Optimizing the Use of a John Deere Slash Bundling Unit in a Tree-Length Logging System

by

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Abstract

The purpose of this project was to explore an avenue that could supply a source of readily available energy in Southeastern forested lands. Typical, southern harvesting operations consist of whole tree harvesting in which trees are felled, and then skidded to a landing. After processing, limbs and tops are usually either deposited over the landscape or piled in wind rows. John Deere currently manufactures a mobile slash bundler which harvests the otherwise non merchantable material and maximizes the marketability of the entire tree. In an effort to reduce costs, maximize efficiency, and implement the bundler in a tree-length harvesting operation, a prototype trailer-mounted slash bundling system was designed and tested. The proposed slash bundling operation is capable of producing 15.9 to 17.2 tons per hour of compressed residue logs without negatively impacting a logger's roundwood production. Bundled material can be produced for approximately \$10 to \$11/ton and could be delivered to a consuming mill within 50 miles for \$19 to \$21/ton. During four months of storage, bundled material lost approximately 156 lbs., and decreased in moisture content by 16.8% (wet basis) through evaporative and transpirational drying.

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List of Abbreviations

AEC	Annual Equivalent Cost
BDT	Bone Dry Ton
CRL	Compressed Residue Log
CSI	Cutting Systems Incorporated
DBH	Diameter at Breast Height
lbs	Pounds
PMH	Productive Machine Hour
SMH	Scheduled Machine Hour
TMC	Total Machine Control

I. Introduction

With instability surrounding the price and source of imported energy streams, some focus has been drawn to biomass as a feedstock for energy production. Nearly 370 million dry tons of biomass are available annually on a sustainable basis from forest-derived resources in the United States (Perlack et al 2005). A large percentage of the forest resources, available as a biomass feedstock, are in the form of forest residues (Perlack et al 2005, Perez-Verdin et al 2008). Forest residue availability is concentrated in the Southeast and South Central regions of the United States (Gan and Smith 2006). Such huge untapped energy sources have been brought to light in recent days and harvesting equipment can make the resource available. Although technologies and markets for such innovative practices have not yet matured, the purpose of this project was to explore a system that could supply a source of readily available energy in southeastern forested lands.

Typical southern timber harvesting operations consist of whole-tree harvesting, in which trees are felled with a feller-buncher and then transported to a logging deck using a grapple skidder (Wilkerson et al 2008). Limbs and tops are removed from the tree at the deck. Harvesting operations produce such large amounts of slash that it hinders not only harvesting operations, but subsequent site prep and planting operations (Visser et al 2008). By harvesting these vast amounts of limbs, tops, and foliage, site prep costs will be reduced and the planting area will be increased (Westbrook et al. 2007). As the forest biomass market grows, site prep and planting impacts could prove to be one of the many fringe benefits.

Loose slash transportation is not an economically viable option because of its low bulk density (McDonald et al 1995). In-woods chipping has long been the answer for forest residue harvesting. Recent studies suggest that to maximize the effectiveness of slash harvesting, transportation, and processing, the logging residue could be compacted to increase its density (Rummer et al 2004, Jylha and Laitila 2007). Condensing slash into a compressed residue log (CRL) is a relatively new slash harvesting technology which could prove advantageous in harvesting, transportation, and storage when compared to chipping.

John Deere’s B380 bundling unit, shown in Figure 1, is designed to harvest forest residues. The bundler unit is operated by feeding slash into a set of four compression feed rollers (Martin 2008). Two sets of compression arms then further compress the slash while sliding the bundle forward. A rotating twine magazine then fastens the bundles with bailing twine. At a predetermined length, the automated cutting saw severs the compressed slash resulting in a slash bundle sometimes referred to as a compressed residue log.

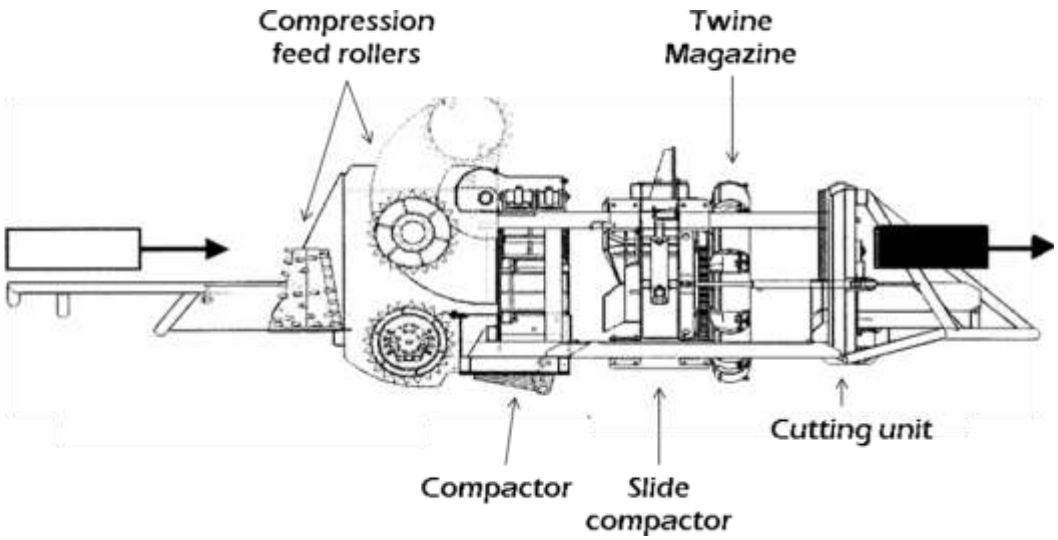

Figure 1. John Deere B380 bundling unit (Picture courtesy of John Deere)

The addition of a stationary trailer-mounted slash bundler in a southern logging system would condense slash material and create a merchantable product potentially creating an additional source of revenue for loggers. The log shaped slash bundles produced by the unit are easily handled by existing equipment (Wilkerson et al 2008, Johansson et al 2006). Because of their uniform shape and density, chipping and grinding efficiencies could increase between 10-30% when processing bundled material (Schmidt 2010).

Transportation and storage are other facets in which bundling could potentially excel over in-woods chipping. Bundles are very conducive to transportation via log trailer (Rummer et al 2004, Johansson et al 2006) or by rail car (Saarenmaa 2005, Andersson 2000). Log trailers are capable of navigating much rougher terrain than chip vans which have much less ground clearance.

Storage is another facet of a biomass supply chain in which bundling has an advantage. Stored, chipped material must be used within a much shorter time frame than bundled material. Microbial activity can cause quick rotting and even self ignition in chipped material (Johansson et al 2006). Bundles are favorable in relatively long term storage which can assist in energy planning and inventory (Cruchet et al 2004, Rummer et al 2004, and Johansson et al 2006). Bundled material air dries while in inventory and in ideal conditions can lose a significant amount of moisture (Steele et al 2008).

Favorable storage, transportation, and harvesting attributes associated with bundling could prove beneficial in a feedstock supply chain for bioenergy markets. A recent study in France indicated that there could be advantages to a lower cost trailer-mounted bundling unit in which slash was concentrated at a deck (Cruchet et al 2004). Because bundling systems have promise in forest residue harvesting, researchers will investigate a prototype trailer-mounted slash bundling system, which can be easily integrated into a tree-length harvesting operation. Field trials will be executed, a production study will be performed, economics will be analyzed, and many questions surrounding this new piece of equipment will be answered.

II. Objectives

The objectives of this project were to:

- Mount a John Deere B380 bundling unit on a motorized trailer.
- Design a deck configuration for the bundling system.
- Conduct a productivity study of the prototype trailer-mounted bundling unit.
- Perform economic analyses of the prototype bundling system.
- Determine moisture content loss of bundled material over a period of time.

III. Literature Review

3.1 Slash Bundler Productivity

The B380 is a proven forest biomass harvesting technology currently mounted on a forwarder and marketed by John Deere as the “1490D Energy Wood Harvester”. The 1490D shown in Figure 2 is typically used in conjunction with cut-to-length logging in which trees are processed at the stump (Rummer et al 2004). Limbs and tops scattered throughout the site are loaded into the feed rollers, compressed, fastened with twine, and cut at predetermined lengths.

Figure 2. John Deere 1490D Slash Bundler

The functions of the 1490D are controlled via the TMC (Total Machine Control®). Electrical power and hydraulic demands for the bundler are met by the 1490D’s onboard batteries, engine, and hydraulic systems. The Energy Wood

Harvester’s loader arm creates a totally self contained bundling operation which serves to condense logging residues spread throughout a site.

Past studies on the forwarder-mounted bundler have shown varying productivity results. The USDA Forest Service performed an operational performance analysis of the slash bundler in Idaho, Oregon, Montana, and California (Rummer et al 2004). The Forest Service’s main goal was to reduce fuel levels on the lands to thwart the threat of wildfires. Material bundled ranged from logging slash to small diameter trees. In Idaho City, Idaho, with large amounts of readily available slash, the bundlers highest productive output was 24, ten-foot bundles per hour. Production levels ranged from five to twenty-four bundles per hour depending on the sites slash density and slash arrangement.

Another study of the 1490D Slash Bundler was performed in Arkansas by a group in the summer of 2006 (Patterson et al 2008). The analysis consisted of four case studies performed on four different sites. A different harvest regime was performed on each site. The first site consisted of a mature stand of loblolly pine clear cut harvested by conventional logging equipment. Logging residue was piled along the roadside to increase accessibility. The slash bundler produced 22.3 ten foot bundles per hour with an average cycle time of 2.69 minutes.

