

FINAL REPORT

**High Tonnage Forest Biomass Production Systems from
Southern Pine Energy Plantations**

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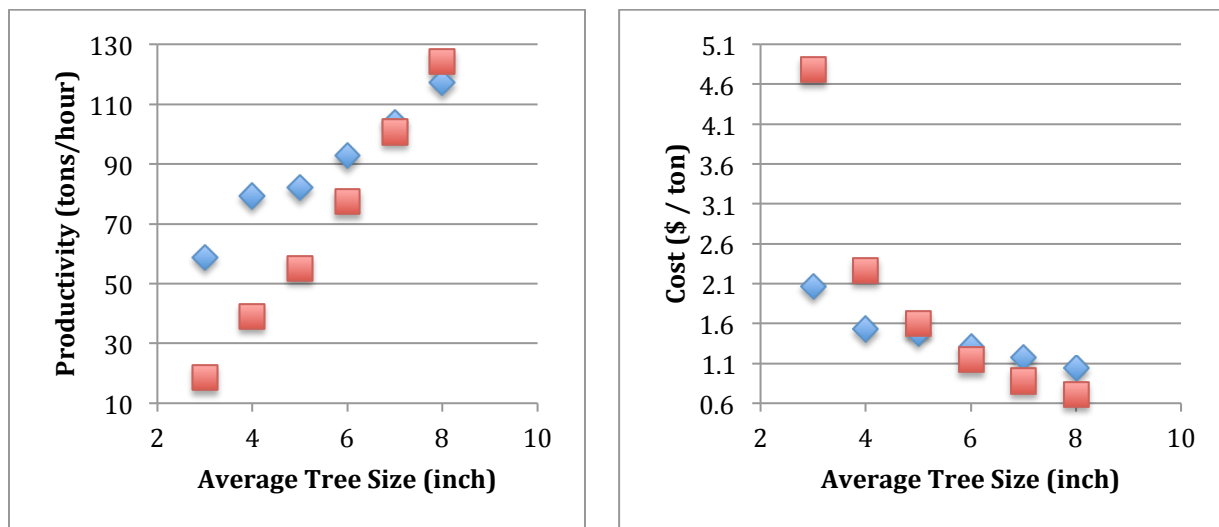
EXECUTIVE SUMMARY

Pine plantation silviculture and harvesting systems in the southern U.S. are optimized for production of roundwood outputs sold into the solid wood and pulp markets. While there are fuel wood products currently being produced from harvest residues or mismanaged plantations, there are not sufficient quantities of biomass available to provide feedstocks for a biofuel industry and therefore justify large-scale investment in the necessary logistics systems. Adapting silvicultural and harvesting systems to maximize biomass production for an energy market requires development of new harvesting and logistical systems to deliver, at low cost, feedstocks matched to a range of potential conversion technologies. The main limitations with existing harvesting equipment in high-density, bioenergy plantation stand types were identified as: a) felling costs increase exponentially when stem sizes are less than about 6 in. DBH; b) skidders can be significantly underutilized when pulling bunches comprised entirely of small stems; c) it is difficult to maximize truck payloads with small-stemmed material hauled tree-length; d) when logs are chipped, the traditional pulp-sized chips may be considered too large for an energy market; and e) if wood has experienced any field drying, it is difficult to reach full payloads in traditional chip vans.

In this study, a high-tonnage harvesting system designed specifically to operate efficiently in the expected stand types of a bioenergy scenario was built, deployed, and evaluated in a production setting. Stands on which the system was evaluated exhibited the heavy stocking levels (> 600 stems per acre) and tree size distributions with significant volume in small stems (down to 2" DBH) that were expected in the modified energy plantation silvicultural approach. The harvest system also was designed to be functional in the traditional plantation stands dominating the commercial forestry landscape in the region.

Felling Productivity in Small Trees

Traditional felling technology commonly employs a drive-to-tree machine that, when piece size becomes small, drops dramatically in productivity. The Tigercat 845D feller buncher, which was a prototype machine designed for the high tonnage harvest system, used a boom-mounted prototype DT1802 shear felling head and incorporated a number of options intended to maximize its small-stem productivity, including: a high-speed shear severing system that was cheaper to operate than a saw; a large-pocket felling head that allowed larger accumulations of small stems to be built before expending the time to drop them for the skidder; efficient, low ground pressure, tracked carrier system to decrease the amount of maneuvering, saving time and minimizing soil disturbance; and various energy-saving devices to lower fuel costs and minimize air quality impacts. Overall, the feller buncher represented a quantum advance in small-stem harvesting technology. Extensive testing showed the machine's production rate to be relatively insensitive to piece size, much less so than comparable traditional equipment. In plantation stands, the feller buncher was able to produce approximately 100 green tons of biomass per productive machine hour (PMH), and in natural stands, it produced nearly 120 green tons per PMH. The ability of the high tonnage feller buncher to maintain high productivity in stands with smaller diameter stems is something that has not been achieved in previous feller buncher designs. The Tigercat 845D feller buncher is now a production machine for Tigercat and is being sold in their current product line.



Modeled productivity and cost for the prototype Tigercat 845D (high tonnage in blue) and the Timber King (conventional in red) wheeled feller buncher as a function of tree size.

Skidding Costs With Small Trees

The high-speed felling system was paired with a Tigercat 630D skidder and high-capacity grapple; one that could match the felling productivity when pulling small stems. The harvesting system minimized hourly costs using a single, high-capacity skidder (with a single operator), rather than two smaller ones, which is the traditional practice. The skidder itself can be considered a mid-range size and had an engine no larger than other machines in its class, but it incorporated a very large capacity 25 ft² grapple. The large grapple is well suited to grabbing and hauling a large bunch of small-diameter trees, as produced by the high tonnage feller buncher. The grapple worked effectively in larger stems as well, but its ability to carry large numbers of small stems meant the average payload did not drop as stand DBH decreased. Tests with the machine indicated its travel speeds were nearly the same as, or perhaps slightly better than, conventionally equipped skidders, but grapple capacity was 75% larger. Productivity and cost per ton of the new skidder were better than conventional skidders for average skid distances of any length greater than 100 feet. Measured skidder productivity was as high as 143 gt/PMH. Its productivity exceeded that of the high-capacity feller buncher for skid distances out to nearly 700 feet, so system productivity could be expected to remain high for stands of a size typical in the southern U.S. The Tigercat 630D skidder is a production machine for Tigercat and the large grapple can now be ordered by customers using it for small diameter trees.

Felling and Skidding Costs

When the feller buncher and skidder are analyzed as a two-machine system, overall productivity is fixed at the level of the least productive machine. Results from a set of side-by-side tests in the same density stand with conventional feller bunchers and skidders showed that the high tonnage system produced 97 gt/PMH versus 68 gt/PMH for a comparable conventional system. Machine rate costs for felling and skidding were \$2.31/gt and \$3.72/gt for the high tonnage, and conventional systems, respectively. However, the most significant result of the project is that the high tonnage system was shown to be relatively insensitive to tree size. This ability to maintain

felling and skidding productivity and cost as tree size decreases is a breakthrough in harvesting systems for southern pine plantations.

Transpirational Drying

The concept of transpirational drying of woody biomass was tested at an industrial scale at multiple locations during this project. Felled trees were allowed to dry in two scenarios: 1) in bunches where they were felled, and 2) in roadside piles. Although the wood piled in large piles at roadside did experience drying, the wood left in bunches experienced a greater moisture reduction. Drying times of 72 days in the late summer resulted in mean wood moisture content of 26% for skidder bunches and 39% for the large pile at roadside as compared to moisture contents of 55% to 58% for freshly cut trees.

Chipping Productivity and Particle Size

An existing whole-tree chipper, Precision 2675, was modified to allow production of chips smaller than the traditional pulp size chip (i.e. “microchips”). Feed rates and knife placements were retained in the new design, while additional pockets were incorporated in the chipper disk to allow the attachment of either four knives for pulp chips or eight knives for microchips. This design facilitated switching between the energy and pulp chip product options at relatively low expense (about ½ day downtime).

Chipping of whole-trees into pulp chips and microchips with the Precision 2675 disk chipper resulted in average productivities of 79.5 gt/PMH and 70.7 gt/PMH, respectively. Production rates of the chipper were lower when producing microchips by about 10% relative to producing pulp chips, but rates were similar to those achievable when making clean pulp chips. Particle size analysis for clean pine microchips revealed 26.6% retention on a 13 mm (slightly less than 3/8-inch) round hole screen and 25.9% retention for whole-tree pine microchips. For comparison, clean pine pulp chips had 52.2% retained. Ash content (% dry basis) was 0.54% for clean pine microchips and 0.62% for whole-tree pine microchips. Ash content for clean pine pulp chips was 0.39%. For transpirationally-dried material there was 38.1% retention for whole-tree microchips on a 13mm screen compared to 70.1% for dried clean pulp chips. Ash content was 0.78% and 0.44% respectively for these two chip types. Clean pine microchips stored at roadside had 25.2% retention on a 13 mm screen and 0.50% ash content. For mixed species (pine and hardwood), whole-tree microchips had 25.1% retention on a 13 mm screen compared to 50.6% for whole-tree pulp chips. Ash content was 2.12% and 2.74% respectively for these two chip types. Clean hardwood microchips stored at roadside had 35.0% retention on a 13 mm screen and an ash content of 1.24%.

Transport Efficiency

There are two significant advantages to using transpirational drying: reduced transportation costs, and reduced drying costs (capital and operating costs) for the biorefinery. This project evaluated the potential to reduce transportation costs through transpirational drying, and it included a component that tested higher capacity chip trailers (23% larger volume) to be able to transport dry wood with a lower bulk density. For transpirationally-dried chips at 35% MC, the high-capacity trailers achieved loads with a mean payload of 24 tons with maximum payloads of 29 tons. The typical legal payload on this trailer is 28.5 tons. Therefore, the project demonstrated that it is possible to achieve maximum legal payloads on chip trailers with

transpirationally dried wood. Assuming that the truck is loaded to the legal payload limit, the transportation costs of chips can be reduced from \$15.91/dry ton (dt) for 56% MC wood to \$10.77/dt for transpirationally dried wood at 35% MC (for an example 50-mile haul distance at \$0.14 per one-way ton-mile). For longer haul distances, these savings in trucking costs become even more significant. These results have demonstrated how significant savings in transportation costs can be achieved through transpirational drying. Also, these results show that it may be possible to increase the procurement radius for a biorefinery by using transpirational drying. Further cost reductions can be realized by the biorefinery when drying costs are reduced.

Overall High Tonnage System Productivity and Cost

The goal of this study was development of a timber harvesting system as productive in stands optimized for biomass production as it was in stands grown for roundwood markets. If that goal is achieved, a logger can invest in a single suite of equipment and operate efficiently in any future silvicultural regime that might include energy feedstocks as an output. It was the premise of the study that a future biomass market would shift the age distribution and stem size in stands grown for energy downward, and the key strategy in developing a harvest system for that scenario would be creating one with logging costs relatively insensitive to tree size.

Our vision for such a system included a felling machine with a large capacity head to minimize time spent building bunches, plus a skidder capable of moving large volumes of small trees. The study proposed building the system and testing it against existing equipment in stands similar to those envisioned as resulting from biomass-optimized silviculture.

As stated previously, the new feller buncher and skidder evaluated on their own merits showed their designs were clearly a step in the right direction - their productivity was indeed high and less sensitive to reductions in stem size. Cost projections based on extensive time and production studies of the high tonnage and benchmark operations showed modest advantages in FOB costs of the new system in both 'average' and simulated 'energy' stands (7.7% and 9.5%, respectively). But it was clear, when coupled into a traditional logging system, the in-woods productivity advantage of the modified equipment was easily overwhelmed by inefficiencies in chipping or trucking. Some additional savings can be achieved by spreading the cost of the feller buncher over multiple chipping operations (another 7.5%), but generally, in stands with average DBH above 6 inches, the in-woods equipment was not limiting productivity, and costs were driven by chipping and transport.

Our results were a positive step in lowering delivered cost of trees grown for energy purposes, but they also argue strongly for a more comprehensive approach in solving this issue. The procurement system in its entirety has to be optimized to take full advantage of the productivity gains achieved with the machines and transpirational drying techniques developed in this project. We have to understand the true costs of all logistical options, particularly those of the choice in chipping strategy and in truck allocation, both of which seemed, in this study, to be the greatest source of variability in cost, and often the most expensive operations as well.

Other Significant Outputs

1. The technology developed for monitoring remotely the production of in-woods machines will, when fully developed, exponentially increase the amount of operating data that can be reliably collected on equipment working in the woods. This will lower costs for collecting much more detailed knowledge of the variability of machine productivity to numerous factors poorly understood at this time, such as terrain, time of day, season, or local stand characteristics. The ability to generate the equivalent of an agricultural ‘yield map’ was also demonstrated with the new technology, which could be as transformative in forestry and silviculture as it has been in farming. This same technology is now being marketed on OEM machine systems, such as through John Deere’s ForestSight™ or Caterpillars CatConnect™.
2. A new capacitive sensor for simultaneous mass flow and moisture content measurements in moving streams of biomass has been developed. This work has overcome a major stumbling block when applying capacitive-type sensors for measuring moisture levels: their sensitivity to total mass being tested. The new methods remove this weakness and will allow development of methods for monitoring of moisture content in field and process control applications.
3. A complete characterization of important physical and chemical properties of a pine biomass feedstock was generated.
4. Focus groups were convened to determine perceptions of loggers and landowners related to high tonnage biomass supply systems as tested in this project. Overall, loggers and landowners were receptive to possible bioenergy markets if supply contracts are in place to reduce risk. They were receptive to the concept of bioenergy plantations and the high tonnage harvest system. Implementation of transpirational drying will need changes in cultural practices as well as changes in the traditional processes for purchasing the biomass from the landowner.



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HIGH TONNAGE FOREST BIOMASS PRODUCTION SYSTEMS FROM SOUTHERN PINE ENERGY PLANTATIONS

INTRODUCTION

The U.S. has established very ambitious goals for production of biofuels through the Renewable Fuel Standard as outlined in the Energy Independence and Security Act of 2007. Specifically, the targets include producing 32 billion gallons of biofuels by the year 2022, with over half of this amount coming from cellulosic biofuels. To meet these targets, logistical systems are needed that will produce high tonnage biomass feedstocks, i.e., at least 100 million dry tons per year, in a manner that is technically, economically, and environmentally feasible.

Out of all the candidate cellulosic feedstocks, forest biomass is the predominant feedstock available today and into the foreseeable future. Although forest residues are discussed frequently as a source of cellulosic biofuels feedstocks, short rotation woody crops hold the greatest promise for producing high tonnage feedstocks in an economically feasible manner. Given the inherently high productivity in southern U.S. forests, we believe that southern pine energy plantations hold the greatest immediate ability to provide high tonnage feedstocks required to meet U.S. energy goals. Therefore, we proposed and conducted a project to assemble and demonstrate a system to harvest, process, and transport woody biomass from what was envisioned as a dedicated biomass plantation of southern pine.

