# Harvesting Small Trees for Bio-Energy

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**ABSTRACT:** A conventional whole-tree logging operation consisting of 4-wheeled and 3-wheeled saw-head feller-bunchers, two grapple skidders and a chipper that produces dirty chips was monitored across several stands and machine performance evaluated. Stands were inventoried to determine density, volume, and basal area per acre and will be used to relate machine performance to stand characteristics. Costs per hour and per ton will be calculated for each function and a total system cost will be determined for the conventional system. These costs will be used to compare the conventional system to a newly designed system for harvesting trees for bio-energy.

Keywords: harvesting, biomass, bio-energy, productivity.

## INTRODUCTION

The US consumes more fossil fuel than any other country and most (51%) of these petroleum products are imported (U.S. EIA, 2011). The federal government has focused R&D and policy initiatives to address the growing dependence on foreign oil and the reliance on finite fossil energy supplies. In 2009 the Department of Energy offered a funding opportunity (DE-FOA-0000060) requesting proposals to develop supply systems that could handle and deliver high volumes of renewable biomass. The overall objective of this program is to stimulate the development and commercial deployment of systems for harvest, collection and processing that will support the rapid expansion of a liquid biofuels industry. Five proposals were selected, three working on systems for agricultural and perennial crops and two addressing woody biomass. A consortia organized by SUNY College of Environmental Science and Forestry, Syracuse NY is working on developing improved short rotation willow systems. Another team led by Auburn University is funded to develop a woody biomass system around intensive southern pine management. Development of a new harvesting system requires benchmarking of current technology to serve as a reference for any improvements attributed to the new technology. This report describes benchmarking evaluations for the pine feedstock project.

The Auburn University High Tonnage project is built around the assumption that a likely feedstock for energy production in the US South would be intensively grown pine. Loblolly pine can achieve yields of 22.4 Mg $ha^{-1}$ $yr^{-1}$ (Munsell and Fox 2010). Assuming a 15-yr rotation, 90M tonnes (green) could be sustainably produced each year from a total of about 4M ha dedicated to intensive pine management. The new mechanized harvesting system (Rummer et al. 2010) will be optimized for this type of stand. Trees would be relatively uniform (diameter and height) and closely spaced.

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The first phase of the project included evaluation of the cost and performance of currently available equipment. Typical southern pine harvesting systems employ wheeled feller-bunchers with sawheads and grapple skidders to move wood to roadside. When biomass is recovered as part of southern pine harvesting a roadside chipper may be added to turn small material into fuel chips before trucking. Clean chips can be produced by the addition of a flail debarker to the system.

This paper discusses methods used to evaluate current harvesting systems operating in small-diameter stands and presents productivity results for felling and skidding components, in addition to stand conditions of the study sites.

## METHODS

### Operation

In May 2010 personnel from the Forest Operations Research Unit in Auburn, Alabama began monitoring two biomass harvesting operations in south Alabama. One operation produced dirty chips while the other produced clean chips. Electronic activity recorders were placed in each machine on both operations to measure total productive machine hours spent on a site. Detailed time-and-motion studies were conducted on the dirty chip operation where felling and skidding functions were evaluated.

The two operations worked mainly in thinnings but occasionally performed clearcut prescriptions. For thinning prescriptions, a fifth row removal with thinning within the stand was performed. On the dirty chip operation, row removal, or corridor cutting, was mainly done with a Hydro-Ax 470[2] drive-to-tree feller-buncher with a circular saw head. Thinning within the stand was done with a Valmet 603 three-wheeled feller-buncher also equipped with a circular saw head. Bundles were built in the corridors by the Hydro-Ax and then skidded to the landing by a John Deere 648 and a CAT 525 grapple skidder. After bundles from a corridor were skidded, the Valmet 603 followed up by thinning within the stand. These bundles were also built in the corridors and then skidded. At the landing trees were feed into a Woodsman 334 chipper which blew the material into chip vans. Two clearcut stands were visited where one utilized the Valmet 603 while the Hydro-Ax was being repaired. The other clearcut stand utilized a Timber King drive-to-tree feller-buncher while the Hydro-Ax was working on a thinning operation.

