Applications of Harvesting System Simulation to Timber Management and Utilization Analyses

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ABSTRACT

Applications of timber harvesting system simulation to the economic analysis of forest management and wood utilization practices are presented. These applications include estimating thinning revenue by stand age, estimating impacts of minimum merchantable tree diameter on harvesting revenue, and evaluating wood utilization alternatives relative to pulpwood quotas and harvesting revenue.

Key Words: Timber harvesting, computer simulation, wood utilization, thinning.

INTRODUCTION

In the search for more efficient timber harvesting systems, several computer simulation programs have been developed in the last 20 years to model harvesting system performance (Goulet and others 1980). The interest in harvesting systems analysis resulted from increasing harvesting costs, the mechanization of timber harvesting, and the increase in "hot" logging that required a systems versus component analysis of the harvesting process (Goulet and others 1979, Corcoran 1973, Martin 1973). Further, reported stumpage prices and costs indicate that harvesting and hauling often constitute a large part of the total cost of delivered roundwood (Engalichev 1989). Accordingly, harvesting costs are a major concern to wood buyers and forest-land owners.

A simulation model essentially represents a set of assumptions regarding the mathematical and logical relationships that define how a system works (Law and Kelton 1982). The harvesting simulation models described and evaluated by Goulet and others (1980) generally model machine performance as a function of system configuration and harvest site attributes such as tree diameter distribution, volume harvested, tract dimensions, and truck haul routes. The system production rate reflects the productivity of system components and the interactions or bottlenecks that limit system output.

One primary advantage of computer simulation is that it allows experimentation with the computer model to gather data on system productivity that might otherwise be too costly or impossible to collect from real systems (Law 1986). The initial experiments with timber harvesting simulation focused on system configuration to identify the most efficient combinations of men and machines (Martin 1973). Subsequent applications have included estimating harvesting costs as a function of variables such as timber stand attributes, tract size, and input costs, as well as system configuration (Cubbage and Granskog 1982, McCollum and Hughes 1983, LeDoux 1985). Harvesting simulation also has been used to estimate harvesting costs and revenue for the economic analysis of forest management alternatives (Reisinger and others 1985, LeDoux 1986).

OBJECTIVE

The objective of this paper is to demonstrate potentially important applications of harvesting system simulation to the economic analysis of forest management and wood utilization alternatives. The applications demonstrated include the effects of:

1. Stand age at first thinning and pulpwood/fuelwood markets on thinning revenue.

2. Minimum merchantable tree diameter on revenues from thinning and regeneration cuts.

3. Pulpwood quotas and the wood utilization practices required to constrain pulpwood production on harvest revenue.

METHODS

The simulation model was developed initially to estimate harvesting costs and revenues from thinning and regeneration entries in Appalachian upland oak stands, and to evaluate the potential for increasing harvesting revenue via multiproduct harvesting (Baumgras 1990). Written in FORTRAN 77, this discrete-event model applies the next-event method of controlling simulation time. Simulation events represent changes in system state that occur at the beginning or end of a machine production cycle or scheduled production time.

The harvesting system simulated included manual chain saw felling, skidding with a rubber-tired cable skidder, and a hydraulic loader/slasher combination to buck, sort, and load hardwood roundwood products. Machine cycle times were estimated using cycle-time equations and delay-time distributions sampled from West Virginia harvesting operations (Biller and Baumgras 1988, Brock and others 1986, Sarles and others 1988). The simulated system production rate reflects component production and system interactions. Estimates of machine cycle time are sensitive to timber stand and tract attributes. The random X and Y coordinates of each cut tree were generated with the tree-location algorithm developed by Bradley and others (1982). The simulation model also tracks individual-tree attributes throughout the process from stump to deck, such that tree attributes that affect machine cycle time will affect all system components.

Inputs to the simulation include tract dimensions, road spacing, harvested stand attributes, minimum merchantable tree diameter at breast height (dbh), and minimum merchantable stem top diameter inside bark (dib). Tract dimensions were 1,400 by 1,600 feet (51.4 acres), with parallel skid roads on 200-foot spacing. Sawlog and pulpwood yields were estimated with tree taper equations (Martin 1981), hardwood log grade estimators (Yaussey and others 1988), and tree grade distribution estimators (Dale and Brisbin 1985). The use of taper functions provides a volume estimate to a variable top dib for evaluating selected wood utilization options. Although minimum merchantable tree dbh and top dib were treated as variables to evaluate utilization options, sawlog volumes were calculated only for trees 12 inches dbh and larger to a 10-inch top dib based on the International 1/4 inch log rule. Pulpwood/fuelwood volume represents bole sections less than 10 inches dib, and larger sections that would not make a grade 3 sawlog.