PROJECT OBJECTIVES

This project designed and demonstrated a high productivity system to harvest, process, and transport woody biomass from southern pine plantations. The specific objectives of this project were to:

1. Develop design improvements in tree-length harvesting machines (feller buncher and skidder) for energy plantations;
2. Configure and assemble a high-productivity, lowest-cost harvesting, in-forest pre-processing and transportation system for biomass from southern pine energy plantations; and
3. Demonstrate the complete and integrated system at full industrial scale and document the performance of the harvesting, storage, drying and pre-processing, and transportation sub-systems to determine the lowest delivered cost and provide high quality pre-processed feedstock to a biorefinery operator for performance testing.

The project was conducted by a consortium composed of forest biomass providers, forest equipment OEMs, university research institutions, and the USDA Forest Service. Auburn University led the consortium, and along with the USDA Forest Service, contributed expertise in monitoring and documenting the performance of the systems. Primary responsibility for demonstration of the biomass harvesting and transportation was coordinated by Corley Land Services, an Alabama land services company. Tigercat, Inc., a forest equipment OEM collaborator designed and manufactured new, high productivity machines to harvest and pre-process the biomass in the forest. Chipped biomass was delivered to multiple biorefinery locations.

PROJECT BACKGROUND

Feedstock Justification

The U.S. is strongly pursuing a new bioenergy economy for reasons that include reducing our dependence on foreign sources of oil and reducing greenhouse gas emissions. In addition to the Renewable Fuel Standard goal of producing 32B gals of renewable fuels by 2022, Congress is currently debating a federal

Renewable Electricity Standard that will mandate significant portions of our electrical generation from renewable sources. Estimates of required feedstocks (combination of agricultural and forest biomass) to supply just the biofuel demand are more than 160M dry tons per year. National assessments of biomass availability indicate that this demand will apply significant pressure on the wood fiber supply, especially with respect to traditional industries of pulp and paper and solid wood products. The current revision of the Billion Ton Report estimates that available logging residues and forest thinnings will provide less than 80 million dry tons per year. To meet all these competing demands, new sources of wood fiber (i.e., from energy crop plantations) will be needed.

The southern U.S. is the primary wood-producing region of the country. Over 60% of US timber production comes from southern forests, nearly all from privately held forestland. This is more timber production than any other single country in the world. Southern pulpwood production in 2006 accounted for more than 80% of total U.S. pulpwood production (about 126M tons). The southern pulpwood industry has more than tripled since the 1950's. This growth in fiber output has been supported by the development of pine plantations. Pine planting has increased from <50,000 acres per year in 1945 to about 2M acres per year in 2006. There are currently more than 35M acres in pine plantation in the South (about 16 % of total southern forestland). With a decline in the pulp and paper sector and solid wood products sectors (due to housing construction reductions), a significant amount of the wood fiber from these plantations is available now for use in a biorefining industry.

The development of the biorefining industry will likely prompt an increase in plantation management to meet demand, similar to what occurred in the 1950's. Assuming average growth rates of 6 to 7 dry tons per acre per year on a 15-yr rotation, an annual supply of 100M dry tons could be sustainably produced from an area of about 15 M to 16.7 M acres. This 16.7 M acres required is well within the capacity of southern forests, which total over 200 M acres. In fact, the 2008 Farm Bill's Biomass Crop Assistance Program (BCAP Section 9011) provides special incentives to develop woody plantations for energy. Under BCAP, eligible landowners can receive cost-share funds for biomass crop establishment, annual payment for lost revenue due to establishment of the new biomass crop, plus a subsidy payment for harvest and delivery. Contracts for woody plantations can run for 15 years.

The most likely scenario for high-tonnage production of woody biomass is dedicated energy plantations in the U.S. South. While there are various alternative species and rotation strategies that could be employed in the South, intensive even-aged loblolly pine management has many advantages, the two greatest of which are:

- a) pine management is well-known and reliable with all of the supporting practices in place (nursery production, site preparation and planting technologies, disease and pest control, etc.)
- b) pine management offers landowners alternative merchandizing options over a rotation and fiber can be diverted to other existing uses such as pulp or OSB if needed.

Proposed Southern Pine Energy Plantation System.

This project proposes that intensive pine plantation management for energy production would use loblolly pine, planted at a higher density (1200 trees per acre, 6 ft by 6 ft spacing), and clearcut at rotation ages between 10 and 15 years to achieve average yields of at least 7 dry tons of biomass per acre per year of growth. The management objective would be to capture as much of site potential early in the rotation through the close spacing and carrying the plantation to economic maturity. Intensive silvicultural practices such as tillage before planting, management of competing vegetation, and fertilization could be used to maximize biomass growth. Compared to conventional pine plantations, energy plantations would have more trees per acre, smaller diameter stems, and closer spacing. While short-rotation hardwoods are not the intended focus of this proposal, it should be noted that planting density and tree size would be similar for either pine or hardwood.

This type of energy plantation will offer very attractive benefits for many of the forest landowners in the southern U.S. Current practice in managing for pulp and paper and solid wood products is to conduct a final harvest at an age of approximately 25 to 30 years. If the landowner invests in artificial regeneration of the stand (rather than relying on natural regeneration), they typically plant at densities of 650 trees per acre, with a final survival of about 550 trees per acre. They should be able to conduct the first commercial thinning of the stand in about 15 years and sell this material for pulp and paper production. At this point, the landowner may be able to receive enough revenue from the thinning to recover the cost of establishing the stand 15 years earlier. They may then wait until the age of 25 to 30 years before receiving the final revenue from the stand when it is harvested for solid wood products. Unfortunately, today's pulp and paper market conditions are such that the first thinning returns very little revenue to the pine plantation landowner. Moreover, with the current reduction in the construction industry, the market for the larger timber harvested at age 25 to 30 is almost nonexistent, which results in very low overall return on investment for the landowner.

An energy plantation system based on a single final harvest at age 15 years (or less) may be more attractive to many landowners today who are interested in more frequent and greater returns on their investment (e.g. real estate investment trusts, timber investment management organizations, or individual private landowners) because they could recover more revenue more frequently. Also, they are not locked in to a long term management strategy that will require 25 to 30 years to see the final results. Biomass harvesting operations currently being conducted by Corley Land Services in southern Alabama are able to harvest, at age 12, as much as 55 green tons per acre in what are considered pre-commercial pine plantation thinning operations that only remove about one-third of the volume of the stand. This amount is equivalent to a total growth rate in the stand of 6.8 dry tons per acre per year. By increasing planting density and continuing to improve genetics and silvicultural practices, we feel confident that 7 dry tons per acre per year of biomass can be produced in well-managed pine plantation systems. Given this type of feedstock management system that has potential application across the southern U.S., the challenge is to develop an improved woody feedstock harvest, processing, and delivery system that takes advantage of energy plantation characteristics to deliver cost-competitive material to biorefineries.

Proposed Biomass Delivery System

The following text describes the proposed biomass delivery system and provides rationale and discussion of the unique features of the system. The biomass delivery system proposed here will include the following functions:

1. Felling of trees using track-type, swing-to-tree feller bunchers with new design features to enhance productivity, reduce energy consumption, and reduce operator fatigue, and new geospatial tools to provide feedback on productivity and assist in product quality monitoring;
2. Transpirational drying of felled trees in the field to reduce moisture content of the biomass and to serve as an intermediate storage area for biomass;
3. Skidding of trees using wheeled skidders with high volume grapples normally installed on larger skidders;
4. Whole-tree chipping of trees in the woods with high-productivity disk chippers equipped with new sensing technology to monitor biomass characteristics (moisture and energy content and particle size);
5. Transport of whole-tree chips from woods to biorefinery using high capacity trucks; and
6. Final storage of whole-tree chips at the biorefinery.

PROJECT SCOPE

To meet the project objectives and goals, the consortium worked collaboratively during two major project phases. Phase I (approximately 12 months) of the project consisted of designing and building an improved high-speed feller buncher and high capacity skidder to fell and skid trees from intensively-managed southern pine plantations. High-capacity chip vans were designed and built to transport woody biomass from the forest to the biorefinery. Additional efforts were devoted to developing advanced sensors and geospatial data collection systems to quantify system performance for felling, skidding, chipping, and transport. Phase I also consisted of conducting benchmarking tests of conventional harvesting systems in southern pine forests in Alabama.

At the end of the Phase I of the project, a formal Stage Gate review meeting was held at the project site to assess progress in the project and to determine when and if to proceed to the second phase of the project. Once the Stage Gate review panel and DOE approved moving on to Phase II of the project, the consortium spent the remainder of the project period conducting field performance tests to demonstrate the productivity and costs of operating various configurations of the system of felling, skidding, in-woods drying, chipping and transport to cooperating biorefineries. One of the most innovative aspects of the project was the use of in-woods storage and transpirational drying of the trees after felling and before skidding and chipping. This drying system was able to reduce the moisture content of the wood from about 55% to about 35%. This reduction in moisture content results in significant reductions in transportation costs. These tests resulted in the cumulative harvest of approximately 182,000 green tons of biomass over the course of the project in a full-scale industrial setting.

TASKS PERFORMED

PHASE I: Research and Development

Task 1 – Establish Scientific Advisory Group

A Scientific Advisory Group was established to provide additional technical advice, counsel and oversight during the conduct of the demonstration phase. The Advisory Group was composed of representatives from pertinent research and industry groups, such as USDA Forest Service and Department of Energy, private and/or industrial forest landowners, forest products industry, forest biomass producers and service providers, original equipment manufacturers, and biorefineries that intend to produce liquid fuel. The members of the Advisory Group included:

- Corey Radtke, Shell Oil
- Mike Griggs, International Paper
- David Helm, International Paper
- Paul Lohman, International Paper
- Eric Owens, International Paper
- Jeff Wilson, Southern Company
- John Cuzens, Bluefire Ethanol
- Robert Corley, Coskata
- Loula Merkel, Coskata
- Mike Cooley, Catchlight
- Sam Jackson, Genera Energy

- Bill Waller, Green Circle Bio
- Richard Hess, Idaho National Labs
- Kevin Kenney, Idaho National Labs
- Steve Casey, Zilkha Biomass

The Advisory Group met as a group on three different occasions: 1) after project initiation (June 3, 2010), 2) during the Stage Gate review (February 18, 2011), and 3) after new system was operational (May 23, 2012). The group members (especially those from potential biofuel producers such as Shell and Coskata) provided guidance on feedstock properties requirements (e.g. moisture content, particle size, etc.). The group highlighted the importance of reducing moisture content through transpirational drying as one of the greatest potential contributions from the project.

Task 2 – Design of Feller Buncher, Skidder, and High Capacity Trailers

Consortium members worked together to complete the design of an improved feller buncher and grapple skidder. Initial machine productivity modeling was completed by the group at Auburn University, USDA Forest Service and Corley Land Services. Concurrently, engineers at Tigercat conducted the detailed design work on the two machines.

In the initial productivity modeling work, spreadsheet models (example shown in Figure 2.1) were developed to predict machine and system productivity and cost. The machine productivity predictions were based on spreadsheet models that modeled the function of a track type feller buncher and wheeled skidder working in a pine plantation. The spreadsheet allowed input of row spacing, tree spacing within the row, time to cut each tree, number of trees to accumulate in the felling head, time to dump the accumulated trees, and time for the feller buncher to move to the next location to fell trees for the subsequent bunch. Similarly, input data for the wheeled skidder included grapple size and speed of the machine. Projections for operational costs of the machines were conducted using machine rate spreadsheets and typical assumptions for operating cost components.

For the feller buncher, the model predicted productivity up to 73 green tons/productive machine hour (gt/PMH). This productivity estimate was based on cutting 6 in. diameter at breast height (DBH) trees at a rate of 511 trees per hour and accumulating 25 trees per bunch. Model predictions for the skidder were 77 gt/PMH using the size of the new larger sized grapple, with a total area of 25 sq. ft., which would be able to theoretically transport up to 80 trees per load (based on assumptions of 30% void space in the grapple, 20% diameter increase due to butt swell, and 97% grapple utilization). Figure 2.2 shows predicted productivities for different plantation configurations for both the feller buncher and skidder.

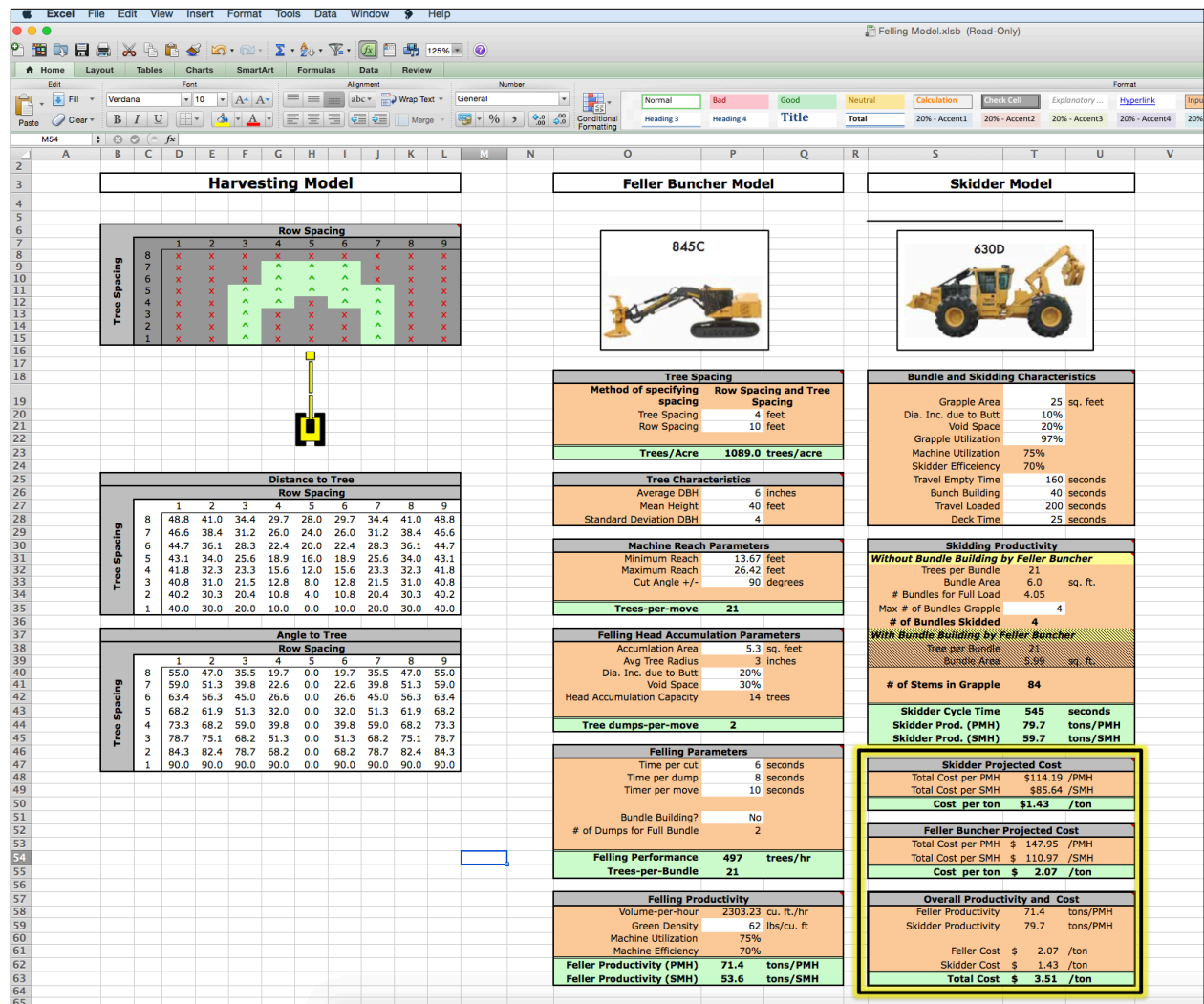


Figure 2.1 Example screenshot of spreadsheet model that summarizes machine modeling and design calculations.