### Study Sites

To determine stand conditions where the equipment was working, fixed radius circular plots were installed on five sites. Either 0.04-ha or 0.02-ha plots were installed, depending on stand density. Within each plot, all trees from a 2.5-cm Dbh class and larger were measured for Dbh

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[2]The use of trade or firm names in this publication is for reader information and does not imply endorsement of any product or service by the U.S. Department of Agriculture or other organizations represented here.

and species recorded. Tree heights were measured on every 5th pine tree using a hypsometer. Hardwood tree heights were occularly estimated to the nearest 1.5 m on all hardwoods within a plot. Regression equations were developed (SAS, 1988) to predict total height as a function of Dbh for trees where total height was not measured. Total-tree green weights of pine trees 15.2 cm Dbh and smaller were calculated using equations developed by Phillips and McNab (1982). Weights for pine trees larger than 15.2 cm Dbh were estimated using appropriate regression equations (Clark and Saucier, 1990). Total-tree green weights of hardwoods were estimated using regression equations (Clark and others, 1985).

Post inventory assessments were completed on each thinned stand for determining percent removals. Rectangular plots 0.1-ha in size were installed in all except one stand where 0.04-ha plots were used. Plots were installed so that the two long sides were each centered in a cut corridor and ran parallel with the corridor. This insured both the corridors and stand area were appropriately represented in the plot.

**Felling**

Feller-bunchers were timed while performing clearcut, corridor and thinning cuts. When possible, Dbh was measured with calipers on trees to be felled and species recorded. A numbered card was attached to each measured tree. Total tree heights were estimated from regression equations developed from cruise data. Machines were recorded on video as they worked thru a study area and tree numbers were verbally recorded. Some sites were too dense for attaching numbered cards to trees and in these cases tree size and species were visually estimated and recorded. Elemental times of interest included move to first tree, accumulation, move-to-dump, and dump defined as follows:

*Move to first tree* began after trees in the head were dumped and the tires began rotating. The element ended when the saw reached the first tree.

*Accumulation* time began when the saw reached the first tree to cut and included all cutting and moving to each tree. Accumulation time ended after the last tree was cut and the tires started rotating for moving to dump.

*Move-to-dump* time included travel from the location of the last tree cut to the location where the feller-buncher was building bundles. The element began when the last tree was cut and tires started rotating and ended when the head started to tilt forward to dump.

*Dump* time was the time required to dump all trees in the head and started when the head began to tilt forward and ended when the head was empty and the tires started rotating to start moving to the first tree again.

Video tapes were time coded and analyzed using The Observer Video Pro software (Noldus Information Technology, 1997). Each time element was defined with a letter code and during viewing the appropriate code was entered at the end of each element to mark its termination.

Individual elements were summed to get total cycle time. Tree volumes for each cycle were calculated and summed to get total volume per cycle and tons per hour.

**Skidding**

To estimate skidder productivity variables of interest included cycle time, turn volume, and travel distances. Stopwatches were used to time cycle elements which included travel empty, position, grapple, intermediate travel, travel loaded, and ungrapple.

*Travel empty* time was the time required for the skidder to travel from the landing to the woods. The element started when the skidder ungrappled its load at the chipper and the tires began forward motion and ended at the point where the skidder stopped before backing up to grapple a bundle.

*Position* time included the time to back up to a bundle and started when the tires began reverse rotation and ended at the bundle when the tires stopped rotating.

*Grapple* time included the time required to secure a bundle in the grapple for transport to the landing. The element started when the tires when the tires stopped moving at the end of the position element and ended when the bundle was clamped in the grapple and forward motion started.

*Intermediate travel* included travel between bundles and occurred for cycles where the skidder grappled more than one bundle for transport. The element started after the previous bundle was grappled and the tires began forward motion and ended when the skidder reached the next bundle and rotation of the tires stopped.

*Travel loaded* time included traveling from the woods to the landing once a load was obtained in the grapple. The element started when grappling was complete and the tires began forward motion and ended at the chipper when forward motion stopped or when the grapple started to open.

*Ungrapple* time included placing skidded trees in a pile next to the chipper. The element began when either forward motion of the tires ended or when the grapple started to open and ended when the load was dropped.

Turn volumes were determined by measuring Dgl (Diameter at ground line) and sampling Dbh of trees within a bundle. Species of each tree was also recorded. Regression equations were developed to predict Dbh from Dgl for both pine and hardwood where Dbh was not accessible for measurement. The model to predict Dbh as a function of Dgl for pine had an R-square value of 0.94 and a C.V. (Coefficient of Variation) of 10.73 percent. The hardwood model had an R-square value of 0.87 with a C.V. of 13.52 percent. Total heights for both species were estimated from regression equations developed from the cruise information. The model to predict total height as a function of Dbh for pine had an R-square value of 0.66 with a C.V. of 16.71 percent.

