Comparisons of two methods of harvesting biomass for energy

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Abstract

Two harvesting methods for utilization of understory biomass were tested against a conventional harvesting method to determine relative costs. The conventional harvesting method tested removed all pine 6 inches diameter at breast height (DBH) and larger and hardwood sawlogs as tree length logs. The two intensive harvesting methods were a one-pass and a two-pass method. In the one-pass method, all material 1 inch DBH and larger was simultaneously harvested. Pines 1 to 6 inches DBH and hardwoods 11 inches DBH and less were chipped for energy wood and all other stems were logged tree length. With the two-pass method, the energy wood (same description as in the one-pass) was harvested in a first pass through the stand, and the commercial size wood being removed as tree length logs was harvested in a second pass. The conventional harvesting system recovery averaged 52 percent of the standing biomass while the one-pass and two-pass methods recovery averaged 85 percent and 76 percent of the standing biomass, respectively. The conventional system had an average harvesting cost of $8.75 per green ton onto the log truck while the one-pass and two-pass methods had average costs onto log trucks and chip vans of $7.60 and $8.85 per green ton. Both the one-pass and two-pass methods produced energy chips into vans at a cost which was well below the value of the material as a fuel source at the mill.

Kluender reported that in 1980 the pulp and paper industry depended on fossil fuels for 52 percent of its energy needs (3). It is currently estimated that this industry is using fossil fuels for only 25 percent of its energy needs. This trend of nondependence on fossil fuels will continue in the near future since there is an ample supply of biomass to provide the needed fuel, Most pulp- 'and papermills can obtain energy wood for their boilers from the residues of their manufacturing process and from small sawmills nearby which need outlets to dispose of their residues. Other wood products firms, such as large sawmills, are adapting heavy energy consuming operations, such as kilns, to rely on wood residues as an energy source.

Logging residues have long been acknowledged as a potential source of additional energy wood, but the high costs of harvesting these materials have restricted their use. Machines have been developed for the specific purpose of capturing these residues. Examples of this are Georgia-Pacific's Jaws II machine (7) and the Nickolson-Koch Mobile Chip Harvester (4, 6).

Harvesting crews with portable chippers have also been used to recover the material normally left during harvest. Chipping harvesting crews have produced as much as 90 percent additional material over the cruise of merchantable volume (2). Another advantage of fuel chip harvesting operations is that the better utilization of the resource reduces the cost of preparing the site for the next stand of trees (8).

The objective of this study was to identify ways to reduce site preparation cost by utilizing conventional harvesting equipment to capture logging residues. The study was accomplished in two phases. The first phase quantified the harvesting costs associated with reducing residue during harvest. In this phase, several test blocks were harvested using conventional utilization

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standards and other test blocks were harvested where all material 1 inch diameter at breast height (DBH) or larger was utilized. The second phase assessed the costs of appropriate site preparation methods at the various levels of harvesting residue. The results of the second phase will be reported in a subsequent publication.

Methods

Three tracts were selected for the tests. Two tracts were 22-year-old slash pine (*Pinus elliottii*) plantations that were being clearcut for pulpwood. Both were in southern Alabama but were on different sites. The third tract was a natural slash/loblolly (*Pinus elliottii*/*Pinus taeda*) pine stand in southern Mississippi. In the natural stand the larger mature pines were approximately 45 years old. The understory in the plantations and natural stand consisted of both pine and hardwood. Each tract was divided into three harvesting blocks that were 660 feet wide and 1,320 feet deep. The 20-acre blocks were the same configuration to maintain average skidding distances among the harvesting methods.

A cruise was conducted to determine the standing inventory of each block. Fixed radius 1/10-acre plots were established to sample trees larger than the 3-inch DBH class. In the center of these plots, a 1/200-acre fixed radius subplot was taken to determine the standing woody biomass for all trees in the 1- to 3-inch DBH classes. Destructive sampling was used on the 1/200-acre plots and the total green weight was recorded for each tree. All heights were measured in the subplots and sampled in the plots.

