Small-scale Forestry
DOI 10.1007/s11842-016-9347-9

RESEARCH PAPER

Application of a Small-Scale Equipment System for Biomass Harvesting

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Accepted: 8 July 2016

Abstract The small-scale harvesting equipment system has been and continues to grow in use in forestry operations in some regions in the world. This harvest system can include a range of equipment types, such as feller-bunchers or chainsaws, skidders or farm tractors, and chippers. These machines are generally smaller, lower cost and less productive than larger, more advanced forestry machines. The objective of this project was to investigate the feasibility of a small scale harvesting system that would produce feedstock for a biomass power plant. The system had to be cost competitive. A boom-type feller-buncher, a small grapple skidder and a chipper were tested as a small-scale system. In this study, feller-buncher and skidder productivity was determined to be 10.5 m^3 per productive machine hour, and production for the chipper was determined to be 18 m^3 per productive machine hour. Production from the system did not reach the desired levels of 4 loads/day (25 m^3/load); however, the system was able to produce about 3 loads/day. The results showed that the system currently could fill a roadside van for \$16.90/m^3, but

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suggested machine modifications could potentially reduce the system cost to \$12.73/m^3. Residual stand damage was minimal, especially on flatter ground and not operating on a slash layer. Soil disturbance from the harvesting system was predominantly undisturbed or classified as a shallow disturbance.

Keywords Small-scale logging system · Machine rates · Harvest system costs · Stand damage · Biomass harvesting

Introduction

Biomass as a renewable energy resource has gained interest again to tackle climate change measures and improve energy security. Among various biomass resources, woody biomass is particularly attracting attention (Nakahata et al. 2014a). This is not only because it is abundant, but also because its energy consumption is expected to contribute to the revitalization of forests and forestry products (Nakahata et al. 2014b). Many landowners are willing to conduct thinning operations and extract thinned wood for biomass. On the other hand, an increasingly large share of the country's timber supply is situated on relatively small tracts or uneven-aged, mixed stands that bring some challenges to harvesting techniques. Large-scale mechanized systems are ideally suited to work in a clearcut, particularly in the large stands, but its application can be limited when working in thinning operations or where partial cuttings are practiced (Updegraff and Blinn 2000). Thus, small-scale timber harvesting systems are becoming more attractive for the forestry community.

In many parts of the world, small-scale harvesting machines have been used in forest operations on various terrain conditions where size was not restricted (Akay 2005). In some counties, farm tractors are commonly used for forest harvesting in small-scale logging systems. This simple technology has a strong potential in developing countries. On the other hand, various animal species such as mules, horses and buffalo have been used for skidding operations (Nakahata et al. 2014b). Melemez et al. (2014) concluded that skidding with a farm tractor is the most productive method compared to others (animal power, forest tractor and skyline), and use of farm tractors needs to be encouraged as a productive method in harvesting small scale forestry in Turkey. But these methods have technical, ergonomic and environmental problems (Nakahata et al. 2014b). To overcome these problems, new alternative small-scale harvesting systems are needed which utilize mechanized harvesting, have a low capital investment requirement, are small in physical size, and are based primarily on adaptations of current harvesting technology (Wilhoit and Rummer 1999). Small-scale harvesting technology offers distinct advantages to the owner who expects a majority of his/her work to be in small tracts, on sensitive sites or in uneven-aged management activities. Some primary advantages are reduced capital investment and operating costs, greater flexibility, easier portability between work sites, easier maneuvering in high stand density, and lower levels of residual stand and soil damage (Updegraff and Blinn 2000). Some of the proposed machines/harvesting functions have been thoroughly tested in timber harvesting applications, but data must be collected for others before actual system productivity can be assessed and costs per unit production can be compared (Wilhoit and Rummer 1999). The impact of small-scale timber harvesting equipment on some parts of the forest ecosystem has always been of concern. One of these areas of concern, which is easily measured, is damage to the residual stand (Huyler et al. 1994). Although several studies have evaluated damage to residual stands caused by various harvesting machines and silvicultural systems (Huyler et al. 1994; Hosseini et al. 2000; Vasiliauskas 2001; Mousavi 2009), little information is available on small harvesting operations. Soil disturbance must also be addressed, as previous studies have shown the impact of harvesting may have impacts on the soil characteristics for several years (Kleibl et al. 2014).

