Wildfire fuel harvesting and resultant biomass utilization using a cut-to-length/small chipper system

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Abstract

Currently, there is a lack of information concerning mechanical forest fuel reduction. This study examined and measured the feasibility of ground-based mechanical harvesting to reduce forest fuel buildup and produce energywood. Cut-to-length (CTL) harvesting coupled with a small in-woods chipper provided a low impact way to harvest pre-commercial trees and tops along with merchantable logs. While CTL harvesting systems have been used successfully with full-sized chippers, it requires two or three CTL teams to meet volume requirements. A smaller, less expensive chipper allowed operations to stay small and more efficient. Productivity and cost results showed the system to be capable of harvesting non-merchantable trees and utilizing non-merchantable portions of merchantable-sized trees as energywood chips, which in the past have been normally left in the woods unutilized. The gain from the value of energywood chips and merchandized logs makes the system economically attractive, not to mention the fuel reduction gains received by potentially altering future fire behavior.

Recent wildfires in the western United States have destroyed billions of dollars of valuable timber and property (National Fire Plan 2001). For many reasons, including fire exclusion, forests that were once relatively open have become dense with trees and understory brush (Hollenstein et al. 2001). Forest fuel loads in the United States have accumulated due to factors including increased fire suppression, reduced prescribed burning, and a reduction in active forest management. The number and size of large, intense fires have grown over the last decade, resulting in higher fire suppression and preparedness costs, and greater damage to the forest resource, both public and private (Anon. 1999). The suppression and stand-replacement costs from these fires could prove to be more expensive than many fuel reduction methods.

Fuel reduction is not an easy operation to execute. Traditionally, forest fuels have been reduced by prescribed fire, but this reduction method is becoming a tool of the past due to increased liability concerns and state and federal regulations associated with smoke management. Manual removal of understory vegetation is another method of forest fuel reduction. The method has been ineffective due to the intensive labor requirements and the small area that can be treated in a given time. Also, without the protection of a machine cab, workers are directly exposed to the hazards associated with timber harvesting; therefore, safety is a major concern in manual reduction treatments. Although, manual operations have downfalls, they benefit from low capital cost which allows greater flexibility which could be beneficial for small landowners or treatment of sensitive and/or urban areas.

The use of commercial thinning in dense stands, either natural or plantations, for fuel reduction can also be difficult and expensive within current merchantability standards that often do not include the potential for economically utilizing small trees (Karsky 1992). Thinning of a stand for fuel reduction where most stems are of non-merchantable size is expensive for any

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harvesting method due to low production, and therefore, high cost of wood produced. Some mechanical systems exist but few have cost and productivity numbers assigned to them. This study examined the feasibility of using low-impact mechanical harvesting to reduce fuel loads and produce an alternative energy source.

In-woods chipping of non-merchantable stems could be a way to recover biomass that has normally been left on the site. In addition, this method may produce a monetary gain through the sale of energywood chips. "U.S. wood energy use has increased steadily since 1972 and is projected to continue to increase" (Kutscha 1999). This increase is partially due to the fact that more industries, including forest products, are beginning to utilize the energy contained in woody biomass. The possibility of utilizing woody biomass for energy has great potential throughout the Nation.

In most cases, reducing forest fuel loads requires a precommercial thinning treatment. Traditional tree-length operations have difficulty extracting small material partially due to small skidding or yarding payloads. These operations also require considerable traffic throughout the stand causing more soil compaction and possible residual stand damage. The high production produced with tree-length operations requires the use of large, industrial whole-tree chippers. Large chippers with a tree diameter capacity of 22 inches or greater and self contained loaders are expensive ($300,000+) and require large tracts of timber due to high setup and moving costs.

A possible alternative equipment configuration would combine a cut-to-length (CTL) harvesting system with a smaller chipper. A feasibility study (Bolding and Lanford 2001) using a small chipper/CTL harvesting system for forest fuel reduction and energywood production showed that the system was promising. CTL systems have been recognized for their low environmental impact and high utilization of merchantable material (Vidrine et al. 1999, Hartsough et al. 1997, Holtzscher and Lanford 1997, Lanford and Stokes 1995). CTL operations differ from typical tree-length systems because trees are delimbed and bucked into log lengths at the stump, leaving limbs and tops evenly distributed throughout the tract (Stokes 1988). This provides a cushion for the harvester and forwarder to travel on while performing their operations in the woods, which in turn reduces soil compaction (Seixas et al. 1995). In CTL operations, the two-machine system, a harvester and a forwarder, balance to give an efficient operation for smaller tracts. However, CTL systems with only a single harvester and forwarder do not match well with large chippers traditionally used with in-woods chipping operations. Large chippers require more wood input, to operate productively, than a single CTL team can provide. A smaller, less expensive chipper might have reasonable ownership and operating cost and allow operations to stay small, efficient, and possibly profitable. This system should be able to reduce stocking and remove biomass normally left after most harvesting operations such as limbs and tops from felled merchantable trees as well as small stagnant understory trees. With this approach, previously non-merchantable stems should become merchantable as energywood. In overstocked, even-aged stands and multi-storied stands alike, reduction in the number of trees per acre will open the forest canopy releasing the better trees to grow in value.

