Estimating and validating harvesting system production through computer simulation

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Abstract

A Ground Based Harvesting System Simulation model (GB-SIM) has been developed to estimate stump-to-truck production rates and multiproduct yields for conventional ground-based timber harvesting systems in Appalachian hardwood stands. Simulation results reflect inputs that define harvest site and timber stand attributes, wood utilization options, and key attributes of the harvesting operation. Statistical validation of GB-SIM was conducted with harvesting production data collected from 16 harvest units and 2 logging operations, including partial cuts and clearcuts in Appalachian hardwood stands. The mean error in estimated production rates was 14.1 ft.^{3}/hour, or 2.6 percent of the observed rates. For 10 of the 16 units, this error was less than 10 percent of the observed production rate. Nonparametric tests conducted with five replications of each simulated harvest did not find a statistically significant difference between the distributions of actual and simulated production rates. These validation results indicate that GB-SIM can be used to estimate harvesting system production rates and product yields; information required to conduct economic analysis of wood utilization and forest management alternatives. Simulation results are also presented that contrast two different logging crews and compare production rates from eight unique wood utilization options.

Unlike most other manufacturing or materials handling processes, timber harvesting systems operate in a dynamic environment that can change with each harvest unit or within a harvest unit. Consequently, harvesting production is as much a function of timber stand and harvest site attributes as harvest system configurations. Therefore, a successful model must necessarily link the real attributes of the operating environment (e.g., skidding distance, slope, topography) to the harvest stand attributes (e.g., stand density, product volume) and harvest system characteristics (e.g., numbers and types of equipment, utilization rates, volumes skidded).

Because of the inherent variability in harvesting system configurations, operating environments, and potential interactions between system components, attempts at modeling these systems have been uniquely challenging. The attempts to capture the variability of timber harvesting in mathematical models has fueled a proliferation of diverse models, from simple regression models to stochastic process models and simulation models. Computer simulation has been used for linking the variable components into production and cost analysis (15). Simulation provides an accepted method of evaluating a wide range of system configurations, operating environments, and timber utilization options (29). Law (17) states, "In a simulation we use a computer to evaluate a model numerically over a time period of interest, and data are gathered to estimate the desired true characteristics (e.g., throughput) of the model." This process permits conducting experiments with the simulation model that would not be possible or cost effective with the actual harvesting system.

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Simulation and validation

Documented applications of harvesting simulations include the evaluation of alternative harvesting system configurations and applications (1,16). Simulation has also been applied to determine the effects of wood utilization levels on harvesting costs (4,28). Equations for estimating harvesting cost as a function of system configuration and harvest site attributes have been developed from harvesting simulation results (20,22). Harvesting simulation also has been applied to the results of forest growth and yield simulations to include harvesting costs in the economic analyses of forest management and wood marketing alternatives (2,19,25).

Whereas the harvesting simulation literature provides numerous descriptions and applications of simulation models, the issue of model validation is seldom addressed. Although there does not appear to be a clear consensus as to the exact methods of validating simulation models, statistical analysis of the results of stochastic simulations is recommended to ensure the model duplicates the real world process, and to have confidence that correct inferences are drawn from simulation results (27). The reliability of simulation results can be evaluated by estimating confidence intervals about the mean simulation result (13).

The few documented validation efforts include comparisons of simulation results to published production rates and costs (7), or comparisons with averages obtained from selected harvesting firms (24). Detailed site and system specific validations are reported by Garner (12) for trucking and loading operations, and by McCollum and Hughes (22) for five loggers working on southern pine sites. Reasons cited for the lack of extensive validation of harvesting simulations include the high cost of collecting detailed production data (22), and low or nonexistent profits for biomass recovery systems (16). Nonetheless, both Garner (12) and Webster (29) emphasize the need for extensive collection of production data to improve and test simulation results.

The purpose of this paper is to describe a Ground Based Harvesting System Simulation model (GB-SIM), to document the validation of this computer simulation model, and to demonstrate the application of simulation to comparisons of logging crews and wood utilization alternatives.