A project was initiated in 2007 in an effort to develop a small scale harvesting system that will economically and efficiently produce a feedstock for a biomass power plant. Several criteria were considered important in the development of this system:

1. The system has to operate in a way to enhance good forestry practices. Landowners are becoming more selective and aware of harvesting practices that meet important state best management practices and increasing aesthetic expectations.
2. Capital requirements for the system should be kept to a minimum as most small logging businesses cannot afford large up-front investments.
3. The system should be fuel efficient.
4. Daily operating costs need to be minimal to economically deliver a low-valued product to market.

The objective of this study was to examine a small-scale harvesting equipment system by installing a series of field tests. This paper summarizes the findings from an initial production study. The objective of this initial study was to determine the production rate and costs of the selected system. In addition, residual stand damage and soil disturbance was assessed to aid in addressing concerns from landowners about environmental impacts. The information presented in this paper may help the eventual adoption of small-scale mechanized timber harvesting alternatives which can help landowners, loggers, and the forest industry productively manage forest land for biomass.

Study Area Description

This study was conducted on the Mark Twain National Forest's Poplar Bluff Ranger District in southern Missouri. This national forest (approximately 40,000 hectare) is characterized by upper Piedmont sites with short slopes ranging from 0 to 60 %. Access is good with state and county highways and year-round roads maintained by the forest service. Four hardwood stands were harvested (Table 1). The stands contained oaks (Quercus alba and rubra), American beech (Fagus grandifolia) and hickory (Carya ovata). Two stands (A and B) had a silvicultural prescription to remove all trees with a diameter at breast height (DBH) of less than 23 cm (9 inch).

Table 1 Stand data and volume removals from study area

Stand	Pre-biomass harvest stand density (trees ha^{-1})	Residual stand density (trees ha^{-1})	Removal (m^3/ha)	Area (ha)	Silvicultural treatment	Slope (%)	Removals	
							Avg. dia. (cm)	Avg. height (m)
A	460	200	43	1.6	Shelterwood	10–25	15	15
B	500	110	32	2.8	Shelterwood	<10	11	14
C	925	280	48	3.2	Open woodland	10–25	12	12
D	600	250	37	3.4	Open woodland	<10 %	14	12

This cut was intended to meet the desired management objective of a "Shelterwood with Reserves". The other two stands (C and D) had a silvicultural prescription to remove all trees with a DBH less than 23 cm (9 inch), but with a follow-up commercial harvest that will meet the desired management objective of an "Open Woodland". The open woodland treatment is a two-stage treatment with a biomass harvest occurring first and a sawtimber harvest occurring at a later date.

Methodology

The harvesting operation took place during the summer months of June and July. Stands were paired to examine the effect of slope on the production rates and costs of the small scale biomass harvesting system. Stands A and B were both scheduled for the same silvicultural treatment (Shelterwood with Reserves) and had similar stand characteristics, except Stand A had steeper slopes. Sawtimber stems had been harvested in both of these stands approximately 1 year before this study was implemented. The biomass harvest was required to fulfill the silvicultural prescriptions, and leave the residual stands with a basal area of 7–11.6 m^2/ha (30–50 ft^2/ac).

Stands C and D were scheduled for the open woodland treatment and were also chosen because of their similar stand characteristics and varying slopes. Only portions of these stands were included in the harvesting study because these were large stands. Approximately 3.2 ha (8 ac) of Stand C was chosen to reflect a high slope (10–25 %) treatment. Stand D received a low slope harvest treatment (<10 %) on 3.4 ha (8.4 ac). The final stand density, after both stages of harvest, was targeted for a residual basal area of 7–11.6 m^2/ha (30–50 ft^2/ac).