Harvested stand attributes were obtained from the stand tables summarized in Table 1. These tables were generated by OAKSIM, a growth and yield simulator for even-aged upland oak stands (Hilt 1985). The initial stand for the growth simulations represented a fully stocked upland oak stand at age 40 and site index 70. Percent of total basal area at age 40 by tree species groups include: white oaks: 38 percent; red oaks: 50 percent; red maple: 2 percent; and yellow-poplar: 10 percent. All simulated thinnings reduced stocking to 60 percent.

Case study results were not available to validate all simulations. However, simulation results compared favorably to the production rates sampled on two hardwood thinning operations (Miller and Sarles 1986, Brock and others 1986).

Table 1. Harvested stand diameter distributions for each thinning at 40 to 70 years (T-40, T-50, T-60, T-70) and regeneration cut at 90 years (R-90)

Entry	*Dbh class (inches)*									
	2	4	6	8	10	12	14	16	18	20+
	No. trees/acre									
T-40	4	64	71	36	11	1				
T-50		27	61	42	17	5	1			
T-60		8	42	41	22	10	2			
T-70		2	24	37	26	12	4	1		
R-90			3	21	39	36	19	10	3	1

Final harvest costs also were comparable to those reported by Bell (1989) for regeneration cuts in southern Appalachian sawtimber stands.

Timber harvesting revenue was calculated by deducting stump-to-truck harvesting costs and hauling costs from total revenue. Total revenue was the sum of the products of delivered product prices and estimated product volumes. Stump-to-truck harvesting costs were estimated from the harvesting simulation results. The harvesting simulations did not include trucking as a simulation event. Instead, haul costs were estimated as a function of haul distance. Road and landing costs were not included in the revenue analysis. These costs are highly variable and influence only revenue levels, not the revenue trends demonstrating differences between thinning ages or wood utilization options. All revenues were calculated on a dollar/acre basis and, therefore, represent derived stumpage values. To simplify the analysis, no effort was made to allocate net revenue between the logger and landowner.

To estimate total revenue, reported sawlog prices (Ohio Agric. Stat. Serv. 1989, Pa. State Univ. 1989) for the relevant tree species were averaged by USDA Forest Service log grades and applied to the sawlog volume estimated by log grade. Accordingly, sawlog prices reflect the species composition that includes high-value red and white oaks. Delivered prices by log grade are: grade 1: $300/Mbf; grade 2: $200/Mbf; grade 3: $100/Mbf. Sawlog hauling costs of $15/Mbf were based on a 30-mile haul.

Revenue estimates also included three pulpwood/fuelwood market scenarios for evaluating the effects of delivered prices and haul distance on harvest revenue. Pulpwood/fuelwood accounted for most of the wood removed in thinning, and most of the yield differences between wood utilization options. As a result, revenue trends were sensitive to pulpwood/fuelwood prices and haul costs. The three market scenarios as defined by delivered price, haul distance, and haul cost include; (1) $50/cord, 15 miles, and $4/cord; (2) $40/cord, 30 miles, and $6/cord; (3) $30/cord, 60 miles, and $10/cord. This range of delivered prices and haul costs effectively spans a wide array of potential market conditions for low-quality hardwood roundwood.

RESULTS

Thinning Cost and Revenue

The first application demonstrated shows the effect of stand age on thinning revenue. The attributes of the cut stands reveal important differences between the thinnings tested. Postponing thinning in 10-year increments increased total volume harvested, sawlog volume, numbers of merchantable trees cut per acre, and average tree volume (Table 2). Numbers of unmerchantable trees decreased with age at first thinning. In this analyses, only trees 8 inches dbh and larger were harvested. However, to satisfy silvicultural objectives, all trees 3.0 inches dbh and larger were felled.

Table 2. Hardwood timber stand attributes and yields by age at first thinning

Age (years)	*No. trees/acre* Merchantable[1]	Unmerchantable	Average vol./tree	*Volume harvested* Total[2]	Pulpwood	Sawlogs[3]
			ft^3	--------*Cords/acre*--------		*Mbf/acre*
40	32	155	11.0	3.8	3.8	0.0
50	51	102	13.5	7.4	6.8	0.3
60	63	62	16.0	10.9	9.2	0.7
70	71	35	18.1	13.9	11.2	1.2

[1]dbh ≥ 8 inches
[2] ≥ 8 inches dbh to 4-inch top dib.
[3]USDA Forest Service factory grade 3 or better, scaling dib > 10 inches.