Methods

This study was conducted in September 2001, near Fayette, Alabama, on a stand that represented a potential fire hazard. The stand consisted of approximately 10 acres of mature overstory comprised of merchantable loblolly pine and hardwood with a dense non-merchantable hardwood understory. Stand conditions were typical to similar sites in west central Alabama that have been periodically thinned, or in some cases high-graded, to remove large overstory trees and allow natural regeneration to re-stock the stand. These practices often result in stands similar to the one in this study where hardwood trees regenerate and become stagnant in the understory. An observation of the rings of several hardwoods (4 to 5 in. in diameter at breast height [DBH] and 12 to 15 ft. tall) indicated that the stagnant trees were 40 to 60 years old. Results from this study should provide information useful for forest managers to make decisions about equipment selection for mechanical forest fuel reduction treatments in stands similar to the one observed in this study. Also, baseline information concerning the feasibility of using CTL systems combined with small chippers should be applicable for most stands characterized by large mature overstories and densely stocked understories.

A logging contractor with a CTL operation and approximately one month of experience cutting small non-merchantable hardwood was selected. Bandit Industries, Inc.[1] provided a small chipper and portable axle scales were rented to perform the tests. Equipment manufacturers and details were:

Harvester – The Timbco T-415C with an 18-inch series 2000 four roller Fabtek head is a 200-hp tracked harvester with double grouser tracks. The harvester weighs 42,000 pounds and applies 6.5 psi of ground pressure. Its boom can reach 21.5 feet.

Forwarder – The Fabtek 546B is a six-wheeled machine with a 22.7-foot loader reach, weighing 32,500 pounds. The forwarder has a load capacity of 30,000 pounds.

Chipper – The Bandit 1850 portable chipper has an 18-inch diameter capacity with a 250-hp Cummins diesel engine and weighs 12,000 pounds. The chipper also has a moving conveyer deck to aid feed speed. It has two 20-inch-long horizontal feeds wheels with a rated feed capacity of 95 feet per minute (fpm). The chipper cutting wheel has a 55-inch diameter disc with two full knife pockets. The infeed hopper opening is 33.75 inches in height and 64 inches in width.

Axle scales – The Intercomp 2 has two 30,000-pound capacity 7- by 3.5-foot weigh pads with a Toledo Lynx Scale Indicator.

Field procedures and analysis

The harvester moved throughout the stand harvesting all non-merchantable trees (between 0.5 and 4 in DBH). Merchantable trees (greater than or equal to 4 in DBH) were thinned to a residual basal area of 60 ft^2 per acre. Time elements for each work cycle included move to next group of trees, swing-to-tree, felling, and processing. Processing of non-merchantable trees included only piling with no delimbing.

[1] The use of brand or model names is for reader convenience only and does not represent an endorsement by the authors, Auburn University, Oregon State University, or the USDA Forest Service.

Processing of merchantable trees included mechanical delimbing and bucking. Merchantable portions were processed into 20-foot log lengths. The harvester piled non-merchantable trees along with limbs and tops from merchantable trees separate from merchantable stems. The brush material was then picked up by the forwarder. The harvester was videotaped cutting individual trees in six, 1-chain by 1-chain study plots (0.1 acres each). All trees on the six plots were measured for DBH, total height, and species. Small tree weight equations (Clark et al. 1986, Clark and Saucier 1990) were used to determine per acre total biomass. Harvester productivity studies, based on the videotape, measured and modeled the effects of the range of tree sizes.

Descriptive statistics (**Table 1**) were summarized for each variable associated with harvester productivity. During harvester studies, 352 trees were harvested on six study plots. **Table 2** shows stand density statistics for pre-harvest, harvested, and residual trees. Pre-harvest totals came from a 100 percent tree tally on each of the six 0.1-acre study plots. The harvester's boom reach was 21 feet 5 inches; therefore, the machine could reach a total area of 42 feet 10 inches in width, which equates to a plot size of 42 feet 10 inches by 66 feet (1-chain) in length or 0.065 acres. This plot size was used to calculate per acre values for the harvested portion.

The forwarder moved through cutting corridors, developed as the harvester bunched and piled harvested material on both sides of the machine. The forwarder loaded and transported non-merchantable harvested material to the chipper. Log lengths were forwarded separately to setout trailers and were not studied. After forwarding non-merchantable material to the landing, the forwarder fed its load into the small chipper (**Fig. 1**). Each forwarder load represented one cycle or observation. Each cycle was videotaped to recover the time elements and number of loading stops.