The model to predict total height as a function of Dbh for hardwood had an R-square value of 0.68 with a C.V. of 28.98 percent. These variables were then used in appropriate regression equations to predict total-tree green weights of pine trees under 15.2 cm Dbh (Phillips and McNab, 1982), pine trees over 15.2 cm Dbh (Clark and Saucier, 1990), and hardwood trees (Clark and others, 1985). Travel empty, intermediate travel, and travel distances were measured with a distance wheel.

## RESULTS

### Study Sites

Detailed time study data were collected on six sites during the initial benchmarking phase; two clearcut sites and four thinning sites. Inventory data were collected on all sites except one clearcut. Mean Dbh of pine and hardwood combined among all five sites was 10.9 cm. Mean Dbh of pine and hardwood was 12.9 cm (n = 1561) and 6.9 cm (n = 758), respectively.

Stands ranged in initial stand density from 1699 trees $ha^{-1}$ to 4202 trees $ha^{-1}$ and ranged from 199 to 524 gt (green tonnes) $ha^{-1}$ (Table 1). These stand conditions were assumed to bracket potential conditions in intensively grown energy plantations of the future. The prescription removed 66 percent of the trees and 57 percent of the volume for the thinned stands. Basal area reduction averaged 59 percent. Most of the trees were in the 5.1 and 10.2 cm classes (Figure 1).

**Table 1. Stand densities and volume levels.**

| Site | Trees $ha^{-1}$ | | | Basal area ($m^2$ $ha^{-1}$) | | | Green tonnes $ha^{-1}$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Initial** | **Residual** | **Removal[1]** | **Initial** | **Residual** | **Removal** | **Initial** | **Residual** | **Removal** |
| **1** | 2891 | 802 | 72.3 | 29 | 10 | 65.5 | 235 | 85 | 63.8 |
| **2** | 1699 | 435 | 74.4 | 37 | 15 | 59.5 | 305 | 130 | 57.4 |
| **3** | 4202 | 953 | 77.3 | 63 | 15 | 76.2 | 524 | 130 | 75.2 |
| **4** | 4156 | 2533 | 39.1 | 29 | 19 | 34.5 | 202 | 134 | 33.7 |
| **5** | 2509 | 0 | 100 | 27 | 0 | 100 | 199 | 0 | 100 |

[1]Percent

**Figure 1. Tree size distribution for five sites combined.**

### Felling

The Hydro-Ax 470 feller-buncher was observed for 37 cycles while thinning and 92 cycles performing corridor cuts. The Valmet 603 was evaluated for 125 thinning cycles and 40 cycles working in a clearcut. The Timber King feller-buncher was observed for 34 cycles while operating in a clearcut.

Move distance to the first tree cut after a dump element and distance traveled to the dump pile were estimated from video tape by counting the number of revolutions traveled by the wheel of the feller-buncher as indicated by a white stripe painted on the tires or noting the number of tree lengths traveled. Productivity while thinning averaged 20.6 gt $PMH^{-1}$ (green tonnes per productive machine hour) for the Hydro-Ax and 15.5 gt $PMH^{-1}$ for the Valmet. Cutting out corridors resulted in a productivity of 44.5 gt $PMH^{-1}$ for the Hydro-Ax. The Timber King feller-buncher averaged 67.2 gt $PMH^{-1}$ while clearcutting.

General Linear Models (SAS, 1988) was used to model feller-buncher cycle time for the Hydro-Ax performing corridor cutting and thinning and the Timber King performing clearcutting. Move to first tree and move to dump distances were used as independent variables to model the dependent variables of move to first tree and move to dump time. A dummy variable for the Hydro-Ax was used to distinguish between corridor cutting and thinning. Number of stems was used to model accumulation time. Mean dump time was used in the equation for total cycle time since it was mainly constant and confidence limits at the 95 percent level specified.

Move to first tree distance was found to be significant at predicting move time ($p<0.0001$) and averaged 13.4 m for the Hydro-Ax while corridor cutting and 6.3 m while thinning. The Timber King averaged 11.4 m while clearcutting. The type of function (corridor or thinning) the Hydro-Ax was performing was not significant. Regression equations for predicting move time to first tree are as follows:

<u>Hydro-Ax:</u>

*Move to first tree time (sec) = 0.897377*MoveDist + 2.56651*

*MoveDist = travel distance to first cut tree (m)*

$R^2 = 0.67$; *C.V. = 39.28; n = 117*

<u>Timber King Clearcutting:</u>

*Move to first tree time (sec) = 0.9470189*MoveDist + 1.596949583*

*MoveDist = travel distance to first cut tree (m)*

$R^2 = 0.97$; *C.V. = 16.25; n = 34*

The number of stems accumulated in the head were significant ($p<0.0001$) for both the Hydro-Ax and Timber King feller-bunchers for predicting accumulation time. Function was also significant for the Hydro-Ax ($p<0.0001$) and regression equations are shown below.