GB-SIM

GB-SIM is a simulation model written in FORTRAN, which estimates stump-to-truck production rates and product yields for conventional ground-based harvesting systems operating in Appalachian hardwood stands (2). It models manual felling and limbing with chainsaws, rubber-tired skidders, and either manual chainsaw bucking or bucking, sorting, and loading with a hydraulic loader/slasher combination. This system configuration is very common in the Appalachian hardwood region. System configuration options include numbers of fellers and skidders employed. The two primary functions of GB-SIM are modeling harvesting system production and estimating roundwood product yields, as described in the following sections.

System production

With regard to modeling harvest system productivity, GB-SIM is a stochastic, discrete-event model that applies the next-event approach to update the system state and advance simulation time. Modeling the interactions between system components is achieved by simulating all components concurrently and continuously updating the inventories of standing trees, felled and delimbed stems, skidded stems, and bucked roundwood products. Stochastic refers to the random sampling of machine delay times not caused by system interactions, the random assignment of tree attributes (including tree species and diameter at breast height (DBH), and the X and Y coordinates that locate each tree within the harvest unit).

The events controlling the simulation include the beginning and end of machine production cycles, scheduled production time intervals, and the end of simulation time when all trees are harvested. The state of the harvesting system is defined by the status of each machine: productive, idle and waiting for wood to process, idle and waiting reductions in excess inventory, or idle and waiting the start of scheduled work time. The system state is also defined by the inventory of trees, stems, or logs at each point in the flow of wood from the stump to the truck. Changes in the state of the system occur at discrete points in time, the beginning or end of a simulation event.

GB-SIM simulates production cycle attributes and calculates cycle times as a function of these cycle attributes using the cycle-time equations specified for each type of equipment. A delay time randomly sampled from an empirical distribution is added to the estimated productive cycle time to calculate the total cycle time. This delay time represents all sources of mechanical or operator-caused delays, but does not include system interaction delays caused by waiting for inventory to process or waiting for inventory reductions.

Tree location

Simulated tree locations determine important attributes of felling and skidding cycles. The distance between successively felled trees affects felling cycle time, numbers of trees hooked per winching cycle, winching distance, and numbers of winching cycles or machine moves required to hook a turn of logs. Trees are conceptually located within each harvest unit subdivision by X and Y coordinates, where each subdivision represents rectangular approximations of the area served by each segment of skid trail. Trees are located within each segment by randomly sampling across the length and width of the new segment. Random X coordinates equal (RN)(SW); where SW is the segment width and RN is a uniformly distributed random number between 0 and 1. Distance along the length of the segment is determined from an exponentially distributed random variable with a mean equal to 43,560/(T)(SW); where T is the number of merchantable trees per acre (5).

To monitor the inventory of trees, stems, or logs at each point in the harvesting process, GB-SIM maintains arrays of tree attributes that include tree location, DBH, and species. The attributes of each tree or stem are tracked throughout the harvesting process so individual tree attributes that can affect felling will also have a logical and sequential effect on skidding and bucking activities. This feature avoids the use of independent samples of tree or stem attributes to model each harvesting function (14).

Roundwood product yields

GB-SIM offers the capability to simulate harvesting with variable wood utilization levels defined by minimum merchantable tree DBH and top diameter inside bark (d.i.b.). This option permits evaluation of wood utilization options with respect to simulated production rates and estimated product yields.

Product classifications include factory-grade sawlogs, sawbolts, and pulpwood or fuelwood. Sawlog yields are estimated by tree species and USDA Forest Service factory log Grades 1, 2, and 3. Sawbolts are defined as low quality sawable roundwood 6-inch d.i.b. and larger that will not make an 8-foot Grade 3 sawlog, but are suitable for the manufacture of wood pallets, blocking, or other low quality sawn products. Pulpwood or fuelwood represents wood with a 4-inch or larger d.i.b. lacking the quality or dimensions required for sawlogs or sawbolts.

Cubic and board foot (International 1/4-in. log rule) volumes are estimated using tree taper functions developed for Appalachian hardwood tree species (21). Sawlog volume by tree species and log grade is estimated using equations that predict percent of trees in each tree grade (8) and tree volume by log grade, given species, diameter, and tree grade (30).