Site 2 was a twenty-six-year-old pine plantation undergoing a second thinning by the same harvesting system. Limbs and tops were piled at the deck and the slash bundler was able to produce 31.3 ten-foot bundles per hour. A production rate of 36.1 ten-foot bundles per hour was achieved on Site 3 which was a stand of eleven-year-old loblolly pine which had recently been thinned.

The fourth site in the study was a thinning operation in 17-year-old loblolly pine plantation. Cut-to-length harvesting equipment was utilized on the site which meant that the 1490D had to travel in-woods to gather material. The resulting 13.8 ten foot bundles per hour reflect the operational differences. The average weight of the ten foot bundles for sites one through four are 883, 916, 950, and 957 lbs. respectively (Patterson et al 2008).

John Deere published production levels in a presentation of a study done in France showing 2006 production numbers (Martin 2008). Study conditions are unknown, but the study in France reported 18 to 25 bundles per hour was feasible with the 1490D. The study noted that these production rates could be achieved with an experienced operator and appropriate site planning.

Cuchet et al (2004) published results from five different bundling sites in France. Bundling was performed by an earlier model of the John Deere 1490D. Production levels ranged from 11.4 to 23.9 bundles per hour. Bundle weights ranged from 756 lbs. to 948 lbs. with productivity ranging from 4.5 to 8.5 tons/hr. In Nordic conditions, bundler models with the same technology were capable of producing 18.1 ten-foot bundles per hour (Karha and Vartiamäki 2006).

The variability in bundler production levels was due to a number of things, such as, operator experience, slash availability, and slash orientation.

3.2 Bundling Economics

Two studies on the costs associated with bundling in the United States have been completed. Rummer et al (2004) evaluated forest residue removal using the

Timberjack/John Deere 1490D in the Northwest. Rummer calculated the cost of owning the $450,000 1490D would equal $58 per scheduled machine hour (SMH). Operating costs were estimated to be approximately $50 per SMH. Twine costs added about $5 per productive machine hour to the variable costs. Including labor and other variable costs the total cost of owning and operating the 1490D was estimated to be $130 per scheduled machine hour.

The study estimated bundles could be delivered to a consuming plant within 50 miles for approximately $26 to $31 per bone dry ton (BDT) (Rummer et al 2004). The cost of bundling was sixteen dollars per bone dry ton. Forwarding costs were $5/BDT, and trucking costs were approximately $5 to $10/BDT, respectively The study reported bundle chipping costs at the mill to be approximately $3 per bone dry ton.

The only bundling study done in the southern United States was performed in Arkansas (Patterson et al 2008). A 68% utilization rate was used to figure hourly costs. Fixed costs for the $480,600 machine was $86.23 per productive machine hour (PMH). Fuel, lube, and maintenance costs for the 1490D's operations in Arkansas were $77.24/PMH. Total operating costs, including an operator, were $200.07/PMH.

Delivered, bundled material costs were dependent on production levels. Production levels ranged from 13.8 to 36.1 ten foot bundles per hour. Reported production levels led to $12.31 to $32.22 per green ton to produce bundles. Clear cut material was bundled for $19.93 per green ton. With $1 per ton added for the landowner and trucking costs $6.50 to $7 per ton, the Arkansas study could deliver bundles to a mill 50 miles away for between $19.81 to $40.22 per green ton of bundled material.

Currently, there are very few markets in the South for bundled material. Dirty chips, which bundles would potentially be processed into, are currently priced at approximately $20.96 per green ton (Timber Mart South 2009) or about $26 delivered. Since there is currently no market for slash bundles, the objective of this project is to show that bundles can be produced and delivered at the United States Department of Energy goal of $47 per dry ton, or approximately $23.50 per green ton (Wilkerson et al 2008).

3.3 Transportation and Storage of Bundled Material

Transportation costs are a huge factor to consider in the use of logging residues for fuel (Stokes et al 1993). Transportation and load configuration require special considerations when dealing with biomass feedstock in order to maximize efficiency of the transportation system (Hall 2009). Moisture content is one of the main factors that must be considered in efforts to maximize compressed residue log payload with the volumetric constraints of trailers (Stokes et al 1993, Hall 2009, Johansson et al 2006, Rummer et al 2004). Several load configurations have been tried in an effort to develop the most economically efficient way to haul bundled material. Bunked trailers (Rummer et al 2004), roll off bins, self-loading truck (Johansson et al 2006), and rail cars (Saarenmaa 2005, Andersson 2000) have all been investigated for bundle transport. One major concern in the mobility of bundled material is the dislodging of debris during on-road travel (Rummer et al 2004, Johansson et al 2006)

Because much of the residue material will potentially be transported to biomass consuming facilities that desire low moisture material and stable storage, slash bundles are ideal (Steele et al 2008). Degradation of bundled material occurs far more slowly than chipped material and thus can be stored for longer periods of time (Johansson et al 2006). Slash bundles have been recorded to maintain structure and resist degradation in field storage for as long as one year (Rummer 2007).

Transpirational drying and evaporative loses provide moisture content reduction in both pine and hardwood logging residue without consumer inputs (Stokes et al 1993). Compressed residue logs have also been shown to reflect the same drying properties (Steele et al 2008, Patterson et al 2008). Temperature, humidity, wind speed, precipitation, season, and tree size can all have an effect on the slash bundles drying rate (Andersson et al 2002). Typical summer weather patterns with high temperatures and low rain fall amounts make it the ideal time of year for maximum moisture loss (Stokes et al 1993, Steele et al 2008, Petterson and Nordfjell 2007, Patterson et al 2008).

IV. Machine Build and Testing

Trailer mounting the B-380 bundling unit could potentially lower the capital investment associated with bundling, and allow for easier integration into tree-length logging operations. Because trees are typically delimbed at the logging deck, the vast majority of the forest residues are present in a localized area. Furthermore, the expensive bundler unit carrier cannot be justified in typical southern harvesting operations. Skidders can provide a constant flow of slash to the bundling operation, and a knuckleboom loader will facilitate the feeding of slash.

Trailer-mounting the bundling unit began in December of 2008. John Deere provided a B-380 bundling unit and a 437c knuckle-boom loader. Cutting Systems Incorporated (CSI) provided a motorized trailer. CSI's rugged trailer design is built for forestry applications with a grapple loop and dual tires on the axle, which are essential for in-woods transportation. The prototype machine was developed with "off the shelf technology" in order to test the bundling concept. Limited modifications were made to produce the test machine.

The bundler's mounting configuration, pictured in Figure 3, was modeled after the John Deere 1490D EcoIII setup. Three, one-inch steel plates were welded at intervals on each side of the trailer directly over the axle. Two, four-inch schedule 40 steel tubes were welded onto the plates for mounting. Some additional bracing was welded into place for added security, and the B-380's mounting pedestal was then lifted into place. After fastening the pedestal to the rail system, the bundler was mounted securely atop the trailer.

Figure 3. Bundler mounting configuration

CSI's self-contained trailer features a 102 horsepower, John Deere diesel engine. The trailer's fixed displacement hydraulic pump was replaced with an Oilgear, model PVM098, variable displacement pump. The load sensing pump was able to satisfy the B-380's hydraulic needs. The trailer was plumbed and the reservoir was filled with hydraulic fluid.

The control system of the bundler also required some modifications. To satisfy the higher voltage required by the bundler, a small amplifier was installed to convert the 12 volt battery power to 24 volts. While the original plan was to have a remote control system, there were too many challenges with the system's software. The controls could be relayed relatively easily through remote control; however, the display module required a much more complex computer language for remote operation. As a result, a 75 foot extension was attached to the wiring harness for both the controls and the display module to ensure operator safety during testing.

Field testing of the trailer-mounted bundler shown in Figure 4 was performed on five different sites to evaluate the machine. The sites were located in east central Alabama and north central Florida. Each site contained different stand conditions. The initial four sites were test and demo sites with the fifth being the production study site. Initial testing ensured proper functionality of the trailer mounted bundler and provided ample operator experience.

Figure 4. Trailer-mounted bundler

V. Materials and Methods

5.1 Deck Configuration

In order to effectively employ this new residue harvesting system, an operational deck configuration was designed for the prototype bundling system. The first layout employed the trailer-mounted bundling unit into a two loader system. Placing the unit in close proximity to one of the loader's enabled bundle production when the roundwood loading operation was not fully consuming loader time. The deck configuration in Figure 5 shows the initial deck configuration. Logging residue were deposited at the rear of the loader and fed into the bundler. Completed bundles fell off the tray after being severed and would potentially be loaded in the same fashion as roundwood when a complete load was produced.

