or in conjunction with yarding, especially if selective logging of smaller timber is to be a common practice in the future. Simultaneously, pre-bunching should permit a reduction in yarding system labor requirements, assuming that pre-bunching is done in such fashion as to eliminate or reduce the need for pre-setting chokers.

Finally, it may be reasonable to assume that carriage speeds could be increased without appreciable increases in yarding equipment costs.

Appendix F contains an analysis based on a set of assumptions regarding all three of the above improvement objectives, and figure 11 illustrates the results of this analysis. As emphasized in appendix F, the assumptions used in developing figure 11 are exceedingly optimistic. Nevertheless, there appear to be significant opportunities for improving both conventional cable yarding systems and the procedures by which they are used, to reduce both total management costs and economic penalties for operation beyond optimum spans.

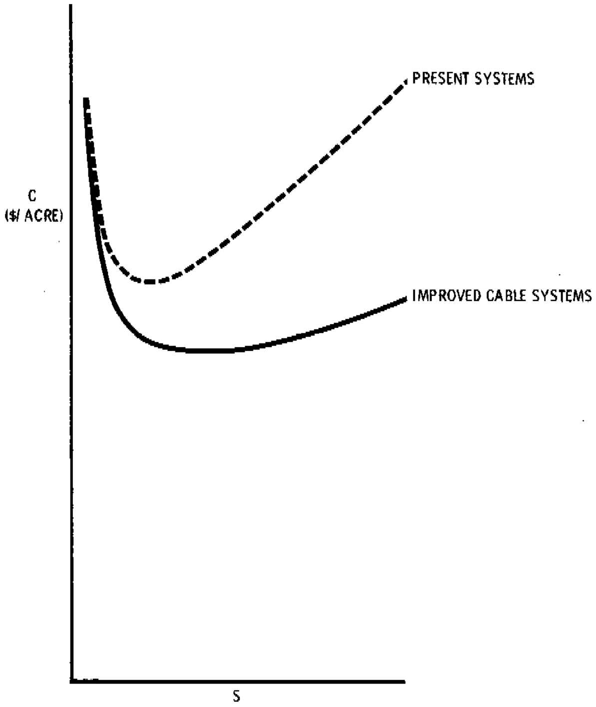

Figure 11.--Potential effect of cable systems improvements on total management cost (C) versus span (S). (Curve labeled "present systems" is from figure 4.)

Combination Yarding and Forwarding Systems

From the foregoing analyses, we realize that when using relatively high road densities (or relatively short yarding distances), road costs have a dominant influence on total management costs per acre. In contrast, at relatively low road densities (or relatively long yarding distances), road costs per acre become relatively minor, while yarding production costs exert the dominating influence on total management cost.

This suggests that, if we could (1) provide relatively inexpensive access for on-site-work--including timber falling and yarding of stems and logs, and (2) transport inexpensively large loads of stems and logs over relatively long distances, we might realize significant improvements both economically and environmentally.

Recently, attention has focused on giant airships to fulfill the latter objective, but little attention has been given to the former objective. Moreover, the sizes of airships being proposed are such that their economic feasibility depends on large quantities of available timber--so large that coordination among numerous logging operations or between logging operations and other transportation tasks may be necessary to justify operation. There are both institutional and natural limits on the scale of technology, and some proposed airships may exceed these limits.

What, then, might we envision as an alternative to airships that would fulfill our objective of low cost, relatively long distance "roadless" transport without commensurate institutional problems and large energy requirements?

The situation represented in figure 12, where a system of "trails" spaced nominally at 10 percent of the road spacing, presents a potential solution. Appendix G analyzes the possibilities of this situation, in which some yet undeveloped yarding, forwarding and personnel transport technologies are assumed. Figure 13 illustrates the potential effects of such technologies on total management cost in comparison with present circumstances and with the optimistic cable yarding possibilities discussed previously.

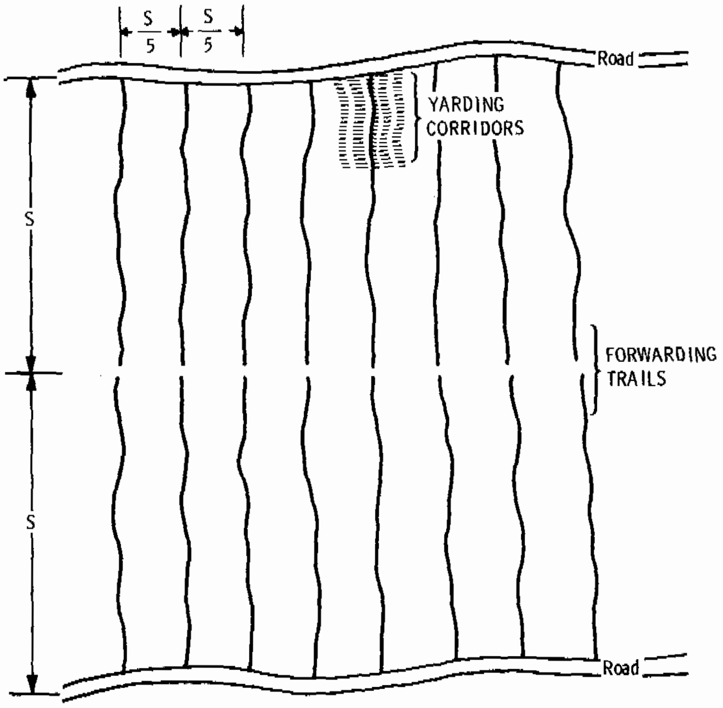

Figure 12.--Layout of roads, forwarding trails, and yarding corridors for hypothetical new yarding-forwarding systems.