After the block boundaries were well established and the stand information obtained, each block was harvested. Harvesting took place from June to December 1983. Servis recorders were mounted on each machine. Recorder disks were collected daily to obtain the number of productive hours each machine operated on each block. The quantity of fuel used by the feller-bunchers, skidders, chippers, and loaders was also recorded on a daily basis for each test tract. A monitor maintained a record of crew hours for each block. Each truckload was weighed at the mill to determine the amount of harvested material by product.

Harvesting methods

Conventional method

All pine trees 6 inches or greater in DBH and all hardwoods of at least 12 inches DBH were harvested. The harvesting system in the plantations consisted of two feller-bunchers and three skidders (Table 1). A skidder with a directional shear was used to fell and skid trees in the natural stand. Chainsaws were used to fell trees larger than shear capacity in the natural stand. Delimbing and topping were done by chainsaws in the stand or at the deck after the trees had been processed through an iron gate. The tree length material was then skidded to a deck where a hydraulic loader was used to sort and load the tree length as pulpwood or sawlogs. No hardwood pulpwood was recovered.

One-pass method

For all tracts, the one-pass harvesting system utilized three feller-bunchers and two skidders. In the natural stand, a skidder with a directional shear was also used for felling and skidding. The feller-bunchers separated the trees into piles of energy wood and roundwood. All pine trees less than 6 inches DBH and hardwood less than 12 inches DBH in the natural stand were placed into piles of energy wood. The feller-buncher would build piles of energy wood so that each pile would make a full grapple bundle for the skidder.

The energy wood was skidded directly to the chipper. Roundwood was skidded full tree to the deck where two chainsaw operators bucked the tops off to nominal merchantable limits. The bucking point was at the lowest live limb in plantations and at a 4- to 6-inch top diameter near the base of the crown in the natural stand. The chipper boom was used to move the tops and feed the tops into the chipper. All the roundwood was sorted and loaded tree length.

Two-pass method

The two-pass harvesting system used three feller-bunchers and two skidders for the first pass to remove the energy wood. The energy wood was cut first to utilize as much of the biomass as possible instead of having it crushed to the ground as in a first pass by a conventional harvesting operation. With this procedure, it is necessary for the feller-buncher to carefully maneuver around the residual merchantable trees. In an operational situation, the energy wood could be allowed to dry to reduce moisture content. The energy wood was skidded directly to the chipper without being topped. This resulted in a clean stand, ready for the second pass.

After the energy wood had been harvested, a second operation was used to remove the merchantable roundwood. The second-pass system utilized two feller-bunchers and three skidders in the plantation blocks. In the natural stand, the skidder with the directional shear did most of the felling and all of the skidding.

TABLE 1. — *Configuration of harvesting systems.*

	Plantations Tract I & II		Natural Tract III	
Harvesting method	Type of machine	No. of machines	Type of machine	No. of machines
Conventional	Feller-buncher	2	Feller-buncher	–[a]
	Iron gate	1	Chainsaw (W)	1
	Skidder	3	Skidder	1[a]
	Chainsaw (D)	1	Loader	1
	Loader	1		
One-peas	Feller-buncher	3	Feller-buncher	3[b]
	Skidder	2	Skidder	3[c]
	Chainsaw (D)	2	Chainsaw (D)	1
	Chipper	1	Chipper	1
	Loader	1	Loader	1
Two-pass energy wood	Feller-buncher	3	Feller-buncher	3
	Skidder	2	Skidder	2
	Chainsaw (D)	1	Chipper	1
	Chipper	1		
Two-pass roundwood	Feller-buncher	2	Feller-buncher	–[a]
	Iron gate	1	Chainsaw (W)	1
	Skidder	3	Skidder	1[a]
	Chainsaw (D)	1	Loader	1
	Loader	1		

D = Deck W = Woods

[a]Felling was done by directional shear on the skidder which did all the skidding.
[b]The directional shear was used to fell trees too large for feller-bunchers. A chainsaw was used to fell trees too large for the directional shear.
[c]One skidder had a directional shear and was also used for felling.