Weight of forwarded non-merchantable material was determined with the portable axle scale. Upon arrival at the landing, the loaded forwarder was weighed. After feeding its load into the small chipper, the empty forwarder was weighed again. The difference between loaded and empty weights equaled the weight of non-merchantable material forwarded. This weight, along with time studies, was used to determine forwarder productivity. Time studies were recorded on the loading and transport of 16 forwarder loads of non-merchantable material. Forwarder time studies also recorded the unloading and feeding of 15 forwarder loads of non-merchantable material into the chipper.

For this study, two forwarder operators were used. Due to the absence of the primary operator, a less experienced operator was used for 25 percent of the observations. The more experienced operator had approximately one month of experience forwarding non-merchantable material prior to this study while the less experienced operator had about two weeks of experience. An operator time experience variable consisting of the total time accumulated performing the treatment for each operator, during this study, was analyzed as an independent variable for predicting all dependents associated with the forwarder. Variation between operators was also analyzed by using an operator dummy variable.

The portable chipper was positioned on the landing so that its out-feed spout could access either of two chip vans. Upon arrival of the forwarder with a full load of non-merchantable material, the chipper's engine was started (engine was shut off between chipping cycles) and prepared to chip. Each forwarder load represented one chipper work cycle. Time elements for each cycle included chipping, waiting-on-forwarder, jam-clearing, and total cycle times. Each chipping cycle was videotaped to recover the time elements, number of waiting-on-forwarder observations, and number of jam-clearing observations. Waiting-on-forwarder observations were recorded when

Table 1. — Harvester analysis descriptive statistics.

		Mean	SD[a]	Min.	Max.
Dependent variables (min/tree)[b]					
	Move time	0.03	0.04	0.000	0.35
	Swing time	0.05	0.04	0.005	0.32
	Fell time	0.04	0.02	0.005	0.15
	Process tune	0.08	0.09	0.000	0.90
	Total productive time	0.20	0.13	0.033	1.16
Independent variables					
Tree size[b]	DBH (in) (all trees)	3.0	2.2	1	13
	Total height (ft) (all trees)	26	16	10	80
Terrain[c]	Slope (%)	10	3	6	16

[a] SD = standard deviation.
[b] Number of observations = 352.
[c] Number of observations = 6.

Table 2. — Harvester analysis stand density [a] (per acre) and biomass statistics.

	Preharvest[b]	Harvested[c]	Residual
All trees			
Total tons	155.15	58.69	96.46
Non-merchantable tons[d]	35.63	17.69	17.94
Merchantable tons[e]	119.52	41.01	78.51
Total trees	1,232	903	329
Non-merchantable trees[d]	873	666	207
Merchantable trees[e]	358	236	122
Pine			
Total tons	97.98	27.21	70.77
Non-merchantable tons[d]	15.18	4.26	10.92
Merchantable tons[e]	82.80	22.94	59.86
Total trees	147	85	62
Non-merchantable trees[d]	0	0	0
Merchantable trees[e]	147	85	62
Hardwood			
Total tons	57.16	31.48	25.68
Non-merchantable tons[d]	20.44	13.41	7.03
Merchantable tons[e]	36.72	18.06	18.66
Total trees	1,085	818	267
Non-merchantable trees[d]	873	667	207
Merchantable trees[e]	212	152	60

[a] Number of observations = 6.
[b] Plot size = 0.1 acres.
[c] Plot size = 0.065 acres.
[d] Trees < 4 inches DBH.
[e] Trees ≥ 4 inches DBH.

Figure 1. — Forwarder feeding non-merchantable stems to the small chipper with its on-board loader.

the chipper was idle with no material to process because the forwarder could not feed material fast enough. Chipper jam-clearing observations were recorded when the chipper was idle due to non-merchantable material being jammed in the chipper. Time studies were recorded on the chipping of 14 forwarder loads of non-merchantable material.

As discussed for forwarding, two forwarder operators were used for feeding the chipper. The less experienced operator chipped four forwarder loads (28% of the observations). As in the forwarder analysis, a time experience variable for each operator was analyzed as an independent for predicting all dependents associated with the chipper. Variation between operators was also analyzed by using an operator dummy variable.

Cost analysis

Costs of the CTL/small chipper system were analyzed using the Auburn Harvesting Analyzer (AHA) spreadsheet model (Tufts et al. 1985). Two spreadsheets, one for the non-merchantable portion and one for the merchantable portion, were constructed. Costs were analyzed separately in order to determine the percentage of yearly contribution for harvesting each portion. Specific assumptions used in each model are outlined by Bolding (2002) and in **Tables 3 and 4**. Formulas used to calculate the percentage of yearly contribution for each model are as follows:

$$NM\% = \frac{NM\ system\,rate^{-1} \times NM\ tons/acre}{(NM\ system\,rate^{-1} \times NM\ tons/acre) + (Merch\ system\,rate^{-1} \times Merch\ tons/acre)}$$

$$Merch\% = \frac{Merch\ system\,rate^{-1} \times Merch\ tons/acre}{(NM\ system\,rate^{-1} \times NM\ tons/acre) + (Merch\ system\,rate^{-1} \times Merch\ tons/acre)}$$

where:

NM = the non-merchantable portion,

Merch = the merchantable portion, and

System rate = tons per scheduled machine hour of the least productive function.