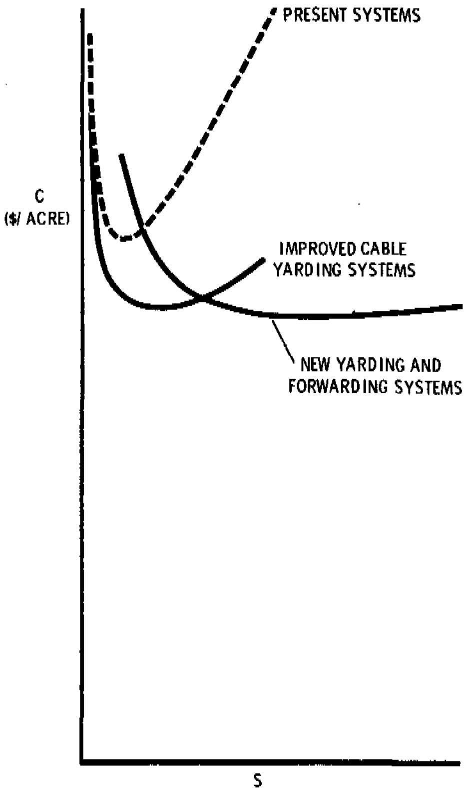

Figure 13.--Potential effects of technological improvements on total management cost (C) versus span (S). (Curves labeled "present systems" and "improved cable yarding systems" are from figure 11.)

SUMMARY AND CONCLUSIONS

As economic and environmental constraints become more severe, as timber sizes decline, and as more of the timber supply is derived from steep, difficult terrain, the prospects grow bleaker for new harvesting technology that will significantly reduce the costs of logging and total forest management. We can envision concepts that would appear to reduce the economic penalties of forest management in adverse circumstances, but it is unlikely that significant cost reductions will occur in the future.

Given the greater opportunities for logging mechanization in gentle terrain, it is virtually certain that management of steep terrain will always be economically disadvantageous. Nevertheless, timber in mountainous terrain is a resource that presumably will be needed. Therefore, there is strong justification for seeking less costly alternatives for extracting and replacing this resource.

Recognizing the risks, obstacles, and costs inherent in the development of radically new technology, it seems prudent first to seek improvements through "small" changes in existing technology and procedures. Given the likelihood of increasing labor, energy, and road construction costs, greater restrictions on road location in difficult terrain, and the likelihood of more intense utilization and more partial or selective logging, the following approaches seem to offer moderate changes for cost reductions or improved operability:

(1) Extension of cable yarding distance capabilities

(2) Increasing the transport speeds of cable yarding systems

(3) Pre-bunching on site in combination with falling operations

Of course, increasing the load carrying capabilities of yarding systems also would theoretically lower costs; but it must be recognized that increasing load capabilities creates greater anchoring problems and/or the need for intermediate skyline supports. Moreover, greater difficulties are encountered in assembling larger loads as timber sizes decline.

The prospects for aerial yarding systems, such as helicopters and airships, are theoretically good, but the difficulties in providing sufficient timber to utilize their capabilities must be recognized and dealt with.

The prospects of a radically new, "trail-based" yarding and forwarding technology are appealing from both economic and environmental standpoints, and such a technology would seem almost as universally applicable as aerial systems. However, a gigantic effort would be required for development of such technology in a short period of time.

Although we have not dealt with the issue of in-woods processing, we suspect there are numerous opportunities for adoption or development of new handling, sorting, processing, and truck loading technologies. Indeed, there may be promising alternatives to conventional trucks for transporting wood products from forest landings to manufacturing facilities.

Finally, and perhaps most important, it must be recognized that minimizing logging costs may not--and probably will not--minimize total on-site forest management costs. In addition, depending on the transportation and harvesting technologies applied, the economic penalties for extending yarding distances beyond economic optima may be acceptable. Thus, while the economic justifications for modifying or developing harvesting technologies may be weak, there may be strong environmental and political reasons for doing so.

APPENDIX A

General Cost Model Derivations

ROAD COSTS

If the average distance between roads (road spacing) is $K_S S$ (where S is the average maximum yarding distance or span, in feet, and K_S is a coefficient reflecting whether the yarding system can yard in one or both directions to the road system), then the average total acreage accessed by each mile of road will be

$$\frac{5280\ (K_S S)}{43560} \approx 0.121\ (K_S S)$$

If only a fraction (say, K_A) of the acreage accessed by the road system will be harvested or otherwise considered appropriate for road cost allocation, then the average acreage over which costs for each mile of road will be distributed is

$$0.121 K_A K_S S$$

Therefore, if road costs are C_R dollars per mile, road costs per acre served (RC) will be

$$RC = \frac{C_R}{0.121 K_A K_S S} = K_R \frac{C_R}{S} \quad ,$$

where $K_R = \frac{1}{0.121 K_A K_S}$

For example, if the yarding system can yard both uphill and downhill over average spans of S (feet), then $K_S = 2$ and average road spacing would be $K_S S = 2S$ (feet); and if road costs were to be allocated over the entirety of the acreage accessed, then $K_A = 1$. Accordingly,

$$K_R = \frac{1}{0.121(1)(2)} = 4.125 \text{ ft-mi/acre}$$

and

$$RC = 4.125 \frac{C_R}{S}$$

Alternatively, if the yarding system could yard only in an uphill direction to the road, then $K_S = 1$; and, if $K_A = 1$, then $K_R = 8.25$. But if only half the total acreage accessed by a road system contains resources that would justify the roads, then $K_A = 0.5$; and if $K_S = 1$, then $K_R = 16.5$ ft-mi/acre.

