High Tonnage Harvesting and Skidding for Loblolly Pine Energy Plantations

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Abstract

The southeastern United States has a promising source for renewable energy in the form of woody biomass. To meet the energy needs, energy plantations will likely be utilized. These plantations will contain a high density of small-stem pine trees. Since the stems are relatively small when compared with traditional product removal, the harvesting costs will increase. The purpose of this research was to evaluate specialized harvesting and skidding equipment that would harvest these small stems cost efficiently. The feller-buncher utilized was a Tigercat 845D with a specialized biomass shear head. The skidder was a Tigercat 630D equipped with an oversized grapple. This equipment was evaluated in a 4-hectare stand with characteristics of a southern pine energy plantation. During the study, the feller-buncher achieved an average production rate of 47 green tonnes/productive machine hour (gt/PMH) and the skidder had an average production rate of 112 gt/PMH. A before-tax cash-flow model was used to determine a cost per ton for each machine. The feller-buncher costs were \$3.85/gt over a 10-year life span, whereas the skidder costs were \$1.95/gt over the same 10-year life. The results suggested that the current system working in a southern pine energy plantation could harvest and skid small stems for approximately \$5.80/gt.

The topic of declining fossil fuels and the need for renewable energy sources is evident in today's society. Because of this necessity, researchers and politicians have assembled different ideas in which renewable fuels will be a major part of the US energy portfolio. Some of the framed ideas include the ''US Billion-Ton Update'' (US Department of Energy [DOE] 2011), ''25x25'' (25x'25 2007), and the Energy Independence and Security Act of 2007. The billion ton study (DOE 2011) illustrates how different areas of biomass feedstocks are allocated to the renewable fuel portfolio in a sustainable manner. The ''25x25'' states that 25 percent of our energy consumed must come from biomass by the year 2025. The one policy that has been enacted is the Energy Independence and Security Act of 2007 (http://www.gpo.gov/fdsys/pkg/PLAW-110publ140/html/PLAW-110publ140.htm). Included in the Act are standards in which biofuels will play a major role in ensuring national energy security and the reduction of greenhouse gases. One of the main goals of the Act is to have 36 billion gallons of biofuels produced annually by 2022. The common attributes of all of these ideas are that they require a tremendous amount of biomass in a relatively short time period. A great deal of this material is expected to be sourced from woody biomass.

Woody biomass is available in such forms as urban residues, mill residues, dedicated energy crops, and logging residues. Currently, mill and logging residues supply the woody biomass market, but they are not sufficient to meet the large-scale quantities set forth. Eventually, dedicated energy crops will likely be utilized by the United States to meet the requirements for biomass feedstocks. Short-rotation woody crop (SRWC) supply systems were first described in the late 1960s and early 1970s as a means of rapidly producing lignocellulosic fiber for use in the wood products industry and for energy (Tuskan 1998). Studies have been completed to determine optimum species, silvicultural techniques, fertilization, genetics, and irrigation to make the crop successful (Tuskan 1998). The barrier with SRWCs is the immense amount of inputs needed for high growth rates. This poses economic and environmental issues that may hinder the introduction of a biofuel market. These two issues happen to be important considerations when choosing a crop for biomass production. Another aspect that should be taken into account is the volatile risk associated with the biofuel market. The need for biomass feedstocks

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for energy has not been constant in the past. To mitigate risk, the biomass feedstock crop should be flexible in its ability to produce different products for the landowner to make a profit from his or her initial investment. Correspondingly, the crop should be well known in different areas such as nursery management, stand management, and disease and pest control.

Southern pine stands have the potential to provide significant feedstocks for the biomass energy market (Scott and Tiarks 2008). Pine plantations have played a major role in the success of the forest products industry in the United States but specifically in the southeastern United States. The Southeast produces more industrial timber products than any other region in the world (Allen et al. 2005). This can be attributed to the Southeast climate and knowledge of intensive southern pine plantation management. The stands proposed for the energy plantations will predominately be composed of loblolly pine (*Pinus taeda*) planted at a density between 2,470 and 2,960 trees per hectare (TPH). Stands will be grown for 10 to 15 years, after which they will be harvested by the clear-cut method. Typically, stands at this age are not merchantable in today's market because of the small stem dimensions at this young age. The shorter rotations will be attractive to landowners looking for a quick return on investment when compared with other timber product types that require much longer rotations.