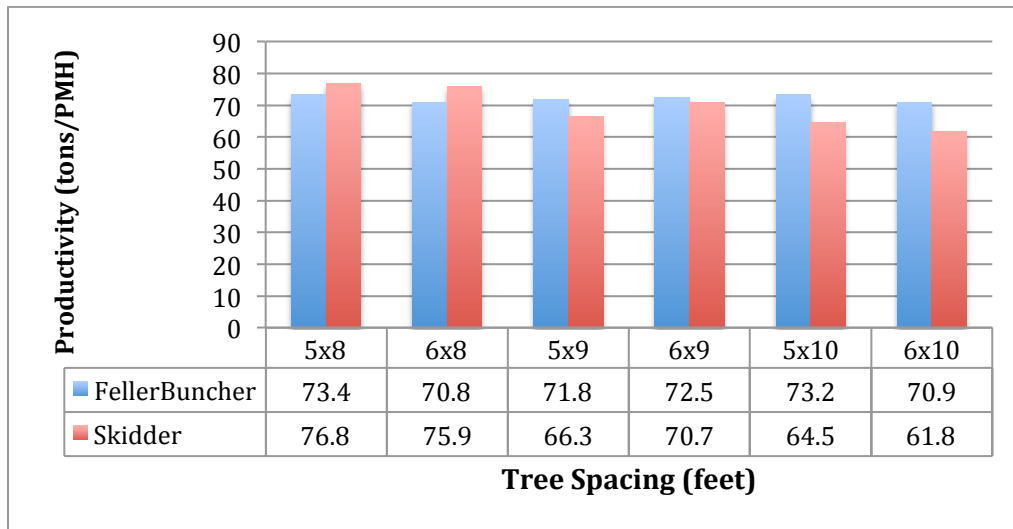


Figure 2.2 Predicted productivities for the feller buncher and skidder conducted during the design process.

Machine rate calculations predicted costs of \$2.02 and \$1.59 per green ton for the feller buncher and skidder, respectively. These machine rate calculations were based on projected purchase prices of \$350,000 and \$250,000, for the feller buncher and skidder, respectively.

Concurrent with the modeling activities, basic machine design activities were conducted by engineers at Tigercat. Their work focused on new features that were incorporated in the design of the feller buncher and skidder.

Feller Buncher

New design features incorporated on the feller buncher include: 1) high-speed shear felling head; 2) higher capacity accumulating felling head; 3) automation of the tree accumulation process; 4) energy efficient ER® boom system; 5) energy recovery swing system; 6) engine that met the Tier 4i (interim) emissions requirements; and 7) the ability to allow telemetric monitoring, recording, and analysis of machine performance data. The result of the work by Tigercat was an entirely new model feller buncher labeled the 845D Biomass Harvester, shown in Figure 2.3.

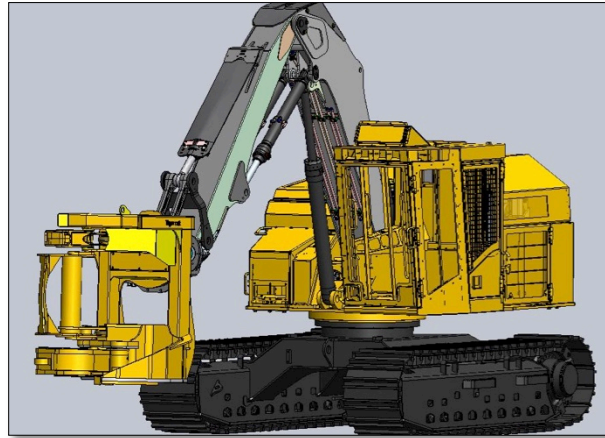
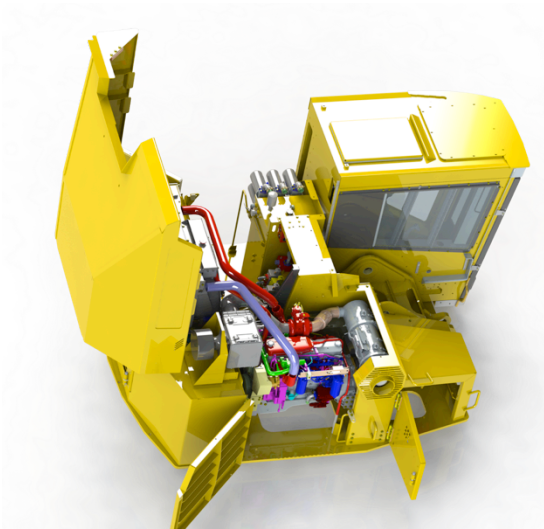


Figure 2.3 Tigercat 845D Biomass Harvester shown in renderings during the design phase and in the field as the final prototype machine.

Even though Tigercat had other similar designs of track type feller bunchers, these earlier machines only met EPA Tier 3 emissions requirements. To provide the desired productivity rates and to comply with the latest requirements for emissions, the project team made the decision to design and build a new machine and one that would meet the Tier 4 emissions requirements as they existed in early 2011 (i.e. Tier 4i). This decision to meet Tier 4i resulted in the design of an entirely new machine for Tigercat. To meet Tier 4i requirements, a larger fresh air intake and a diesel particulate filter and catalytic converter exhaust after treatment system was coupled with a Cummins QSB 6.7 engine. The QSB 6.7 is a 6.7 liter displacement engine package, rated at 260 hp, that met the EPA Tier 4 Interim emissions requirements. This new

machine, at 260 hp (which was nearly the same horsepower as its predecessor - the 845C feller buncher, which was rated at 275 hp) would require 33% greater cooling capacity due to the additional demands of the exhaust treatment systems. The additional cooling system capacity required a redesign of the entire engine compartment and upper portion of the feller buncher. In the 845D, the various oil coolers were reoriented to provide sufficient oil cooling capacity and additional air flow over hot engine components, while maintaining fuel storage capacity.

The design team decision to use the shear felling head was based on the knowledge that the shear should have a lower initial and operating cost than high-speed disk saws, which are commonly used in the southern U.S. on feller bunchers. The decision to use a shear-head also resulted in a more simplified hydraulic system design that would, in turn, allow the installation of the energy recovery system during swing movements of the feller buncher. The hydraulic pump arrangement for the 845D is shown in Figure 2.4.

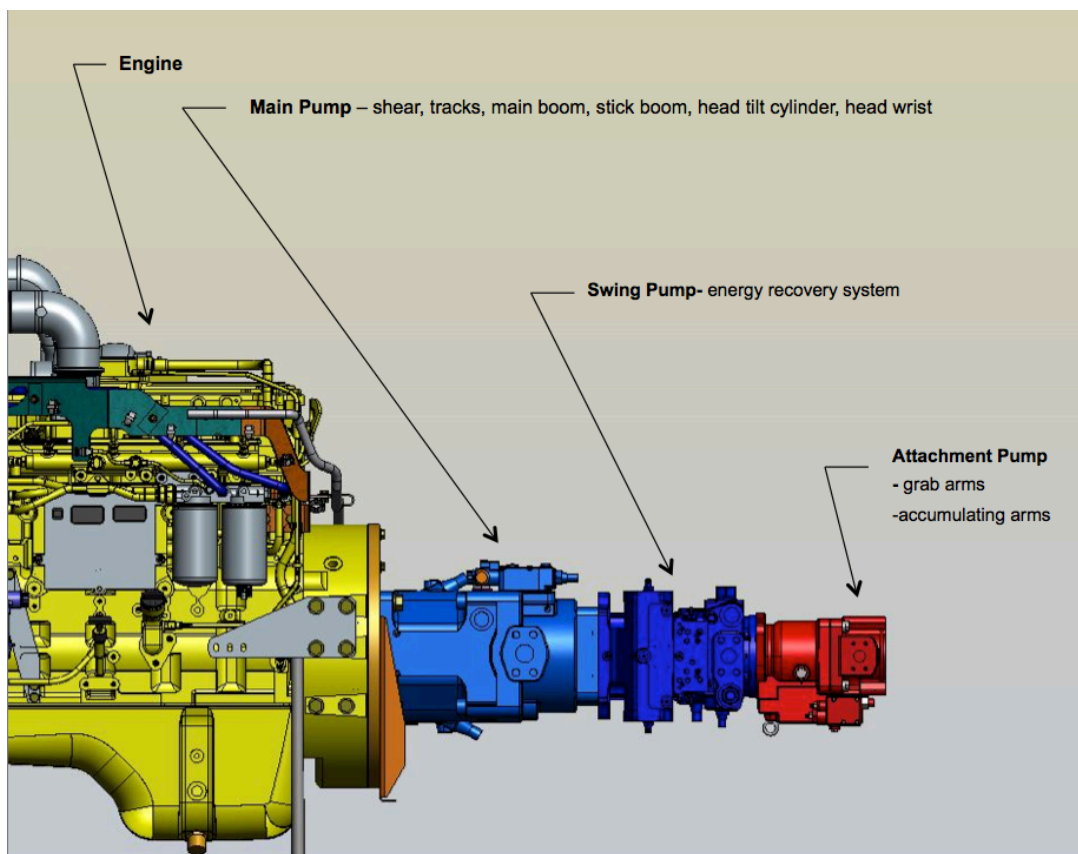


Figure 2.4 845D Biomass Harvester hydraulic pump layout.

The 845D energy recovery system eliminates energy losses from the swing relief valves during swing acceleration. The system recovers energy stored in the swinging boom and upper frame assembly during braking. The system had been proven to save fuel in Tigercat knuckleboom loaders, but it had not been previously incorporated into the design of a feller buncher. The dedicated swing drive system reserves all main hydraulic pump flow for boom and attachment functions, which results in increased speed and productivity for the machine.

Other design advances in the hydraulic system design included placing the shear mechanism and the accumulator arms on different hydraulic circuits, which allowed the machine's computer system to

control each subsystem separately. This increased control ability allowed for incorporation of automated accumulation using one button control on one of the operator's joysticks. The shear open position also is adjustable in the computer system so that the machine can be configured to harvest a specific tree size. This adjustment can prevent the shear mechanism from opening to a position that is wider than necessary, thereby reducing overall shear cycle time and reducing fuel consumption.

The feller buncher also was outfitted with Tigercat's patented ER[®] technology boom system. This ER[®] system provides energy recovery for increased fuel efficiency. Moreover, the ER[®] technology allows the operator to make one joystick movement to move the main and stick booms in a planar motion, as illustrated in Figure 2.5. This ease of movement allows for smoother cuts and high machine productivity.



Figure 2.5 ER[®] technology boom system allows planar movement of the boom system (both main boom and stick boom) through a single joystick movement.

Tigercat developed design improvements that led to the DT1802 shear felling head used in this project. Since the traditional disk saws are perceived to provide a rapid method for severing the tree, the goal of this effort was to design a shear system that would be able to fell trees at productivity levels that met that of the traditional disk saw, yet with lower operating costs. The DT1802 shear is a high-speed shear that can open or close in less than 1.5 seconds. The DT1802 was designed to fell trees with average DBH of 6 in. with maximum DBH up to 18 in. At 6 in. DBH, the felling head can theoretically hold up to 19 trees. The DT1802 is equipped with a 340 degree wrist mechanism that allows the operator to easily turn the feller buncher and place bunches behind and on either side of the machine. The shear was fitted with 0.625 in. thick shear blades for reduced shearing energy; however, it is possible to refit the shear with thicker blades if necessary. The shear also was equipped with hardened wear resistant steel plates to resist wear in sandy soil conditions. The DT1802 is shown in Figure 2.6.



Figure 2.6 DT1802 high-speed shear felling head illustrating the ability to rotate the head with the 340 degree rotation wrist.

Wheeled Skidder

New design features incorporated on the grapple skidder include: 1) use of the industry's largest grapple attachment; 2) the ability to allow telemetric monitoring, recording, and analysis of machine performance data; and 3) implementation of new ergonomic systems for improved operator comfort and performance. The skidder chosen for the high productivity system was a Tigercat 630D wheeled skidder. This is not the largest and traditionally highest productivity skidder in the Tigercat's corporate line; however, the design team made the decision to use a medium-sized skidder outfitted with a new larger grapple based on the concept that the system would be skidding smaller trees that would not require the larger machines. The team chose the 630D wheeled skidder configured with the 25 sq. ft. grapple, which was available for use on Tigercat's larger 635D skidder (the standard size grapple for the 630D skidder is 17 sq. ft.). The Tigercat 630D skidder is shown in Figures 2.7 and 2.8.



Figure 2.7 Tigercat 630D wheeled skidder.



Figure 2.8. Visual comparison of the Tigercat 630D skidder (on right) with the 25 sq. ft. grapple and the Caterpillar 525 skidder (on left).

The 630D skidder is equipped with a 260 hp Cummins diesel engine meeting EPA's Tier 3 emissions requirements. At the time of the design phase, the skidder was not required to meet Tier 4 emissions limitations, therefore, a Tier 3 solution was chosen. Currently, Tigercat offers the 630E skidder, which does meet Tier 4 emissions limitations.

The 630D skidder uses advanced electronic control technology coupled with Tigercat's unique hydrostatic drive system to allow the skidder to operate at variable engine speeds, automatically increasing engine speed when additional power is needed. This control technology results in improved fuel economy and reduced engine noise, and it does not require the operator to change gears, thereby reducing operator fatigue. The 630D was also equipped with Tigercat's TURNaround™ system that features a two-position rotating seat. This rotating seat is equipped with all machine controls on the seat arms, which allows the operator to comfortably back up the machine while facing rearward. This rotating seat reduces operator fatigue and allows for more productive operation of the machine.

High Capacity Chip Trailers

Design discussions were conducted with a chip trailer manufacturer to develop a larger volume trailer capable of transporting the maximum legal payload of chips at lower moisture contents after transpirational drying. Three chip trailers were fabricated by Peerless Trailers. These trailers were 45 ft long, 102 in. wide and 104 in. tall. These trailers had a 23% greater volume than the traditional chip trailers used for in-woods operation in Alabama. An example trailer is shown in Figure 2.9.



Figure 2.9 High-capacity chip trailer.

Additional Machines

Additional machines in the system included a knuckleboom loader, chain flail delimber, and disk chipper. These machines were existing models that were either in use by Corley Land Services or leased from Precision Husky, Inc. during the project period. The knuckleboom loader, which was owned by Corley Land Services, was used to feed logs into the chipper or load logs onto log trucks was a Tigercat T234 track loader. The T234 is configured with a six cylinder Cummins engine rated at 173 horsepower (most recently, the T234 is equipped with a Cummins QSB6.7 Tier 4i engine and emissions system). Current product literature for the T234 is shown in Appendix A.

The disk chipper, which was leased from Precision Husky, was a Precision Husky Model 2675 disk chipper. The chipper was equipped with an 875 horsepower Caterpillar diesel engine. The chipping disk is a 75 in. diameter disk with the ability to attach four knives for pulp size chips or eight knives for microchips. Product literature for the chipper is also provided in Appendix A. The loader and chipper are shown in Figures 2.10 and 2.11.