Control parameters

The success of any harvesting simulation model is dependent upon incorporating logical and descriptive control parameters that can be linked directly to the harvesting system to be simulated. The control parameters in GB-SIM were carefully selected and tested for efficiency and effectiveness in modeling the systems of interest. Those selected permit a significant level of flexibility, particularly in modeling wood utilization options.

The inputted stand table contains numbers of harvestable trees/acre in each 1-inch DBH class and tree species group, which ultimately controls product attributes. The total area to be harvested and dimensions of the area served by each skid trail are obtained from the input skid-trail file.

The key to the effective use of the model requires the user to have prior knowledge of the harvesting system in order to successfully simulate the relationships between harvest site attributes and system production. Control variables based on the harvest system include the maximum inventory of felled trees, maximum number of stems skidded per cycle, maximum number of winching cycles per skidder cycle, and maximum cubic volume per skidder cycle. Except for the maximum inventory of felled trees, these simulation control variables are applied by the model to control the tree-hooking process and determine skidder cycle attributes, given the attributes of trees available for skidding. Observed differences between harvesting operations employing similar technology and working in similar environments indicate the need to use these simulation control variables to model specific harvesting operations. Harvest system configuration and cut stand attributes alone are not sufficient to calibrate the simulation to model actual operations. For example, a more productive logging operation strives to maintain a relatively large inventory of felled trees and consistently large skidder turn volumes, while other operations may not.

Target volume is another control variable, one that represents the maximum average volume skidded per cycle observed on high-volume sites. On such sites, cycle volumes are much less constrained by the opportunity to hook additional volume than by the willingness of the machine operator to hook additional trees, or the capability of the machine to handle larger loads. The use of target volume does not ensure that the average volume skidded will equal the target volume, only that average volumes do not exceed those observed under very favorable operating conditions.

GB-SIM results provide a detailed description of simulated production cycle attributes for each harvesting system component. Results also include: total scheduled system time to harvest the specific unit, total machine operating time for each machine type, and total volume harvested by tree species group and roundwood product class. From these results, machine operating cost rates and system fixed cost rates can be applied to estimate harvesting costs. Product values applied to product volume estimates provide harvesting revenue estimates. Not including cost and revenue rates in the simulation allows a single set of simulation results to be applied to alternative sets of assumptions regarding cost rates and product values.

Model validation

Law and Kelton (18) recommend using sensitivity analysis to evaluate model behavior over a wide range of conditions and performing statistical comparisons of simulation results and actual system performance. The initial application of GB-SIM provided a sensitivity analysis that included thinnings in hardwood stands aged 30 to 70 years and regeneration cuts at age 90 (2). These simulation results showed logical and consistent trends in machine cycle attributes and system production rates with changes in average tree volume and trees per acre. Harvesting costs estimated for regeneration cuts at age 90 compared favorably to Appalachian logging costs reported by Bell (3). Production rates from simulated thinnings were very similar

TABLE 1. — *Harvest unit attributes and observed production rates.*

Harvest unit no.	Area	Type of cut[a]	No. of merchantable trees/acre	Average tree volume	Total merchantable volume	Average skid distance	Production rate
	(acre)			($ft.^3$)	($ft.^3$/acre)	(ft.)	($ft.^3$/hr.)
1	26.3	P	12	55.7	668	1,060	294
2	31.2	P	7	43.2	302	741	449
3	23.1	P	9	47.6	428	875	451
4	24.0	P	16	42.8	685	834	353
5	25.9	P	9	38.2	344	1,340	290
6	30.0	P	23	52.7	1,212	833	320
7	2.0	C	197	28.1	5,536	1,874	400
8	1.0	C	163	30.1	4,906	1,342	306
9	1.4	C	200	29.4	5,880	933	377
10	2.0	C	157	23.8	3,737	663	415
11	2.1	C	166	27.0	4,482	303	468
12	2.0	C	139	25.7	3,572	1,580	365
13	1.0	C	262	17.5	4,585	1,423	260
14	1.5	C	145	34.0	4,930	1,305	448
15	1.0	C	148	29.7	4,396	622	373
16	1.0	C	220	23.7	5,214	1,021	336

[a] P = partial cut, C = clearcut.

to those reported from case studies of hardwood thinnings (6,23).