Equipment Selection

The equipment for the harvesting system was procured in late 2007 and early 2008. The system consists of the following three pieces of equipment: (1) Felling: Felling

Fig. 1 John Deere 75C with a Fecon shear head (**a**), Turbo Forest skidder with a grapple attachment (**b**), Morbark Typhoon chipper with a loader attachment (**c**)

was completed by a small excavator (John Deere 75C) with a Fecon shear head (Fig. 1a). This was a new type of harvester configuration that has not been evaluated. The ability of this machine to reach for trees (maximum 5 m) rather than driving from tree-to-tree should enhance productivity when working with small stems. The selection of a boom machine should aid in minimizing residual stand damage and ground disturbance. The Fecon shear head (model FBS1400EXC) had a single action knife and an empty weight of 900 kg. (2) Extraction: The primary extraction machine was a small 37 kW (50 hp), hydro-static drive Turbo Forest skidder (Fig. 1b) mounted with a Fecon swing arm grapple. There is currently only one manufacturer of a small skidder in North America, so demonstrating the viability of a small machine might open this market for additional manufacturers. (3) Processing: Once the material was brought to the landing, it was fed to a Morbark Typhoon chipper (240 kW, 325 hp) (Fig. 1c). The chipper was equipped with a small loader for easy handling of the material and eliminated the need for a separate loader. This configuration was chosen because it allowed one operator to complete all the work on the landing. If the entire system was purchased new, the complete cost should be less than $300,000 (<50 % of the cost of a conventional mechanized system).

The operators were given a few days to gain experience in harvesting the mostly hardwood stands, especially where slope was involved. Data was then collected by several methods, including the use of data recorders, videotaping the machines during operation, and in some cases manually recording data. Turn times and turn distances were collected for the skidder using a MultiDAT recorder. Distance was measured for the full roundtrip cycle as was turn time. Turn volume was estimated by measuring the size of each tree in a bunch and calculating the volume of each skidder turn based on local volume tables (Clark III et al. 1986). This turn volume estimate was verified by determining the volume in a truck (from the scale ticket) and dividing by the total number of skidder turns per truck.

System production was based on observation of the machines operating within each stand over the days they could operate. Total production was measured over the operating time for each stand and summarized as cubic meter per productive machine hour (m^3/pmh). Several delays occurred due to trucking, which was being coordinated by an independent supplier. An excel spreadsheet program, CashFlow, was used to estimate the total cost per cubic meter to load the material into a van (Tufts and Mills 1982). This program uses the current depreciation schedule from the IRS (Internal Revenue Service), and includes costs for maintenance, fuel, and equipment loan interest to calculate an after-tax cost analysis. This method summarizes the total cost of owning and operating a machine over the economic life of the machine.

Residual Stand and Soil Damage Assessments

Damage to the residual stand was assessed after all harvesting was completed. Damage was divided into stem and crown damage, then further categorized into minor and major damage for each category. Minor damage is damage from which a tree can typically recover, whereas major damage could result in adverse effects for the tree. Minor stem damage includes bark and/or wood damage measuring 10 cm^2 or less. Damage of 10 cm^2 or more is classified as major stem damage. Minor crown damage includes damage up to 33 % of the crown. Major crown damage includes damage above or equal to 33 %.

Soil disturbance was surveyed after harvesting using the point transect method and disturbance classifications adapted by McMahon (1995). Soil disturbance classifications are shown in Table 2.

Results and Discussion

Stand volume and removal varied for each stand (Table 1). The variability in Stands A and B were primarily due to the prior sawtimber harvest and the residual sawtimber sized trees that were left in the stands. Stand C was the most heavily stocked of all the stands, resulting in the highest cubic meters per acre removal. The average removal for the entire study area was 39.5 m^3 per hectare.