Figure 2.10 Tigercat T234 loader and Precision Husky 2675 disk chipper.



Figure 2.11 Precision Husky 2675 disk chipper.

Task 3 – Development of Geospatial Tools

Activities in this task were devoted to development of geospatial tools that were installed in the machines to provide additional productivity assistance to the operators, productivity monitoring, geospatial mapping of biomass yield, and final bunch locations and felling dates. Description of the geospatial tools and sensor development and performance is provided in Section 8.2.

Task 4 – Benchmarking of Traditional Biomass Harvesting Systems

Although the land services group has extensive performance information on pre-commercial thinning operations, they have not clearcut the new type of plantations, and therefore, this portion of the project established a baseline for the cost and productivity of machines that are commonly available today. Field demonstration activities began with a benchmarking period where the land services company operated a

conventional harvesting system consisting of drive-to-tree wheeled feller bunchers, conventional grapple skidders, and their existing whole tree chippers to conduct clearcut operations in the pine plantations described above. This benchmarking period occurred over approximately a nine-month period using a conventional workday schedule. Corley procured stumpage from approximately 12- to 15-year-old southern pine plantations.

4.1 Objective

The primary objective of this task was to establish production and cost rates for conventional harvesting equipment, including feller-bunchers, grapple skidders, knuckleboom loaders, and chippers. Stand information and harvesting system time-study data were collected from several sites during the benchmarking phase. The sites studied during the benchmarking phase included both plantation thinnings as well as clearcuts.

4.2 Methods

To assess stand characteristics such as density and stocking levels, fixed radius plots were installed in each stand where time-study data were collected. Within each plot, tree DBH data were measured on trees 3.6 inches and larger and tree species was recorded. Total tree height was measured on every fifth plot tree. Tree diameters were measured to the nearest 0.1-inch using calipers while total heights were measured to the nearest 0.5 feet using an electronic hypsometer.

Elemental time study data for felling were collected by recording on video the drive-to-tree rubber-tired feller-bunchers working in study plots that were installed within a stand. Both 3-wheeled and 4-wheeled machines were used and studied in thinning and clearcut operations. Thinning operations consisted of removing corridors three rows wide and thinning within the remaining stand. A corridor was removed every fifth row. The 3-wheeled machine studied was a Valmet 603 (as shown in Figure 4.1). Four-wheeled machines evaluated included a Hydro-Ax 470 and a Timber King 340 (Figure 4.2). Both 4-wheeled machines were equipped with circular saw heads while the 3-wheeled machine utilized a shear head. The main emphasis was on the 4-wheeled machines, since they are the most common type used in the southeast. Each plot tree was marked with a number for identification purposes during recording. Tree numbers were printed onto heavy stock paper cards and stapled onto trees. Tree weights were calculated using local weight equations to determine productivity. A complete observation, or cycle, of a feller-buncher began after trees in the head were dumped and the machine initiated travel to cut the first tree and ended when trees in the head were dumped. Cycle elements consisted of move to first tree, accumulate, move to dump, and dump.

A CAT 525B and a John Deere 648 (shown in Figure 4.3) grapple skidder were both evaluated in thinnings and clearcut operations. Elemental time study data and productivity data were measured using stopwatches and numbering of bunches for identification during a cycle. For most bunches a sample of trees were measured for DBH and a total stem count was conducted. For bunches where measurements could not be obtained, a total stem count was taken. A complete observation, or cycle, began when the skidder left the landing and ended when the skidder returned to the landing and ungrappled its load. Cycle elements included empty travel, position and grapple, intermediate travel, loaded travel, and ungrapple. Distances traversed by a skidder were measured using either a Garmin GPS unit or a Rolotape measuring wheel.



Figure 4.1 Valmet 603 feller buncher used in benchmarking tests.



Figure 4.2 Timberking 340 feller buncher used in benchmarking tests.



Figure 4.3 Caterpillar 525 grapple skidder used in benchmarking tests.

Productive machine hours were determined for each machine using activity recorders placed in each machine (an example of activity recorder information is shown in Figure 4.4). Utilization data were developed based on the productive hours measured by the datalogger divided by the total scheduled work hours for the harvesting crews.

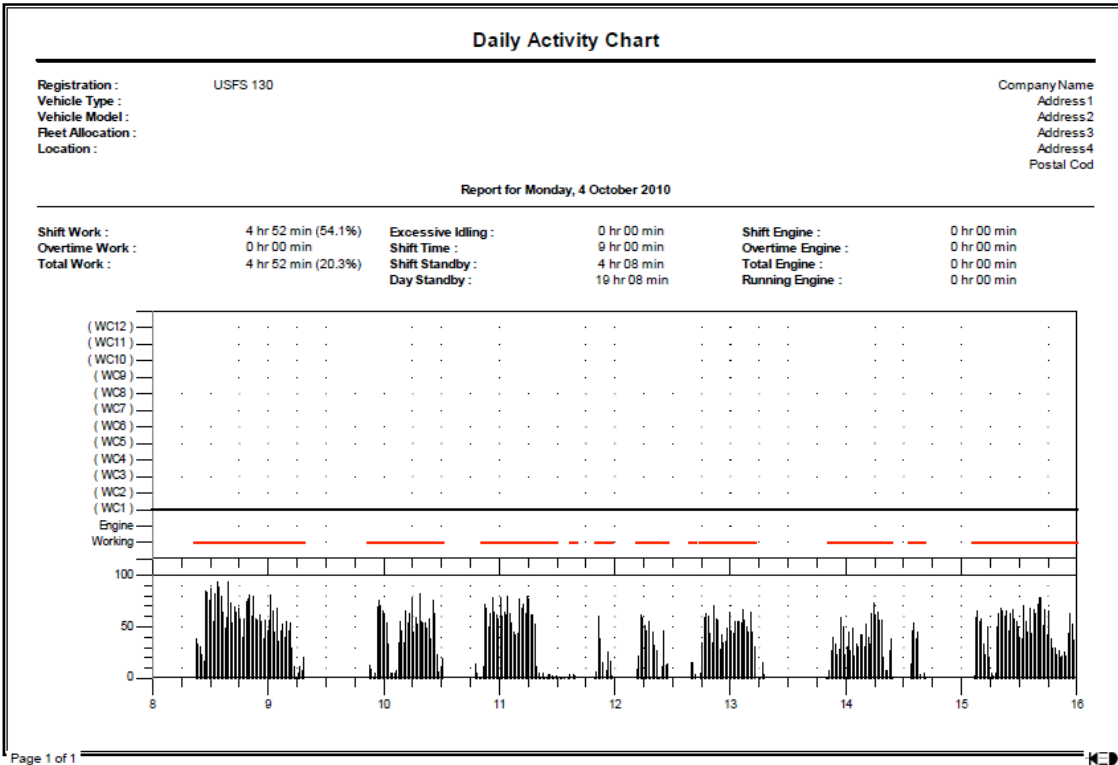


Figure 4.4 Example of activity recorder data used to determine productive hours for each machine.

Additional cost calculations were performed to develop machine rate costs for felling, skidding, loading, and chipping. Cost calculations were conducted using standard methodology for machine rates (Brinker et al., 2002). Machine rates are an accepted method to determine an average cost of owning and operating a machine over its life; they do not necessarily reflect the actual costs of operation by a particular machine owner. Pricing and depreciation information for the machines were based on the Green Guide (Equipment Watch, 2014). Observed utilization rates from the benchmarking tests were used in the machine rate calculations.

A "machine rate" is a calculated hourly charge for owning and operating a piece of capital equipment. The classical approach was defined by Matthews (1942) and more recently by Miyata (1980). Costs are averaged over the ownership life of the asset to estimate a constant hourly charge. The formulae have been used in many forms as a simple method of cost estimation (e.g. Brinker et al., 2002). The machine rate calculations are simple, easy to understand, do not require detailed cost history, and are constant over the life of the machine.

However, a number of authors (Rickards 1983; Burgess and Cubbage 1989; Stenzel et al 1985) note the limitations of the machine rate:

1. The treatment of depreciation and interest does not consider the effect of compound interest on capital recovery.
2. The machine rate does not consider the effect of tax treatment for various cost categories
3. Costs are assumed constant (average) for all years of ownership

While the limitations are well-known, the standard machine rate is still widely used for estimation of machine costs when actual costs are unknown (e.g., FAO 1992).

A more exact approach to estimating machine costs is the discounted cash flow, incorporating additional cost categories such as tax effects. The detailed calculations are particularly important for economic analysis of expensive equipment (helicopters, yarders, harvesters). Butler and Dykstra (1981) and Tufts and Mills (1982) illustrate the application of discounted cash flow analysis to equipment replacement decisions.

While the machine rate method has limitations, it has advantages for specific applications. The machine rate calculator presented here uses a modified approach to address some of the stated concerns with earlier formulations such as Miyata (1980):

1. Capital costs (interest and depreciation) are estimated using an equivalent annual cost calculation (Riggs 1977)
2. Insurance is calculated as % of average annual investment
3. Taxes here are property taxes which may not be applicable to all forest machine situations
4. Salvage values are estimated based on Cubbage et al (1991)
5. Potential Repair is estimated as a % of depreciation, but charged at a variable rate depending on utilization.

4.3 Results

Inventory data were collected at each study site. Stand density of pine trees in the 4-inch diameter class and larger averaged 602 trees/acre (TPA). Stocking levels in whole-tree green tons averaged 136 green tons/acre (gt/ac). A stand summary by diameter class is displayed in Table 4.1.

Table 4.1 Stand summary for benchmarking sites.

DBH Class (in)	STAND AND STOCK TABLE	
	TPA	Tons/Ac ¹
4	142	8.1
5	119	11.7
6	105	16.4
7	85	20.0
8	58	19.3
9	43	19.1
10	23	13.7
11	11	8.6
12	10	10.3
13	4	5.2
15	2	4.0
Total	602	136.4

¹Whole-tree green tons.

Productivity data were collected from seven sites during the benchmarking phase. Of these, four were thinnings and two were clearcuts. Data were also collected on conventional equipment while performing a clearcut operation after the benchmarking phase during a side-by-side comparison with the new system. For felling, productivity averaged 38.5 gt/PMH (green tons per productive machine hour) for the 4-wheeled feller-bunchers performing thinning operations and 86.6 gt/PMH while performing clearcut operations. The 3-wheeled machine averaged 14.8 gt/PMH while thinning and 52.1 gt/PMH while clearcutting. A summary of statistics for both machine types and operations are presented in Tables 4.2 and 4.3.

Table 4.2 Felling summary of 3-wheeled machine for benchmarking sites.

CONVENTIONAL FELLING (3-Wheeled Feller-Buncher)			
Variable	n	mean	s
Thinning			
Total time (sec)	125	81.3	43.49
Trees/cycle	125	9.6	4.77
gt/cycle ¹	125	0.3	0.23
gt/PMH	125	14.8	9.05
Trees/min	125	7.7	3.50
Mean DBH/cycle (in)	125	3.0	1.22
Clearcutting			
Total time (sec)	40	63.6	28.12
Trees/cycle	40	6.8	4.13
gt/cycle ¹	40	0.7	0.38
gt/PMH	40	52.1	36.17
Trees/min	40	7.4	4.51
Mean DBH/cycle (in)	40	4.8	1.56

¹Whole-tree green tons.**Table 4.3 Felling summary of 4-wheeled machines for benchmarking sites.**

CONVENTIONAL FELLING (4-Wheeled Feller-Bunchers)			
Variable	n	mean	s
Thinning			
Total time (sec)	129	81.6	33.19
Trees/cycle	129	8.9	5.06
gt/cycle ¹	129	0.70	0.39
gt/PMH	129	38.5	30.24
Trees/min	129	6.6	3.06
Mean DBH/cycle (in)	129	4.5	1.75
Clearcutting			
Total time (sec)	292	44.0	14.65
Trees/cycle	292	4.3	1.90
gt/cycle ¹	292	1.0	0.33
gt/PMH	292	86.6	35.10
Trees/min	292	5.8	1.81
Mean DBH/cycle (in)	292	6.9	1.60

¹Whole-tree green tons.

4.3.1 Feller Buncher Productivity Equations.

The General Linear Models Procedure (SAS, 1988) was used to model elemental times for a 4-wheeled feller-buncher, since that is the machine most typically used in the southeast. Move to first tree and move to dump distances were used as independent variables to model the dependent variables move to first tree and move to dump time. Number of stems per cycle was used to model accumulation time. Dummy variables for the type of cut or function (thin or corridor cut) were used to test for significant effects on accumulation time while working in thinnings. Mean dump time was used since it was mainly constant, and confidence limits at the 95 % level ($t=2$) were calculated (Klepac et.al. 2011). Move to tree time was highly correlated with move distance for both thinning and clearcut operations ($p<0.0001$). Average move to tree distance was 38 feet in thinnings and 35 feet in clearcuts. Accumulation time was correlated to the number of stems per cycle ($p<0.0001$). While operating in thinnings, the operational function (thin or corridor cut) the feller-buncher performed was significant ($p<0.0001$) and was used as a dummy variable. Move to dump time was correlated to move distance ($p<0.0001$) for both thinning and clearcut operations. Also, in the thinned stands, the operational function (thin or corridor cut) was significant ($p=0.0213$). Move to dump distance averaged 19 feet while thinning and 44 feet while cutting out corridors. Average move to dump distance while clearcutting was 32 feet. The following text contains the regression relationships developed for felling.

4-Wheeled Feller-Buncher Thinning:

$$\text{Move to first tree time (sec)} = 0.26139 * \text{MoveDist} + 3.33911$$

MoveDist = travel distance to first cut tree (ft)

$$R^2 = 0.57; \text{C.V.} = 46.18; n = 118$$

$$\text{Accumulation time (sec)} = 3.99303 * \text{Stems} + 20.89168 * \text{Func} + 10.86906$$

Stems = No. of stems accumulated per cycle

Func = 0 for corridor; 1 for thin within stand

$$R^2 = 0.72; \text{C.V.} = 32.44; n = 129$$

$$\text{Move to dump time (sec)} = 0.19067 * \text{MtdDist} - 2.37388 * \text{Func} + 5.21009$$

MtdDist = travel distance from last tree cut to dump pile (ft)

Func = 0 for corridor; 1 for thin within stand

$$R^2 = 0.52; \text{C.V.} = 37.01; n = 120$$

Dump time averaged 3.94 seconds in thinned stands. Confidence limits at the 95% level for dump time ranged from 3.51 to 4.37 seconds.

4-Wheeled Feller-Buncher Clearcutting:

$$\text{Move to first tree time (sec)} = 0.25122 * \text{MoveDist} + 0.94279$$

MoveDist = travel distance to first cut tree (ft)

$$R^2 = 0.88; \text{C.V.} = 25.68; n = 105$$

$$\text{Accumulation time (sec)} = 5.00584 * \text{Stems} - 0.25021$$

Stems = No. of stems accumulated per cycle

$$R^2 = 0.68; \text{C.V.} = 30.51; n = 292$$

$$\text{Move to dump time (sec)} = 0.22746 * \text{MtdDist} + 1.77435$$

MtdDist = travel distance from last tree cut to dump pile (ft)

$$R^2 = 0.60; \text{C.V.} = 34.68; n = 105$$

Dump time in clearcut stands averaged 2.54 seconds. Confidence interval limits at the 95 % level ($t=2$) ranged from 2.45 to 2.64 seconds. Therefore, the true value for dump time has a 95% chance of residing within this confidence interval.