A detailed analysis of actual versus simulated production rates was conducted with the results of three studies of rubber-tired skidder production conducted at West Virginia University's Experimental Forest near Morgantown, W.Va. (9-11). Two of these studies closely monitored rubber-tired skidder production on harvest units 1 through 6, 23.1 to 30 acres each, with skid distances averaging 741 to 1,340 feet (Table 1). These partial cuts in predominantly mixed oak and yellow-poplar stands harvested only the sawlog portion of sawtimber trees, yielding 302 to 1,212 $ft.^3$/acre. Average merchantable volume per tree ranged from 38.2 to 55.7 $ft.^3$ The same logging crew (logger A) harvested all six partial-cut units, working with a single skidder and two fellers using chainsaws to fell, limb, and top sawtimber trees to a 10- to 12-inch-top d.i.b.

The third study monitored stump-to-deck production on small clearcut or group selection units 0.5 to 2.1 acres each. Results from 10 units 1 acre and larger were used in the validation test (units 7 through 16, Table 1). The minimum tree diameter harvested was 4 inches on half of these units, and 6 inches on the remaining units. Tree species composition of these 10 units was similar to that on the 6 partial-cut units. Clearcutting yielded 3,572 to 5,880 $ft.^3$/acre. Average merchantable volume per tree ranged from 17.5 to 34.0 $ft.^3$ The logging crew (Logger B) that harvested all 10 clearcut units used 3 skidders and 3 fellers, each feller working with 1 skidder.

Production rates were derived from the average total cycle time and average volume per cycle recorded on each harvest unit. Applying total cycle times that included delay times caused by the felling-skidding interactions provided estimates of the average stump-to-deck production rates sampled at each harvest unit. These rates varied from 260 to 468 $ft.^3$/scheduled hour (Table 1).

The information required to define the harvesting environment for the simulation of each harvest unit was obtained from timber stand cruise data collected prior to harvesting and surveys of skid trails conducted after harvesting. Although validation data were not available for large clearcuts, the location of the log landings resulted in skid distances for the small clearcut units that often exceeded those of the larger partial-cut units (Table 1). Other than skid distance, the production cycle attributes simulated by GB-SIM are generally independent of harvest unit area. If the input files adequately describe the length and spacing of skid trails, there is no reason to expect that validation results would be affected by the area of the clearcut units.

Simulation control variables defined observed operator or system imposed constraints. For logger A, those included a maximum of four trees, 200 $ft.^3$, and four winch cycles per skidder cycle. For logger B, the simulation control variables included a maximum of seven trees, 240 $ft.^3$, and three winch cycles per skidder cycle. The target volume was 90 $ft.^3$ for logger A and 140 $ft.^3$ for logger B. Skidder cycle time equations applied were those developed from the time study data collected from these same harvest units.

For the validation test, the simulation of harvesting each harvest unit was replicated five times, changing the initial random number seeds for each replication. This procedure is recommended to obtain independent replications for terminating stochastic simulations, which is applicable to timber harvesting because the length of the simulation is completely specified when all trees are harvested. Five replications were sufficient to yield a relative precision level (R) less than .05, indicating the half-width of the confidence interval about the mean simulated production rate was less than 5 percent of the mean (18):

$$R = [(t_{n-1,\ 1-\alpha/2}) ((S^2/n)^{1/2})] / \overline{X}_n$$

where:

n = number of replications
a = probability that the mean falls outside the confidence interval
$\underline{S}^2$ = variance of the simulation result
X_n = mean simulation result

The average skidder production rate including all delays was the simulation result tested. This variable is a primary determinant of harvesting system efficiency and cost, and reflects both system interactions and production cycle attributes. Validating harvesting cost would require including several additional assumptions regarding operating costs and fixed costs, variables not included in the simulation process.