TABLE — *Plantation and natural stands cruise summary.*

Tract	Block	All 1 to 3 in.	Pine 4 to 5 in.	Pine 6 in.	Hardwood 4 to 11 in.	Hardwood 12 in.	Total
		DBH class (green tons/acre)					
Plantation I	1	14.2	4.9	50.4	9.9	—	79.4
	2	5.4	7.9	68.8	3.0	—	85.1
	3	20.8	10.8	59.3	9.6	—	100.5
Avg.		13.5	7.9	59.5	7.5	—	88.3
Plantation II	1	6.9	12.7	63.9	9.3	—	92.1
	2	7.4	8.3	61.9	7.3	—	84.8
	3	7.0	9.9	57.9	7.5	—	82.0
Avg.		7.1	10.3	61.2	8.0	—	86.3
Natural III	1	25.0	7.0	62.7	11.9	0.0	106.6
	2	22.5	2.5	58.1	22.0	3.3	108.4
	3	23.4	1.2	40.4	16.2	19.8	101.0
Avg.		23.6	3.6	53.7	16.7	7.7	105.3

Chainsaws were used to fell trees too large for the shear, and to delimb and top the trees. An iron gate was used for delimbing in the plantations.

Post-harvest data collection

A post-harvest inventory was taken in a similar manner as the preharvest cruise. Again fixed radius l/lo-acre plots were establishd to inventory standing trees after harvest which were greater than 3 inches DBH. The l/ZOO-acre plots were used to inventory the standing trees in the 1- to 3-inch DBH class and to assess the logging residue. All standing stems in the 1- to 3-inch class and all logging residue were weighed on the l/200-acre plots.

Results

Biomass data

A summary of the total standing preharvest biomass is shown in Table 2. Total tree weight equations were developed during the study for the hardwoods (1). These equations and equations for pines (5) were used to determine the total wood biomass for each block.

In tract I, the pulpwood (trees greater than 5.5 in. DBH) accounted for 67 percent of the total standing woody biomass. Tract II, the other plantation, had 73 percent pulpwood. In the natural stand, tract III, about 58 percent of the total standing biomass was pulpwood and sawlogs.

The blocks in the first plantation, tract I, were not as consistent in stand composition as tract II. To compensate for differences between blocks, harvesting methods were assigned over the range of conditions. Even though there was some variation among the individual stand components of the natural stand blocks, the overall biomass between blocks was relatively consistent on tract III.

A careful examination of the harvested tonnage (Table 3) gives some insight into the various harvesting methods. In all cases the cruised roundwood was the largest component of the total standing biomass. A high percentage of this component was harvested by each method. However, the one-pass method did not recover as much of the total stand as roundwood. In tract II, there was a significant reduction in roundwood harvested. The trend continued for the other one-pass blocks. The tops being sent to the chipper included more of the bole to facilitate feeding the chipper. This partially accounts for the reduction in the roundwood in this system.

TABLE 3. — *Harvested green tons per acre.*

Tract	Block	Harvesting method	Energy wood	Roundwood (sawlogs & pulpwood)	Total	Percent"
			(green tons/acre)			
Plantation I	1	Conventional	—	40.7	40.7	51.3
	2	One-pass	34.4	43.3	77.7	91.3
	3	Two-pass	30.3	48.0	78.3	77.9
Plantation II	1	Conventional	—	60.6	60.6	65.8
	2	One-pass	40.6	35.0	75.6	89.2
	3	Two-pass	29.1	41.0	70.2	85.6
Natural III	1	Conventional		42.5	42.5	39.9
	2	One-pass	35.0	45.9	80.9	74.6
	3	Two-pass	19.8	46.0	65.4	64.8

'Percent of cruised total standing biomass.

TABLE 4. — *Machine and labor rates.*

Function	Machine	Machine rate per operating hour	Labor rate[a] per scheduled hour
		($)	
Felling	Feller-buncher[b]	35.40-55.82	10.00
Trimming	Chainsaw	4.50	8.00
Skidding	Skidders'	33.12-38.11	10.00
Chipping	22-in. chipper	83.03	10.00
Loading	Knuckle-boom	21.94	10.00

"Includes fringe benefits.

[b]Cost depended on the type of feller-buncher used. Models used were Hydro-Ax 411, Caterpillar 910, Hydro-Ax 711, and Timberjack 450 with directional shear.