Hydro-Ax:

*Accumulation time (sec) = 3.99303*Stems + 20.89169*Func + 10.86906*

*Stems = No. of stems accumulated during a cycle*

*Func = 0 for corridor; 1 for thinning*

$R^2 = 0.72$; *C.V. = 32.44; n = 129*

Timber King Clearcutting:

*Accumulation time (sec) = 4.978090120*Stems – 1.746217445*

*Stems = No. of stems accumulated during a cycle*

$R^2 = 0.61$; *C.V. = 39.13; n = 34*

Move to dump distance was found to be significant at predicting move to dump time for both machines ($p<0.0001$) and averaged 12.3 m for the Hydro-Ax while corridor cutting and 5.8 m while thinning. The Timber King averaged 8.5 m moving to dump while clearcutting. Function was also found to be significant for the Hydro-Ax ($p=0.0376$). Equations for predicting move to dump time are as follows:

Hydro-Ax:

*Move to dump time (sec) = 0.6676721*Mtdd – 2.08534*Func + 4.67663*

*Mtdd = travel distance from last tree cut to dump pile (m)*

*Func = 0 for corridor; 1 for thinning*

$R^2 = 0.54$; *C.V. = 35.66; n = 119*

Timber King Clearcutting:

*Move to dump time (sec) = 0.7793195*Mtdd + 2.515319618*

*Mtdd = travel distance from last tree cut to dump pile (m)*

$R^2 = 0.80$; *C.V. = 22.92; n = 34*

Dump time for the Hydro-Ax was statistically the same between thinning and corridor cutting using Duncan's Multiple Range Test (SAS, 1988) and averaged 3.95 sec. Confidence interval limits at the 95 percent level (t=2) were calculated for dump time and ranged from 3.55 to 4.34 sec. Dump time for the Timber King averaged 2.39 sec. Confidence interval limits at the 95 percent level (t=2) ranged from 2.11 to 2.67 sec. Therefore, the true value for dump time for each machine has a 95 percent chance of residing within its confidence interval. Table 2 summarizes time study data for each machine and function.

**Table 2. Feller-buncher production for different functions.**

| Function | Machine | Mean | | | | |
|---|---|---|---|---|---|---|
| | | N | Dbh/accum (cm) | Trees/ accum | Time/ cycle (sec) | Green tonnes $PMH^{-1}$ |
| **Thinning** | Hydro-Ax | 37 | 7.4 | 13.8 | 109.3 | 22.7 |
| | Valmet | 125 | 7.6 | 9.6 | 81.3 | 15.4 |
| **Corridor** | Hydro-Ax | 92 | 13.2 | 6.9 | 70.4 | 44.5 |
| **Clearcut** | Timber King | 34 | 15.2 | 5.7 | 51.2 | 67.2 |
| | Valmet | 40 | 12.2 | 6.9 | 63.6 | 44.3 |

## Skidding

The John Deere 648 grapple skidder was observed for 30 observations across two sites. Standard operation of the skidder included traveling to an area where bundles built by the feller-buncher were ready for transport to the landing, stopping, and then backing up to a bundle for grappling. The operator quickly determined the number of bundles that could be grappled during a particular cycle by scanning what was on the ground. When multiple bundles were combined for skidding the operator traveled in reverse past the number of bundles that were planned for grappling and worked toward the first bundle, combining bundles on the way out.

The skidder averaged 29.6 gt $PMH^{-1}$ and had a mean one-way distance of 680 m. Travel empty distance averaged 346 m and ranged from 162 m to 497 m. Travel loaded distance averaged 334 m and ranged from 165 m to 610 m. Payload averaged 3.1 gt with 69.3 stems $cycle^{-1}$. A summary of measured skidder parameters is shown in Table 3.