4.3.2. Skidder Productivity Equations.

Skidding productivity averaged 54 gt/PMH while operating in thinnings and 70.1 gt/PMH operating in clearcuts. Total distance traveled per cycle averaged 1836 feet in thinnings and 1429 feet in clearcuts. Table 4.4 summarizes the descriptive statistics of performance variables for each type of treatment.

Table 4.4 Skidding summary for benchmarking sites.

CONVENTIONAL SKIDDING (Rubber-Tired Grapple Skidders)			
Variable	n	mean	s
Thinning			
Total time (min)	46	5.6	2.89
Trees/cycle	46	52.8	37.40
gt/cycle ¹	46	3.9	1.64
gt/PMH	46	54.0	34.97
Bunches/cycle	46	1.8	1.09
Mean DBH/cycle (in)	46	4.0	1.32
Total distance (ft)	46	1836	707.1
Clearcutting			
Total time (min)	99	4.3	1.29
Trees/cycle	99	16.5	4.97
gt/cycle ¹	99	3.8	1.11
gt/PMH	99	70.1	45.69
Bunches/cycle	99	1.4	0.61
Mean DBH/cycle (in)	99	6.5	0.73
Total distance (ft)	99	1429	552.4

¹Whole-tree green tons.

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 bunches was used to model intermediate travel time. Position and grapple time was correlated with the number of bunches per cycle for the thinning but was fairly constant for the clearcut. Unggrapple times were constant for both prescriptions so confidence intervals were calculated at the 95% level ($t=2$).

Travel empty distance was found to be significant at predicting travel empty time ($p<0.0001$). The number of bunches per cycle was found to be significant at predicting position and grapple time in thinning operations ($p<0.0001$). Confidence limits at the 95% level were calculated for position and grapple time in clearcut operations. Distance between bunches was measured on a sub-sample of cycles while thinning and was found to be significant at predicting intermediate travel time ($p=0.0071$). Intermediate travel distances were measured during the clearcut operations and were found to be

significant at predicting intermediate travel time ($p < 0.0001$). Travel loaded distance was found to be significant at predicting travel loaded time ($p < 0.0001$). Ungrapple time was not highly correlated with any independent variables, therefore, an average time was used for each type of cut and confidence interval limits at the 95% level were calculated. The following text contains the productivity equations for skidding functions.

Grapple Skidder Thinning:

$$\text{Travel empty time (min)} = 0.0019993 * \text{TEDist} - 0.18388$$

TEDist = travel empty distance (ft)

$$R^2 = 0.84; \text{C.V.} = 19.49; n = 46$$

$$\text{Position \& grapple (min) for thinning} = 0.4248327 * \text{NBunches} + 0.1865917$$

NBunches = number of bunches

$$R^2 = 0.43; \text{C.V.} = 56.13; n = 46$$

$$\text{Intermediate travel time (min)} = 0.0022417564 * \text{DBundle} + 0.5438016119$$

DBundle = distance between bunches (ft)

$$R^2 = 0.57; \text{C.V.} = 32.49; n = 11$$

$$\text{Travel loaded time (min)} = 0.00225981 * \text{TLDist}$$

TLDist = travel loaded distance (ft)

$$R^2 = 0.92; \text{C.V.} = 34.61; n = 46$$

Ungrapple time averaged 0.348 min. Confidence interval limits at the 95% level ranged from 0.273 to 0.423 min.

Grapple Skidder Clearcutting:

$$\text{Travel empty time (min)} = 0.0015743 * \text{TEDist} + 0.30595$$

TEDist = travel empty distance (ft)

$$R^2 = 0.77; \text{C.V.} = 21.93; n = 99$$

Position and grapple time for clearcutting was found to be a constant and averaged 0.811 min. Confidence interval limits for position and grapple time for clearcutting ranged from 0.717 to 0.905 min.

$$\text{Intermediate travel time (min)} = 0.00189723 * \text{IntDist} + 0.14770033$$

IntDist = intermediate travel distance (ft)

$$R^2 = 0.86; \text{C.V.} = 20.47; n = 12$$

$$\text{Travel loaded time (min)} = 0.00191925 * \text{TLDist} + 0.20625277$$

TLDist = travel loaded distance (ft)

$$R^2 = 0.85; \text{C.V.} = 13.67; n = 99$$

Ungrapple time averaged 0.162 min. Confidence interval limits at the 95% level ranged from 0.144 to 0.180 min.

4.3.3 Chipping Productivity

During chipping operations on all of the tracts, there were a total of 78 trailer loading cycles. The mean loading time was 34 minutes with a standard deviation of 7.7 minutes. Trailer positioning at the chipper also was examined. Out of 69 positioning elements studied, the mean positioning time was 27 minutes with a maximum of 153 minutes and median of 24 minutes. The mean total chipping cycle time was 58 minutes. Overall mean chipping productivity was 30 gt/PMH.

4.3.4 Overall Productivity and Cost Summary

Table 4.5 and Figure 4.5 contain summary statistics for productivity and costs for the benchmarking sites. Utilization rates for felling, skidding, loading, and chipping were 0.67 (Valmet) and 0.62 (Hydro-Ax), 0.64 (John Deere 648) and 0.54 (Caterpillar 525), 0.50, and 0.59, respectively. Machine rates for the feller bunchers, skidders, loader, and chipper were \$60/SMH (Valmet) and \$88/SMH (Hydro-Ax); \$75/SMH; \$47/SMH; and \$76/SMH, respectively.

By using the tons produced from each tract, a machine productivity can be calculated. When the machine rates (\$/SMH) are divided by productivity (tons/hr), an estimated function cost (\$/gt) can be developed. Figure 4.5 contains estimated function costs for each tract. Felling costs ranged from \$3.49/gt to \$5.26/gt. Skidding costs ranged from \$2.63/gt to \$4.49/gt. Chipping and loading costs ranged from \$2.68/gt to \$5.01/gt. Indirect costs from the logging contractor were used as representative data in Figure 4.5. Harvest costs (felling, skidding, loading, chipping) ranged from \$12.18/gt to \$17.10/gt.

Table 4.5 Overall productivity summary for benchmarking sites.

Tract ID	Productive Machine Hours (PMH) Recorded on Each Tract						Total PMH	Total Green Tons	Chipper Production (gt/PMH)
	Valmet Feller Buncher	Hydro-Ax Feller Buncher	John Deere 648 Skidder	Cat 525 Skidder	Tigercat 234 Loader	Woodsman Chipper			
CL6089	55.8	27.2	44.4		40.1	34.0	201.5	286.8	8.4
CL6090	7.5	9.3	9.1		12.6	11.6	50.1		
CL6087	84.9	68.3	61.4	33.6	59.3	69.0	376.5	866.0	12.6
CL6041	136.8	116.6	104.2	76.9	88.9	101.3	624.8	3567.2	35.2
CL6095	98.2	100.6	108.2	39.5	91.4	89.5	527.4	4211.2	47.1
CL6105	265.2	343.0	225.8	224.4	215.1	260.6	1625.1	6289.3	24.1
Total	648.4	664.9	553.1	374.4	507.4	566.0	3405.3		
Utilization	0.67	0.62	0.64	0.54	0.50	0.59			

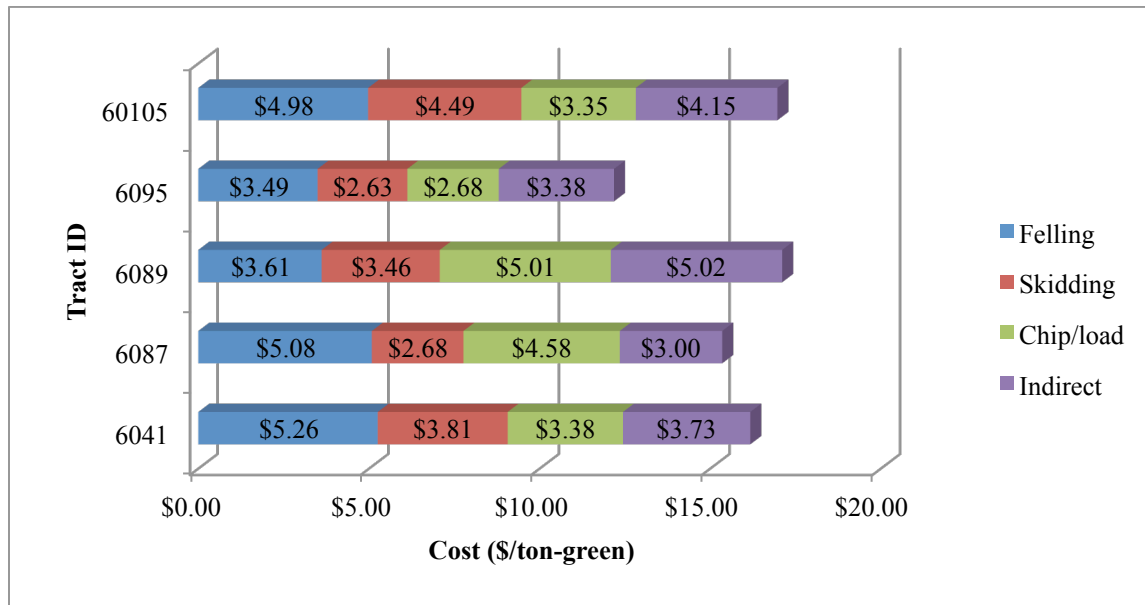


Figure 4.5 Summary Machine Rates and Estimated Harvest Costs for Biomass from the Benchmarking Sites.

4.4. Summary

Conventional drive-to-tree feller-bunchers (3-wheeled and 4-wheeled) were evaluated while performing both thinning and clearcut operations. The 3-wheeled machine had a 352% increase in productivity while clearcutting as compared to thinning. Productivity of the 4-wheeled machine performing clearcutting increased 220% when compared to thinning. The 4-wheeled machine had a higher productivity in both thinning and clearcut operations as compared to the 3-wheeled machine. Percent difference in productivity between the two machines was 89% in thinnings and 50% in clearcuts. Conventional skidder productivity averaged 54 gt/PMH while operating in thinnings and 70.1 gt/PMH in clearcut operations. This resulted in a percent increase in productivity of 30%.

Individual machine utilization rates ranged from 0.5 for the knuckleboom loader to 0.59 for the chipper to 0.67 for the Valmet feller buncher. Chipping productivity rates ranged from 8.4 gt/PMH to 47.1 gt/PMH. Harvest costs (felling, skidding, loading, and chipping) ranged from \$12.18/gt to \$17.10/gt.

4.5 Output

Klepac, J., B. Rummer and J. Thompson. 2011. Harvesting Small Trees for Bio-Energy. In: Proceedings of the 34th annual meeting of the Council on Forest Engineering. COFE, Morgantown, WV.

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Task 5 – Stage Gate Review Meeting

The Stage Gate Review was conducted on February 18, 2011 at the offices of Corley Land Services in Chapman, AL. An independent Stage Gate review panel consisting of several knowledgeable individuals was assembled to participate in the review discussion. The project team presented benchmarking harvest data and they presented the designs of the new high tonnage machine system. After the Stage Gate review, the panel members and DOE personnel recommended that the project proceed as planned in the statement of project objectives.

PHASE II: Commercial-scale Demonstration

Testing of newly designed biomass harvesting and delivery machinery began after the initiation of Phase II and after the new machines were delivered in the fall of 2011. During Phase II, Corley Land Services procured additional stumpage from approximately 12- to 15-year-old southern pine plantations to demonstrate the full-scale industrial biomass harvesting and delivery system.

Task 7 – Analyze Wood Storage and Handling Issues

The project team worked with Corley Land Services to analyze wood storage and handling issues and begin making recommendations for operational improvements. New types of biomass harvesting system will have the capability to inventory woody feedstock at different physical locations in the feedstock supply chain. In this section, the text describes investigations into storage of wood chips in outdoor piles for longer periods of time than are currently used in the pulp and paper industry.

7.1 Objective

The objective of this task was to monitor temperature and relative humidity over time at various locations inside piles of whole-tree chips and also to monitor moisture content at the center of each outdoor pile over time. After the monitoring period, moisture content at various locations within each pile was of interest, in addition to particle size analysis.

Additional wood storage information on storing logs in piles is provided in Section 8.3 in the discussion on transpirational drying.

7.2 Methods

The study was initiated on October 8th, 2010 and completed on March 16th, 2011. Piles were located at an idle woodyard in Georgiana, Alabama and constructed on concrete slabs.

Two whole-tree chip piles were constructed using a John Deere tracked excavator (Figure 7.1). Pile size and geometry is shown in Table 7.1. Chips were transported by chip vans to the study area. During pile construction, EL-USB-2+ sensors by Lascar Electronics were placed near the center of each pile at approximately 3 feet, 6 feet, and 8 feet from the ground. Sensors were also placed on the North and South face at approximately 18 inches deep. Each sensor recorded temperature and relative humidity every hour during the study period.



Figure 7.1 Chip pile construction using an excavator.

During pile construction, samples were collected and placed in 5 gallon buckets and sealed with lids for moisture content, ash content, and particle size analysis. Five samples were collected from each pile. A 5-ft PVC pipe was also placed in each pile about 4 feet above ground for periodic sample collection. A soil auger was to be used by inserting it into the pipe and collecting a sample. Samples were weighed wet, placed in a drying oven and dried at 105 °C for 48 hours. After piles were constructed measurements were taken on each pile and included vertical height, base circumference, and slope length. From these measurements total volume for each pile was calculated. Moisture content trends from samples collected from the center of each pile are shown in Figure 7.2.

Piles were deconstructed on March 16th, 2011. Prior to deconstruction, total height, base circumference, and slope length were measured. During deconstruction, each pile was split vertically and half removed. This was done so that an internal profile could be revealed and samples collected at strategic locations (Figure 7.3). Two samples were collected at each location for moisture content determination. Samples collected from locations A, B, and C were also analyzed for bulk density. Also, three samples were collected from the surface on the North and South face of each pile. Once samples were collected deconstruction was completed and sensors were recovered.

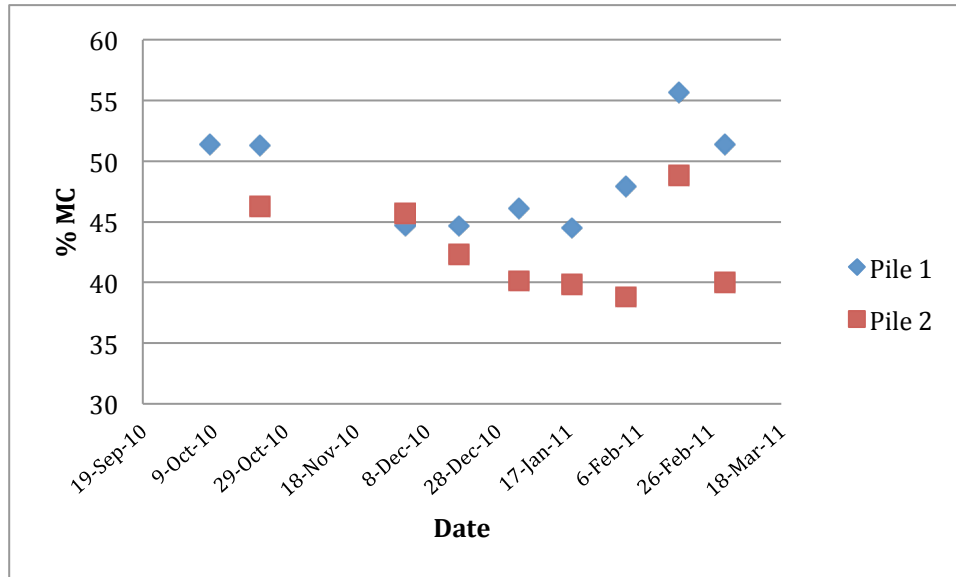


Figure 7.2 Moisture content trends over time for each pile.