The problem lies in the logistics of felling the small-diameter stems and delivering them to the mill in a form that is economically feasible (Spinelli et al. 2006). Harvesting systems must be balanced for the characteristics of the forest, machine types, and intensity of the harvest to reflect the equipment's productivity (Akay et al. 2004). The main issue in the logistics process is the production costs associated with harvesting and handling the smaller stems.

In the Southeast, conventional whole-tree harvesting systems incorporate a feller-buncher to fell and bunch the trees while a rubber-tired grapple skidder drags the bundle (several bunches from the feller-buncher laid together) of trees to the loading deck (Wilkerson et al. 2008, Soloman and Luzadis 2009). These two machines are essential to the operation and must be productive for profitability. The stems are processed at the loading deck into logs, tree-length material (delimbed and bucked), or chips. In full tree systems, the residues such as foliage, limbs, bark, and tops are typically left on the loading deck or the skidder distributes the slash back into the harvested stand. These residues, along with the main bole of the tree, provide a large amount of low-cost biomass. Additionally, large amounts of logging residues could potentially hinder future operations such as site preparation (Visser et al. 2009). In an energy plantation setting, the conventional whole-tree harvesting system configuration will follow traditional harvesting techniques and the whole tree will be chipped. When chipping, the equipment should be utilized to maintain wood flow for the highly productive chipping application. Using a whole-tree chipping system aids the harvesting process in several areas.

Investment in biomass harvesting productivity research studies have been minimal since the late 1980s because of the low interest in biomass feedstocks, resulting in a gap in the understanding of production potential of modern harvesting machines. On the basis of an unpublished benchmarking study of a current harvesting system operating in south Alabama, the US Department of Agriculture Forest Service found that current felling and skidding costs range from \$5.44 to \$8.21 per green tonne (gt; Klepac 2011). The use of more specialized and technologically advanced equipment could lower the cost per unit. Also, it is essential that the harvesting system be composed of as few machines as possible to save money in maintenance and labor costs, moving costs, and reduced interference delays (Klepac and Rummer 2000). These systems do not need to be capital intensive to lower costs, but must have the flexibility and capability to be used for conventional round wood production in case of a biomass market collapse. Because of the high volume and low product value, a highly productive operation that uses an economy-of-scale approach must be developed. High production rates lower the fixed costs by spreading the costs over more units harvested. The system designed for this study is a high-speed, high-accumulation feller-buncher and a modified high-capacity rubber-tired skidder. A small case study was performed on this new equipment to analyze productivity and costs associated with owning and operating the machines.

Methods

Study site

Corley Land Services purchased a 4.4-hectare stand of 11-year-old timber on a site outside Monroeville, Alabama (Fig. 1) to demonstrate the system and implement a production study. The site was in the upper coastal plain and contained minimum slope. The stand used for the study represents an ideal energy plantation with the following characteristics: planted pine plantation, minimum of 1,482 TPH, age class between 10 and 15 years, and more than 40 hectares. The stumpage acquired had a 10 percent cruise implemented to get an accurate estimate of the timber inventory on the property. TPH, volume per hectare, total volume, average height, and species composition were determined from the cruise.

Production study

To investigate the feller-buncher engineered by TigerCat, a time study was implemented to calculate utilization and production capabilities. Several methods were used to collect data including using a stopwatch, a video recorder, and a MultiDat field recorder. The video was analyzed to obtain the number of trees per accumulation. Trees per accumulation can be described as the total number of trees severed and placed in the feller head before deployment into a bunch.

The productivity of the skidder was evaluated using the same three methods as the feller-buncher time study. First, a stopwatch was used to gather the cycle time for the skidder to leave the loading deck and return with a bundle of felled biomass. These cycle times were analyzed along with the distance traveled per cycle, which was obtained by the global positioning system function of the MultiDat recorder placed in the skidder. Last, video was taken to analyze grapple functions and estimate bundle size.

Fuel usage was another variable investigated. The machines were filled in the morning before the operation began. The machines' productive hours were measured throughout the day along with the scheduled hours set forth by Corley Land Services. At the end of the day, the

Figure 1.—Location of landing on the harvested plantation.

machines were filled with a pump equipped with a fuel meter to determine consumption levels.

Results and Discussion

Stand results

On the basis of the cruise data, the average total pine biomass was 195.68 gt/ha. Stand density was measured by TPH and basal area. Average TPH was 1,423, whereas the basal area was 27.60 m^2/ha. Other key descriptive stand statistics can be seen in Table 1.

From TPH and green tonnes per hectare, average tree size was formulated. On the basis of the data, average size resulted in 303 pounds or 0.14 tonnes per tree. This value was utilized in productivity calculations for both the feller-buncher and grapple skidder.