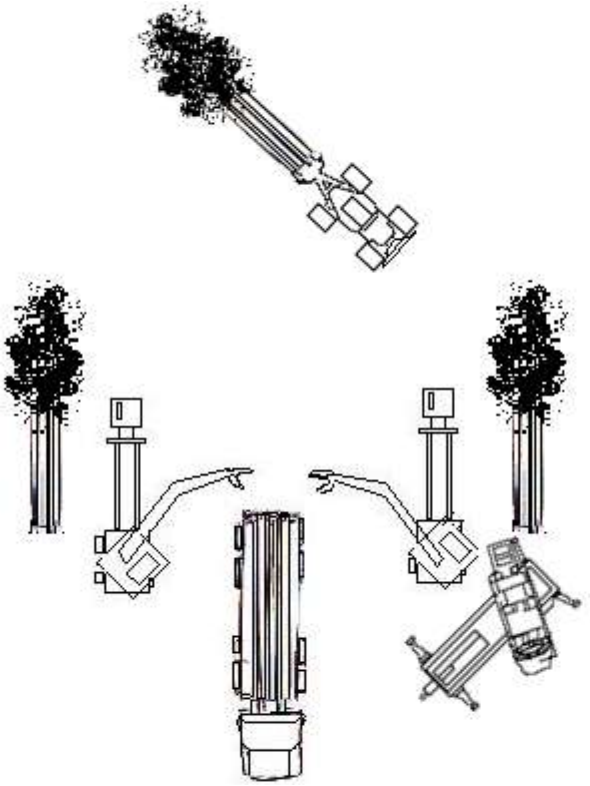

Figure 5. Initial deck configuration proposed

The second deck configuration was more of a satellite operation. A separate loader and the trailer-mounted bundler were located within 100 yards of the active logging deck in an effort to negate any effects on skidder production during slash delivery. The bundling unit was located within reach of the knuckle-boom loader to ensure adequate slash feeding and bundle handling operations. The satellite deck configuration would enable bundles to be loaded immediately onto a set-out trailer. The deck configuration that created the best integration into the tree-length harvesting operation was selected and used in the productivity study.

5.2 Work Sampling

In order to quantify the effects of bundling on the cooperating logger's productivity, a form of work study was performed on the skidding element. The study analyzed skidding because it was deemed the most impacted element of the logging system when a bundling system is implemented.

The cooperating logger ran a two loader, two skidder, one feller-buncher tree-length logging operation. Data was collected on the operation's two skidders for two productive days prior to bundling, and three days during bundling. Monitoring began when the skidder operator initiated productive movement and ended when the skidder operator concluded daily operations. Work sampling data was collected every four minutes. The machines' operational state was noted by two observers who record activity at each interval. Skidder data collection was based on prior studies (Klepac and Rummer 2000, Kluender and Stokes 1996), but was tailored to reflect the effects of the addition of the bundling operation. Total effective work time was divided into the following elements: travel unloaded, position and grapple, travel loaded, drop wood, deck maintenance, gate delimbing and maintenance, slash movement, equipment movement, bundle removal, and delay.

Travel unloaded described instances when the skidder operator initiated movement with intent to proceed to the next pull and ended when the machine began maneuvering in reverse to grapple a load. Position and grapple began when the skidder operator initiated reverse movement with intent to grapple an in-woods load and ended when the skidder operator began movement after grappling. Travel loaded included skidder motion with a loaded grapple of roundwood. Drop wood started with the skidder operator maneuvering and opening its grapple at the deck in order to drop off a load of wood. Deck maintenance included any time the operator spent grading and making improvements to the conditions on the log deck. Gate delimbing and maintenance began when the skidder operator deviated from its path with intent to delimb or clean the gate. The element of slash movement began when the skidder operator initiated grappling of limbs or tops, typically located at the end of the pull through delimber. Slash movement concluded when the slash was deposited on the landscape. Equipment movement described any time the skidder operator was tasked with winching trucks and/or relocating equipment. Bundle removal was an element recorded that reflected time spent by the skidders removing bundled material to ensure sufficient operational space for the bundling procedure. Delays were recorded when the machines were not in motion or not in operational status to reflect utilization.

Before bundling commenced, the cooperating logger was using a gate delimber to remove limbs from trees. Because gate delimbing significantly reduces the amount of forest residues present at the deck (Stokes and Watson 1988, 1991), gate delimbing was not performed during bundling operations. During bundling operations, all trees were delimbed utilizing the loader's pull-through delimbers and slash was transported to the bundling operation via skidders.

5.3 Production Study

The site of the production study and work sampling activities was Roanoke, Alabama. Our area of interest included a 25 acre portion of the 100 acre tract. The site was a gently sloping, naturally regenerated loblolly pine stand with a small hardwood component.

Stand attributes were collected during a pre-harvest cruise. The cruise consisted of 16, 0.1-acre plots distributed evenly over three transects. The six percent inventory analysis was performed simply to determine the amount of merchantable and non-merchantable material on the site. Total height and diameter at breast height (DBH) were measured for all pine chip-n-saw, pine pulpwood, hardwood sawtimber, and hardwood pulpwood trees within the 37.2-foot radius of plot center. Pine chip-n-saw was classified as a pine tree with a DBH of 10 inches or larger and a top diameter of 7 inches. Pine and hardwood pulpwood trees were stems that measured 6 inches DBH up to a 2 inch top diameter. Hardwood sawtimber was based on 16-foot logs for a tree at least a 12 inch DBH. Clark and Saucier's pine weight tables were used to calculate total and merchantable weights for all pine trees (Clark and Saucier 1990). All hardwood species weights were based on Clark, Saucier, and McNabb's southeastern hardwood weight tables (Clark et al 1986).

In order to provide an estimate of available forest residues, the merchantable pine weights were subtracted from the total pine tree weights (which included wood, bark, and foliage). To account for the loss of slash due to piece size, transportation, and other factors, a rate of recovery was applied to the total available forest residues to assess the total harvestable residues (Perlack et al 2005, Perez-Verdin et al 2008, Gan and Smith 2006, Wall and Numi 2003).

The bundling operation was set up within 100 yards of the active logging deck using the optimal deck configuration. The bundler operator was set up approximately 50 feet away from the bundler opposite the loader. Skidders transported slash from the cooperating logger's pull-through delimbers to the rear of the bundling system's loader. The loader operator then grappled some of the forest residues and placed the material into the grasp of the bundler's feed wheels. The bundler then fed, compressed, fastened, and cut the bundles at the designated lengths in an automated sequence.

In an effort to analyze the trailer-mounted bundler's performance, a production study was performed. Bundler productivity was collected over a one week period. The number of loader turns and saw bar cuts were collected as independent variables for cycle time equations. Number of loader turns was defined as the number of times the John Deere 437 fed a grapple of slash into the bundler to produce a particular bundle. Saw bar cuts denoted the number of times the B380's cut off saw cycled down in an attempt to sever a single bundle. Delays were noted for data analysis and machine evaluation. Delays constituted periods of time when bundle production was stalled for more than 20 seconds. Cycles were timed from the severing of one bundle until the severing of the next.

Cycle times were collected by a worker stationed beside the bundler operator. A stop watch was used to gather all time data. The worker tallied each loader turn and each saw bar cut. The majority of data was collected during 8 foot bundle production. A number of 12 foot bundles were produced to compare production rates.

SAS statistical software was used to develop a cycle time equation for both 8 and 12 foot bundle production (SAS System for Windows V9.1 2002-2004). The cycle time data were analyzed using a step-wise regression model.

5.4 Load Configuration and Storage of Bundled Material

Transporting bundled material is a major concern in a bundle supply chain. This study investigated two load configurations. Twelve foot bundles were loaded parallel with the trailer to assess the configuration's potential as a mode of transportation. Eight foot bundles were loaded in the same manner as short wood pulpwood, or across the trailer. Both loading configurations were examined to determine the most effective bundle transport configuration.

Bundle weight and moisture content was a concern in drying and transporting compressed residue logs. Forty-nine CRLs were measured to determine physical properties of slash bundles. Each bundle was weighed at the harvest site. Lifting tongs were attached to a crane scale and lifted by the knuckle-boom loader. The Salter Brecknell CS series crane scale was used in this study to measure weights to the nearest 1 pound (Salter 2010). Every bundle was tagged, weighed, and then transported to a drying site on Auburn University property. Precipitation, average temperature, and bundle weights were monitored for 18 weeks in 2 week intervals to assess bundle drying ability in outdoor storage.

Bundles were stored in a large grassy circular area with approximately 1-2 feet between them. All compressed residue logs were stored on the ground. The bundle weights at the Auburn storage site were measured using the same scale and lifting tongs. An initial moisture content value was assessed through destructive sampling of a slash bundle. The 4 to 6 inch section cut off the end of the representative bundle was split into three pans and oven dried for 28.5 hours. The sample was used as a reference for the 49 initial moisture content values.

5.5 Economic Analysis

An economic analysis was performed on the prototype bundling system to estimate costs of owning and operating this prototype system. Production levels for eight and twelve-foot bundling operation were used to calculate costs. During the study data were collected on fuel consumption, bar and lubrication oil consumption, and twine consumption to aid in variable cost estimates. Costs associated with the sharpening and replacement of the saw chain were also analyzed.

All of the cost figures were entered into an after tax cash flow model to determine hourly and per ton costs (Tufts et al 1989). The model allowed for factors such as taxes, inflation, and time value of money to be applied during economic analysis (Tufts and Mills 1982). Because the prototype bundling system consisted of the trailer-mounted bundler and a knuckleboom loader, the costs for both machines were included in the economic analysis. Fixed cost inputs for the model included payments on the machines, insurance, taxes, and depreciation (Tufts and Mills 1982). Variable, or operational, costs included labor, fuel and lube, and maintenance and repair for each machine. A utilization rate was applied to each machine to reflect the ratio of productive machine hours (PMH) to scheduled machine hours.

An estimated life span was applied to both machines and an annual equivalent cost was returned by Tufts et al's (1982) economic model. The annual equivalent cost (AEC) was the cost per year to own and operate the piece of machinery over its entire lifespan. The year with the minimum AEC reflected the machines optimal economic life (Tufts and Mills 1982).

Capital investment and revenue streams were uncertain with this prototype system. The analysis reflected the purchase price of new machines. Although accurate estimates of the loader were possible, the prototype bundler's purchase price was unknown. A sensitivity analysis was performed to show how the purchase price of the trailer-mounted bundler unit affected the cost per ton to produce bundles.