Table 3. — Auburn Harvesting Analyzer input assumptions for the non-merchantable portion.

General information			
Hours/day	9		
Days/week	5		
Weeks/year	50		
Tract size	10 acres		
Move-to-tract	4 hours		
Move rate	$2.75/mile		
Move distance	110 miles		
Distance home	5 miles		
Support			
Pickups	1 @ $0.45/mile		
Foreman	$2,500/month		
Overhead	$2,000/month		
Machine productivity[a]			
Harvester[b]			
Total productive time (min)	[0.1123 – (0.083 × DBH) + (3.824 × DBH × TPA$^{(-0.5)}$)]		
Forwarder[c]			
Number of landings	1		
Tons/cycle	5.17		
Stops/cycle	13.94		
Travel empty distance	1,654.06 feet		
Travel-while-loading distance	539.75 feet		
Travel loaded distance	1,574.06 feet		
Travel empty time (min)	0.0028 × TE DIST		
Travel-while-loading-time (min)	0.0087 × TWL DIST		
Travel loaded time (min)	0.0028 × TL DIST		
Loading time (min)	[5.3186 + (0.7320 × # of STOPS)]		
Feeding time (min)	0.0010 × WT		
Waiting-on-chipper (min)	0.0005 × WT		
Cleanup-around chipper (min)	0.509		
Chipper[d]			
Tons/cycle	5.17		
Chipping (min)	2.4186 × WT		
Waiting-on-forwarder (min)	1.25		
Jam-clearing (min)	1.5		
Total cycle time (min)	2.9648 × WT		
Hauling			
Haul distance	94 miles		
Average speed	45 miles/hour		
Load size	22 tons		
Unload time	30 minutes		
Machine cost			
	Harvester	Forwarder	Chipper
Initial cost ($)	193,016	168,000	69,500
Pay life[e] (yr)	5	4	5
Insurance & taxes[e] (% of initial)	0.035	0.04	0.02
Fuel and lubrication[e] ($/PMH)	10.44	7.65	11.31
Maintenance and repair[e] ($/PMH)	18.23	22.97	6.59
Labor ($/SMH)	15	15	0
Labor overhead (%)	30	30	0
Availability (%)	85	85	70
% of work day	100	100	100
Number of machines	1	1	1

[a] Production equations were generated during productivity analysis.
[b] DBH = 4.5 ft; TPA = total trees per acre.
[c] TE DIST = Travel empty distance; TWL DIST = Travel while loading distance; TL DIST = Travel loaded distance; # of STOPS = Number of stops per turn; WT = Weight of forwarded material per turn (lb).
[d] WT = Weight chipped per load (tons).
[e] Brinker et al. 2002.

Table 4. — Auburn Harvesting Analyzer input assumptions for the merchantable portion.

General Information		
Hours/day	9	
Days/week	5	
Weeks/year	50	
Tract size	10 acres	
Move-to-tract	4 hours	
Move rate	$2.75/mile	
Move distance	110 miles	
Distance home	5 miles	
Support		
Pickups	1 @ $0.45/mile	
Foreman	$2,500/month	
Overhead	$2,000/month	
Machine productivity		
Harvester[a]		
Total productive time (min)	$0.0539 \times$ DBH	
Forwarder[b]		
Number of landings	1	
Pounds/cord	5,350	
Forwarding distance	1,614.06 feet	
Load size	15 tons	
Cords/stop[c]	[(0.0126 × CDS AC) + (1.0750 × CDS AC / Merch TPA)]	
Travel empty and loaded (min)[d]	[2 × (5.4600 + 0.0013 × (FOR DIST-1500))]	
Woods travel (min)[e]	[(CDS CYCLE / CDS STOP) – 1) × 0.0480 + (0.0061 × WDS DIST) – (0.00000168 × WDS DIST^2)]	
Load and unload (min)	[(CDS CYCLE / CDS STOP) × (0.2430 + 2.4740 × CDS STOP) + (0.2430 + 2.4740 × CDS CYCLE)]	
Hauling		
Haul distance	70 miles	
Average speed	45 miles/hour	
Load size	26.75 tons	
Load time	5 minutes	
Unload time	30 minutes	
Machine Cost		
	Harvester	Forwarder
Initial cost ($)	193,016	168,000
Pay life[f] (yr)	5	4
Insurance and taxes[f] (% of initial)	0.035	0.04
Fuel and lubrication[f] ($/PMH)	10.44	7.65
Maintenance and repair[f] ($/PMH)	18.23	22.97
Labor ($/SMH)	15	15
Labor overhead (%)	30	30
Availability (%)	85	85
% of work day	100	100
Number of machines	1	1

[a] Production equation was generated during productivity analysis, DBH = 4.5 ft.
[b] Production equations are from Lanford et al. (in review).
[c] CDS AC = Total cords per acre; Merch TPA = Merchantable trees per acre (DBH ≥ 4 in).
[d] FOR DIST = Forwarding distance (ft).
[e] CDS CYCLE = Cords per cycle; CDS STOP = Cords loaded per stop; WDS DIST = Distance between stops (ft).
[f] Brinker et al. 2002.