'Cost depended ***on*** the type of rubber-tired skidder used. Models used were Caterpillar 518, Franklin 175, Timberjacks 350 and 450, and International S8.

Use of trade names and brands is for the convenience of the reader and is not an endorsement by Mississippi State University or the USDA Forest Service.

Harvesting test

As expected, utilization was higher for the one-pass than the other harvesting methods. This was a result of

TABLE 5. -*Harvesting costs by function.*

Tract	Block	Harvest method	Felling	Trimming	Skidding	Chipping	Loading	Total
			($/green ton)					
Plantation I	1	Conventional	3.14	0.48	5.77	—	0.71	10.10
	2	One-pass	2.57	0.57	2.29	1.45	0.51	7.39
		Energy wood	2.85	—	2.23	3.27	—	8.35
		Roundwood	2.36	1.02	2.16	—	0.91	6.45
	3	Two-pass	3.70	0.43	3.44	1.03	0.37	8.97
		Energy wood	6.38	0.51[a]	3.15	2.66	—	12.70
		Roundwood	2.01	0.37	3.62	—	0.60	6.60
Plantation II	1	Conventional	3.65	1.25	3.96	—	1.02	9.88
	2	One-pass	2.81	0.75	2.37	1.48	0.35	7.75
		Energy wood	3.45	—	2.08	2.76	—	8.30
		Roundwood	2.04	1.61	2.70	—	0.76	7.11
	3	Two-pass	3.61	0.51	3.46	0.93	0.38	8.89
		Energy wood	5.91	0.71[a]	3.26	2.24	—	12.11
		Roundwood	1.98	0.37	3.60	—	0.66	6.61
	1	Conventional	—[b]	1.21	4.05	—	0.99	6.25
	2	One-pass	3.18	0.30	2.62	1.32	0.28	7.70
		Energy wood	4.24	—	2.86	3.05	—	10.15
		Roundwood	2.37	0.53	2.44	—	0.50	5.84
	3	Two-pass						8.71
		Energy wood	3.93	—	4.65	4.76	—	13.34
		Roundwood	—[b]	0.91	2.81	—	0.91	4.62

[a]Chainsaw worked as general utility.
[b]Felling was completed with a directional shear on a skidder. The cost of felling with this machine is included with skidding cost. Larger trees were felled with chainsaws, thus the cost of felling these trees was included in trimming cost.

chipping the limbs and tops of the merchantable roundwood in addition to the small diameter trees. There was generally better utilization in the plantation stands than in the natural stand.

Machine and labor cost estimates (Table 4) were used instead of actual costs to develop cost estimates for the various harvesting practices. The machine rates were developed for each specific machine using new replacement costs. Labor rates were assumed to include fringe benefits. These rates were used to develop cost estimates per green ton to roadside for the different harvesting methods. These harvesting costs (Table 5) do not include service equipment, crew transportation, and hauling costs.

Felling costs for the natural stand were included with skidding because one machine performed both functions. Some chainsaw felling cost was included under trimming. In the two-pass method, a chainsaw operator was charged to the energy wood system as a trimming cost even though he did more general utility work.

The costs of producing the roundwood and energy wood products were calculated for each tract. For the one-pass tests this was accomplished by using a time study to determine the amount of time the feller-bunchers and skidders spent harvesting the energy wood and roundwood. For the two-pass system, the cost per function for all products was accurately developed from time records since each pass was conducted at different times. Having the skidder with a directional shear accomplish both the felling and skidding made it impossible to reconstruct the cost for the felling and skidding functions for the second pass in the natural stand.