VI. Results

6.1 Initial Testing

A great deal was learned about the most effective way to employ the new bundling system. Initial testing in Auburn, Alabama, proved that the unit was capable of bundling full tree material. Eighteen-year-old loblolly pine (pinus taeda) trees with an average DBH of 6 inches were bundled for almost two days. The bundler did not have any major operational or mechanical defects. Figure 6 shows the first bundle produced by the trailer-mounted bundler.

Figure 6. First bundle produced by the prototype bundler in Auburn, Alabama.

The next field testing site was located in Midway, Alabama. Results from the study found that a harvesting system that employs a gate delimber does not produce the most ideal material mix for processing bundles. As the residue material is compressed within the B380, the twine magazine wraps bailing twine around the compressed slash bundles. The outward pressure of the limbs, tops, and foliage is contained by the twine as the slash bundle expands after being released by the compactors. The combination of the twine and outward pressure allow bundles to maintain their cylindrical shape. The larger diameter tops and negligible amount of small diameter limbs and foliage encountered in Midway did not produce the spring back effect that is necessary to keep the bundles tightly bound by the twine. Bundle integrity was compromised because of the material mix.

Mature hardwood tops were also encountered on this same site. Large diameter forked tops shown in Figure 7 were very problematic in the bundling process. The crooked material would stall the process at times and even broke a vital part during the trial period.


Figure 7. Bundling hardwood slash at the Midway, AL test site.

During a demonstration in Live Oak, Florida, piled logging slash was bundled. Because the residues were pushed into a pile after a recent harvest, the loader operator took additional time to orient the slash during feeding. It was very helpful to gather and feed most of the material parallel to the direction of slash flow. As the brown, brittle slash was processed, it simply broke when compressed causing some bundle integrity issues.

The most ideal material mix for bundling was found at the Notasulga, Alabama, test site. The bundling operation was set up within 150 yards of the active logging deck. The 15 acre clearcut of 23-year-old loblolly pine, and a 40 acre loblolly pine thinning provided the limbs and tops for the bundling operation. Skidders deposited slash which contained a few 3 to 6 inch tops with a large amount of small diameter limbs. The majority of the slash was oriented in the same direction which led to a constant flow of slash to the bundler. The satellite deck configuration worked well and the material mix was very conducive to bundling.

6.2 Deck Configuration

During testing, ratios of slash to merchantable logs were found to be consistent to those published in the literature. Almost twenty percent of the merchantable volume harvested in Steele et al (2008) stands were collected as post harvest residue. Clearcut southern pine stands typically yield 25-45 tons per acre of logging residues (Beardsell 1983, Watson et al 1986). At 20-30 bundles per hour production from the bundler, it was determined that a separate loader needed to be allocated specifically for bundling to maintain both the logger's roundwood production levels and feed the bundler.

The deck configuration selected for use during the study was a revised layout that resembled the second deck configuration tested. Figure 8 is the most efficient bundling deck configuration found during the trial period. Forest residues should be deposited at the rear of the loader. Slash should be fed into the bundler from left to right so that the boom does not impede the operator's line of sight. Using set-out trailers and loading finished bundles directly onto a trailer reduces handling, increases production and helps maintain bundle integrity.

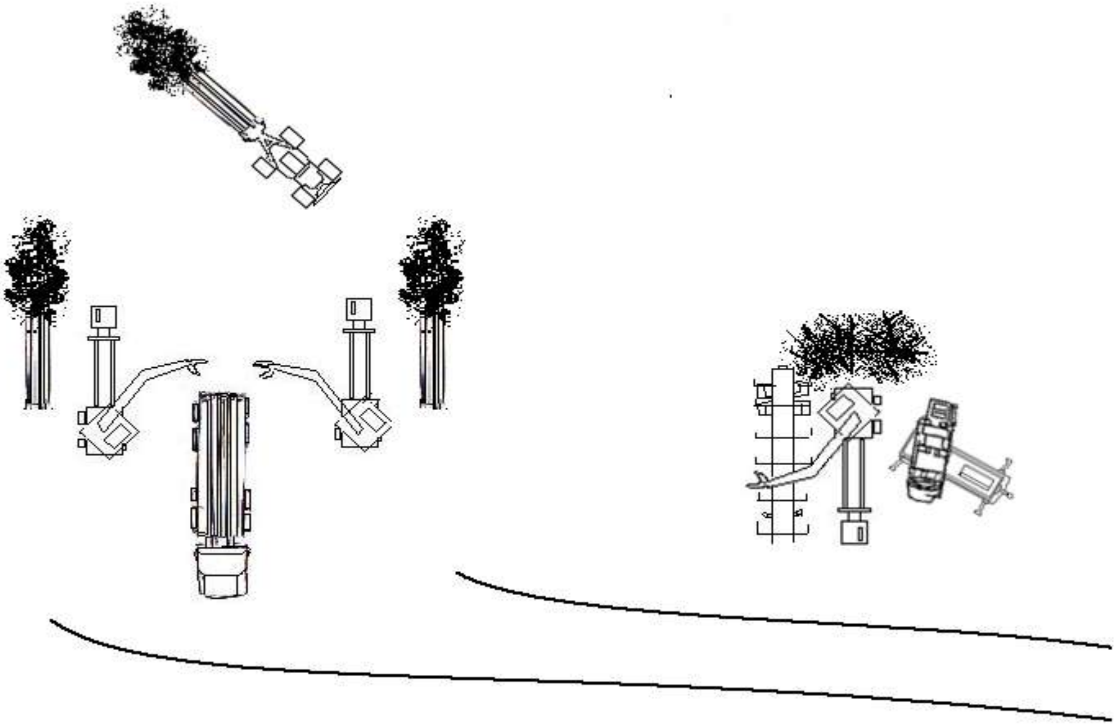

Figure 8. Deck configuration for the prototype bundling operation

The bundler's position enables smooth feeding and extraction of bundles. Positioning the loader in this fashion allows the operator effective reach of all necessary elements. Locating the bundling system on a nearby satellite deck enables slash delivery and bundle production without negatively affecting roundwood production, but requires a much larger deck area.

6.3 Work Sampling

Table 1 summarizes the skidders' pre-bundling work study findings. Both pre-bundling and post bundling data is separated into groups based on weather conditions. In clear conditions, in-woods operations consisting of travel unloaded, position and grapple, and travel loaded consumed a total of 65.1% of the delay free events. Deck operations, consisting of drop wood and deck maintenance, consumed 11.6% of delay free time on the pre-bundling clear day. On the same day, delays accounted for 12.5% of the total events and slash movement consumed 15.1% of delay free events.

Table 1. Pre-bundling skidder work sampling breakdown

	Day 1 (Pre-Bundling) Condition: Clear				Day 2 (Pre-Bundling) Condition: Muddy			
Activity	**Deere**	**CAT**	**% of Total Events**	**% of Delay-Free Events**	**Deere**	**CAT**	**% of Total Events**	**% of Delay-Free Events**
Travel unloaded	40	23	23.8%	27.2%	15	21	18.3%	27.1%
Position and grapple	4	3	2.6%	3.0%	1	1	1.0%	1.5%
Travel loaded	41	40	30.6%	34.9%	13	15	14.2%	21.1%
Drop wood	2	2	1.5%	1.7%	0	2	1.0%	1.5%
Deck maintenance	2	21	8.7%	9.9%	6	6	6.1%	9.0%
Gate	10	7	6.4%	7.3%	3	5	4.1%	6.0%
Delay	15	18	12.5%		35	29	32.5%	
Slash movement	18	17	13.2%	15.1%	3	7	5.1%	7.5%
Equipment movement	0	2	0.8%	0.9%	23	12	17.8%	26.3%
Bundle removal	0	0	0.0%	0.0%	0	0	0.0%	0.0%
Total events	132	133			99	98		

Muddy conditions caused some differences in skidder data. More than 32% of pre-bundling skidder time was accounted for by delays. Because skidders had to pull many of the trucks to the highway in the muddy conditions, equipment movement took place 26.3% of the delay free time. In woods operations and deck operations consumed 49.7% and 10.5% of delay free events respectively.

Table 2 shows the skidder's work sampling breakdown during the three days of data collection while bundling operations were taking place. Delays accounted for 11.9% of the total events during clear conditions and 10.4% in muddy conditions. During clear conditions, in-woods operations consumed 82.8% of delay free time and deck operations consumed 5.4% of delay free time. Slash movement and bundle removal accounted for 8.1% and 3.8% of delay free events on Day 3 and 5.

Table 2. Skidder work sampling during bundling operations

	Day 3 (Bundling) **Condition: Clear**		**Day 5 (Bundling)** **Condition: Clear**				**Day 4 (Bundling)** **Condition: Muddy**			
Activity	**Deere**	**CAT**	**Deere**	**CAT**	**% of Total Events**	**% of Delay-Free Events**	**Deere**	**CAT**	**% of Total Events**	**% of Delay-Free Events**
Travel unloaded	26	36	41	33	32.3%	36.7%	25	29	25.6%	28.6%
Position and grapple	11	0	4	14	6.9%	7.8%	4	8	5.7%	6.3%
Travel loaded	40	35	33	34	33.7%	38.3%	12	31	20.4%	22.8%
Drop wood	3	0	2	2	1.7%	1.9%	0	6	2.8%	3.2%
Deck maintenance	2	4	1	6	3.1%	3.5%	1	5	2.8%	3.2%
Gate	0	0	0	0	0.0%	0.0%	0	0	0.0%	0.0%
Delay	5	12	12	21	11.9%		13	9	10.4%	
Slash movement	5	8	6	11	7.1%	8.1%	2	9	5.2%	5.8%
Equipment movement	0	0	0	0	0.0%	0.0%	42	7	23.2%	25.9%
Bundle removal	3	0	11	0	3.3%	3.8%	8	0	3.8%	4.2%
Total events	95	95	110	121			107	104		

After a rain, the muddy conditions caused the skidding operations to be slightly altered. During bundling, the muddy conditions again caused the percentage of equipment movement to increase. Almost 26% of delay free time in muddy conditions was accounted for by equipment movement. Deck operations consumed 6.4% of delay free time and slash movement consumed 5.8%. Travel unloaded, position and grapple, and travel loaded consumed a combined 57.7% of delay free skidding time during bundling.