Table 2 Disturbance classification scheme. *Source* McMahon, 1995

Disturbance type	Description
Undisturbed	No evidence of machine or log passage, litter and understory intact
	Includes non-soil (rock, stumps)
Shallow disturbance	Litter still in place, evidence of minor disruption
	Litter removed, topsoil exposed
	Litter and topsoil mixed
	>5 cm topsoil on litter
Deep disturbance	Topsoil removed
	Erosion feature
	Topsoil puddled
	Rutted—5–15 cm deep; 16–30 cm deep; >30 cm deep
	Unconsolidated subsoil or base rock deposit
Slash/understory residue	10–30 cm, >30 cm
Non-soil	Stumps, rock, etc.

Equipment Production

Felling

Bunch size was limited by the size of the grapple on the skidder, so the feller-buncher operator sized the bunches to optimize skidding. It took between 5 and 6 trees to make most bunches, and it took approximately 40 bunches to fill a chip van.

Productivity data for the feller-buncher is summarized in Table 3. Stands A and B were harvested after a commercial sawtimber operation, so trees were spaced further apart. In the other two stands where the biomass thinning was occurring before the sawtimber harvest, there was less travel between trees and therefore greater felling productivity. The average production rate for Stands A and B was 9.1 m^3/pmh (productive machine hours), and was 12.3 m^3/pmh for Stands C and D. The overall production rate for the feller-buncher was 10.6 m^3/pmh. There was also an indication of an operator learning curve, but this impact was not measured in this study.

The 10.6 m^3/pmh observed productivity of the feller-buncher was slightly higher than the 10.34 m^3/h productivity by the chainsaw as reported by Nakahata et al. (2014b). There are many factors affecting the felling productivity. A major factor was the speed of the shear head. Limited hydraulic flow restricted the open and close capabilities of the shear head, causing lower productivity. Other factors

Table 3 John Deere feller-buncher production data

Stand	Total number of bundles produced	Trees/minute	Average number of trees/bundle
A	255	1.13	17.38
B	251	1.64	12.78
C	95	1.68	19.06
D	571	1.97	14.69

limiting productivity are not easy to identify and even more difficult to quantify. Productivity of felling may be affected by stand composition, the operator's skills and motivation, silvicultural method, tree species, weather conditions, chain condition (sharp or dull), and terrain slopes (Mousavi 2009).

Skidding

Over 600 cycles for the skidder were recorded (Table 4). A skidding cycle began when the skidder left the landing. The complete cycle consisted of the time it took to drive to a bundle, intermediate travel to the next bunch if more than one was gathered, and return loaded travel back to the landing. With an average cycle time of 222 s, the operator was able to make approximately 16 cycles/pmh. Average volume per cycle was 0.64 m^3. Total observed skidder production was 10.4 m^3/pmh. These cycle times are much quicker than those found by Vusić et al. (2013) over a similar distance, most likely due to faster gathering of trees by the mechanical attachment on the Turbo Forest.

The observed productivity of the skidder was higher than other skidding devices such as a farm tractor with an average production rate ranging from 2.43 to 2.60 m^3/h with an average skidding distance of 665 m (Gilanipoor et al. 2012) and a farm tractor with an average production of 4.18 m^3/h with a skidding distance of 100 m (Acar 1997a). In another study, a production value of 3.31 m^3/h for a Koller K300 skyline over a distance of 250 m was reported by Acar (1997b) and the average production of a forest tractor was 6.33 m^3/h over a skidding distance of 50 m (Menemencioglu and Acar 2004). Melemez et al. (2014) reported average productivity for five alternative extraction methods with 100 m skidding distance as 3.80, 6.24, 2.80, 5.25 and 10.09 m^3/h for the methods of skidding by animal power, skidding with farm tractor, hauling with farm tractor and forest tractor and extraction by skyline, respectively. The 10.4 m^3/pmh production of the Turbo Forest skidder with a 235 m average skidding distance was higher than the 5.07 m^3/h productivity of the mini-forwarder as reported by Nakahata et al. (2011) with a 92.2 m average forwarding distance. Spinelli and Magagnotti (2012) found that extraction productivities of a 70 kW farm tractor with a 15 m winching distance and 100 m skidding distance were about 4.0, 5.0, 6.5 and 7.8 m^3/h, respectively. Mousavi (2009) observed that the average productivity of a Timberjack 450C skidder was 10.8 and 11.11 m^3/effective hour in the short- and long-log method, respectively.