LABOR INTENSIVE COSTS

There are many reconnaissance, inventory, and planning activities that occur before roads are constructed, involving both aerial and on-site methods. These will be ignored in this derivation and considered to be a part of general forest management cost, similar to cost of fire surveillance. However, once roads are in place, the costs for on-the-ground cruising, timber marking, boundary surveying, slash disposal, planting and other activities before and after harvesting are affected by road spacing. We recognize that the cost per acre for some of these activities, such as unit boundary surveying and marking or fire line construction, are dependent upon the sizes and shapes of the harvest units. Nevertheless, we will ignore relationships between unit perimeters and unit areas in this development. Basically, we need consider only the production rate for on-site activities and the distance from site to road.

In any workday, the hours spent by a worker in walking to and from the work site may be expressed as

$$2\left(\frac{1}{2}\right)\left(\frac{K_S S}{2}\right)\left(\frac{1}{V_w}\right) = \frac{K_S S}{2V_w}$$

where $K_S S/2$ is the average maximum distance, in feet, from roadside to the work site; and V_w is the average walking speed, in feet per hour. If the total available time in a workday is T hours (exclusive of time spent in vehicle travel at the beginning and end of the workday) then the average net time available for work on site is

$$T - \frac{K_S S}{2V_w} = T\left(1 - \frac{K_S S}{2TV_w}\right) .$$

If the hourly production rate for the i^{th} labor intensive activity is P_i, in acres/hour, then the acres treated per workday will be, on the average,

$$P_i T_i \left(1 - \frac{K_S S}{2T_i V_w}\right) ,$$

and the cost per acre treated will be

$$\frac{C_i}{P_i T_i}\left(\frac{1}{1 - \frac{K_S S}{2T_i V_w}}\right)$$

where C_i is the daily cost for labor, equipment, travel, and administration corresponding to the hourly production rate of P_i, and T_i is the available working hours in the workday for the i^{th} system.

Therefore, letting

$$K_i = \frac{K_S}{2T_i V_w} ,$$

the total of all labor intensive costs will be

$$\mathrm{LIC} = \sum_{i=1}^{m} \frac{C_i}{P_iT_i}\left(\frac{1}{1 - K_iS}\right)$$

where m is the total number of discrete pre-and post-harvest labor intensive activities or treatments to be conducted, and LIC is expressed in dollars per acre so treated.

As an example, suppose the i^{th} activity is lopping and scattering of slash after logging, and the i^{th} system is a worker and chainsaw. Suppose C_i is \$100 per day, P_i is 0.1 acre per hour, and T_i is 6 hours per workday. If $K_S = 2$ and $V_w = 2500$ ft/hr, then $K_i = 6.67\mathrm{x}10^{-5}\mathrm{ft.}^{-1}$ and, if S = 1000 ft., then $K_iS = 0.067$. Accordingly,

$$\frac{C_i}{P_iT_i}\left(\frac{1}{1-K_iS}\right) = \$178.57/\mathrm{acre} \quad .$$

Note that C_i/P_iT_i = \$166.67/acre is the basic cost for lopping and scattering in this example, where no time is used walking from the roadside to the work site.

LOGGING COSTS

Logging comprises three major elements: (1) falling, limbing and bucking, (2) yarding or skidding, and (3) loading and hauling.

In most circumstances, the falling system is a sawyer and chainsaw and, as such, can be treated in a manner analogous to that used for other labor intensive work. That is, the sawyer must spend time walking to and from his work site each day--just as does a timber cruiser or tree planter--and the amount of such time depends on the average distance between roads. During the remaining available time, the sawyer will have an hourly production rate, say P_f, that is most conveniently expressed in volume or number of stems or logs processed per hour. The cost for a sawyer, say C_f, can be expressed in dollars per day.

If $\overline{V}$ represents the total volume (or number of stems or logs) per acre to be processed by the sawyer, then the cost per acre for falling, limbing and bucking (FC) during any particular entry can be expressed as

$$\mathrm{FC} = \frac{C_f\overline{V}}{P_fT_f}\left(\frac{1}{1 - \frac{K_SS}{2T_fV_w}}\right)$$

where P_f and $\overline{V}$ are expressed in compatible units. T_f is the available working hours in the workday and S, K_S, and V_w are as previously defined. Letting

$$K_f = \frac{K_S}{2T_fV_w} \quad .$$

we can express falling, limbing and bucking costs as

$$FC = \frac{C_f \overline{V}}{P_f T_f} \left(\frac{1}{1 - K_f S}\right) \quad .$$

It should be noted that P_f will depend on a large number of variables, including stand characteristics, silvicultural prescription, utilization standards, and terrain.

Skidding or yarding fallen timber is conducted by systems of workers and machines (or animals). Most of these systems require some time to set up or prepare to move wood, the amount of which depends on the average transport distance (or length of span, in the case of cable yarding systems). For example, ground skidding systems (e.g., horses or tractors) require skid trail clearing and landing preparations, and cable yarding systems must be moved from corridor to corridor. Perhaps only helicopters can be considered unique in this respect; whatever their necessary preparatory expenditures, they are generally unrelated to the yarding transport distance.