During bundling operations, the skidder operators bypassed the gate delimbing procedure. Eliminating the gate delimbing procedure could also positively affect the skidders' productivity (Kluender and Stokes 1996, Klepac and Rummer 2000). Gate delimbing did consume between 6.0 to 7.3 percent of delay free time during pre-bundling data collection. The productive time freed up during bundling operations could increase skidder production.

Comparing the pre-bundling data to the data taken during bundling operations did not indicate that bundling would decrease skidder productivity. During clear conditions, the skidders performed in-woods operations 82.8% of the productive time during bundling and only 65.1% during pre-bundling. Muddy condition data showed that 57.7% of delay free time was spent performing in-woods operations during bundling. In-woods operations consumed 49.7% of delay free skidding time during the pre-bundling period. When bundling was implemented in both clear and muddy conditions, the percentage of delay and slash movement elements decreased. These factors all led to the conclusion that skidder production is not negatively impacted by bundling and may even be positively effected.

Because slash movement was described as any time the skidders were in motion carrying slash, production gains or losses should be further investigated. Although a skidder may have been carrying slash during pre-bundling data collection, the machine may have been traveling in route to the next bunch of trees.

During a production bundling operation, bundle removal would not take place. As bundles are made, they would be loaded onto a set-out trailer to limit handling. Bundle removal, which consumed about 4% of the skidders' total delay free time during bundling operations, could potentially be another source of increased skidding productivity when this operation is employed.

6.4 Production Study

Data from the study site cruise estimated 121 tons per acre of merchantable timber. Eighty-six tons per acre of the merchantable timber was accounted for by pine chip-n-saw. Pine pulpwood, hardwood pulpwood, and hardwood sawtimber made up the remaining 22, 11, and 2 tons per acre. Based on the timber cruise, the standing pine timber contained 32.5 tons/acre of forest residues available. A total of 16 tons/acre were harvested during bundling operations. Several researchers believe that seventy percent may be applied as the recovery rate to reflect the amount of harvestable residues (Gan and Smith 2006, Wall and Nurmi 2003); however, this study found that only about 50% of the residues were processed. The lower volume was due to a number of factors. Some of the material was used on skid trails and a portion was removed at the delimbing gate before the skidder operators were given new instructions. A small fraction of the material was left on the site because it was too inefficient to gather it together.

Production study results for the eight-foot bundling operation included analysis of 377 bundles. The production levels are based on the machine's performance and do not take into consideration a utilization rate. Measured production levels showed the prototype unit was capable of producing an average of 33.4 eight-foot bundles per hour (15.9 tons/hr) with no delays. Accounting for minor operational delays that were observed during the production study (such as extra saw cuts and minor feeding delays), the average production for the bundling operation was 30.8 eight-foot bundles per hour

(14.6 tons/hr). A string repair occurred every 2.6 hours of run time with an average repair time of 12 minutes. To maintain proper functionality, saw chains were changed every 2.2 hours with a standard repair time of 14 minutes.

A limited number of 12-foot bundles were produced during the study. Without any delay considerations, 25.5 twelve-foot bundles per hour (17.2 tons/hr) were produced. Minor delays slightly decreased production to 24.2 bundles per hour (16.4 tons/hr). String and saw chain repair delays were estimated to be equivalent to those that occurred during 8-foot bundle production.

Cycle time equations were formulated using SAS System for Windows (SAS System for Windows V9.1 2002-2004). Cycle times (Y) are measured in seconds. The eight-foot bundle cycle time equation was based on 270 bundles, and the twelve foot bundle equation was based on 25 bundles. The cycle times used for the statistical analysis were selected to return an equation based on a regression model for bundle processing times with minor operational delays. Minor operational delays consisted of extra saw cuts and minor feeding delays. Saw cuts ranged from one to five cuts per eight-foot bundle and one to four per twelve-foot bundle. Minor feeding or operational delays were defined as delays that stalled or slowed the process less than 20 seconds. Loader turns ranged from 0 to 3 per eight-foot bundle and 1 to 3 per twelve-foot bundle. Loader turns and saw bar cuts were treated as categorical variables.

Eight-foot bundle cycle time data was modeled using a regression model with all variables in the equation. Using a stepwise regression technique, the best model was selected. The equation that best described the cycle time data was:

$$Y= 124.04 + 2.62 \text{ (Load2x)} - 17.52 \text{ (Cut1x)} - 10.12 \text{ (Cut2x)} + 26.46 \text{ (Cut5x)}.$$

The regression equation showed that a single loader turn did not significantly increase cycle time when compared to zero loader turns. However, two loader turns were on average 2.62 seconds longer than the reference.

During a cycle in which the bundle is severed in a single saw cut, the predicted cycle time is reduced by 17.52 seconds. Two saw cuts increased the predicted cycle time by 7.4 seconds when compared to a single cut. Three to four saw cuts would result in a predicted cycle time 10.12 seconds longer than a cycle that received only two cuts. Five saw cuts increased the predicted cycle time for an eight-foot bundle.

Eight-foot bundle cycle times ranged from 96 to 156 seconds with an average of 111 seconds per bundle. The model chosen through the stepwise selection had an R^2 value of 0.46. The following table shows that the model is statistically significant. Most commonly, an eight-foot bundle would require a single loader turn and one saw bar activation resulting in a cycle time of 106.5 seconds, or 33.8 bundles per hour.

Table 3. Eight-foot bundling cycle time ANOVA table

	Df	Sum of Sq	Mean Square	F	Pr(>F)
Model	4	15473	3868.35	55.35	<0.0001
Error	264	18451	69.89		
Corrected total	268	33925			

The twelve-foot bundle cycle time equation was also developed using stepwise regression. Variables were excluded from the model based on their F statistic which reflects their significance to the model. The resulting regression model for a twelve foot bundle is

$$Y = 141.69 + 7.36\ (\text{Load1x}) - 7.54\ (\text{Cut1x}) + 31.63\ (\text{Cut3x}) + 38.94\ (\text{Cut4x}).$$

A single loader turn added 7.36 seconds to the predicted cycle time; however, multiple loader turns did not have a significant effect on twelve-foot bundle cycle time. A bundle with a single cut and a single loader turn had an estimated cycle time of 2.36 minutes. Two cuts added 7.54 seconds to the cycle time, and three cuts increased the predicted cycle time by 39.17 seconds over a bundle with a single cut. A fourth cut also significantly increased cycle time.

Table 4 shows the twelve-foot bundle cycle time statistics in a table. The regression model had an R^2 value of 0.72. Cycle times ranged from 132 seconds to 188 seconds with an average cycle time of 145.68 seconds.

Table 4. Twelve-foot bundling cycle time ANOVA table

	Df	Sum of Sq	Mean Square	F	Pr(>F)
Model	4	4825.62	1206.41	13.17	<0.0001
Error	20	1831.81	91.59		
Corrected total	24	6657.44			

Although the cycle time equations accurately predict cycle time of both eight and twelve-foot bundles, it was noted that the number of saw cuts may not have been the only independent variable that should have been included in the model describing saw delays. Time since chain replacement should have been included in the analysis. As the chain became duller, saw delays increased. Severing bundles became much more problematic as the time since the last chain replacement increased.

6.5 Load Configuration

Two load configurations were examined by the study. The eight foot bundle configuration shown in Figure 9 consisted of compressed residue logs stacked perpendicular to the direction of travel. Bundles were individually loaded in a bunk with dimensions of 12’x 7.8’x 8’ (length x width x height). The single bunks volumetric capacity was 24 eight-foot bundles with an approximate weight of 21,500 pounds (lbs.) (10.75 tons) green. The load was not stable and could prove problematic with width restrictions associated with highway travel. A new tie down system would be required to secure the load configuration during travel.

Figure 9. Eight-foot bundle load configuration

The twelve-foot bundle load configuration in Figure 10 seemed much more conducive to on-road transportation using a traditional log trailer design. Bundled material was loaded on the trailer in the direction of travel which eliminated the loader operator’s constant width concern associated with the perpendicular configuration. The 11’x 7.8’x 7.4’ bunk had a 14 bundle volumetric capacity. Fourteen 12-foot green bundles from the study site weighed approximately 19,000 lbs (9.5 tons).

Figure 10. Twelve-foot bundle load configuration

The twelve-foot configuration was very stable and could be secured using traditional tie down systems. Twelve-foot, green bundled material of similar composition could produce a triple bunk trailer load weighing 28.5 tons. Twenty-eight and a half tons is more than a legal load in most states and thus eliminates density and weight concerns associated with the transportation of forest residues. Transporting green material, the twelve-foot load configuration tested could create an optimal transportation mode for the growing biomass feedstock market.

6.6 Bundle Drying and Storage

Many of the biomass consuming plants desire material with low moisture content. After analyzing 49 compressed residue log samples over 18 weeks, this study does confirm other findings (Steele et al 2008, Patterson et al 2008) that bundles do undergo drying in outside storage. Daily precipitation and temperature data was gathered from the AWIS website (AWIS 2010). Average temperature and rainfall totals for the two week intervals were used to analyze the effects of weather on bundle moisture loss. Data collected confirms that rainfall and temperature could have an effect on the moisture content losses.