Table 4 Skidder production data

Stand	Number of turns	Distance (m)			Time (s)		
		Mean	Min	Max	Mean	Min	Max
A	105	239	40	510	261	38	701
B	178	282	5	1049	235	66	694
C	213	203	31	415	227	59	648
D	149	215	35	446	164	57	322
Total	645	235			222		

For this study, the productivity of the skidder was similar to the productivity of the skyline skidding and Timberjack 450 C skidder operations although the systems including the operators and the distance and stand conditions were different. Level of skill and operational conditions all effect the productivity of felling and skidding. More research is needed to develop curves indicating the impact of tree size on felling performance and how distance affects skidding production.

Chipping

Collecting production data for the chipper was less comprehensive because the chipper could far out-produce the other two machines. Several vans were filled in just over 1 h each; others took longer because of tree size or crooked material. Both of these characteristics negatively impacted chipper production. Average load size was 23.85 m^3. Production for the chipper was 18 m^3/pmh, which is significantly higher than the production found by Spinelli and Magagnotti (2013), though this was a dedicated chipper and not an attachment to a farm tractor. Fuel consumption measured on a per ton basis for the Morbark machine was similar to those found in the same study.

System Costs

Several assumptions were made for the cost analysis (Table 5), including: (1) Fuel cost of $3.75/gallon for off-road diesel; (2) Economic life of 5 years for all three pieces of equipment (new machines being tested in a different application, so

Table 5 Machine cost assumptions

Costs	Feller-buncher	Skidder	Chipper
Machine price ($)	95,000	90,000	110,000
Economic life (years)	5	5	5
Scheduled machine hours (h/year)	2000	2000	2000
Utilization (%)	80	80	47
Loan life (months)	48	48	48
Interest rate (%)	6.0	6.0	6.0
Indirect cost rate (%)	33	33	33
Marginal tax rate (%)	28	28	28
Discount rate (%)	5.0	5.0	5.0
Fuel and lube ($/hour)	8.75	8.00	40.00
Inflate F&L (%)	5.0	5.0	5.0
Maintenance and repair ($/hour)	8.00	8.00	24.00
Inflate M&R (%)	15	15	15
Labor rate ($/hour)	12.00	12.00	12.00
Inflate labor (%)	3.0	3.0	3.0
Fringe benefit (%)	30	30	30
Insurance and taxes (%)	4.0	4.0	4.0
Residual value end of life (% of purchase price)	20	20	20

5 years is considered a conservative estimate of machine life without a major rebuild); (3) Loan life of 4 years with no down payment; (4) 6 % interest rate on loans; (5) Total production rate of 16,800 m^3 per year; (6) 33 % indirect cost was added onto total equipment estimates. For the cost analysis, utilization was set at 80 % for the feller-buncher and skidder. This higher utilization was used because the utilization rate observed in the study was impacted by downtime due to data collection, trucking delays, and other common sources of delays seen when implementing a new harvesting system. The utilization for the chipper was calculated to be 47 % and indicates there is a significant amount of time the machine could be producing more chips if the wood was available on the deck.

Capital costs for the three machines were estimated at \$95,000 for the feller-buncher, \$90,000 for the skidder, and \$110,000 for the chipper. Costs were calculated to be \$4.88/m^3 for the feller-buncher, \$4.75/m^3 for the skidder, and \$7.27/m^3 for the chipper over 5 years. The \$4.88/m^3 cost of the feller-buncher is lower than the \$6.65/m^3 by a medium-sized chainsaw (Spinelli and Magagnotti 2010). Unit cost of skidding in this study is \$4.75/m^3, which is approximately 50 % lower than in Mousavi's (2009) study on skidding with Timberjack 450 C skidder and similar to the Naghdi's (2005) study. This study is also lower than Spinelli and Magagnotti's (2010) study with a 40 kW farm tractor equipped with a radio-controlled forestry winch.