Table 3. Estimated harvesting costs and net harvest revenue by age at first thinning and pulpwood/fuelwood market

Age (years)	*Stump-to-truck harvest cost* Unit	Total	*Net Revenue* $50/cord and 15-mile haul	$40/cord and 30-mile haul	$30/cord and 60-mile haul
	Dollars/cord	*Dollars/acre*	*Dollars/acre*		
40	54	205	-30	-76	-129
50	38	280	58	-24	-119
60	31	340	153	43	-86
70	28	388	255	121	-36

As a result, postponing thinning results in more time available to fell merchantable trees because fewer unmerchantable trees must be felled.

The response of simulated thinning cost and estimated revenue to changes in harvest stand attributes demonstrates the importance of entry timing. Total harvesting cost increased with total volume per acre, from $205/acre at age 40 to $388/acre at age 70 (Table 3). However, unit costs declined from $54/cord at age 40 to $28/cord at age 70. Most important, revenue estimates show negative cash flows at age 40 for all price/distance levels (Table 3). Thinning at age 50 yielded a positive cash flow only with high pulpwood/ fuelwood prices and short hauls. With low pulpwood/ fuelwood prices and a 60-mile haul, no thinning was economically feasible. Only thinnings at ages 60 and 70 yielded positive cash flows with a medium price and haul distance. Further, inclusion of road and landing costs would create additional negative cash flows. These results demonstrate the importance of estimating harvesting cost and revenue as a function of haul distance and the stand attributes associated with each thinning option. These costs and revenues are essential for effective planning of forest management activities.

Minimum Merchantable Dbh

The objective of the second type of simulation application was to show the effects of minimum merchantable tree dbh and pulpwood/fuelwood markets on net revenue. The harvesting entries evaluated included a first thinning at age 60 followed by an even-age regeneration cut at age 90. Since thinning at age 60 was not feasible with a low pulpwood/fuelwood price and a 60-mile haul distance (Table 3), that scenario was omitted. Although all trees in the cut stand tables were felled, only trees greater than or equal to the specified minimum merchantable dbh were harvested. However, costs reflect the effects of felling unmerchantable trees on simulated production rates.

The reductions in merchantable volume per acre and increases in average volume per tree that occur when the minimum merchantable dbh is increased are shown in Table 4. Due to differences in the diameter distributions between the thinning and regeneration entries, increasing the minimum dbh from 6 inches to 10 inches reduced thinning yields by 53 percent, but reduced final harvest yields only by 10 percent. Over the range of minimum diameters evaluated the average merchantable volume per tree increased by 18.1 and 25.4 ft^3, respectively, for the thinning and harvest entries.

With a price of $40/cord for pulpwood/fuelwood and a 30 mile haul, the simulation results indicate that net revenue from both entries was maximized with a minimum merchantable dbh of 9 inches (Table 5). Thinning revenue was sensitive to increases or decreases in minimum dbh harvested. Because there were relatively few small trees in the age 90 stand table, final harvest revenue was relatively stable at 6 to 9 inches dbh, decreasing sharply from $1,098/acre at 9 inches dbh to $565/acre at 14 inches. All changes in minimum dbh affected pulpwood/fuelwood volume harvested, but sawlog volume changed only when the minimum dbh exceeded 12 inches. It is important to note that reduced haul distance and increased pulpwood/fuelwood prices reduced the minimum

Table 5. Estimated net revenue from first thinning at age 60 and final regeneration harvest at age 90, by minimum merchantable tree dbh[1] and pulpwood/fuelwood market

Minimum merch. dbh (inches)	*Thinning at age 60* $50/cord and 15-mile haul	*Thinning at age 60* $40/cord and 30-mile haul	*Harvest at age 90* $50/cord and 15-mile haul	*Harvest at age 90* $40/cord and 30-mile haul
	Dollars/acre			
6	98	-46	1363	1085
7	137	-6	1366	1088
8	153	43	1366	1092
9	132	48	1354	1098
10	75	18	1311	1081
11	10	-25	1205	1028
12	-53	-68	1048	934
13	--[2]	--[2]	833	754
14	--[2]	--[2]	620	565

[1]Trees smaller than minimum merchantable dbh felled but not harvested.
[2]Too few trees/acre to harvest.

The pulpwood/fuelwood came from below-grade bole sections 10 inches dib and larger.