Table 3. Summary of skidder production data.

| Variable | N | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| **Travel empty (min)** | 30 | 2.03 | 0.824 | 0.25 | 3.45 |
| **Position & grapple (min)** | 30 | 1.36 | 0.564 | 0.28 | 2.51 |
| **Intermediate travel (min)** | 30 | 0.90 | 0.669 | 0.00 | 2.56 |
| **Travel loaded (min)** | 30 | 2.39 | 1.342 | 0.58 | 5.64 |
| **Ungrapple (min)** | 30 | 0.38 | 0.179 | 0.14 | 0.81 |
| **Total time (min)** | 30 | 7.07 | 2.276 | 1.78 | 11.05 |
| **Total distance (m)** | 30 | 680 | 167.3 | 326 | 954 |
| **No. of bundles** | 30 | 2.3 | 1.12 | 1.0 | 5.0 |
| **No. of stems** | 30 | 69.3 | 36.30 | 21 | 200 |
| **DGL (cm)** | 30 | 11.4 | 2.39 | 6.6 | 20.3 |
| **DBH (cm)** | 30 | 8.1 | 2.03 | 4.1 | 15.2 |
| **Distance between bundles (m)** | 11 | 66.7 | 50.12 | 20 | 181 |
| **Tonnes cycle$^{-1}$** | 30 | 3.13 | 1.144 | 1.35 | 6.07 |
| **Tonnes PMH$^{-1}$** | 30 | 29.6 | 13.36 | 10.3 | 55.1 |

To model skidder cycle time General Linear Models Procedure (SAS, 1988) was used. Travel empty and loaded distances were used as independent variables to model the dependent variables of travel empty and travel loaded time. Distance between bundles was used to model intermediate travel time. Position and grapple and ungrapple times were fairly constant so means were used in the model.

Travel empty distance was found to be significant at predicting travel empty time ($p<0.0001$).

The equation for predicting travel empty time was

$$\textit{Travel empty time (min)} = 0.0076197 * TEDist - 0.6073183873$$

$$TEDist = \textit{travel empty distance (m)}$$

$$R^2 = 0.81;\ C.V. = 18.20;\ n = 30$$

The time required to position and grapple a load was found to be a constant and averaged 1.36 min.  Confidence interval limits at the 95 percent level (t=2) were calculated for position and grapple time and ranged from 1.15 to 1.57 min.

Distance between bundles was found to be fairly significant at predicting intermediate travel time (p=0.0071).  This model had a lower R-square value than for travel empty time which is probably a result of the low sample size.  The equation for predicting intermediate travel time was

*Intermediate travel time (min) = 0.00735*Distbund + 0.5438016119*

*Distbund = distance between bundles (m)*

$R^2 = 0.57$; *C.V. = 32.49; n = 11*

Travel loaded distance was found to be significant at predicting travel loaded time ($p<0.0001$). The equation for predicting travel loaded time was

*Travel loaded time (min) = 0.0121066*TLDist – 1.651069636*

*TLDist = travel loaded distance (m)*

$R^2 = 0.76$; *C.V. = 27.80; n = 30*

The time required to ungrapple a load at the landing was also found to be a constant and averaged 0.38 min.  Confidence interval limits at the 95 percent level (t=2) were calculated for ungrapple time and ranged from 0.31 to 0.45 min.

## DISCUSSION

Harvesting southern pines for energy production will generally mean harvesting smaller diameter trees.  In traditional forest management this material might be produced in an early thinning or by treating overstocked even-aged stands.  If energy markets develop, intensively managed pine stands may be harvested on shorter rotations with clearcut operations.  Conventional equipment (feller-bunchers and skidders) can perform these operations however costs are known to increase as piece size and diameter get smaller.

The system observed in this study used smaller wheeled feller-bunchers appropriately matched to smaller trees.  Felling productivity was most affected by the type of cut with clearcutting more than twice as productive as thinning.  This is primarily due to the extra time per tree required to select and maneuver in the stand.  Assuming a standard machine rate of $100/PMH, the felling cost would be about $5.50/green tonne in thinning and only $1.43/green tonne in clearcutting.

As expected, skidding productivity was simply a function of distance traveled and payload.  With the small trees in these stands payload ranged from 21 to 200 stems.  This required the operator to collect on average 2.3 bunches to make up a load. Assuming a standard machine rate of $100/PMH, the skidding cost from either thinning or clearcutting would be approximately $3.30/green tonne.

This benchmarking analysis suggests that intensive pine plantation clearcutting will reduce feedstock costs by almost $3.30/green tonne over biomass produced from thinnings. Further cost reductions may result from improvements to feller-buncher cycle time or skidder payload.

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