Total cost to operate the system and load vans was calculated to be \$16.90/m^3 over a 5-year ownership period. The cost of transportation is dependent upon the distance from the stand to the delivery facility, therefore, costs presented in this study are to roadside. This system can produce nearly 3 loads/day. When costs for trucking, stumpage, and profit, are added to the system costs, the required delivery price is higher than most biomass markets can currently pay. Higher production is needed to make the system economically feasible.

Several improvements could be implemented to improve productivity of the feller-buncher and skidder. The feller-buncher should become more productive with some slight modifications (which we could not perform on a leased piece of equipment). Purchasing the machine without a boom and retro-fitting the machine with a boom better configured for a woods application will make the machine more productive. Also, getting more flow to the shear head through use of an auxiliary hydraulic pump should improve the felling cycle times. For the skidder, changing the grapple configuration to a more conventional arrangement should be considered. This modification would have two benefits: it would reduce downtime, but should also allow for greater sized bunches to be pulled to the landing, thus making the skidding function more productive. The chipper is currently being underutilized, so attaining additional production if the roundwood was available on the deck requires no changes.

Total system costs were re-analyzed with the changes mentioned above. The capital cost of the feller-buncher was increased by \$5,000 to allow for the modifications. Machine production was raised from 10.5 m^3/pmh to a theoretical production rate of 15.6 m^3/pmh, reflecting the improvements in performance from the modifications. Total system production was raised to 25,000 m^3/year, or 100 m^3/day. Total system cost decreased to \$12.73/m^3. If haul distance is kept under 40 miles, the market price should allow enough to pay the trucker, landowner stumpage, and still have a profit for the logger.

Residual Damage

Residual tree damage varied from site to site (Table 6). In Stands A and B, all sawtimber harvest damage from the previous harvesting entry was omitted and values reflect only that damage caused by the biomass harvest. It should be noted that the percent damage is based on the residual stand, and some comparable damage studies base the percentages against the pre-harvest stand (the original TPA). The only notable damage was the amount of minor stem damage in Stand A. This stand was a high slope treatment with heavy slash. Nearly all of the damage observed was caused by the skidder. It appears that the combination of slash and high slope caused difficulties for the skidder driver in avoiding residual trees. Additionally, no damage was recorded in Stand D, a stand with low slope and no slash.

Table 7 is a list of the soil disturbance classes and their percentage within the sampled stand areas. Soil disturbance results are strongly correlated with treatment. More specifically, the disturbance differences in treatment types can most likely be attributed to the prior sawtimber harvest in Stands A and B. As can be seen from the table, the open woodland treatment areas (C and D) had a much higher initial undisturbed area than that of the shelterwood treatments (A and B). Yet, post-harvest disturbance shows that the undisturbed areas are relatively similar, with open woodland treatments being only slightly less disturbed. Shelterwood treatments also have higher slash contents than the open woodland treatments; this is a direct result of the previous sawtimber harvest. Overall, the vast majority of harvested stands are undisturbed or have shallow disturbance. Of those stands with deep disturbance, most are less than 5 cm deep. While the disturbance from this system was greater than that found by Savelli et al. (2010), the generally low amount of deep disturbance should not have long lasting impact on the site.