If the time, in minutes, spent in preparatory or rigging activities can be estimated as

$$R_0 + R_1 S$$

and the area served by a single set up (i.e., skid trail or corridor) is

$$b\ S$$

(where b is the average distance between skid trails or corridors, in feet), then the set-up or rigging time, in hours/acre, for skidding or yarding is

$$\frac{43560}{(60)b} \left(\frac{R_0}{S} + R_1\right) \quad .$$

Now, if the average skidding or yarding cycle time, in minutes, can be expressed as

$$Y_0 + Y_1 S + Y_2 b + Y_3 n$$

(where *n* is the average number of stems or logs extracted per cycle and Y_0, Y_1, Y_2 and Y_3 are time coefficients), then the operating time, in hours per acre, for skidding or yarding will be

$$\frac{(\overline{V} + V_R)}{60(v)} \quad (Y_0 + Y_1 S + Y_2 b + Y_3 n) \quad ,$$

where v is the average volume per cycle and V_R represents the residues quantity to be extracted per acre in excess of the quantity processed by the sawyers ($\overline{V}$), all expressed in equivalent units. Therefore, the total yarding or skidding cost, in dollars per acre, will be

$$YC = \frac{C_y}{60 T_y} \left[\frac{43560}{b} \left(\frac{R_0}{S} + R_1\right) + \frac{(\overline{V} + V_R)}{v} \quad (Y_0 + Y_1 S + Y_2 b + Y_3 n)\right]$$

where C_y is the daily cost, in dollars, for the yarding or skidding system, and T_y is the available on-site hours per workday.

Finally, we may assume that loading and hauling costs relate only to volume, so the cost per acre for these operations may be expressed simply as

$$HC = C_h\,(\overline{V} + V_R)$$

where C_h is the loading and hauling cost per unit volume, with the unit volume being consistent with the units of $\overline{V}$ and V_R.

APPENDIX B

Effects of Road Spacing or Span

To examine this matter, we make the assumptions listed in table B-I. Note that $K_S = 2$ (i.e., the yarding system can yard both uphill and downhill to the road system).

If S = 1000 feet, equation 8 yields

$$b_{opt} = \sqrt{\frac{43560\ \text{ft}^2/\text{acre}\ \left(0.3\,\frac{\text{MBF}}{\text{cycle}}\right)\left(\frac{30\ \text{min.}}{1000\ \text{ft.}} + 0.03\,\frac{\text{min.}}{\text{ft}}\right)}{(0.0125\ \text{min/cycle - ft})\ (10\ \text{MBF/acre})}}$$

or $b_{opt} = 79.2$ ft.;

and equation 9 yields

$$\begin{aligned} C = {} & 4.125\left(\frac{50{,}000}{1000}\right) + 210\left[\frac{1}{1 - 0.05}\right] + 20\ (10)\left[\frac{1}{1 - 0.05}\right] + \frac{1000}{60(8)}\left\{2\sqrt{\frac{43560\ (0.0125)\ (10)\ \left(\frac{30}{1000} \bullet 0.03\right)}{0.3}}\right. \\ & \left. + \frac{10}{0.3}\ [3 + 0.0025\ (1000) + 0.1\ (3)]\right\} + 20\ (10) \end{aligned}$$

or $C \simeq \$1378$/acre.

Table B-II shows the total management cost (C) and components thereof, the daily production rate (P), and the optimum spacing between corridors versus yarding distance or span (S) under the assumptions in table B-I. Note that the daily production rate is determined from

$$P = \frac{C_y\overline{V}}{YC}$$

Table B-I.--Basic assumptions.

$\frac{C_f}{P_f T_f}$ = \$20/M bd. ft.

C_h = \$20/M bd. ft.

C_R = \$50,000/mi

C_y = \$1,000/day

$K_A = 1$

$K_S = 2$

$$\sum_{i=1}^{m} \frac{C_i}{P_i T_i} = \$210/\text{acre}$$

n = 3 pieces/cycle

R_0 = 30 min

R_1 = 0.03 min/ft

T_i = 8 hours/day; i = 1, 2, ...m

T_y = 8 hours/day

$\overline{V}$ = 10 M bd. ft./acre

$V_R = 0$

V_w = 2,500 ft/hr

Y_0 = 3 min/cycle

Y_1 = 0.0025 min/cycle-ft.

Y_2 = 0.0125 min/cycle-ft.

Y_3 = 0.1 min/cycle-piece

v = 0.3 M bd. ft./cycle

$$K_R = \frac{43560}{5280 K_A K_S} = 4.125 \text{ ft-mi/acre}$$

$$K_f = K_i = \frac{K_S}{2 T_i V_w} = 5 \times 10^{-5} \text{ ft}^{-1}; \; i=1, 2, \ldots m$$

Table B-II.--Costs and production rates vs. span, under the assumptions in table B-1.

S (ft)	b_{opt} (ft)	RC ($/acre)	LIC ($/acre)	FC ($/acre)	YC ($/acre)	HC ($/acre)	C ($/acre)	P (M bd. ft./day)
250	125.2	825	212.7	202.5	490.0	200	1,930.2	20
400	104.8	515.6	214.3	204.1	480.5[1]	200	1,614.5	21
500	97.0	412.5	215.4	205.1	484.4	200	1,517.4	21
1,000	79.2	206.2	221.1	210.5	540.3	200	1,378.1	19
1,100	77.4	187.5	222.2	211.7	554.5	200	1,375.9[1]	18
2,000	68.6	103.1	233.4	222.2	695.5	200	1,454.2	14
3,000	64.7	68.8	247.1	235.3	862.3	200	1,613.5	12
4,000	62.6	51.6	262.5	250.0	1,032.3	200	1,796.4	10
5,000	61.3	41.2	280.0	266.7	1,203.7	200	1,991.6	8

[1] Designates minimum costs.