Moisture content for the compressed residue logs was figured based on one representative sample. The bundle sample was then put in an oven to dry for 28.5 hours to determine the initial moisture content. Table 5 shows the results of the oven dried sample which showed the representative initial moisture content for the bundled material. The moisture content was calculated by dividing the water weight in the wet material by the weight of the wet woody material.

Table 5. Initial moisture content of the bundled material

	Initial Wet Weight	24 Hours	28.5 Hours	Wet Weight	Dry Weight	Moisture Content (Wet Basis)
Pan 1	1534	797	797	1534	797	
Pan 2	3852	1894	1886	3852	1886	
Pan 3	3417	1717	1717	3417	1717	
Total	8803	4408	4400	8803	4400	**50.02%**

N=1 sample
sample was divided into 3 trays for drying.

Monitoring the bundle weights every two weeks, the study was able to determine the approximate moisture content by assuming the initial moisture content of all the bundled material to be 50.02%. The weight of water was then determined for each of the 49 bundles using the following equation:

$$Water\ Weight = Initial\ Moisture\ content\ (\%) * Initial\ Weight\ of\ Wet\ Wood$$

Assuming all weight loss was due to loss of water, the following equation was used to calculate weeks 2-18 estimated bundle moisture contents.

$$\textbf{Bundle Moisture content } (\%) =$$

$$\frac{\textbf{Initial Water Weight} - (\textbf{Initial Weight of Wet Wood} - \textbf{Current Weight of Wet Wood})}{\textbf{Initial Weight of Wet Wood}}$$

Length measurements were also collected to determine the bundles' pounds per foot. The following table summarizes the study's temporal findings with respect to bundle moisture weights, moisture content, and pounds per foot.

Table 6 shows the average weight loss of bundles to be approximately 156 lbs. over 18 weeks. The 49 sample bundles lost an estimated 16.8% moisture content on average. The large amount of weight loss due to transpiration and evaporation confirms the hypothesis that bundles do lose a large percentage of moisture in storage without any costly inputs.

Table 6. Summary table of bundle weights, pounds/foot, and moisture content

	Bundle Weight (lbs.)	**Pounds/foot**	**Estimated Bundle Moisture Content**
Week 0	950.39 (129.54, 0.14)*	112.65 (15.85, 0.14)	50.02%
Week 2	926.43 (132.8, 0.14)	109.83 (16.31, 0.15)	47.43% (1.95, 0.04)
Week 4	922.78 (135.14, 0.15)	109.39 (16.55, 0.15)	47.01% (2.24, 0.05)
Week 6	909 (136.4, 0.15)	107.76 (16.68, 0.15)	45.52% (2.54, 0.06)
Week 8	862.06 (132.06, 0.15)	102.19 (16.09, 0.16)	40.55% (2.56, 0.06)
Week 10	871.04 (137.03, 0.16)	103.25 (16.69, 0.16)	41.45% (2.95, 0.07)
Week 12	874.73 (138.64, 0.16)	103.69 (16.88, 0.16)	41.83% (3.1, 0.07)
Week 14	846.35 (136.85, 0.16)	100.32 (16.64, 0.17)	38.81% (3.21, 0.08)
Week 16	848.08 (138.88, 0.16)	100.53 (16.88, 0.17)	38.97% (2.06, 0.09)
Week 18	793.67 (132.44, 0.17)	94.08 (16.07, 0.17)	33.23% (3.4, 0.10)

*(Standard Deviation, Coefficient of Variance) (n = 49)

Figure 11 shows the interaction of temperature and rainfall with bundle moisture content. Bundle moisture content represents the average moisture content of the 49 sample bundles. Over the 18 weeks, the average bundle moisture content dropped from 50.02% to 33.23%. It can be noted that bundle moisture content decreased most dramatically when the average precipitation was the lowest during the study period. Weather patterns between weeks 6 and 8, as well as 14 and 16 were most conducive to bundle moisture loss. The minimal rainfall in weeks 8 and 18 resulted in the largest moisture content losses in the compressed residue logs. The drying trend was slowed or even slightly reversed as a result of an abnormally high amount of rainfall in mid to late

December and late January. Precipitation and moisture content loss did seem to be closely correlated.

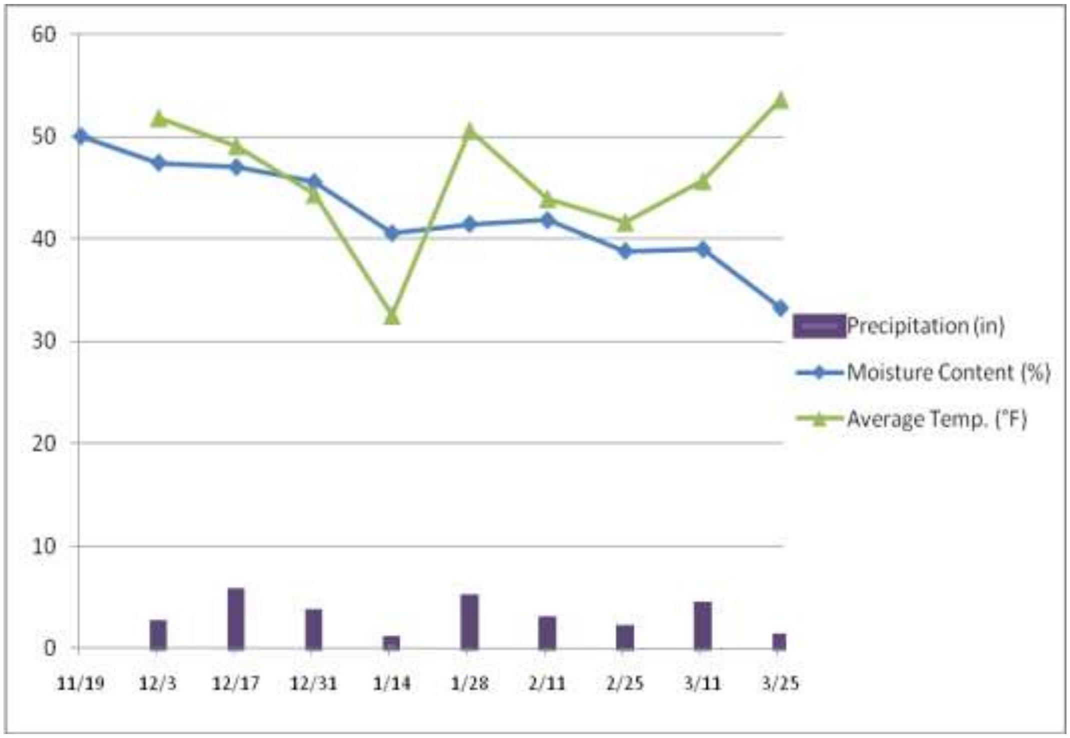

Figure 11. Graph showing the relationship between bundle moisture content, average temperature, and precipitation.

A regression model using the data collected showed that precipitation, temperature, and an interaction between precipitation and temperature did not significantly impact bundle moisture content. Temperature did not seem to have a profound effect on the bundles' ability to lose moisture. As temperatures began to rise in late March, summer-like weather conditions did cause significant moisture loss; however, both temperature and precipitation reflected ideal drying conditions.

6.7 Economic Analysis

Fuel, lube, maintenance and other variable costs were investigated during the field testing of the machine to produce an accurate cost model for the prototype bundling operation. Fuel consumption for the John Deere 437C loader averaged 2.5 gallons per hour. The bundler also consumed approximately 2.5 gallons per hour. One roll of Bridon Cornage Forest Revolver Bundling Twine (7250 feet of 190 lbs tensile strength) was consumed every 25 bundles with our 8 foot bundling parameters. Effective chain life was deemed roughly 2 hours. After 2 hours of sawing, the chain would not sever a bundle within 1 or 2 sawing cycles.

A 65% utilization rate (1300 PMH/2000 SMH/yr) was assumed for both the loader and the bundler to account for saw chain delays, string delays, fuel and lube delays, restroom delays, and other miscellaneous delays. Fuel consumption for analysis purposes was assumed to be 3 gallons per hour. A fuel cost of $2.50/gal. and a lube cost of $2.50/ hr (total fuel and lube was $10/PMH) were applied to both machines. Fuel and lube was inflated by 5% each year.

Maintenance and repair costs for the bundler were based on conclusions from the field study. The operation consumed 1 roll of twine per 25 eight foot bundles. At a cost of $23 per roll, twine costs equated to roughly $2 per ton. Chains for the chainsaw consumed another large portion of the maintenance costs. Assuming 5 sharpenings per chain, and an effective chain cutting life of ½ day, chain costs totaled approximately $12,500 per year or $0.60 per ton. Allowing for some repair costs, total maintenance and repair for the trailer-mounted bundler was estimated to be $50/PMH. Maintenance and repair costs for the loader were estimated to be approximately $10/PMH. A 15% inflation rate was applied to each machine's maintenance and repair costs.

For the economic analysis, both the loader and the trailer-mounted bundler are purchased new without any trade-in. The initial analysis assumes the trailer-mounted bundler’s purchase price to be $250,000. A sensitivity analysis was also completed on the prototype’s purchase price because the figure has not yet been determined by the manufacturer. The purchase price of both machines were financed with no down payment for 48 months with an annual percentage rate (APR) of 10%. Insurance and taxes were set at 6% and is applied to the beginning year value of each machine. Fire, theft, and vandalism insurance made up 4%, and property tax accounted for the other 2%. The marginal tax rate is based on income. This cash flow analysis was based on a married owner filing jointly with his or her spouse. The 30% marginal tax rate included a federal tax rate of 25% and a state tax rate of 5% on a joint income of $67,900 to $137,300 (CCH 2009).