Figure 2. — After harvest photo showing few non-merchantable stems remaining. The majority of the remaining stems were in the 1-inch DBH class.

Results

Harvester productivity

Table 2 shows that 207 non-merchantable and 122 merchantable trees per acre remained following the harvest. Residual trees were not actually measured after the harvest. These numbers are the difference in pre-harvest and harvested trees. The existence of residual non-merchantable trees is explained by the fact that the harvester could not effectively handle some of the smallest trees. The majority of residual non-merchantable trees were in the 1-inch DBH class. The value for residual non-merchantable trees is also higher than actual because the harvester ran over some of the very small trees that were not actually observed as being harvested. **Table 2** also shows harvested and residual non-merchantable green tons per acre to be 17.69 and 17.94, respectively. This seems to indicate that only approximately one-half of the non-merchantable tonnage was removed. This is untrue due to the fact that the non-merchantable tonnage values consist of not only small trees, but also limbs and tops from merchantable trees. The residual merchantable trees were larger and contained more volume in their limbs and tops than those harvested. After visually examining the study site, few non-merchantable trees remained standing after the harvest (**Fig. 2**).

Total productive time per tree was defined as the sum of the harvester's productive time elements that included move, swing, fell, and process times. All independent variables and combinations with their cross products were initially analyzed. This procedure indicated a strong significant difference between the total productive time of non-merchantable and merchantable trees. The significance led to splitting the data into two sets. Therefore, regression models were formulated separately for non-merchantable trees and merchantable trees. All statistical analysis for this study was evaluated at the $\alpha = 0.05$ level.

Two hundred and sixty non-merchantable hardwood trees were harvested (there were no non-merchantable pine trees in the study). The best model for predicting the total productive time of these trees included the independent variables of DBH in inches and the square root inverse transformation of total trees per acre (merchantable and non-merchantable) ($TPA^{-0.5}$) (TPASQIN). The cross product of these two terms was also significant, (DBH × TPASQIN). TPASQIN was no longer significant after including the cross product in the model. The addition of DBH^2, total height, and slope were also non-significant after including DBH.

Total productive time (min) per tree for non-merchantable hardwoods:

$$= 0.11 - 0.08 \times DBH + 3.82 \times DBH \times TPASQIN$$
$$r^2 = 0.15, \text{F-ratio} = 22.87, S_{y.x} = 0.067, p\text{-value} < 0.0001 \quad \textbf{[1]}$$

Ninety-two merchantable trees were harvested consisting of 33 pine and 59 hardwood. The best model for predicting the total productive time of these trees included the independent variable of DBH in inches. The addition of DBH^2, total height, trees per acre, species variation, and slope was non-significant after including DBH in the model. The intercept variable was also non-significant after including DBH; therefore, it was removed. For models without an intercept, the r^2 value is not corrected for the mean and is no longer comparable to corrected r^2. Fit parameters are reported for the same model including intercept.

Total productive time (min) per tree for merchantable pine and hardwood:

$$= 0.05 \times DBH$$
$$r^2 = 0.51, \text{F-ratio} = 94.63, S_{y.x} = 0.120, p\text{-value} < 0.0001 \text{ (including intercept)} \quad \textbf{[2]}$$

Table 5. — Forwarder analysis descriptive statistics.

	Count	Mean	SD[a]	Min.	Max.
Dependent variables (min/load)					
Moving					
Travel empty	16	4.7	1.3	1.9	8.0
Travel-while-loading	16	4.8	2.7	1.4	10.5
Travel loaded	16	4.5	1.2	2.4	6.4
Stationary					
Loading	16	16.5	4.5	10.1	27.0
Feeding	15	10.8	2.1	7.3	15.0
Waiting-on-chipper	15	4.6	2.6	0.8	9.9
Cleanup-around chipper	15	0.5	0.2	0.2	0.8
Total time	15	46.4	8.7	34.1	70.1
Independent variables					
Travel empty distance (ft)	16	1,654.1	414.3	478	2,190
Travel-while-loading distance (ft.)	16	539.8	302.3	88	1,052
Travel loaded distance (ft)	16	1,574.1	382.0	997	2,047
Number of stops	16	13.9	4.5	5	21
Operator time experience[b] (hr)	13	4.3	2.7	0	8.2
Operator time experience[c] (hr)	4	1.1	1.1	0	2.5
Weight (lb) per turn	15	10,365.3	1,747.3	7,600	13,260

[a] SD = standard deviation.
[b] Operator 1 (more experienced).
[c] Operator 2 (less experienced).