APPENDIX C

Effects of Reducing Cutting Intensity

Continued controversy relative to timber harvesting, and a tendency to increase the use of selective or partial cutting, tend to reduce the volumes per acre. Thus, consider the effect of reducing $\bar{V}$ from 10 M bd. ft./acre to 5 M bd. ft./acre, while retaining all remaining assumptions in table B-I. The resulting costs are shown in table C-I, and they show that the optimum yarding distances with respect to both yarding cost alone and total management cost are increased in comparison with table B-II. Moreover, the economic penalties incurred in total management cost by extending yarding distances beyond optimum are less severe as volume removed per acre is decreased.

Table C-I.--Costs and production rates vs. span for selective logging example.
(C_1 = total first entry management cost)

S (ft)	b_{opt} (ft)	RC ($/acre)	LIC ($/acre)	FC ($/acre)	YC ($/acre)	HC ($/acre)	C_1 ($/acre)	P (M bd. ft./day
250	177.1	825	212.7	101.3	290.0	100	1,529.0	17
500	137.2	412.5	215.4	102.6	277.1[1]	100	1,107.6	18
1,000	112.0	206.2	221.1	105.2	298.6	100	931.1	17
1,500	102.2	137.5	227.0	108.1	333.5	100	906.1[1]	15
2,000	97.0	103.1	233.4	111.1	372.4	100	920.0	13
3,000	91.5	68.8	247.1	117.6	454.4	100	987.9	11
4,000	88.5	51.6	262.5	125.0	538.7	100	1,077.8	9
5,000	86.8	41.2	280.0	133.4	623.9	100	1,178.5	8

[1] Designates minimum costs.

Of course, when costs are expressed in terms of the merchantable volume removed, they become higher as volume decreases, as shown in Table C-II.

Table C-II.--Comparison of costs per unit of merchantable volume for complete ($C/\bar{V}$) and partial ($C_1/\bar{V}_1$) removal on first entry.

S (ft)	$C/\bar{V}$[1] $\bar{V}$ = 10 M bd. ft./acre ($/M bd. ft.)	$C_1/\bar{V}_1$ $\bar{V}_1$ = 5 M bd. ft./acre ($/M bd. ft.)
250	193.0	305.8
500	151.7	221.5
1,000	137.8	186.2
2,000	145.4	184.0
3,000	161.4	197.6
4,000	179.6	215.5
5,000	199.2	235.7

[1] Based on appendix B.

If, on second entry, the remaining volume ($\bar{V}_2$) is removed, where

$$\bar{V}_2 = \bar{V} - \bar{V}_1 = 10 - 5 = 5 \text{ M bd. ft./acre,}$$

then we may assume no road costs but that all remaining costs are the same as in table C-I. Table C-III shows the total of the second entry management costs, C_2, as well as the combined total of first and second entry costs ($C_1 + C_2$) and the corresponding combined cost per unit volume, or

$$\frac{C_1 + C_2}{\bar{V}_1 + \bar{V}_2} = \frac{C_1 + C_2}{\bar{V}} .$$

Table C-III.--Second entry costs and combined first and second entry costs vs. span for selective logging example.

S (ft)	C_2 ($/acre)	$C_1 + C_2$ ($/acre)	$(C_1 + C_2)/\bar{V}$ ($/M bd. ft.)
250	704.2	2,233.4	223.3
500	695.1	1,802.7	180.3
1,000	724.9	1,656.0	165.6
2,000	816.9	1,736.9	173.7
3,000	919.1	1,907.0	190.7
4,000	1,026.2	2,104.0	210.4
5,000	1,137.3	2,315.8	231.6

APPENDIX D

Effects of Residues Removal

Suppose (1) that residues with characteristics similar to merchantable timber (e.g., standing or down dead trees) are to be removed, (2) that their volume, V_R, is equivalent to 2.5 M bd. ft./acre, (3) that the sawyer's rates must be increased (to compensate for falling or processing the residues) from \$20 per M bd. ft. to \$25 per M bd. ft., and (4) that all else in table B-I remains unchanged. Accordingly, the total management cost per acre, $C_{\overline{V}+V_R}$, and the corresponding cost per merchantable volume would be as shown in table D-I.

Table D-1.--Total management cost per acre and per unit of merchantable volume vs. span for V_R = 2.5 M bd. ft./acre and C_f/P_fT_f = \$25/M bd. ft.

S (ft)	$C_{\overline{V}+V_R}$ (\$/acre)	$C_{\overline{V}+V_R}/\overline{V}$ (\$/M bd. ft.)
250	2,124.6	212.5
500	1,717.5	171.8
1,000	1,597.6	159.8
2,000	1,717.8	171.8
3,000	1,923.0	197.3
4,000	2,152.6	215.3
5,000	2,395.2	239.5

If removal of residues causes no reduction in other site treatment costs (e.g., slash disposal) then, to avoid economic penalty, it is necessary that the residues contain an equivalent net merchantable volume of ρV_R, where

$$\rho \geq \frac{\overline{V}}{V_R}\left(\frac{C_{\overline{V}+V_R}}{C} - 1\right) .$$

Table D-II shows the minimum values of ρ needed to enable removal of the residues in this example.

Table D-II.--Minimum values of ρ vs. span for residues removal example ($\overline{V}$ = 10 M bd. ft./acre, V_R = 2.5 M bd. ft./acre)

S (ft)	$C_{\overline{V}+V_R}$[1] ($/acre)	C[2] ($/acre)	ρ
250	2,124.6	1,930.2	0.40
500	1,717.5	1,517.4	0.53
1,000	1,597.6	1,378.1	0.64
2,000	1,717.8	1,454.2	0.73
3,000	1,923.0	1,613.5	0.77
4,000	2,152.6	1,796.4	0.79
5,000	2,395.2	1,991.6	0.81

[1] From table D-I.
[2] From Table B-II.