Because production models of the trailer-mounted bundler will have controls integrated into the loader, the economic analysis only applies a labor rate to the loader. A $15.00 labor rate is applied for a knuckleboom loader operator. Thirty percent fringe benefits were applied for the operator.

For the economic analysis of both the eight foot and twelve foot bundling operations, most of the variables remain the same. The only variable that differs between the two operations is the production. Production estimates are based on the observed performance during the production study. During eight-foot bundle production, the operation produced approximately 14.6 tons per productive machine hour. Processing twelve foot bundles, the operation was capable of nearly 16.4 tons/PMH with minor delays.

The annual equivalent cost (AEC) is the cost per year to own and operate the piece of machinery over its entire lifespan with adjustments made to account for the time value of money. Assuming a life span of four years, the eight foot bundling operation (Table 7 and 8) cost estimates were $11.23 per ton to produce bundles. The loader had an AEC of $74,210 and a cost per ton of $4.34. At a cost of $6.89 per ton, the trailer-mounted bundler had an AEC of $117,681.

The twelve foot bundling operation (Table 9 and 10) totaled $10.00 per ton to own and operate the loader and trailer-mounted bundling unit. The annual equivalent cost does not change based on production; however, the cost per ton decreases as production increases. The trailer-mounted bundler produced 12-foot bundles for $6.13 per ton and the loader costs $3.87 per ton.

By adding $6 per ton for trucking, $2 per ton profit for the logger, and $1 per ton for stumpage to the land owner, bundles could potentially be delivered to a facility within 50 miles for approximately $19 to $21 per ton.

Table 7. Loader economics (8-ft bundles)

Loader Analysis (8-ft bundle operation)				
Purchase price	$150,000		Discount rate	6.00%
Trade-in	$0		Finance APR	10.00%
BV of trade-in	$0		Marginal tax rate	30.00%
Down payment	$0		Amount financed	$150,000
Number of payments	48		Monthly payment	$3,804
Expense Option	$0		Adjusted basis	$150,000
Hours per day	8.00		Expected life, years	4
Days per year	225		Residual value end of life	40.00%
Fuel & Lube	$10.00		Inflate F&L	5.00%
Maint & Repair	$10.00		Inflate M&R	15.00%
Labor rate	$15.00		Inflate labor	5.00%
Fringe benefit %	30.00%		Utilization	65.00%
Insurance & taxes	6.00%		Production (tons/PMH)	14.6

AEC	($83,759)	($80,243)	($77,010)	($74,210)
Cost per ton	($4.90)	($4.70)	($4.51)	($4.34)
	Year 1	Year 2	Year 3	Year 4
Salvage value	114,000	87,000	69,000	60,000
ACRS Dep	30,000	48,000	28,800	17,280
Book value	120,000	72,000	43,200	25,920
Fuel & Lube	13,000	13,650	14,333	15,049
Repair & Maint.	13,000	14,950	17,193	19,771
Labor	35,100	36,855	38,698	40,633
Insurance	9,000	6,840	5,220	4,140
Total Expenses	70,100	72,295	75,443	79,593

Table 8. Bundler economics (8-ft bundles)

Bundler Analysis (8-ft bundle operation)				
Purchase price	$250,000		Discount rate	6.00%
Trade-in	$0		Finance APR	10.00%
BV of trade-in	$0		Marginal tax rate	30.00%
Down payment	$0		Amount financed	$250,000
Number of payments	48		Monthly payment	$6,341
Expense Option	$0		Adjusted basis	$250,000
Hours per day	8.00		Expected life, years	4
Days per year	225		Residual value end of life	20.00%
Fuel & Lube	$10.00		Inflate F&L	5.00%
Maint & Repair	$50.00		Inflate M&R	15.00%
Labor rate	$0.00		Inflate labor	5.00%
Fringe benefit %	30.00%		Utilization	65.00%
Insurance & taxes	6.00%		Production (tons/PMH)	14.6

AEC	($136,915)	($129,608)	($123,111)	($117,681)
Cost per ton	($8.02)	($7.59)	($7.21)	($6.89)
	Year 1	Year 2	Year 3	Year 4
Salvage value	170,000	110,000	70,000	50,000
ACRS Dep	50,000	80,000	48,000	28,800
Book value	200,000	120,000	72,000	43,200
Fuel & Lube	13,000	13,650	14,333	15,049
Repair & Maint.	65,000	74,750	85,963	98,857
Labor	0	0	0	0
Insurance	15,000	10,200	6,600	4,200
Total Expenses	93,000	98,600	106,895	118,106

Table 9. Loader economics (12-ft bundles)

Loader Analysis (12-ft bundle operation)				
Purchase price	$150,000		Discount rate	6.00%
Trade-in	$0		Finance APR	10.00%
BV of trade-in	$0		Marginal tax rate	30.00%
Down payment	$0		Amount financed	$150,000
Number of payments	48		Monthly payment	$3,804
Expense Option	$0		Adjusted basis	$150,000
Hours per day	8.00		Expected life, years	4
Days per year	225		Residual value end of life	40.00%
Fuel & Lube	$10.00		Inflate F&L	5.00%
Maint & Repair	$10.00		Inflate M&R	15.00%
Labor rate	$15.00		Inflate labor	5.00%
Fringe benefit %	30.00%		Utilization	65.00%
Insurance & taxes	6.00%		Production (tons/PMH)	16.4

AEC	($83,759)	($80,243)	($77,010)	($74,210)
Cost per ton	($4.37)	($4.18)	($4.01)	($3.87)
	Year 1	Year 2	Year 3	Year 4
Salvage value	114,000	87,000	69,000	60,000
ACRS Dep	30,000	48,000	28,800	17,280
Book value	120,000	72,000	43,200	25,920
Fuel & Lube	13,000	13,650	14,333	15,049
Repair & Maint.	13,000	14,950	17,193	19,771
Labor	35,100	36,855	38,698	40,633
Insurance	9,000	6,840	5,220	4,140
Total Expenses	70,100	72,295	75,443	79,593

Table 10. Bundler economics (12-ft bundle)

Bundler Analysis **(12-ft bundle operation)**				
Purchase price	$250,000		Discount rate	6.00%
Trade-in	$0		Finance APR	10.00%
BV of trade-in	$0		Marginal tax rate	30.00%
Down payment	$0		Amount financed	$250,000
Number of payments	48		Monthly payment	$6,341
Expense Option	$0		Adjusted basis	$250,000
Hours per day	8.00		Expected life, years	4
Days per year	225		Residual value end of life	20.00%
Fuel & Lube	$10.00		Inflate F&L	5.00%
Maint & Repair	$50.00		Inflate M&R	15.00%
Labor rate	$0.00		Inflate labor	5.00%
Fringe benefit %	30.00%		Utilization	65.00%
Insurance & taxes	6.00%		Production (tons/PMH)	16.4

AEC	($136,915)	($129,608)	($123,111)	($117,681)
Cost per ton	($7.14)	($6.75)	($6.42)	($6.13)
	Year 1	Year 2	Year 3	Year 4
Salvage value	170,000	110,000	70,000	50,000
ACRS Dep	50,000	80,000	48,000	28,800
Book value	200,000	120,000	72,000	43,200
Fuel & Lube	13,000	13,650	14,333	15,049
Repair & Maint.	65,000	74,750	85,963	98,857
Labor	0	0	0	0
Insurance	15,000	10,200	6,600	4,200
Total Expenses	93,000	98,600	106,895	118,106

Because the purchase price of the trailer mounted bundler is unknown, a sensitivity analysis was performed at $200,000, $250,000, and $300,000. Varying the purchase price in the modified Tufts et al (1989) models enabled the study to analyze the effects of purchase price on the cost per ton to own and operate the trailer-mounted bundler for the 4 year operating period. The costs per ton to own and operate a trailer-mounted bundler producing eight-foot bundles was $6.28, $6.89, and $7.49 based on the fluctuation in purchase price. Twelve-foot bundling cost per ton was $5.59, $6.13, and $6.67 respectively. Figure 12 illustrates the increase in the purchase price by $50,000 would constitute a $0.54 to $0.61 increase in cost per ton for bundling.

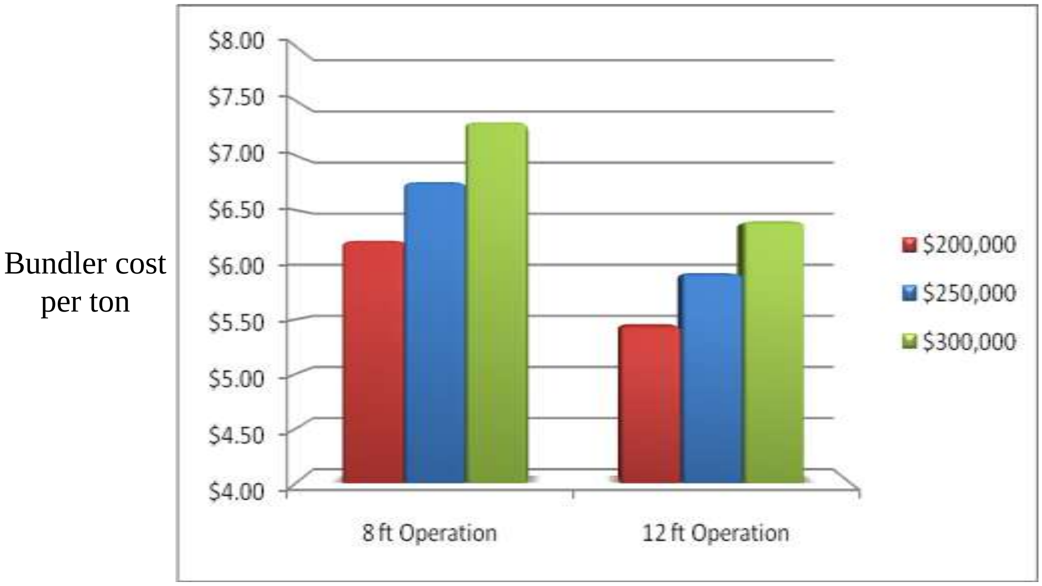

Figure 12. Sensitivity analysis based on purchase price of the trailer-mounted bundler

6.8 Design Modification

Extensive work with the prototype trailer-mounted bundler led to some recommended design modifications. Production gains, higher utilization rates, and safer operation and transportation could result from the following modifications.