7.3 Results

After piles were constructed a total of nine sample collections were made prior to the end of the study period from pile 1 and eight collections from pile 2 for moisture content analysis (Figure 7.2). Initial moisture content from Oct. 8th for pile 1 and Oct. 22nd for pile 2 are also included in Figure 7.2.

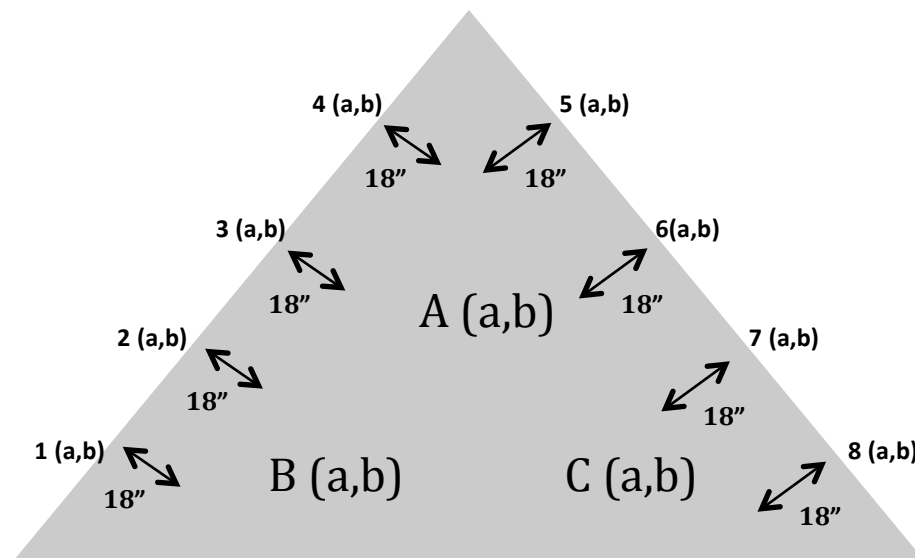


Figure 7.3 Sample locations during pile deconstruction.

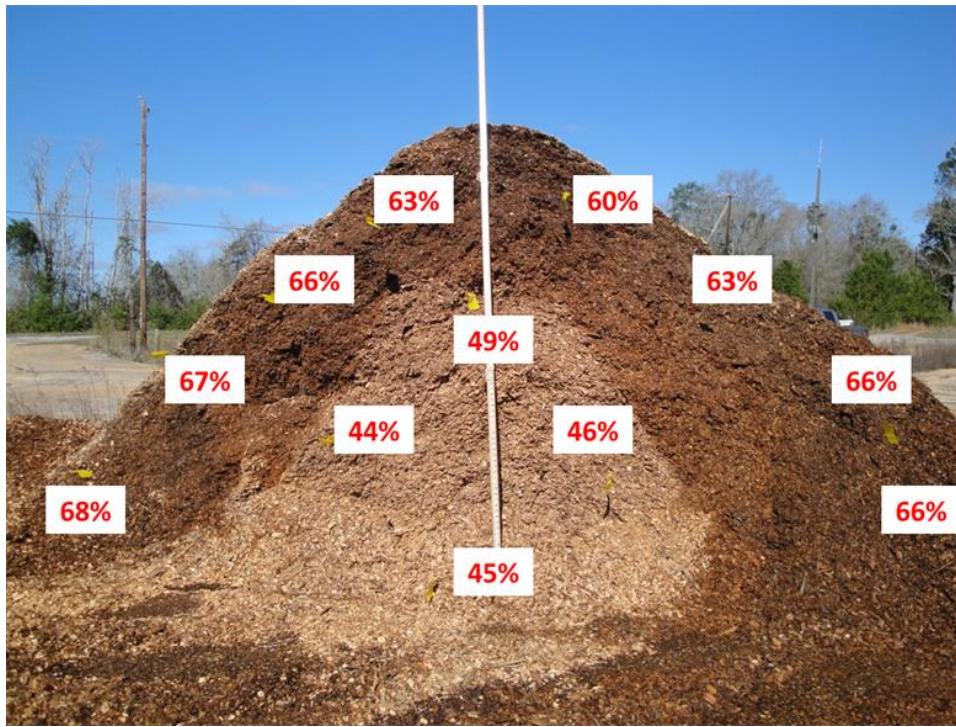


Figure 7.4 Moisture content at various locations during deconstruction of Pile 1.

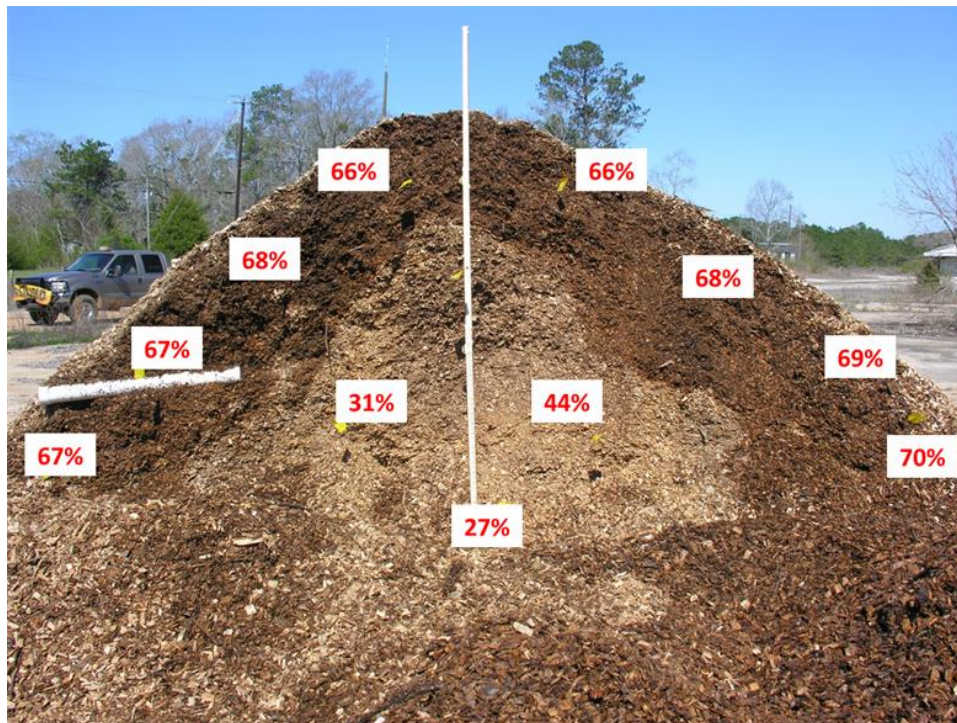


Figure 7.5 Moisture content at various locations during deconstruction of Pile 2.

Table 7.1 Measured parameters for both piles.

WHOLE-TREE CHIP PILES				
Pile	Vertical Height (ft)	Base Circumference (ft)	Slope Length (ft)	Volume (ft ³)
1	10	78.4	15.4	1303
2	9.5	80.0	17.0	1412

Tables 7.2 and 7.3 display the descriptive statistics for each pile and sensor location. The lower sensor in Pile 2 had some significant outliers so those data should be viewed with caution.

Table 7.2 Descriptive statistics of temperature and relative humidity for Pile 1.

WHOLE-TREE CHIP PILES										
Sensor Location	Temperature (F)					Relative Humidity (%)				
	n	mean	s	min	max	n	mean	s	min	max
Lower	2484	94.5	15.57	63	126	2484	98.3	2.49	83.5	100
Middle	1201	118.9	17.13	73	139	1201	99.8	1.08	83.5	100
Upper	270	127.1	22.32	72	146	270	98.2	2.43	69.5	99.5
North	3815	62.7	25.40	36	118	3815	99.9	0.78	63.5	100
South	2040	71.1	1.84	66	74	2040	66.6	9.54	51.5	84.5

Table 7.3 Descriptive statistics of temperature and relative humidity for Pile 2.

WHOLE-TREE CHIP PILES										
Sensor Location	Temperature (F)					Relative Humidity (%)				
	n	mean	s	min	max	n	mean	s	min	max
Lower	2371	78.3	26.45	-40	214	1143	132.6	125.49	1	555
Middle	771	100.9	12.39	86	135	459	86.7	28.29	1.5	100
Upper	3330	79.4	15.90	48	137	789	81.6	31.06	3.5	100
North	3500	49.7	15.00	32	99	3500	99.8	0.64	86.5	100
South	3500	67.2	9.52	52	105	3446	96.0	9.20	3	100

Particle size analysis was performed from material collected at locations A, B, and C for each pile. At each location two samples were collected for replication. Oven dried material was processed in a TMI chip classifier which contained 3 mm, 7 mm, 10 mm, and 45 mm screens.

To test for significant differences in mean particle size within each size class among the three locations, Duncan's Multiple Range Test (SAS 2011) was used. The only significant differences found were in the 12.7 mm size class for Pile 1. For Pile 1, locations A, B, and C were significantly different with 10 % of the material being retained in the 12.7 mm size class at location A compared to 12 % at location B and 14 % at location C. For Pile 2, locations A and C were significantly different in the 0.850 mm size class. In the 2 mm size class location A was significantly different from locations B and C. For the 4 mm size class location A was significantly different from location B. For the 19 mm size class locations A and B were significantly different.

Moisture contents measured from each sample location within each pile are summarized in Table 7.4. For locations 1-9 moisture contents ranged from 45.5 to 68.1% for Pile 1 and 26.8 to 69.5% for Pile 2. At the center of the pile at locations A, B, and C moisture contents ranged from 44.2 to 48.7% for Pile 1 and 31.3 to 44.0% for Pile 2.

Bulk density was measured from samples collected at points A, B, and C and are summarized in Table 7.5. Values ranged from 10.3 to 10.7 lb/ft³ for Pile 1 and 10.2 to 10.7 lb/ft³ for Pile 2. Climatological data for the drying period are summarized in Table 7.6.

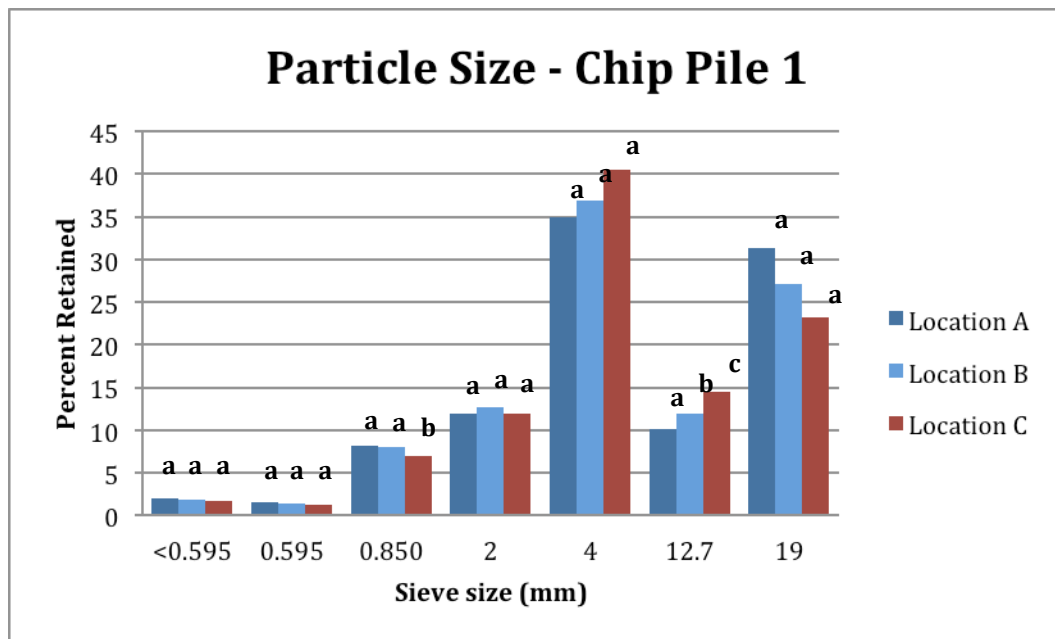


Figure 7.6 Particle size analysis for Pile 1.

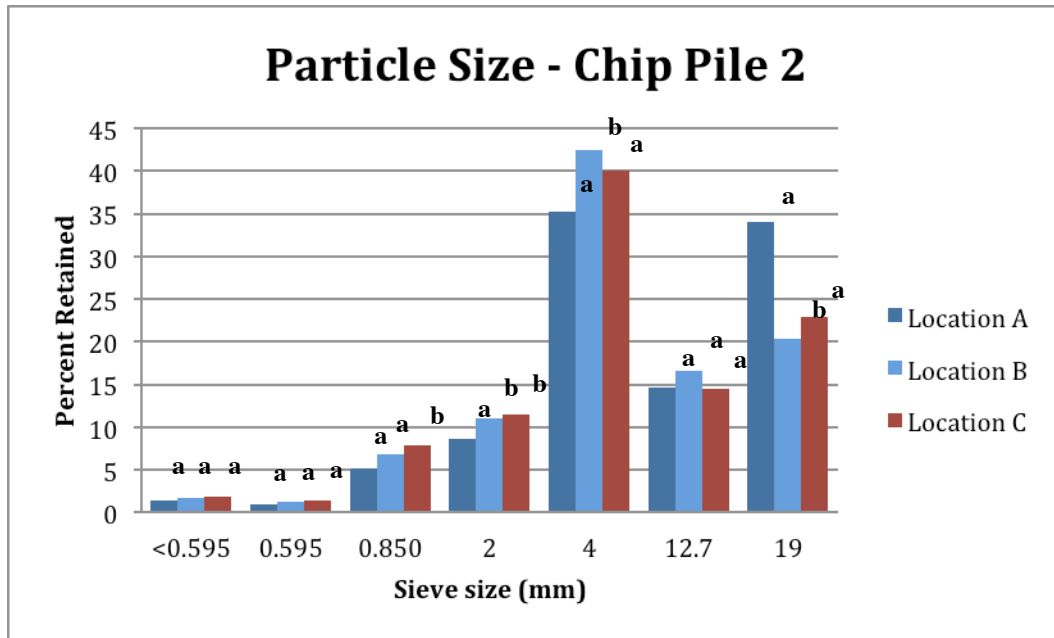


Figure 7.8 Particle size analysis for Pile 2.

Table 7.4 Summary of moisture contents after drying period for both piles.