APPENDIX E

Analysis of Aerial Yarding Systems Prospects

We may assume that "rigging time" for aerial systems is negligible, and that there is no lateral yarding component in the yarding cycle. Accordingly, we may rewrite the expression for total per acre management cost as

$$C = K_R \frac{C_R}{S} + \sum_{i=1}^{m} \frac{C_i}{P_i T_i} \left(\frac{1}{1 - K_i S} \right) + \frac{C_f \overline{V}}{P_f T_f} \left(\frac{1}{1 - K_f S} \right) + \frac{C_y}{60 T_y} \frac{(\overline{V} + V_R)}{v} (Y_0 + Y_1 S + Y_3 n) + C_h (\overline{V} + V_R) \quad . \qquad \text{(E-1)}$$

Consider first a "small" helicopter system. Assume its cost, C_y, is $2,000 per day; its speed is such that Y_1 = 0.00025 min/cycle-ft.; its load carrying capability is such that v = 0.1 M bd. ft./cycle and n = 1 piece/cycle; that Y_0 = 2 min/cycle; and that all else is as assumed in table B-I. Table E-I shows the resulting costs based on equation E-1, as well as the corresponding daily production rates. (Note that the production rates in table E-I are comparable to those for the yarding system in table B-II.)

Table E-I.--Costs and yarding production rates for small helicopter system.

S (ft)	RC ($/acre)	LIC ($/acre)	FC ($/acre)	YC ($/acre)	HC ($/acre)	C ($/acre)	P (M bd. ft./day)
250	825.0	212.7	202.5	901.0	200	2,341.2	22.2
500	412.5	215.4	205.1	927.1	200	1,960.1	21.6
1,000	206.2	221.1	210.5	979.2	200	1,817.0	20.4
2,000	103.1	233.4	222.2	1,083.3	200	1,842.0	18.5
3,000	68.8	247.1	235.3	1,187.5	200	1,938.7	16.8
4,000	51.6	262.5	250.0	1,291.7	200	2,055.8	15.5
5,000	41.2	280.0	266.7	1,395.8	200	2,183.7	14.3

Next, consider a relatively "large" helicopter system, costing $20,000 per day, and having a load carrying capability equivalent to v = 2 M bd. ft./cycle. As for the small helicopter, we assume Y_1 = 0.00025 min/cycle-ft. and Y_0 = 2 min/cycle. However, we assume also that falling costs are doubled, owing to the need to gather or bunch stems or logs such that n = 1 "piece"/cycle. (We are assuming here the existence of some unspecified technology that would permit a sawyer or team of sawyers to maneuver logs or stems over short distances on steep slopes such that small piles or bunches equivalent to the helicopter's load capability would result.) Table E-II shows the costs and production rates for this system.

Table E-II.--Costs and yarding production rates for large helicopter system.

S (ft)	RC ($/acre)	LIC ($/acre)	FC ($/acre)	YC ($/acre)	HC ($/acre)	C ($/acre)	P (M bd. ft./day)
250	825.0	212.7	405.0	450.5	200	2,093.2	444
500	412.5	215.4	410.2	463.5	200	1,701.6	432
1,000	206.2	221.1	421.0	489.6	200	1,537.9	408
2,000	103.1	233.4	444.4	541.7	200	1,522.6	369
3,000	68.8	247.1	470.6	593.8	200	1,580.3	337
4,000	51.6	267.5	500.0	645.8	200	1,659.9	310
5,000	41.2	280.0	533.4	697.9	200	1,752.5	287

Finally, we assume the possibility of using some new, large capacity airship costing $20,000 per day and having a load capacity of v = 10 M bd. ft./cycle and a cruising speed equivalent to Y_1 = 0.0005 min./cycle-ft. We will further assume that its acceleration and deceleration rates, and its load retrieval rates, are such that Y_0 = 4 min/cycle and Y_3 = 1 min/cycle-piece; and again that n = 1 "piece"/cycle and that falling costs are doubled to account for load concentration in the woods. Table E-III shows the estimated costs and production rates for this system.

Table E-III.--Costs and production rates for hypothetical airship.

S (ft)	RC ($/acre)	LIC ($/acre)	FC ($/acre)	YC ($/acre)	HC ($/acre)	C ($/acre)	P (M bd. ft./day)
250	825.0	212.7	405.0	213.5	200	1,856.2	937
500	412.5	215.4	410.2	218.8	200	1,456.9	914
1,000	206.2	221.1	421.0	229.2	200	1,277.5	873
2,000	103.1	233.4	444.4	250.0	200	1,230.9	800
3,000	68.8	247.1	470.6	270.8	200	1,257.3	739
4,000	51.6	262.5	500.0	291.7	200	1,305.8	686
5,000	41.2	280.0	533.4	312.5	200	1,367.1	640
10,000	20.6	420.0	800.0	416.7	200	1,857.3	480
15,000	13.8	840.0	1,600.0	520.8	200	3,174.6	384

APPENDIX F

Analysis of Cable Yarding System Prospects

Consider the optimistic prospect that, by pre-bunching in advance of yarding, the average load capacity could be doubled. Consider further that carriage speed could be doubled and that, because of pre-bunching, the system cost could be reduced by 25 percent as a result of labor savings. Finally, assume that pre-bunching could be accomplished by sawyers through some unspecified technology that would merely double their production costs.