Most important, the results in Table 6 show the estimated net revenue per acre and pulpwood/fuelwood production per day for each utilization option tested. These results demonstrate the potential effects of pulpwood quotas on maximum harvesting revenue. For example, with no quota, revenue is maximized at $1,098/acre by utilizing only trees 9 inches dbh and larger to a 4-inch top dib (Table 6). To maximize revenue with increasingly stringent pulpwood/fuelwood quotas of 20, 15, and 10 cords/day requires implementing tree- and stem-diameter limits of 9 inches dbh - 6 inches dib, 12 inches dbh - 6 inches dib, and 12 inches dbh - 10 inches dib, respectively. The resulting relative reductions in maximum net revenue by pulpwood/fuelwood quotas were: 20 cords/day, 6 percent; 15 cords/day, 18 percent; and 10 cords/day, 35 percent. Since trees 12 inches dbh and larger were harvested with all quotas, total sawlog volume and revenue were not affected. Adjusting merchantable dbh and top dib altered only the system production rate, product mix, pulpwood/fuelwood production rate, and net revenue.

DISCUSSION

The results demonstrate that timber harvesting simulation can be applied to develop information essential to planning forest management and timber harvesting operations. The examples presented also demonstrate the advantages of linking flexible product-volume estimators with harvesting simulation to evaluate forest management and wood utilization alternatives with respect to product yields, system production rates, and the resulting projected cash flows. Whereas the results presented are directly applicable only to the harvesting system, timber stand, and market conditions simulated, the procedures used have widespread applications.

The three applications presented use simulation to evaluate the relationships between cut stand attributes and the resulting system production rate and product yields. Cut stand attributes are a function of stand age and simulated wood utilization practices. Stand age determines the attributes of trees available for harvest. Utilization options determine the attributes of trees actually harvested.

Table 6. Estimated effects of minimum merchantable tree dbh and top dib[1] on volume harvested, pulpwood mix, pulpwood production rate, and net revenue per acre

Minimum merchantable: Dbh	Top dib	Total merch. volume	Product mix[2]	Pulpwood/ fuelwood production	Net revenue
----(inches)----		*Cords/acre*	*Percent*	*Cords/day*	*Dollars/acre*
6	4	40.6	57	21.1	1085
7	4	40.4	57	21.2	1088
8	4	40.0	57	21.4	1092
	6	38.0	54	19.5	1025
9	4	38.8	55	21.8	1098[3]
	6	36.9	53	19.9	1034[3]
10	4	36.4	52	21.6	1081
	6	34.8	50	19.9	1032
	8	30.9	44	15.6	907
11	4	32.1	46	20.0	1028
	6	30.9	44	18.4	989
	8	27.9	38	14.5	894
12	4	26.8	35	15.6	934
	6	25.9	33	14.1	905[3]
	8	23.8	27	10.6	836
	10	20.2	14	4.7	718[3]
13	4	20.7	32	11.7	754
	6	20.2	30	10.7	736
	8	18.7	24	8.2	690
	10	16.4	14	4.0	613

[1]Smaller trees and stem sections felled but not harvested.
[2]Pulpwood/fuelwood volume as percent of total volume harvested.
[3]Maximum revenue for no pulpwood/fuelwood quota and quotas of 20, 15, and 10 cords/day.

The results of these simulations indicate that thinning cash flows are dependent on the age of the stand when first thinned, that thinning is not economically feasible at ages 40 to 70 years with relatively low pulpwood prices and long hauls, and that commercial thinning at ages 60 and 70 years requires a pulpwood/fuelwood price of $40/cord combined with a haul of 30 miles or less. The results also indicate that cash flows from thinning and regeneration entries can be sensitive to the minimum tree dbh harvested, and that simulation results can define the marginal costs and revenues required to identify utilization options that maximize revenue. Finally, the estimation of pulpwood production rates and harvesting revenue indicates the extent to which altering merchantable tree dbh and top dib can reduce volume harvested and harvesting revenue to satisfy quotas on pulpwood/fuelwood production. Where the quotas imposed only on pulpwood production, a viable fuelwood market would allow increased utilization and harvesting revenue.

The analyses described are essentially experiments conducted with a computer simulation model and projected stand tables to evaluate harvesting and utilization options. It might not be feasible to conduct these experiments through numerous case studies of actual operations; nor is it practical to validate every simulation with case study data. Accordingly, computer simulation can be viewed as a method of developing cost and revenue estimates to identify the most promising options from a large number of possibilities. Field

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