Forwarder productivity

Descriptive statistics (**Table 5**) were summarized for each variable associated with forwarder productivity. Loading time per load was defined as the total time it took the forwarder to fill its bunk with non-merchantable material during machine stops. Loading time was recorded when the machine's tires were stopped and its boom was in use loading material. The best model for estimating loading time per load included the independent variables of number of loading stops per turn, a dummy variable to account for operator variation (OPER DUMB), and their cross product (OPER DUMB × # of STOPS). Weight of forwarded material, operator time experience, and OPER DUMB were non-significant after including # of STOPS and OPER DUMB × # of STOPS in the model. To use the model, OPER DUMB should be a zero for an experienced operator and a one for a less experienced operator.

Loading time (min) per load:

$$= 5.3 + 0.2 \times \text{OPER DUMB} \times \text{\# of STOPS} + 0.7 \times \text{\# of STOPS}$$
$$r^2 = 0.87, \text{F-ratio} = 42.54, S_{y.x} = 1.764, p\text{-value} < 0.0001 \quad \textbf{[3]}$$

Feeding time per load was defined as the time it took the forwarder to unload and feed its load of non-merchantable material into the small chipper. Feeding time was recorded when the forwarder's boom was in motion. Motion included grappling material on its load, swinging to the chipper, placing material on the chipper bed, and swinging back to the forwarder for another grapple load. The best model for estimating feeding time per load included only the independent variable of weight (WT) (lb) of material forwarded. Operator time experience and the operator dummy variable were non-significant after including load weight in the model. The intercept was also non-significant; therefore, it was not included.

Feeding time (min) per load:

$$= 0.001 \times WT$$
$$r^2 = 0.30, \text{F-ratio} = 5.25, S_{y.x} = 1.901, p\text{-value} = 0.0408 \text{ (including intercept)} \quad \textbf{[4]}$$

Chipper productivity

Descriptive statistics (**Table 6**) were calculated for each variable associated with chipper productivity. During chipper cycles, 14 forwarder loads of non-merchantable material were observed. Total cycle time per load was defined as the sum of the chipper's time elements that included chipping, waiting-on-forwarder, and jam-clearing times. The best model for estimating total cycle time included the independent variable of weight (lb) per forwarder load chipped (WT). Operator time experience and the operator dummy variable were non-significant after including WT in the model. The intercept was also non-significant; therefore, it was removed.

Total cycle time (min) per load:

$$= 0.0015 \times WT$$
$$r^2 = 0.63, \text{F-ratio} = 20.55, S_{y.x} = 2.466, p\text{-value} = 0.0007 \text{ (including intercept)} \quad [5]$$

Harvesting system costs

Costs for the CTL/small chipper operation were analyzed in two parts. AHA (Tufts et al. 1985) spreadsheet models were formulated for estimating the productivity and cost of 1) harvesting only the non-merchantable portion of the stand, and 2) harvesting only the merchantable portion of the stand. This approach was taken in order to understand the effects of harvesting non-merchantable material on an operation that was also removing merchantable material and follows the assumptions used by Bolding and Lanford (2001). Harvesting only the non-merchantable portion consisted of 55 percent of the total yearly scheduled hours if stands similar to that of the study site were harvested for an entire year; therefore, fixed costs of the total system were proportioned by the same percentage. The same procedure was used for harvesting only the merchantable portion, which made up 45 percent of the total yearly scheduled hours. The costs for harvesting each portion are shown in **Figure 3**.

Table 6. — Chipper analysis descriptive statistics.

	Count	Mean	SD[a]	Min.	Max.
Dependent variables (min/load)					
Chipping time	14	12.5	2.6	7.2	17.9
Waiting-on-forwarder time	14	1.2	0.8	0	2.4
Jam-clearing time	14	1.5	1.7	0	5.0
Total cycle time	14	15.3	3.9	7.9	24.7
Independent variables					
Weight (lb) per turn	14	10,346	1,812	7,600	13,260
Operator time experience[b] (hr)	10	1.1	0.8	0	2.3
Operator time experience[c] (hr)	4	0.3	0.3	0	0.8
Waiting-on-forwarder observations	14	5.0	3.1	0	11
Jam-clearing observations	14	3.2	2.5	0	8

[a] SD = standard deviation.
[b] Operator 1 (more experienced).
[c] Operator 2 (less experienced).