MOISTURE CONTENT (% wet-basis)						
Location in Pile	Pile 1			Pile 2		
	n	mean	s	n	mean	s
1	2	68.1	0.91	2	66.7	0.16
2	2	67.0	0.46	2	67.2	0.06
3	2	66.0	0.63	2	68.1	0.01
4	2	62.8	1.01	2	65.7	0.87
5	2	60.1	1.79	2	65.5	0.46
6	2	63.0	0.39	2	67.7	0.39
7	2	65.8	0.94	2	68.7	0.04
8	2	66.2	0.59	2	69.5	0.32
9	2	45.5	1.14	2	26.8	0.09
A	2	48.7	1.33	2	42.9	0.79
B	2	44.2	0.21	2	31.3	5.03
C	2	45.9	0.46	2	44.0	0.01
North surface	3	39.8	1.21	3	44.4	1.60
South surface	3	26.2	2.10	3	33.9	1.69

Table 7.5 Summary of bulk densities for both piles.

BULK DENSITY (lb/ft ³)						
Location in Pile	Pile 1			Pile 2		
	n	mean	s	n	mean	s
A	2	10.6	0.074	2	10.7	0.056
B	2	10.3	0.022	2	10.2	0.56
C	2	10.3	0.22	2	10.3	0.039

For the climate data in Table 7.6, high and low values for temperature, humidity, and dew point are averages over the course of the drying period. Mean values for temperature, humidity, and dew point were calculated by summing all high and low values and dividing by two times the number of drying days. For precipitation, high and low values reflect the maximum and minimum rainfall recorded on a particular day. Values for high wind speed and gust reflect averages over the drying period. A total of 18.78 inches of rainfall was recorded at the weather station in Greenville, Alabama during the drying period. During the last three days of the drying period 0.47 inches of rainfall was recorded. A total of 2.71 inches of rainfall was recorded during the last week of the drying period.

Table 7.6 Climatological data for drying period from October 8, 2010 to March 16, 2011.

Variable	High	Mean	Low	Gust	Total
Temperature (°F)	61.8	50.7	40.1	-	-
Humidity (%)	90.7	67.7	45.6	-	-
Dew Point (°F)	46.3	39.7	33.7	-	-
Precipitation (in)	3.2	0.12	0.0	-	18.78
Wind Speed (mph)	11.5	5.0	-	23.2	-

7.4 Summary

Climate data showed there were 2.71 inches of rainfall during the last week of the drying period. Of this, 0.47 inches fell during the last three days. For both piles the highest mean temperature occurred at the middle and upper locations. Mean relative humidity for Pile 1 had very little deviation among the upper, middle, bottom locations (98.2 to 99.8%), while the north and south faces averaged 99.9 and 66.6%, respectively. For Pile 2, excluding the lower location, mean relative humidity ranged from 81.6 to 99.9% for the middle, upper, and north face locations, with a mean of 96.0% on the south face.

Task 8 – Test and Demonstrate New Machine Concepts

8.1 Industry and Landowner Acceptance

8.1.1 Objective

The objective of this subtask was to characterize acceptance by the landowner and the forest harvesting sector of biomass harvesting systems.

8.1.2 Methods

Work in this subtask consisted of conducting focus group discussions with groups of landowners and loggers in the southern U.S. Focus groups of landowners were convened at five locations in Alabama during 2011 and 2012. From the landowner focus groups, 97 exit surveys were completed. Four focus groups were conducted for loggers at various locations in Alabama. In the logger sessions, there were 25 loggers that completed exit surveys. The focus groups consisted of presentations on the high tonnage harvesting system followed by open discussion of biomass harvesting issues. The participants completed exit surveys at the conclusions of the focus group sessions.

8.1.3 Results

Landowners

During the five landowner sessions, 97 exit surveys were completed. The median age of the landowners participating was in the category 60 to 69 years old. The median acres of forest land owned by the landowners were in the category of 100 to 500 acres. Fifty-seven percent of the landowners had obtained certification for their forest land in at least one of the forest certification programs. Sixty-one percent of the landowners had participated in at least one cost-share program for forest management. Seventy percent of the landowners were members in a forestry or conservation organization.

Figure 8.1.1 contains results that illustrate landowner forest management priorities. These data indicate that the landowners value highly objectives like investment, enjoying the scenery, passing the land to their heirs, protecting biological diversity, etc. The production of biofuel from their forests was ranked lower than all other management objectives; however, the ranking for this objective was still above the midpoint in the scale from “very important” to “not important.” Also, the figure shows that the production of sawlogs, pulpwood, or other timber was ranked highly on the importance scale, which indicates that landowners are comfortable with a focus on production of forest resources for a biobased products market.

The landowners were asked to respond to the importance of targeted questions about their management strategies. Table 8.1.1 shows the ranking of responses to the question “My decision to produce and sell trees for conversion to energy is influenced by which factor?” Table 8.1.2 shows the ranking of the responses to the question “Short rotation forest management practiced on some of my property will likely fit with my objectives to do what?”

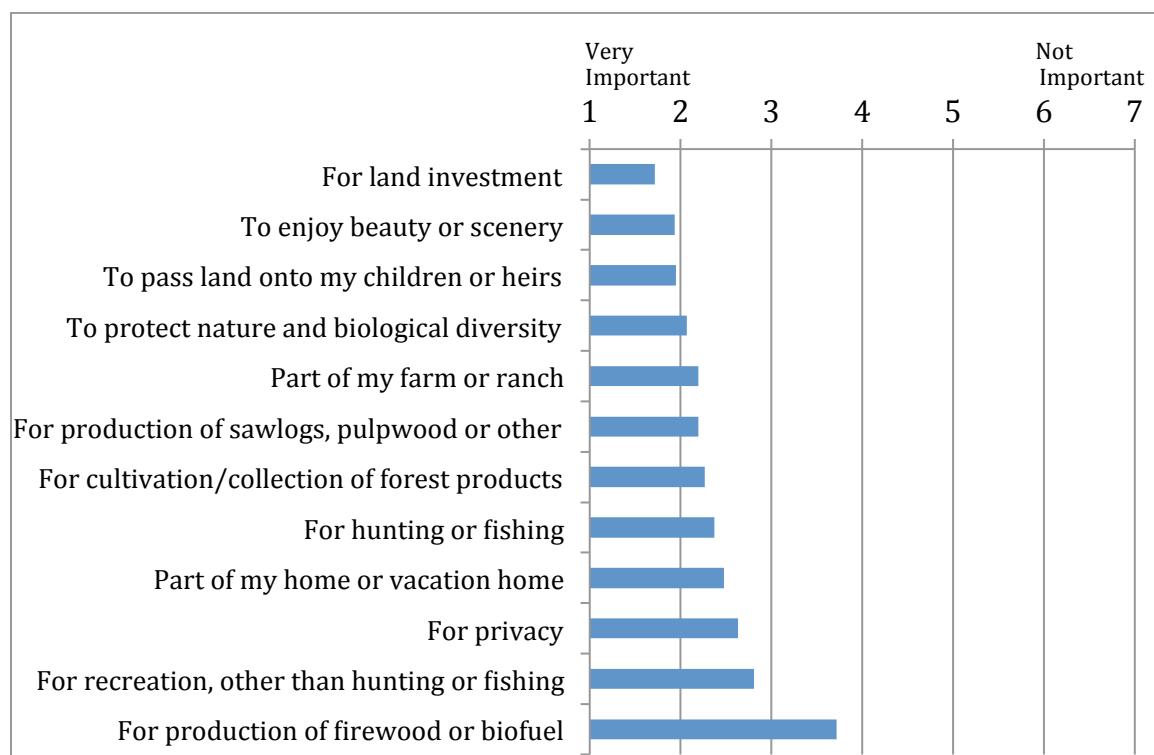


Figure 8.1.1 Forest management objectives ranked by landowners in Alabama.

Table 8.1.1 Factors in the forest landowner decision to produce and sell trees for bioenergy. A score of 1 indicates “very important” while a score of 7 indicates “not important.”

My decision to produce and sell trees for conversion to energy is influenced by?	
The right price	1.3
A steady market	1.6
The environmental impacts of intensive forest management	2.6
The benefit to the local economy	2.7
A sense that I am addressing a larger problem	2.9
Long term contracts with buyers	3.1
Enrollment in BCAP	3.6

Table 8.1.2 Factors in the forest landowner decision to practice short rotation forest management. A score of 1 indicates “very important” while a score of 7 indicates “not important.”

Short rotation forest management practiced on some of my property will likely fit with my objectives to....?	
Provide income	1.9
Protect soil and water resources	3.0
Protect the visual appearance of my property	3.1
Provide wildlife habitat	3.2
Enhance my personal enjoyment	3.5

The landowner discussion highlighted the following points:

- Minimum tract size needed for economically feasible harvest implies that small landowners may not be able to participate in this system.
- Most landowners were interested in converting only a portion of their land to short rotation, integrating the system into other objectives.
- Land owners are not confident investing in establishment costs until they have reliable contracts and well established markets for the wood. There was sufficient skepticism expressed for government subsidies and incentive programs. This skepticism indicates that substantial outreach is needed to educate landowners.
- Insect and disease threats could be augmented in more dense plantings envisioned for the high tonnage system.
- The perennial issue surfaced of development funding inciting local support, followed by limited returns... “we have seen this before.”
- Substantial changes are likely in nutrient management for sustainable harvest levels.
- Increased site preparation and establishment costs (even with assistance) may still be too high.
- How will short rotation and an established biomass market effect pulp and sawtimber prices?
- What is the ratio of energy input to fuel produced?
- Will transpirational drying increase fire hazard on their property?

Loggers

During the four logger sessions, 25 exit surveys were completed. The median age of the loggers participating was in the category 40 to 49 years old. The median years of experience of the loggers were in the category of 11 to 20 years. The mean production rate of the loggers participating was 37 truck loads of wood per week (using a net weight of 25 green tons per load, this would be a production rate of 925 green tons per week). The loggers had an average of six machines each in their crews.

Table 8.1.3 shows the ranking of responses to the question “My decision to invest in equipment for harvesting biomass could be determined by which factor?”. Table 8.1.4 shows the ranking of responses to the question “Current barriers to investing in harvesting equipment for harvesting biomass are which of the following?”

Table 8.1.3 Factors in the logger decision to invest in equipment for harvesting biomass. A score of 1 indicates “very important” while a score of 7 indicates “not important.”

My decision to invest in equipment for harvesting biomass could be determined by which factor?	
Profitability	1.9
Long term contracts with buyers	2.0
A steady market	2.0
The “right” price	2.1
The benefit to the local economy	2.8
A sense that I’m addressing a larger problem	3.1

Table 8.1.4 Current barriers to investing in equipment for harvesting biomass. A score of 1 indicates “very important” while a score of 7 indicates “not important.”

Current barriers to investing in equipment for harvesting biomass	
Markets for biomass	2.0
Availability of long term contracts	2.3
Source of timber for biomass	2.4
Adoption of new technology	2.6
Access to financing	2.7
Availability of trucking (contractors or drivers)	2.8
Labor availability	2.8

The logger discussion highlighted the following points:

- Transpirational Drying:
 - separate crews /equipment may over tax supervisors and isolate equipment that may be needed on same tract for efficient operation.
 - weather variability and harvest timing challenges
 - contractor does not get paid until wood reaches mill, drying delays payment substantially
- There are perceived challenges handling and chipping dry, juvenile, quickly grown wood.
 - Breakage, dust, chip size, separation of straw in clean chips
- There are logistical challenges in coordinating trucking capacity and accommodating larger chip vans in the woods
- There are increased equipment requirements to maintain chipper productivity.
- Minimum tract size for harvest and proximity of multiple tracts for “cold logging.”
- Is a shear head faster and more efficient than a saw head in this application?
- Payment criteria at mill needs to be adjusted from weight to energy content.
- Overall cost of the system-financing could be challenging.
- General skepticism with fuelwood/energy wood production due to historic challenges.

8.1.4 Summary

Many landowners see their ownerships as too small to participate in high tonnage biomass harvesting due to the minimum tract size frequently encountered when identifying a logger willing to harvest a tract. Landowners want to know how converting a portion of their ownership into short rotation management can support their other objectives. There is uncertainty on the impact of the system on pulpwood and timber prices.

Landowners’ and loggers’ confidence in the biofuel market is low and they were concerned with large up front investment required for short rotation management and new equipment purchases. The reliability of new market players is untested and landowners are skeptical of government subsidies and incentive programs. They had a sense that initial interest will be followed by limited follow through and returns... “we have seen this before.”

Landowners were concerned about forest management of short rotation systems. They expressed concern in more possible forest health threats at higher planting densities; substantial changes in nutrient management for sustainable harvest level; increased site preparation and establishment costs; and the possibility that transpirational drying will increase fire hazards.

Loggers expressed concern in the management, logistics, and methods of payment for transpirationally dried wood. Specific issues included managing multiple crews; harvest timing; contractor payment; and challenges in handling transpirationally dried wood.

There were positive aspects revealed in the focus groups. Landowners and loggers both indicated a willingness to participate in high tonnage biomass production with reduced uncertainty in the markets and biomass supply contracts. Landowners recognized the opportunities for more frequent income generating events, particularly in older landowners. Landowners also viewed the short rotation management as a funding opportunity for other management objectives.

8.2 Geospatial Tools and Sensors

8.2a Feller buncher productivity and tree size monitoring

8.2a.1 Background

Information technology will become the driving force in timber harvesting productivity gains, as it has in many other industries. Detailed understanding of the limits of system performance under various conditions, and the means to track it, are key requirements in a management approach to pushing production gains. Decision-making tools and the timely information needed to implement them will be the enabling forces behind systemic gains in timber harvesting efficiency.

Such information systems have yet to be fully developed in timber harvesting, but it is fairly straightforward to predict some of their necessary characteristics to be successful. First would be timeliness, or the availability of information to the right persons at the appropriate decision point. Next would be the ability to track performance at all points in the system. Finally, the information must be acquired at reasonable cost and without adding significant burden of responsibility to operators or managers. Once such a system were in place, the generated data could be mined to develop insight into practical efficiency gains that might be achieved in practice.

Development of timber harvesting information systems is risky in that significant financial and time investment would be required on the part of the creators and first adopters. As part of the overall biomass harvesting system demonstration project, we are seeking to build a working example of a comprehensive, integrated data acquisition system from which meaningful data might be gained to drive productivity improvements.

First steps in the development have been in building the in-machine systems for tracking production. This report provides details of the implementation of a data acquisition system for measuring production of a feller-buncher.

8.2a.2 Objectives

Objectives of this subtask were: a) to work with Tigercat, as far as possible, integrate data collection functions into the machine itself, b) develop cost-effective means of accessing, processing, and storing the data, and c) verify that the information tracked could be used to duplicate a human-derived time study.

8.2a.3 Methods

Data Acquisition System

Our goal was to accurately identify elements of the work cycle of the Tigercat 845D such that a simple gross time study could be performed. We wished in particular to detect cutting of trees plus the building of bunches, time stamp each event, and map its location. It was also desirable that this be accomplished with as little modification to the machine as possible. Our measure of success was that data from the information system could be used to duplicate time study as performed by a person.

Hardware Elements

To achieve this end, a vehicle data acquisition system was developed integrating information from at least three sources. Figure 8.2.1 depicts visually the components of the system.