A summary of the validation test results shows the differences between actual and average simulated production rates (Table 2). These differences are also shown as a percentage of actual values. The largest negative and positive differences were encountered with units 1 and 3, respectively. The average simulated production rate for unit 1 was 48.4 ft.^{3}/hr. or 16.4 percent greater than the actual rate. The simulated production for unit 3 was 95.8 ft.^{3}/hr. or 21.2 percent less than the actual rate. For 10 of the 16 units, the absolute relative error was less than 10 percent. The mean difference in the production rate of all 16 units indicates very little bias in the simulation results. The average error in estimating production rates for all sites was only 14.1 ft.^{3}/hr., or 2.6 percent of the observed rates.

TABLE 2. — *Differences in production rates between actual and average of five simulations for each unit.*

Harvest unit no.	(ft.^{3}/hr.)[a]	(%)[b]
1	-48.4	-16.4
2	58.4	13.0
3	95.8	21.2
4	-4.6	-1.3
5	-2.4	-0.8
6	-30.2	-9.5
7	54.3	13.6
8	-6.2	-2.0
9	-3.8	-1.0
10	31.2	7.5
11	57.0	12.2
12	38.2	10.5
13	0.5	0.2
14	27.6	6.2
15	-26.7	-7.2
16	-14.5	-4.3

[a] Actual – simulated.
[b] [(Actual – simulated)/actual] × 100.

A more rigorous statistical validation was conducted with two nonparametric procedures recommended for validating simulation results (26). These procedures apply individual tests to the results from all replications for each harvest unit, and then combine the results in an overall test of the null hypothesis H: F(Y | $\underline{X}$) = G(Y | $\underline{X}$). F(Y | $\underline{X}$) is the distribution function of real production rates conditional upon the vector $\underline{X}$, which represents the site and system-related variables used to simulate production rates. G(Y | $\underline{X}$) represents the distribution function of simulated values. Because $\underline{X}$ does not include all variables that potentially affect the real production rate, values of Y reflect the resulting random error and simulation can only approximate the distribution of Y.

The two nonparametric tests (Eq. **[1]** and **[2]**) do not require normal distributions or homogeneous variances. Both tests are based upon the rank of the observed production rate (R_i) in the set that includes the observed rate and the simulated rates for all replications conducted for each site.

$$V_1{*} = [(V_1 - n\,(m + 2/2))]/[(nm\,(m + 2)/12)\,]^{1/2} \quad \textbf{[1]}$$

where:

$$V_1 = \sum_{i=1}^{n} R_i$$

$$V_2{*} = [V_2 - n\,((m + 1)/4)]/[n\,((m + 3)\,(m + 1)/48)]^{1/2} \quad \textbf{[2]}$$

where:

$$V_2 = \sum_{i=1}^{n} \left| R_i - \frac{m+2}{2} \right|$$

For both equations n = 16 and m = 5.

According to Reynolds and others (26) the statistic $V_1{*}$ is sensitive to bias and $V_2{*}$ is sensitive to bias as well as differences in the variance of the real and simulated distributions. Compared to the standard normal distribution, the computed values ($V_1{*}$ = 0.439 and $V_2{*}$ = 1.50) were not large enough to reject the null hypothesis that F(Y | $\underline{X}$)=G(Y | $\underline{X}$). Thus, the model's accuracy and validity appear acceptable.

TABLE 3. — *Cut stand attributes and simulated production rates for eight unique wood utilization options.*

Minimum merchantable					Simulated production	
DBH	Top d.i.b.	No. of trees/acre	Average volume/tree	Total volume/acre	Logger A	Logger B
(in.)	(in.)		(ft.^{3})	(ft.^{3})	(ft.^{3}/hr.)	(ft.^{3}/hr.)
6	4	69.6	22.0	1,531	290	346
7	4	60.1	25.0	1,502	313	366
8	4	50.5	28.2	1,424	340	405
9	4	41.2	32.4	1,335	354	438
10	4	29.8	39.4	1,175	385	480
11	4	24.1	44.8	1,081	362	497
12	4	16.0	57.1	914	400	512
12	10	16.0	42.8	685	358	453