In accordance with our optimism, let v = 0.6 M bd. ft./cycle; Y_1 = 0.00125 min/cycle-ft; C_y = $750/day; C_f/P_fT_f = $40/M bd. ft.; n = 2 "pieces"/cycle; and assume that all remaining values are as in table B-I. The results are shown in table F-I, based on equations 8 and 9 in the text.

Table F-I.--Costs and production rates vs. span for optimistic improvements in cable yarding technology.

S (ft)	b_{opt} (ft)	RC ($/acre)	LIC ($/acre)	FC ($/acre)	YC ($/acre)	HC ($/acre)	C ($/acre)	P (M bd. ft./day)
250	177.1	825.0	212.7	405.0	206.8	200	1,849.5	36
500	137.2	412.5	215.4	410.2	188.9	200	1,427.0	40
1,000	112.0	206.2	221.1	421.0	188.8	200	1,237.1	40
2,000	97.0	103.1	233.4	444.4	211.6	200	1,192.5	35
3,000	91.5	68.8	247.1	470.6	240.5	200	1,227.0	31
4,000	88.5	51.6	262.5	500.0	271.2	200	1,285.3	28
5,000	86.8	41.2	280.0	533.4	302.6	200	1,357.2	25

APPENDIX G

Combination Yarding and Forwarding Systems

Consider the possibility that trail-based harvesting technologies could be devised such that yarding systems capable of spanning 1,000 feet could be maneuvered on trails, and that forwarding systems could move logs on these trails to truck roads. Obviously, personnel could also be readily transported on the trails.

Let the average distance between truck roads be represented by 2S, and assume that the average distance between trails would be 0.2S. If C_T represented the total cost per mile for trails, and if $K_A = 1$, then the average cost per acre served by the trails would be

$$TC = \frac{43560C_T}{5280(0.2S)} = 41.25 \quad \frac{C_T}{S} \quad .$$

Obviously, the cost per acre served by the truck roads would still be

$$RC = 4.125 \quad \frac{C_R}{S} \quad .$$

Now, based on our prior analysis, the cost per acre for labor intensive work, including falling, would be multiplied by a factor of

$$\left(\frac{1}{1 - \frac{0.1S}{T_i V_w}}\right) \quad ,$$

because the walking distance would have been reduced by a factor of 10. Similarly, the model for yarding cost would be modified; thus,

$$YC = \frac{C_y}{60T_y} \left[\frac{43560}{b} \left(\frac{R_0}{0.1S} + R_1\right) + \frac{\left(\overline{V} + V_R\right)}{v} \left(Y_0 + 0.1Y_1S + Y_2b + Y_3n\right)\right] \quad .$$

Our forwarding system would cost C_F dollars per day, and its average travel distance would be S/2. Accordingly, the hours spent per acre for forwarding would be

$$\frac{\left(\overline{V} + V_R\right)}{60v_f} \left(Y_{f0} + Y_{f1}S + Y_{f3}n_f\right)$$

where v_f is the volume carried per forwarding cycle; Y_{f0} is the average fixed amount of time, in minutes, spent in each cycle (such as for maintenance, decking of logs at the truck roads, etc.); Y_{f1} is the travel time coefficient in min/cycle-ft.; Y_{f3} is the minutes per piece for loading and unloading the forwarder; and n_f is the number of pieces transported per cycle.

Accordingly, if loading of trucks and truck hauling costs remained the same as at present,

$$\text{or } C_h \left(\overline{V} + V_R\right) \quad ,$$

then our total cost per acre would become

$$\begin{aligned} C = 4.125\,\frac{C_R}{S} + 41.25\,\frac{C_T}{S} + \sum_{i=1}^{m} \frac{C_i}{P_i T_i}\left(\frac{1}{1-\frac{0.1S}{T_f V_w}}\right) + \frac{C_f \bar{V}}{P_f T_f}\left(\frac{1}{1-\frac{0.1S}{T_f V_w}}\right) + \frac{C_y}{60T_y}\left[\frac{43560}{b}\left(\frac{R_0}{0.1S} + R_1\right)\right. \\ \left. + \frac{(\bar{V} + V_R)}{v}\,(Y_0 + 0.1Y_1 S + Y_2 b + Y_3 n)\right] + \frac{C_F}{60T_F}\,\frac{(\bar{V} + V_R)}{v_f}\,(Y_{f0} + Y_{f1}S + Y_{f3}n_f) + C_h\,(\bar{V} + V_R) \quad . \qquad \text{(G-1)} \end{aligned}$$

The optimum spacing between yarding corridors would now be

$$b_{opt} = \sqrt{\frac{43560(v)\left(\frac{R_0}{0.1S} + R_1\right)}{Y_2\,(\bar{V} + V_R)}} \quad , \qquad \text{(G-2)}$$

so that when equation G-2 is substituted for b in equation G-1, the total per acre management cost becomes

$$\begin{aligned} C = 4.125\,\frac{C_R}{S} + 41.25\,\frac{C_T}{S} + \sum_{i=1}^{m} \frac{C_i}{P_i T_i}\left(\frac{1}{1-\frac{0.1S}{T_f V_w}}\right) + \frac{C_f \bar{V}}{P_f T_f}\left(\frac{1}{1-\frac{0.1S}{T_f V_w}}\right) + \frac{C_y}{60T_y}\left[2\sqrt{\frac{43560\ Y_2\ (\bar{V} + V_R)\ \ (R_0/0.1S + R_1)}{v}}\right. \\ \left. + \frac{(\bar{V} + V_R)}{v}\,(Y_0 + 0.1Y_1 S + Y_3 n)\right] + \frac{C_F}{60T_F}\,\frac{(\bar{V} + V_R)}{v_f}\,(Y_{f0} + Y_{f1}S + Y_{f3}n_f) + C_h\,(\bar{V} + V_R) \quad . \qquad \text{(G-3)} \end{aligned}$$

Now, because we would be operating from trails, it is likely that forwarding rates would have to be compatible with yarding rates. Accordingly, before proceeding further, we should examine whether operation in this fashion would be technically feasible.