Production study

During the study period, a total of 186 feller-buncher cycles were measured and recorded, which consisted of the harvest of 1,404 trees. Descriptive statistics for the feller-buncher cycle times are listed in Table 2. The feller-buncher averaged 47 gt/productive machine hour (PMH) during the study.

The mean estimate for time per accumulation was 1.36 minutes (95% confidence interval = 1.30 to 1.42). A scatterplot shows the relationship between the number of trees harvested per accumulation and cycle time (Fig. 2). The figure illustrates a trend of increasing cycle time with the increase in trees harvested per accumulation. Although the harvesting head was designed to hold 15+ trees (15 cm diameter at breast height) per accumulation, crooked stems, branches, and operator visibility resulted in an average of 8 trees. The average payload per accumulation was estimated at 1.02 gt.

The feller-buncher productivity was estimated by developing a linear regression model. The response variable was cycle time, which was the time to harvest and release one accumulation of trees. The predictor variable was the number of trees harvested per accumulation. The number of trees per accumulation was proven to be significant using

Table 1.—Study site density and weight statistics.

					95% CI	
	Max.	Min.	Mean	SD	Lower	Upper
Basal area/ha (m^2)	30.70	21.92	27.60	2.67	25.69	29.50
Trees/ha	1,630.86	1,186.08	1,423.3	135.44	1,326.41	1,520.19
Weight/ha (tonnes)	220.03	150.02	195.68	22.75	179.40	211.95

Table 2.—Key statistics for feller-buncher cycles.

	n	Min.	Max.	Mean	SD
Accumulation (acc) time (min)	186	0.22	3.48	1.36	0.33
Trees/acc[a]	186	1	15	7.55	2.19

[a] Count of trees in feller-buncher head before dropped into bunch.

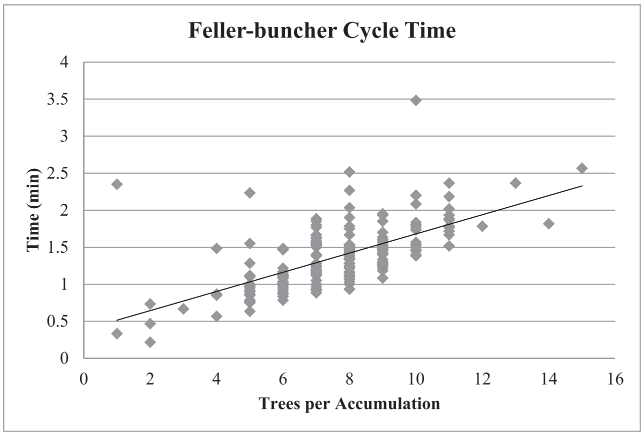

Figure 2.—Scatterplot of feller-buncher cycle time versus trees per accumulation.

Table 3.—Regression equation details for the feller-buncher cycle.

	Coefficients	SE	t stat.	P value
Intercept	0.300	0.138	2.17	0.031
Trees/accumulation[a]	0.144	0.018	8.21	<0.0001

[a] Count of number of trees cut and accumulated in the feller-buncher head before dropping the full accumulation in a bunch.

the t test approach. Table 3 represents the regression equation details.

Table 3 illustrates that the P value exhibited for the variability in tree accumulations is statistically significant ($\alpha = 0.05$). This indicates that the number of trees harvested per accumulation is statistically important and helps explain some of the variability in the feller-buncher cycle time. The fit of the prediction model reflects the variability associated with felling trees in small time increments.

Table 4.—Descriptive statistics for skidder delay-free cycles.

	n	Max.	Min.	Mean	SD
Cycle time (min)	59	9.25	1.1	3.92	1.88
Bunch (no.)[a]	59	3	1	1.68	0.502
Distance (m)	59	1,096	103	459	251

[a] Bunch (no.) = number of bunches per skidder cycle.

To determine skidder productivity, a stopwatch was used to record a total of 59 delay-free cycles (Table 4). From these observed cycles, a linear regression model was developed to estimate skidding cycle time. Figure 3 displays a scatterplot of the relationship between distance and cycle time. To achieve a good fit of regression model residuals, additional variables were needed. Distance was transformed and an interaction variable was needed. The interaction between skidding distance and number of bunches was added to the model to reflect a relationship observed in the field. Skidding cycles with few bunches were more often observed with shorter skidding distances. The distance variable was the most significant of the parameters, as shown in the respective P values calculated (Table 5).