Demonstrated applications

To demonstrate specific applications of GB-SIM, the simulation of harvest unit 4 (Table 1) was conducted applying a series of unique wood utilization alternatives. Minimum merchantable DBH was reduced from 12 to 6 inches in 1-inch increments (Table 3). The 4-inch-top d.i.b. limit represents harvesting pulpwood and sawlogs. The 10-inch-top d.i.b. limit represents a sawlog-only harvest. Decreasing the minimum merchantable DBH increased the number of merchantable trees per acre from 16 at 12-inch DBH, to 69.6 at 6-inch DBH. This also increased merchantable volume per acre, but decreased average tree volume (Table 3). For both loggers, the production rate was highest with a 12-inch-DBH limit and a 4-inch-top d.i.b. This option felled and skidded the same number of trees as the option with a 10-inch-d.i.b. limit, but increased volume per tree by 14.3 $ft.^3$ by utilizing wood with a 4- to 10-inch d.i.b. Reducing the minimum merchantable DBH from 12 to 6 inches reduced the maximum production rate by 28 percent for logger A and 32 percent for logger B.

Conducting simulations with two sets of simulation control variables to represent observed differences between loggers A and B resulted in large differences in estimated production rates. The rate for logger B is 19 percent greater than that estimated for logger A with a 6-inch-DBH limit, and 37 percent greater than the rate estimated for logger A with an 11-inch-DBH limit (Table 3). The differences in simulated production rates reflect important differences between logging operations with respect to observed inventories of felled trees and volume skidded per turn. These differences also demonstrate the importance of applying appropriate simulation control variables to improve the reliability of simulation results and reflect the important differences between logging operations.

Summary

Computer simulation provides an accepted method of conducting systems analyses of timber harvesting operations to obtain information not readily available through conventional time and motion studies. Because simulation only approximates the harvesting process, a high level of precision is not always expected. However, experimenting through simulation can provide considerable insight to potential relationships between system configuration or operating environment and harvesting cash flows — information applicable to subsequent field testing or planning harvesting and forest management activities.

The principal focus in developing GB-SIM was to estimate timber harvesting cost and revenue trends as a function of cut stand attributes when these attributes are determined by forest management decisions or wood utilization alternatives. Statistical validation of GB-SIM with actual production rates and site attributes from 16 harvest units showed little bias in the simulation results. The validation tests also failed to reject the null hypothesis that the distribution of simulation results, conditional upon site attributes, was equal to the distribution of actual production rates. These results indicate that valid inferences regarding the effects of harvest site and system attributes on production rates can be drawn from the simulations conducted with this model.

The precision of simulation results reflected the inherent variability of timber harvesting production. For example, the relatively low numbers of merchantable trees per acre on harvesting units 1 through 6, which often were unevenly distributed over the harvest unit, contributed to the lack of precision. Absolute differences between actual and simulated production rates exceeded 10 percent of the actual rates on 6 of 16 units; 2 units exceeded 15 percent. It is expected that precision can be improved by identifying unique timber stands within larger harvest units and by including skid trail profiles in the simulation process. Including additional site-related variables and operator characteristics may also improve the precision of simulation results.

For the applications demonstrated, differences in operating methods employed by loggers produced large differences in estimated system production rates. The evaluation of several wood utilization alternatives also demonstrated a method of jointly estimating product yields and production rates, which is required information to express cost and revenue as a function of minimum merchantable tree DBH and stem d.i.b., and to define optimal levels of wood utilization.

Continuing research and development will be required to expand future applications of GB-SIM to include additional harvest system configurations and forest types, and to improve the precision of production rate estimates by incorporating additional harvest site attributes in the simulation process. Continued study of harvesting machines and systems will also be required to ensure the validity of the assumptions controlling the simulations and to acquire the machine production and delay time data required to model alternative harvesting activities. Whereas the authors do not expect stochastic simulation models such as GB-SIM to be applied directly by commercial loggers, these research applications can continue to provide valuable information regarding harvesting production and cash flows for the economic analyses of timber harvesting, wood utilization, and forest management alternatives.

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