Compatibility of Forwarding and Yarding Systems

Compatibility of the forwarding and yarding systems means essentially that the time spent per acre by each of the systems should be approximately equal, or that

$$2\sqrt{\frac{43560\ Y_2\ (\bar{V} + V_R)\ \left(\frac{R_0}{0.1S} + R_1\right)}{v}} + \left(\frac{\bar{V} + V_R}{v}\right)(Y_0 + 0.1Y_1 S + Y_3 n) = \frac{(\bar{V} + V_R)}{v_f}\ \ (Y_0 + Y_{f1}S + Y_{f3}n_f) \quad .$$

From this we can obtain

$$Y_{f1} = \frac{v_f}{(\bar{V} + V_R)S}\left[2\sqrt{\frac{43560\ Y_2\ (\bar{V} + V_R)\left(\frac{R_0}{0.1S} + R_1\right)}{v}} + \frac{(\bar{V} + V_R)}{v}\,(Y_0 + 0.1Y_1 S + Y_3 n) - \frac{(\bar{V} + V_R)Y_{f0}}{v_f} - (\bar{V} + V_R)Y_{f3}\,\frac{n_f}{v_f}\right] \quad .$$

Because our yarding system is likely to be of lower power and lower load carrying capability than conventional systems, n and v will probably be less, and Y_1 will probably be greater than for conventional systems. Nevertheless, to be conservative, we will assume these factors to be unchanged--that is, that $n = 3$ pieces/cycle, $v = 0.3$ M bd. ft./cycle, and $Y_1 = 0.0025$ min/cycle-ft.

We will assume further that $Y_{f0} = Y_0 = 3$ min/cycle, but that $Y_{f3} = 10\ Y_3 = 1$ min/piece (recall from table B-I that $Y_3 = 0.1$ min/cycle-piece). Retaining $Y_2 = 0.0125$ min/cycle-ft, $(\overline{V} + V_R) = 10$ M bd. ft./acre, $R_0 = 30$ min, $R_1 = 0.03$ min/ft, and assuming $n_{f/v_f} = n/v = 10$ pieces/M bd. ft., we obtain the following relationship:

$$Y_{f1} = 0.1\ \frac{v_f}{S}\left[269.4\ \sqrt{\frac{300}{S} + 0.03}\ + 33.3\ (3.3 + 0.00025S) - \frac{30}{v_f} - 100\right]$$

Our worst condition would occur when S is large and v_f is small. Suppose, for example, that $S = 10{,}000$ feet and $v_f = 2v = 0.6$ M bd. ft. /cycle. Then Y_{f1} would have to be less than or equal to 0.00065 min/cycle-ft, which is equivalent to an average forwarder speed of $1 \div 0.00065 = 1538$ ft/min, or about 17 miles per hour. If $v_f = 4v = 1.2$ M bd. ft./cycle, and $S = 10{,}000$ feet, the average forwarder speed would only need to be about 7 miles per hour.

In short, it would appear technically feasible to maintain forwarder production equivalent to yarder production over relatively long distances. Of course, the forwarder would probably be under-utilized at shorter distances, but for simplicity and conservatism, we will assume the forwarding costs would be lumped with yarding costs. Accordingly, we may rewrite equation G-3 as follows:

$$C = 4.125\ \frac{C_R}{S} + 41.25\ \frac{C_T}{S} + \sum_{i=1}^{m} \frac{C_i}{P_i T_i}\left(\frac{1}{1 - \frac{0.1S}{T_i V_w}}\right) + \frac{C_f \overline{V}}{P_f T_f}\left(\frac{1}{1 - \frac{0.1S}{T_f V_w}}\right) + \frac{(C_y + C_F)}{60T_y}\left[2\sqrt{\frac{43560\ Y_2\ (\overline{V} + V_R)\left(\frac{R_0}{0.1S} + R_1\right)}{v}}\right.$$

$$\left. + \frac{(\overline{V} + V_R)}{v}\ (Y_0 + 0.1Y_1S + Y_3n)\right] + C_h\ (\overline{V} + V_R) \quad . \qquad \text{(G-4)}$$

Assuming $C_y + C_F = \$1{,}000$/day, that $C_T = 0.1\ C_R = \$5{,}000$/mi, and that all other values remain the same as in table B-I, we obtain the results listed in table G-I.

Table G-I.--Costs and production rates vs. S for combined yarding and forwarding system.

Road Spacing (ft)	S (ft)	b_{opt} (ft)	RC ($/acre)	TC ($/acre)	LIC ($/acre)	FC ($/acre)	Yard & forward ($/acre)	HC ($/acre)	C ($/acre)	P (M bd. ft./day)
2,000	1,000	185.7	206.3	206.3	211.1	201.0	569.0	200	1,593.7	18
4,000	2,000	137.2	103.1	103.1	212.1	202.0	502.0	200	1,322.3	20
8,000	4,000	104.8	51.6	51.6	214.3	204.1	480.5	200	1,202.1	21
12,000	6,000	91.5	34.4	34.4	216.5	206.2	492.1	200	1,183.6[1]	20
16,000	8,000	84.0	25.8	25.8	218.8	208.3	513.9	200	1,192.6	19
20,000	10,000	79.2	20.6	20.6	221.1	210.5	540.3	200	1,213.1	18

[1] Designates optimum.