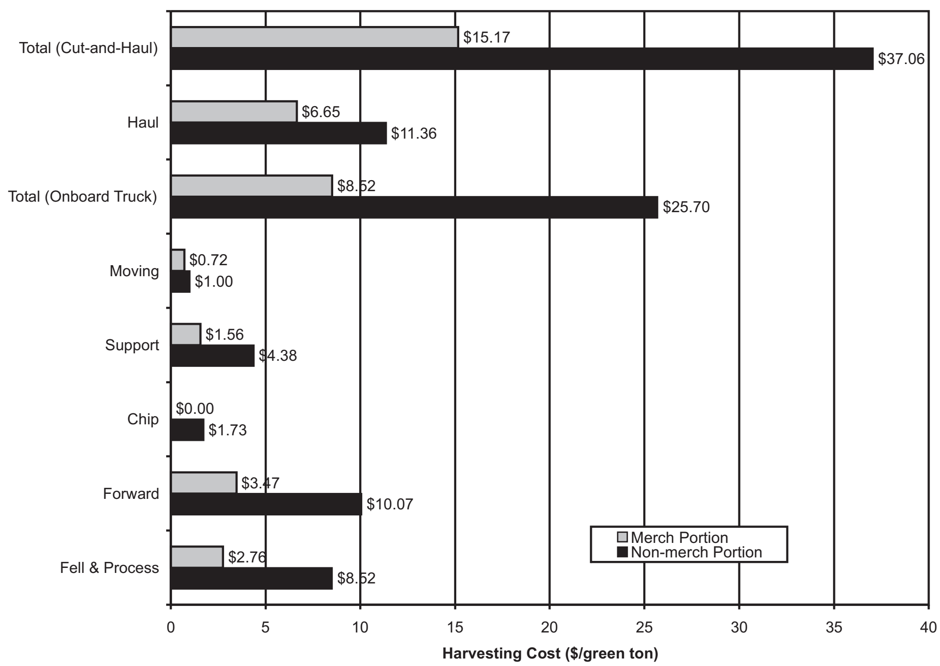

Figure 3. — Non-merchantable and merchantable portion harvesting cost estimates.

Non-merchantable portion costs

Felling and processing costs for the non-merchantable portion were estimated with the AHA by inputting only the non-merchantable DBH classes for the harvester along with non-merchantable portions (limbs and tops) of merchantable trees. Regression Equation [**1**] for the total productive time of harvesting non-merchantable trees was used to estimate minutes per tree for the harvester. For the variable TPASQIN, 1,232 trees per acre was used. This value represents the total trees per acre for the entire stand, not just the non-merchantable portion. This procedure allowed the AHA to project costs for actually harvesting only the non-merchantable portion but within the context of a stand consisting of 1,232 total trees per acre. When applying this treatment, the harvester can produce at a rate of 1.79 hours per acre. The harvester's average production was 10.00 tons per productive machine hour (PMH). Harvester availability was set at 85 percent; therefore, production per scheduled machine hour (SMH) was 8.50 tons. After combining all machines in the system, cost for the harvesting function was $8.52 per ton.

Productive machine minutes per turn for the forwarder were estimated to be 45.28 with an average forwarding distance of 3,768 feet, and average production capability was 6.85 tons per PMH. Availability was set at 85 percent and production per SMH was 5.82 tons. After combining all machines in the system, cost for the forwarding function was $10.07 per ton.

For the chipper, productive machine time per cycle was estimated to be 15.33 minutes using regression Equation [**5**]. Average production was 20.24 tons per PMH. Availability was set at 70 percent resulting in a production of 14.17 tons per SMH. After combining all machines in the system, cost per ton for the chipping function was $1.73.

Haul distance for the non-merchantable portion was 94 miles. Maximum load size observed was 22 tons of chips per vanload. Loading time per chip van averaged 192.7 minutes. This time includes the entire time a van was sitting on the landing being loaded and waiting to be loaded. Since only one forwarder was used for feeding the chipper, van-loading time was directly related to forwarder productivity. For the hauling function, tons per SMH were 2.51, and cost per ton of chips was $11.36.

For harvesting the non-merchantable portion only, the forwarder was found to be the least productive machine (5.82 tons per SMH). This is directly related to the small payload size of material forwarded per load and the length of distance forwarded (**Table 5**). The fluffy nature of the non-merchantable material reduced payloads from 15 tons to approximately 5 tons per load. Utilization percentages, after balancing with all machines, were: harvester 58, forwarder 85, and chipper 29. On-board truck cost for harvesting only the non-merchantable portion was $25.70 per ton of chips produced, which equates to $460.96 per acre. With the addition of hauling ($11.36), the cut and haul costs were $37.06 per ton or $664.78 per acre.

Merchantable portion costs

Felling and processing costs for the merchantable portion were estimated with the AHA by inputting only the merchantable DBH classes for the harvester. Regression Equation [**2**] was used to estimate minutes per tree for the harvester. This procedure allowed the AHA to project costs for harvesting only the merchantable portion. For performing the treatment used in this study on a stand similar to that of the study site, the harvester can perform at a rate of 1.29 hours per acre. The harvester's average production was 31.69 tons per PMH. Harvester availability was set at 85 percent; therefore, production per SMH was 26.94 tons. After combining all machines in the system, cost for the harvesting function was $2.76 per ton.