To test for statistical differences in these costs, an analysis of variance was performed on the total, felling, and skidding costs. The following treatments were in-

TABLE 6. -Analysis *of variance of the cost per ton data.*

Source	d.f.[a]	Mean square error	F statistic	Significance[b]
Total cost				
All treatments	5	18.91	25.46	S
Single degree of freedom tests				
Energy wood (one- and two-pass) versus roundwood (one- and two-pass)	1	51.30	69.08	S
Energy wood one-pass versus energy wood two-pass	1	21.47	28.91	S
Conventional versus roundwood (one- and two-pass)	1	19.33	26.03	S
Roundwood one-pass versus roundwood two-pass	1	0.41	0.55	NS
Natural versus plantation	1	2.03	2.97	NS
Error	10	0.74		
Felling cost				
All treatments	4	5.35	24.55	S
Single degree of freedom tests				
Energy wood (one-pass) versus other methods	1	19.16	87.98	S
Conventional versus roundwood (one- and two-pass)	1	0.71	3.24	NS
Roundwood one-pass versus roundwood two-pass	1	0.042	0.19	NS
Energy one-pass versus roundwood (one- and two-pass)	1	1.50	5.50	NS
Error	5	0.22		
Skidding cost				
All treatments	4	1.96	3.08	NS
Error	5	0.64		

[a]d.f. = degrees of freedom.
[b]S = Significant at the .01 level; NS = Not significant.

TABLE 7. -Fuel consumed by function.

Tract	Block	Harvest method	Felling	Skidding	Chipping[a]	Loading[a]	Total
			(gallons/green ton)				
Plantation I	1	Conventional			0.26	0.04	0.46
	2	One-pass	0.19	0.22	0.50	0.06	0.66
	3	Two-pass					
		Energy wood	0.48	0.26	0.47	—	1.21
		Pulpwood	0.14	0.18	—	0.03	0.34
Plantation II	1	Conventional	0.15	0.25	—	0.04	0.43
	2	one-pass	0.20	0.19	0.42	0.052	0.64
	3	Two-pass					
		Energy wood	0.41	0.25	0.38	—	1.04
		Pulpwood	0.17	0.23	—	0.03	0.42
Natural III	1	Conventional	0.45		—	0.05	0.49
	2	One-pass	0.49		0.70	0.03	0.81
	3	Two-pass					
		Energy wood	0.94	0.35	0.55	—	1.84
		Roundwood	0.29		—	0.04	0.31

[a]Chipping and loading fuel consumption is based on only the tons chipped or loaded.

cluded in the analysis: 1) conventional, 2) one-pass energy wood, 3) one-pass roundwood, 4) two-pass energy wood, and 5) two-pass roundwood, The effect of differences in costs between plantations and natural stands was tested for the total cost only, since the skidding and felling costs could not be separated in some natural stand tests. The 'resulting analyses of variance are shown in Table 6.

Comparison of costs for the different functions by harvesting methods gave some interesting results. In the two-pass system, the felling costs for the energy wood were significantly higher. The reason for this was that only the small diameter trees were felled and the feller-bunchers had to maneuver extensively between the merchantable trees. Once the stand had been cleaned, the felling productivity for the second pass was high and resulted in a lower felling cost. There were no significant differences in skidding costs among the treatments in the plantations. This is a very important result because it demonstrates that skidding costs do not change by stem size if the feller-bunchers can build full-capacity loads for the skidders. The industrial co-operator in this study has been producing energy wood at a competitive cost with the two-pass system. However, this study shows that the one-pass method is the most cost-efficient method of harvesting the stands. The one-pass method produced energy wood at a significantly lower total cost than the two-pass method. The total cost of producing roundwood was not significantly different for the one-pass and two-pass methods. However, both the one- and two-pass methods produced roundwood at a significantly lower total cost than did the conventional method (Table 5).

Some problems with the one-pass system could be overcome through management. Higher chipping costs were associated with the one-pass method as compared to the two-pass method. This is directly related to chipper utilization. During the process of removing the tops at the deck from the merchantable trees, the interaction of the skidders, buckers, loader, and chipper caused delays and affected chipper production. More refinement in the harvesting system components and methods might eliminate some delays and decrease

TABLE 8. -Analyses of variance for the fuel consumption data

Source	d.f.[a]	Mean square error	F statistic	Significance[b]
Total fuel consumed				
All	4	0.49	13.51	S
Single degree of freedom tests				
Conventional and roundwood versus one-pass and energy wood	1	1.17	32.28	S
Conventional versus roundwood (one-pass versus two-pass)	1	0.02	.44	NS
One-pass versus energy wood	1	0.65	17.96	S
Natural versus plantation	1	0.12	3.40	NS
Error	7	0.03		
Fuel consumed in felling				
All	3	0.040	54.92	S
Single degree of freedom tests				
Energy wood versus other methods	1	0.12	160.68	S
One-pass versus conventional and roundwood	1	0.003	3.99	NS
Conventional versus roundwood	1	0.000006	0.01	NS
Error	4	0.0007		
Fuel consumed in skidding				
All	3	0.002	4.17	NS
Error	4	0.0005		