Small-scale harvesting systems offer benefits to landowners, such as less damage to the residual trees and reduced impacts on soils (Moss et al. 2012; Hedderick 2008; Russell and Mortimer 2005.) In this study, based on residual damage assessment, the system can do an acceptable job for a landowner, especially on

Table 6 Residual tree damage for harvested sites

Stand	Percentage of Damage to the residual stand			
	Stem minor (<10 cm^2)(%)	Stem major (>10 cm^2)(%)	Crown minor (<1/3)(%)	Crown major (>1/3)(%)
A	32	2.5	0	2.5
B	3	3	3	3
C	1	2.2	0	1
D	0	0	0	0
Average	9	1.9	0.73	1.63

Table 7 Soil disturbance summary

Stand	Sample	Disturbance class				
		Undisturbed (%)	Shallow disturbance (%)	Deep disturbance (%)	Slash cover (%)	Non-soil (%)
A	Pre	41.43	41.19	1.43	12.38	3.57
	Post	30.25	45.5	8.25	14.50	1.50
		−11.18	4.31	6.82	2.12	−2.07
B	Pre	39.29	42.86	7.38	10.00	0.48
	Post	34.00	51.5	1.50	10.50	2.50
		−5.29	8.64	−5.88	0.50	2.02
C	Pre	95.71	2.14	0.00	0.00	2.14
	Post	36.43	46.67	9.77	3.81	3.33
		−59.28	44.53	9.77	3.81	1.19
D	Pre	87.00	9.75	0.00	0.00	3.25
	Post	42.62	43.57	8.33	2.86	2.62
		−44.38	33.82	8.33	2.86	−0.63

flatter ground and in first harvest. Minor stem damage was found on 9 % of residual stems, while major stem damage was only found on 1.9 % of the residual stands. The average minor (<1/3) and major (>1/3) crown damage was 0.75 and 1.63 %, respectively. The level of damage to the residual stand were significantly better than Mousavi's (2009) study which showed that the harvesting operation caused significant damage to the residual stand and approximately 32 % of the trees were damaged by their harvesting system (felling by chainsaw, skidding by Timberjack 450 C, loading by front-end loader Volvo 4500 BM, and transportation by truck Benz 2624 and 2628). The vast majority of the soil in the harvested stands in this study were undisturbed or had shallow disturbance. For those areas classified as having a deep soil disturbance, the majority of it is less than 5 cm deep. Deep soil disturbance was found in the high slope stands (A and C), but harvesting in stand D (<10 % slope) also resulted in some deep soil disturbance. While slope appears to be a factor in soil disturbance, the number of residual trees per acre also appears to have an impact on soil disturbance. Stand B, which was a low slope stand with fewer residual trees/ha has the lowest observed amount of deep disturbance. Since most of the soil disturbance appears to have been due skidding, operators will need to use more care in choosing their travel paths.

Conclusion

Small-scale harvesting systems not only have the versatility, relatively low capital cost, and high maneuverability characteristics, but offer some other benefits to landowners, including less damage to the residual trees and reduced impacts on soils (Moss et al. 2012). In this small-scale harvesting system, felling production averaged 10.6 m^3/pmh. Felling production in the stands that had previously had the sawtimber removed was slightly lower than in the stands that had not received recent harvesting activity. Tree spacing, resulting in a longer travel time between trees, may have contributed to the lower production rate.

Skidding production averaged 10.4 m^3/pmh. Grapple size limited the volume per cycle (turn). The chipper could only operate when the skidder supplied enough wood and when trucks were available. The chipper production rate of 18 m^3/pmh was higher than the feller-buncher and skidder production rate resulting in the chipper being underutilized. Average load size was 23.85 m^3 and the average time to fill a van was over an hour (approximately 80 min). Residual stand damage was found to be minimal from the harvesting. Most of the occurrence was from the skidder, but minor in classification. For soil disturbance, the vast majority of harvested stands are undisturbed or have shallow disturbance. Of those stands with deep disturbance, most are less than 5 cm deep.

Production from the system did not reach the desired levels, but some modifications should make the four load/day goal attainable. Some modifications to the feller-buncher and skidder would be necessary to get the last load to meet the goal of four loads/day. Specifically, changing the boom configuration and adding an auxiliary hydraulic pump for the feller-buncher shear head and a modified grapple configuration on the skidder are potential recommendations for system improvements. With these modifications, the cost to deliver processed woody biomass could be reduced to a level where it could be a viable option for harvesting in the southern United States.

Acknowledgments This project was funded from various sources, including the Missouri Forest Product Association.

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