Productivity was calculated for each delay-free skidding cycle. The average payload for the delay-free cycles was calculated to be 6.85 gt. Average productivity for the skidder resulted in 112.25 gt/PMH. The high productivity can be attributed to multiple factors in the study. First, the modified skidder has an oversized grapple, which gives it the ability to grapple larger payloads. Because the skidder can acquire more tonnage with each skid without increasing cycle time, the productivity is increased. Also, the tract offered many short skids, which minimize cycle time. This is confirmed by the regression developed that showed that distance was the most significant variable. Maximum productivity was achieved when the skidder grappled multiple bunches near the landing. In these cases, the skidder could produce 255.8 gt/PMH. This unusually high productivity was not typical in the study. In other situations,

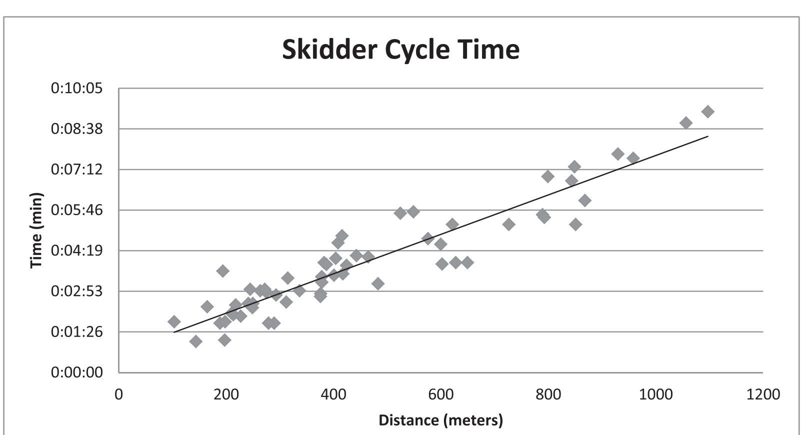

Figure 3.—Scatterplot showing delay-free cycle time and distance ($n = 59$ cycles).

Table 5.—Regression coefficients and statistical information for the skidder cycle model.[a]

	Coefficients	SE	*t* stat.	*P* value
Intercept	−0.296	0.68234	−0.43	0.6658
Distance (m)	0.00664	0.00223	2.98	0.0043
Distance (m)	0.00000348	0.00000143	2.42	0.0188
Distance × bunch (no.)[b]	−0.00210	0.00104	−2.02	0.0482
Bunch (no.)	1.176	0.41513	2.83	0.0065

[a] Total cycle time in minutes.

[b] Bunch (no.) = number of bunches per skidder cycle.

long skid distances reduced the productivity to 49.9 gt/PMH.

Economic analysis

The cost of each machine was estimated on the basis of production rates found in this study. All costs were input into a before-tax cash-flow spreadsheet developed by Dr. Robert Tufts of Auburn University (Tufts and Mills 1982).

The manufacturer's suggested retail price (MSRP) for a new 845D feller-buncher was acquired from Tigercat (Fig. 4). The initial expected capital investment for this specific machine is $495,080. This includes all extra components such as the biomass shear head ($65,945), upgrade on tracks ($5,590), and the Cummins interim Tier IV engine ($18,750). The 630D skidder MSRP was $330,000 (Fig. 5). For the purpose of this study, a $50,000 down payment was paid on both pieces of equipment with the rest of the investment financed. Escambia County Bank was contacted for the finance rate and length of loan for the both machines. A typical annual percentage rate for each machine would be 7 percent for 60 months (B. Cox, personal communication, 2012). Insurance and property taxes were combined as a percentage for the analysis. The insurance (fire, theft, and vandalism) was set at 4 percent and the property tax rate used was 2 percent.

All variable costs associated with operating the feller-buncher and skidder were used in the cash-flow model. Fuel use was determined on the basis of the detailed records maintained by Corley Land Services. The feller-buncher used approximately 9.9 gallons of off-road diesel per productive/operating hour. The skidder consumed an average of 6 gal/PMH. Off-road diesel was priced during the study at $3.80/gal. Lube cost was determined as a percentage of fuel usage (Brinker et al. 2002). These costs were combined in the analysis for a resulting figure of $54.10/PMH for the feller-buncher and $39.16/PMH for the skidder. Repair and maintenance costs were determined using the Caterpillar Performance Handbook. Total repair and maintenance costs were estimated at $16.00/PMH for the feller-buncher. The maintenance and repair rate used for the skidder was $10.00/PMH. If the assumption error is 50 percent, the overall annual equivalent cost (AEC) of the machine had a minimal change (<1%). Major repairs or replacements were also included into the analysis. The two main components that would need to be replaced during the life of the feller-buncher would be the undercarriage and engine. The feller-buncher engine would need to be rebuilt at year 5 at a cost of approximately $15,000 (J. Robinson, diesel mechanic, personal communication, 2011). The undercarriage would have a low rebuild at ages 3 and 9 years. Also, it would have a major rebuild of the undercarriage at age 6. Both rebuilds include track replacement. Tires (at $8,000 every 3 yr) would be the main component with a replacement schedule for the skidder. The labor rate was set at $15.00/h with 33 percent fringe benefits for the operator. An inflation rate of 3 percent was used on labor, maintenance, and fuel. A utilization rate of 75 percent was used for the analysis for the feller-buncher