[a]d.f. = degrees of freedom.
[b]S = Significant at the .01 level; NS = Not significant

chipping costs. The ratio of products going to the deck also affected balanced production. This may restrict the one-pass effectiveness in some stand types because of lower utilization of the chipper.

Fuel consumption

The fuel required to process 1 ton of material is summarized in Table 7. One-way analyses of variance were run on the total fuel required to move 1 ton of wood to the deck, the amount of fuel to fell 1 ton of material, and the amount of fuel to skid the material to the deck. The single degree sources of error are shown for each of these tests in Table 8. Again the skidding and felling analyses did not include the natural stand results. In the analysis of the fuel data, the one-pass treatment was not separated into products. The data that were collected did not support this refinement of the analysis.

The tests showed that the chippers required significantly more total fuel to process the material. There was no difference in total fuel required to process a ton of wood in the conventional operations and the second pass of the two-pass operations. Significantly more fuel was required to fell the energy wood than was required for felling in any of the other tests on a unit of product basis. There were no significant differences in fuel consumed per ton for felling in any of the other tests. There were no significant differences among the various tests for the fuel required to skid **1** ton of wood.

Post-harvest study

The differences in harvesting residue on the tracts following the various harvest treatments are shown in Table 9. The one-pass plantation blocks look as though they had been mechanically site prepared after harvest. The two-pass blocks looked as clean since the trees were delimbed with delimbing gates and the tops were placed in large piles. (One pile on tract I was estimated as having 24 green tons of tops in the pile.) The conventional harvest treatment left significantly more material to be handled during site preparation than did either intensive harvest treatment. However, the intensive harvest methods were not as successful in recovering biomass in the natural stands as they were in the plantations. This is probably due to the wet ground conditions in the natural stand. More complete recovery could probably be expected in upland natural stands with the intensive harvesting methods.

Conclusions

This study demonstrated that conventional equipment and systems can be used to economically harvest more of the total woody biomass. The one-pass method resulted in better utilization and lowest costs among the harvesting alternatives considered in these stand types. The one-pass method does have opportunities for refinement since some component costs are higher than in the two-pass and the biomass is usually delivered at a higher moisture content than with the two-pass method.

This study also demonstrates that skidders afford an economically viable way of moving biomass for energy when this energy material can be accumulated in large bundles for grapple skidders. Felling costs were highest for the energy material; thus, felling systems offer the greatest opportunity for improvement in energy wood harvesting systems.

More information is needed on harvesting the energy wood components of different stands and stand compositions. Studies are needed to identify the optimal equipment mix and to refine the operation of the one-pass method. Also these energy wood harvesting methods should be evaluated over **a** range of stand conditions and levels of biomass.

TABLE *for the various blocks.*

Tract	Harvest method	Residue on ground	Standing residue	Volume in top piles	Total residue
		(green tons/acre)			
Plantation I	Conventional	15.3	3.7	—	19.0
	One-pass	5.6	—		5.6
	Two-pass	3.4	—	2.4	6.9
Plantation II	Conventional	17.2	6.6	—	23.8
	One-pass	3.4			3.4
	Two-pass	3.3	—	a	3.3
Natural III	Conventional	28.62	12.5	—	41.2
	One-pass	11.9	—	—	11.9
	Two-pass.	15.8	—	a	15.8

“Piles of tops were not estimated but were present.

Note that the preharvest estimates of standing biomass do not equal the amounts harvested plus the estimates of the residual biomass on the test blocks. (Table 2 values do not equal the values in Table 3 plus Table 9 values.)

Most likely, either the sampling or volume estimation techniques used to obtain the values in Table 2 are inaccurate. Further research is needed to identify accurate methods for estimating understory biomass.

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