Productive machine minutes per turn for the forwarder were 46.74 and consisted of travel, loading, and unloading times. Since forwarding merchantable trees was not studied, regression equations from Lanford et al. (in review) were used to estimate the time elements. The forwarder's average production capability was found to be 19.25 tons per PMH. Availability was set at 85 percent and production per SMH was 16.37 tons. After combining all machines in the system, cost for the forwarding function was $3.47 per ton.

Average haul distance for the merchantable portion was 70 miles. Load size averaged 26.75 tons of roundwood per truckload. For the hauling function, tons per PMH were 7.24. Cost per ton of roundwood was $6.65.

For harvesting the merchantable portion only, the forwarder was found to be the least productive machine (16.37 tons per SMH). Utilization for the functions was: harvester 52 percent and forwarder 85 percent. On-board truck cost for harvesting only the merchantable portion was $8.52 per ton, which equates to $349.45 per acre. With the addition of hauling ($6.65), the cut and haul costs were $15.17 per ton or $622.16 per acre.

Cost vs. revenue

Seven vanloads of chips were produced from the non-merchantable portion of the stand. Each load was sold for energywood at a rate of $14.50 per green ton. Cut and haul costs for harvesting only the non-merchantable portion generated by the AHA were $37.06 per ton. Subtracting these costs from the revenue received yields a loss of $22.56 per ton or $404.73 per acre.

Discussion

Harvester productivity was most affected by DBH and trees per acre. DBH was significant for estimating total productive time for merchantable-sized trees, and both DBH and trees per acre were used for estimating total time to harvest non-merchantable-sized trees. As expected, the harvester and forwarder were more productive when harvesting merchantable trees. At times the harvester was unable to fell small-diameter trees (1 to 3 in DBH) due to the amount of brush surrounding the machine and head. Stand statistics in **Table 2** show that 207 non-merchantable trees per acre were left after harvesting. This amount reflects that many of the very small non-merchantable stems could not be effectively handled and processed by the harvester, and therefore, were knocked down and/or run over by the machines. To recover small trees, not effectively processed by the harvester, a possible alternative would be to use a saw-head feller-buncher for felling since the trees require no processing. If forwarders were used for primary transportation and merchantable trees were to be harvested, a harvester would also be required.

Forwarder productivity was most affected by travel distance and weight of material forwarded. The chipper feeding process was slowed by waiting and cleanup times. There seems to be room for improvement in this process. A possible alternative would be to use a tub grinder or drum chipper. This would allow the forwarder to feed at its own rate with less machine interaction. However, when chipper size and features increase, purchase price also increases. Future studies are needed to investigate the benefits vs. costs of a more expensive, but easier to feed chipper. Also, for this study only 14 forwarder loads were observed. More observations might have shown feeding times to decrease due to added experience by the forwarder operator. A time experience variable was analyzed, but found non-significant for estimating any times associated with the forwarder. More observations might have detected significant differences.

Forwarder productivity for the non-merchantable portion was 6.85 tons per PMH which was the least productive function in the harvesting system. A possible solution would be to add another forwarder to the operation. This alternative would again increase capital expenditures as mentioned earlier. A better alternative might be to add another forwarder operator who could work an extra shift to aid in balancing the system. Another approach might investigate forwarding non-merchantable material in a cylindrical bale (Murphy et al. 2003). This methodology has been studied in the Scandinavian countries and can possibly increase forwarder payloads (Andersson et al. 2000). Packing material in bale form allows forwarders to haul neat packages; this in turn could increase forwarder productivity, although, another machine would be needed to bale material.

Chipper productivity was the highest of all machines in the system. Similar to the forwarder, chipper productivity was also affected by waiting times. Waiting-on-forwarder time could be reduced or possibly eliminated as forwarder operator experience increases. Jam-clearing time is directly related to the chipper's design limits. The chipper could not effectively handle as much material as the forwarder was capable of feeding. This in turn, reduced both chipper and forwarder productivity.

Hauling costs of chips produced from the non-merchantable portion were $11.36 per ton (the highest of all functions). During the study, a maximum load size of 22 tons was observed. Load size is a very important factor in this operation and must be maximized due to the current low price of energywood and high hauling cost. Load size increased as the study progressed due to better chip van and chipper out-feed spout positioning. Also, higher volume chip vans are currently available that could be incorporated into the operation.

Conclusions

Based on results from the study, there appears to be an opportunity to reduce fire hazards and generate revenue from energywood using a CTL/small chipper system. For fuelwood systems in the United States to become more viable, utilization of the finished product must be increased. Much research is needed to explore appropriate harvesting systems as well as processing and consumption possibilities. There are a number of questions to be addressed with future studies such as:

1. using a tub grinder or drum chipper to increase forwarder productivity and decrease feeding time,
2. system balancing aspects by adding another forwarder or operator,
3. forwarding material in bale form,
4. exploration of different stand, terrain, and species types,
5. system costs vs. fire suppression costs,
6. the amount of merchantable material that must be removed to make the system economically feasible, and
7. using masticating technology for fuel structure change of the non-merchantable portions.

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