Bundler modifications

1) Rotation configuration

   The piston driven rotation configuration within the turnstile needs to be redesigned. A gear based design seems much more effective. The middle “dead zone”, when the piston is fully extended, renders the rotation function useless. When not in use, the unit occasionally drifts around and could potentially cause damage to the loader or bundler.

2) Cutting configuration

   In our studies, the cut off saw was one of the biggest sources of operational delays. The chainsaw hangs up without completely severing the bundles. At times, the saw bar will cycle down 2 to 5 times before cutting through the bundle entirely. Chain life is also an issue. Chains seem to have an effective cutting life of 2 to 4 hours. The chain can cut for a longer period of time; however, the saw delays become more prevalent. Some of these problems could possibly be reduced by issuing pressure recommendations for the hold down arm and saw bar depending upon bundle length.

3) In-feed configuration

   For the most part, feeding the material into the machine was not a huge concern. After a short period of time, feeding slash comes naturally to a loader operator. A chain in-feed tray on the bottom seems like a viable option to aid the forward movement of the slash. Extending the vertical rollers would enable the bundler to grasp material more effectively.

4) Protection for the hold down bar

The hold down bar is a must; however, on multiple occasions a crooked or forked stem maneuvered itself into a position to bend the bar. These incidents, although few in number, are extremely costly both monetarily and in productivity. Extension of the protective steel guide is recommended in order to the steer the bundles away from this critical part.

Figure 13. Location of the hold down bar protection.

5) Overall protection

The valve bank is protected by a piece of sheet metal. The cover should be reinforced and have some type of metal stops instead of resting on hydraulic hoses at the bottom. With such an extensive hydraulic system, the numerous hoses are inevitable, but should be more protected in some areas.

Both compactor 2 and 3 have some exposed fittings that could be covered by simply extending existing protective pieces.

6) Remote control

Remote control is crucial for this unit's success. A lone loader operator must be able to feed and bundle to make bundling safe and economical. The remote must be able to operate all the functions; however, remote operation of the display and bundle configuration options is not required.

7) Display and bundle length

The unit's display needs to be in English units for ease of operation. During eight-foot bundling operation, bundle length varied from 254 cm to 272 cm. Length variation could cause problems when hauling bundles on a trailer.

Trailer modifications

Although the CSI trailer was adequate, it was utilized because of the project's timeline. A purpose built trailer should be constructed with the following suggestions in mind.

8) Power requirements

The 102 hp diesel engine used to power the unit was adequate. The only power issue with the tested unit existed in low temperatures when the hydraulic oil was more viscous than normal. This problem could be minimized by installing a pre-heater for the hydraulic oil or by running a lower viscosity oil.

9) Height of the unit

Height is a valid concern for a trailer mounted unit. The prototype trailer mounted unit is 13 feet, 6 inches tall. The production unit must have a lower center of gravity to ensure safe transportation. Lowering the unit would also give the operator a better line of sight during loading. On the other hand, in order to conserve bundling integrity, the unit must be high enough that bundles can freely drop after being severed. Examination of the proto-type reveals many opportunities to reduce the height, including different mounting configurations as well as lowering the height of the trailer's metal housing.

10) Axle(s)

The current unit does not meet DOT standards for transport on a single axle trailer. The bundler, including the mounting configuration, weighs approximately 9 tons. The CSI trailer weighs nearly 6 tons. A tandem axle trailer setup would not only legally bear the weight, it would also aid in the stability during travel on the highway and on rough in-woods roads.

11) Maintenance

In order to ensure the safety of workers, a maintenance deck should be built into the production model. Climbing on oily, slick surfaces is a safety hazard. A trailer mounted collapsible or folding platform would aid in the ease of maintenance for this machine.

12) Outriggers

Outriggers assist in the leveling of the unit on uneven surfaces. The production model trailer should feature outriggers because the added stability aids in safe and efficient bundling.

13) Towing

The trailer and tongue weight of the trailer mounted bundler should be within the towing capabilities of a heavy duty service truck for transportation. The pintle hook setup should protrude further from the grapple loop to ensure a more conducive towing configuration. The grapple loop is essential for in-woods transportation by skidders.

14) Additional transport considerations

A tie down system should be adapted to the trailer in order to ensure the bundler does not rotate in transit.

VII. Conclusions

Trailer mounting a John Deere B380 bundling unit does provide a new configuration that employs innovative slash bundling technology, which easily integrates into southern tree-length harvesting operations. The prototype design has proven that a self contained motorized trailer can fully satisfy all hydraulic and electrical demands of the slash bundler. Although the study's objective was to test the trailer-mounted bundler concept within a relatively short time frame and with a relatively low monetary expenditure, a purpose-built trailer could potentially aid in the trailer-mounted bundler's success. Minor modifications to both the trailer and bundler would create a safer and more productive slash harvesting machine.

The study's deck configuration, which incorporates a satellite bundling operation, is the ideal setup for similar harvesting operations and stand conditions. Well coordinated slash flow from the roundwood operation would enable the bundling operation to maintain the 14.6 to 16.4 tons/hr production rate observed during the production study. Assuming the average pounds/foot measured during bundling operations, a 25 ton trailer load of bundled material could be achieved in just over 1.5 hours. Set-out trucking would be ideal in these conditions. Instead of trucks sitting idle waiting to be loaded, they would simply pick up a full load of bundles and drop off an empty trailer to be loaded. Set-out trucking would also limit handling of the compressed residue logs which would aid in maintaining bundle integrity.

The tested prototype bundling operation did not negatively affect the skidding component of the roundwood operation and according to the cooperating logger had no effect on roundwood production. This conclusion is very important to the success of any forest residue harvesting operation. Any decline in the loggers more lucrative roundwood production would lead to significant problems in the economics of introducing the new bundling operation.

According to the production study and economic analysis, a similar trailer-mounted bundling operation could deliver green bundles for approximately $18 to $20/ton. Twelve foot bundling seemed to be the most conducive system for a bundle supply chain. With lower costs per ton to own and operate, twelve foot bundles were not only cheaper to produce, but they were also easier to transport.

Triple bunk trailers, which are already in production, could be purchased by a logger and used to transport saw timber, pulpwood, and bundles. The middle bunk could be moveable to facilitate all unloading methods. Transporting three bunks of green twelve foot bundles would allow trucker to achieve a full payload before exceeding volumetric capacity.

The studies' bundle storage and drying experiment returned a lower drying rate than expected. Bundles lost on average 156 pounds over 18 weeks or approximately 16.8% moisture content. The unusually wet, cold conditions impeded moisture loss. However, the storability of bundles exceeds that of chipped material. Some industrial consumers that depend on inventory and forecasting will consider these attributes as bioenergy markets develop.

VIII. Recommendations for Future Research

The prototype design of the trailer-mounted bundler needs much more refining before a production model will be available. Additional research and development is underway by the manufacturers. After operating the prototype, this study recommended changes to the bundler's piston based rotation design, cutting system, component protection, and controls. The purpose-built trailer for the production unit should have an additional axle for stability and weight distribution. The final design should incorporate a mounting system that allows for a lower center of gravity and a locking mechanism to secure the unit's range of motion during travel.

This case study indicates the unit's capabilities in a single environment. More studies should be performed to reinforce or discount these findings. A complete work sampling of an entire cooperating operation before and after implementing a trailer-mounted bundling operation would be needed to quantify the amount of interference caused by the additional operation. Several production studies of the manufacturer's production unit need to be completed to return accurate production rate figures for customers. Studies should be performed in different stand conditions and alongside different logging operations.

This study's bundle drying experiment should continue to provide additional information on the effect of temperature and precipitation on drying. Weather monitoring and bundle weight monitoring should continue for approximately five more months. After the time period, samples of each bundle should be taken and oven-dried to accurately assess the moisture content of each bundle. Additional storage studies should pursue the optimal storage configurations for inventory analysis.

With many questions surrounding the bundle supply chain, bundle transportation could continue to be an issue. A purpose built trailer to haul bundles should be investigated. Loading bundles seems intuitive; however, unloading and tying down a trailer of compressed residue logs could be a challenge. Another driver of trailer design is the moisture content at which bundles will be transported. Challenges of a trailer design lie in achieving a maximum payload in a finite volume with material of low bulk density. A purpose built trailer to haul bundles would greatly improve a logger’s ability to transport bundles.

In order for a bundle supply chain to succeed, research into equipment to efficiently process bundled must be performed. Grinder and chipper design should be investigated to ensure bundled material can be processed into piece sizes desirable in the bioenergy market.

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