Figure 4.—Tigercat 845D harvesting study area.

Figure 5.—Tigercat 630D with 635 grapple skidding timber.

instead of the measured 86 percent. This is the maximum that could be seen for the machine owing to expected operational delays. However, the skidder utilization rate of 32 percent was used because it was limited by the feller-buncher and deck delays.

The AEC is the cost to own and operate a piece of equipment over its entire life span while taking into account the time value of money (Tufts and Mills 1982). For the purpose of this study, the feller-buncher and skidder were placed on a 10-year or 20,000 scheduled machine hour life span. Assuming this 10-year span, the feller-buncher has an AEC of $275,066.94. By applying the 47 gt/PMH found in the study to the economic analysis, the feller-buncher could produce a ton of wood for $3.85/gt. The skidder cost-analysis model returned an AEC of $141,323 over the 10-year life span. By applying the productivity of 112 gt/PMH and a utilization rate of 32 percent for the skidder (matching the production from the feller-buncher, which is the limiting machine for balancing the harvesting system), the 630D can skid wood for $1.95/gt. Thus, the two machines combined can harvest and skid wood for $5.80/gt before tax in an energy plantation setting.

To better understand the system under government tax rates, an after-tax analysis was performed while assuming the same parameters. The marginal tax rate used in the analysis was 25 percent, which was for a married sole proprietor owner tax-filing status and having a joint income of $70,700 to $142,700 (CCH 2011). This rate was used because the logger must net this amount of income to pay for the machinery. After applying the federal tax rate, the feller-buncher has an AEC of $206,984 and a cost per green tonne of $2.90. The skidder's AEC decreased to $106,559 and cost per tonne decreased to $1.47. The decrease in cost for both machines reflects a reduction in tax liability owing to expenses. These deductions are applied to expenses and interest payments.

This study was completed after a fairly short period of time for the operators to get comfortable with the equipment. In addition, there were several challenges for the feller-buncher operator, such as significantly crooked trees (hurricane damage) and various distractions. With greater performance from expected learning-curve improvements (Purfurst 2010), it was estimated that production from the feller-buncher could increase from 71,645 to 96,446 gt/yr. The underutilized skidder can easily process the additional volume and the greater system production will decrease the unit costs by $1.20/gt, delivering the harvested material to the landing for $4.60/gt.

Conclusions

In this study, a Tigercat 845D feller-buncher equipped with a biomass shear head was used to harvest and a modified 630D skidder was used to skid the whole trees to the deck. The analysis of the machines took place on an 11-year-old pine plantation near Monroeville, Alabama. The 4.4-hectare tract took a total of 22.5 hours to harvest. Production and cost numbers were calculated for each machine working separately. These numbers were further analyzed for prospective system improvements.

The feller-buncher averaged 47 gt/PMH during the study. Crooked trees, operator inconsistency, and lack of experience hindered production. The before-tax annual equivalent cost for the feller-buncher was determined to be $275,067/yr. By applying the productivity observed in this study, the cost per green tonne over a 10-year life span would be $3.85. Skidder production was determined to be 112 gt/PMH. The annual equivalent cost for the skidder was determined to be $141,323. By applying the productivity rates observed in this study, the cost per green tonne over a 10-year life span would be $1.95.

The estimated felling and skidding cost for the two machines in an energy plantation setting is $5.80/gt with a production level of 71,645 gt/yr. With improved feller-buncher productivity as a result of operator experience, production levels could be increased to 96,446 gt/yr. This would decrease costs for felling and skidding by $1.20/gt, which would have huge implications on the viability of the system.

This study indicates that the modified equipment met the need of a highly productive system for harvesting young southern pine energy plantations. In addition, the system is flexible in that it can operate in stands with traditional forest product removals to address market fluctuations.

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