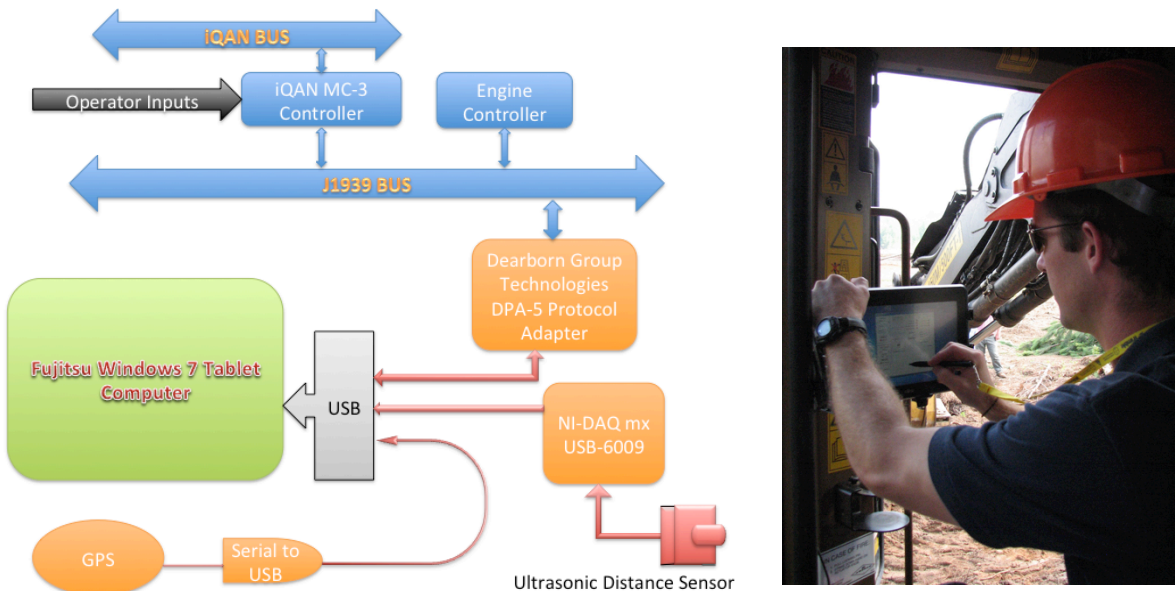


Figure 8.2.1 A schematic of the data acquisition hardware and a photo of the user interface for the data collection system in the cab of the Tigercat 845D. The blue elements were existing information systems accessed through a CANbus protocol adapter. Information was collected and stored on a Windows 7 tablet computer running a custom data acquisition program.

The simplest approach to detecting tree cutting and bunch building events was through monitoring operator inputs to the machine, for example the press of a button to close the shear would likely be part of a tree felling event. This information was already detected by the control system of the machine itself to, for example, activate the hydraulics to close the shear. Tigercat modified their onboard hydraulics controller software to pass these operator input signals from the proprietary iQAN bus to the more easily accessible J1939 bus used for control of the power train on the machine.

It was also required to measure location at the time of the event, and the logical means of doing so was using a GPS. The location of interest was most often the position of the felling head at the end of the boom and this requirement presented a dilemma – how to mount the GPS such that it survived for any length of time. The simplest solution was to measure the location of the head itself by mounting the GPS directly on it, but that approach also required a cable to be run along the boom back to the cab to interface to the data acquisition system. The survivability of such a long, partially exposed cable was believed to be unlikely, so the GPS was instead mounted on the cab roof. This solved a cabling issue, but introduced the problem of resolving head location from the actual GPS position. Two additional measures were required to make the transformation, the simplest being heading to indicate in what direction the cab was pointed plus distance from the cab to the felling head. Heading could be derived fairly easily using a marine GPS. Distance measurements were less easy to implement, but were feasible given we could incorporate an exogenous sensor into the entire data acquisition system. The capacity to incorporate additional sensors also made possible other important measurements not already captured by the machine itself, for example, the ability to measure tree size as it was cut.

Data Acquisition Software

The vehicle data acquisition system (VDAS), therefore, integrated real-time information from three sources: CAN bus, GPS, and custom sensors. Its function was to interpret the flow of information, extract low-level events from the data stream, display machine and interface status, and record time- and location-stamped information. The integration was achieved using a custom program coded (Figure 8.2.2) using National Instrument's Labwindows CVI development system, which provided custom widgets for construction of user interfaces, plus facilities to connect with external data acquisition devices.

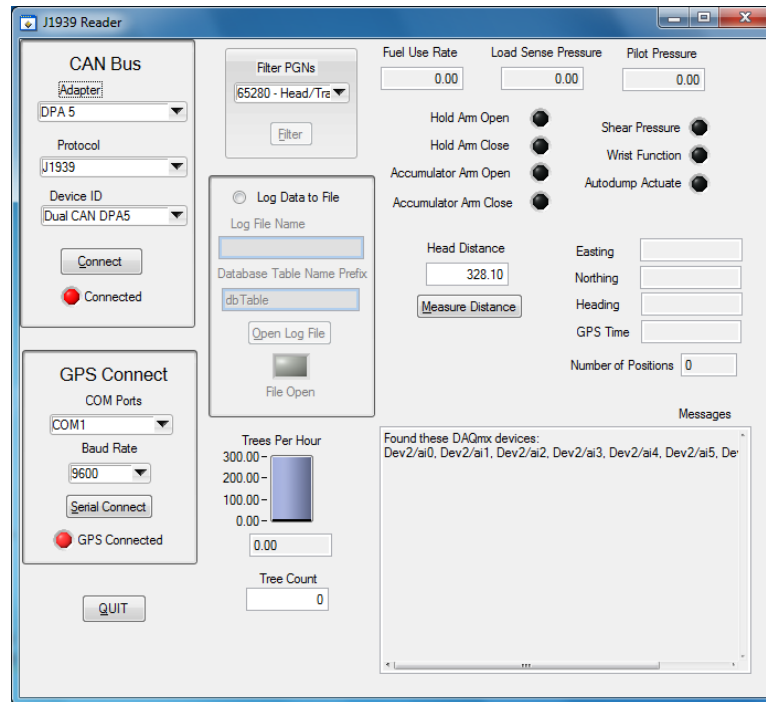


Figure 8.2.2 The data collection system interface as implemented in Labwindows. The software provided elements to connect to the CANbus adapter, a serial port for GPS information, plus a means of identifying a file in which to store data. Various indicators of current machine state were also available.

The connection to the CAN system was made through an RP1210 API to a Dearborn Group Technologies DPA5 Dual CAN adapter. The adapter read and buffered messages from the machine's J1939 bus. The RP1210 interface provided software hooks to initialize and configure the interface, plus send and receive messages. RP1210 is a communication standard published by the Technology and Maintenance Council of the American Trucking Association. The API has nine function calls and was provided as a dynamically linked library by Dearborn Group along with the CAN adapter.

The software was driven using two timed loops. One loop periodically (every 15 ms) polled the CAN interface for the most recently received message. The volume and frequency of data flowing over the J1939 bus was such that the VDAS had trouble keeping up, so a method was provided to configure the protocol adapter to filter out all messages other than those of interest. There were ordinarily two J1939 messages tracked for these tests: PGN 65280 transmitted every 40 ms, and PGN 65266 transmitted every 100 ms. The 65280 PGN is officially listed as 'Proprietary B' and was configured by Tigercat to transmit the information shown in Table 8.2.1 from the iQAN bus to the engine J1939. The 65266 PGN is listed as 'Fuel Economy (Liquid)' in the J1939 standard and its constituents are also summarized in Table 8.2.1.

The second loop polled every 1 s the serial port for GPS data received. The GPS used (Hemisphere GPS Vector V101) was a marine design that employed a dual antenna configuration to calculate a heading. It transmitted every 1 s a NMEA GGA sentence plus a non-standard HDG message that contained a single data element, the current heading in degrees. The locations were recorded to a data file, along with other recurring data such as fuel consumption, every two seconds. Each value was also tagged with the GPS time.

Table 8.2.1 A summary of data made available from the iQAN bus interface, plus the relevant J1939 PGNs used in the data collection system.

PGN	SPN	Position (bits)	Description
65280	2551	1-8	Clamp Arm function % (0.8 % per bit, offset -128)
		9-16	Accumulator Arm function % (0.8 % per bit, offset -128)
		17-24	Wrist function % (0.8 % per bit, offset -128)
		25-32	Fan function % (0.8 % per bit, offset -128)
		33-48	Shear pressure (.2900755 psi per bit, offset 0)
		57	Left track active
		58	Right track active
		64	Auto-dump feature active
65266	183	1-16	Engine fuel rate (0 to 3,212.75 L/h, 0.05 L/h per bit)
	184	17-32	Engine instantaneous fuel economy (0 to 125.5 km/L, 1/512 km/L per bit)
	185	33-48	Engine average fuel economy (0 to 125.5 km/L, 1/512 km/L per bit)
	51	49-56	Engine throttle valve 1 position (0-100%, 0.4% per bit)
	3673	57-64	Engine throttle valve 2 position (0-100%, 0.4% per bit)

The VDAS tracked and stored events of interest by reading and interpreting the SPNs related to three variables: accumulating arm function, grabbing arm function, and shear hydraulic pressure. Figure 8.2.3 shows typical data from the two felling arms over about a 20 second interval of time. The SPN value for both arms was 128 when not in motion. When it was closing the grab arm SPN value increased to 256 and went to 0 as the arm opened. The grab arm and shear acted simultaneously. The accumulating arm SPN values were essentially the same, except reversed – it took a high value when opening and a low value when closing.

Interpreting machine function, therefore, meant tracking changes in the state of these two arms. Whenever a change was observed (open-to-close, open-to-neutral, etc.), the VDAS recorded the transition to a data file along with the current GPS time.

Shear actuation was actually controlled via the grabbing arm, but shear hydraulic pressure was also available and was useful in identifying events of interest. Figure 8.2.4 shows hydraulic pressure for four closures of the shear mechanism without a tree in the head. As the shear blades made contact, the cylinder pressure went to a relief setting somewhere above 275 bar. This turned out to be a useful marker for identifying those instances when the shear was being closed inadvertently, or at least without the intention to cut a tree. That kind of event happened quite often and, in later analysis, tended to inflate estimates of the number of trees cut. By recording when hydraulic pressure exceeded 275 bar, it was possible to separate partial from full closures of the shear mechanism and add a degree of certainty to tree cut event identification. It was also possible to track average cylinder pressure from the time the shear began to close until the trigger setting was exceeded, and it was thought this value might indicate something about tree size.

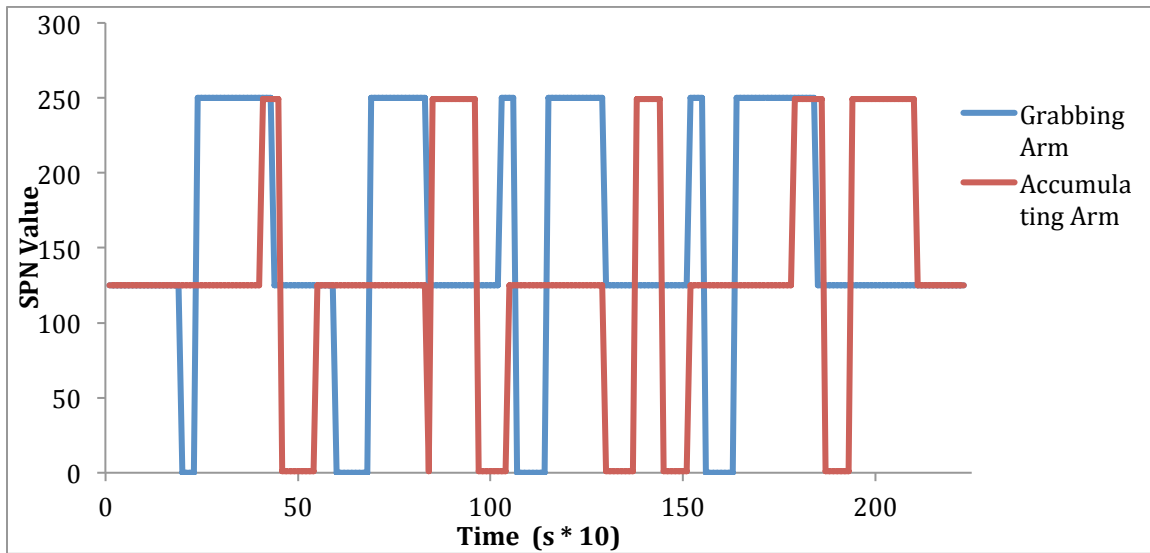


Figure 8.2.3 Typical data derived from the 65280 PGN CAN message related to the state of the felling head arms. Value of the parameter essentially implies motion of the arm. When it is anything other than the neutral value (128), the arm is either opening or closing. The Grabbing Arm function also implied shear activation – the two traveled in concert.

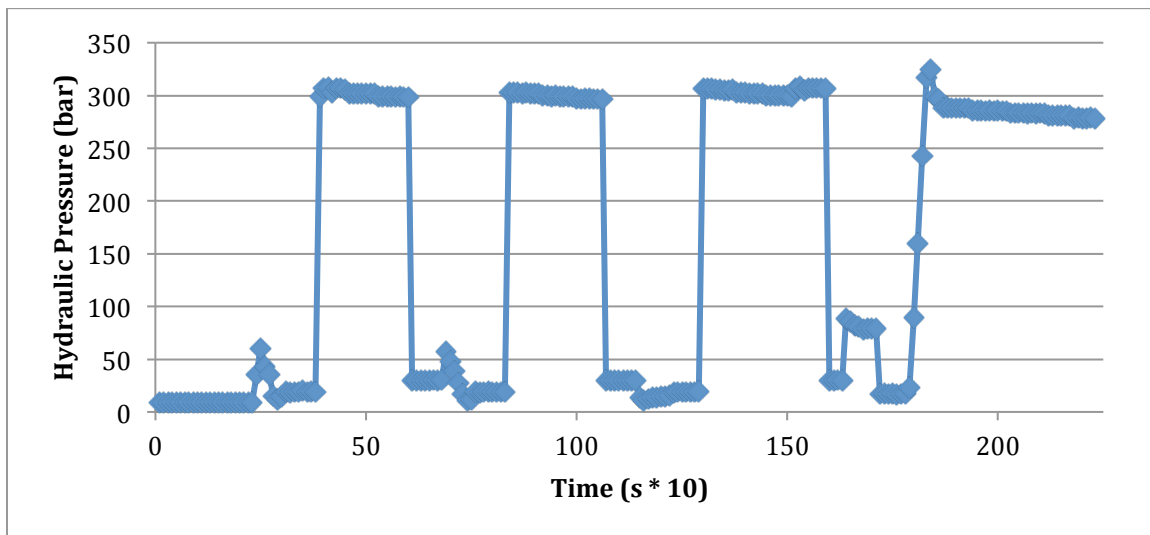


Figure 8.2.4 Typical sequence of hydraulic pressure readings during closure of the shear head. In this case, there were four total closures, each one ending with the pressure exceeding 275 bar (the relief setting) when the blades made contact.

Measuring Tree Size Using Hydraulic Pressure

Diameter at breast height (DBH) of standing trees (plantation loblolly pine) was measured and recorded. Normally about 10 trees were measured and were typically in a single row, although at times adjacent rows were also included. The feller operator was told to cut the trees in order along the row. A program similar to the VDAS described above was used to measure and record shear cylinder hydraulic pressure during the cutting of the trees. The actual value recorded was the sum of pressure readings from the time the cut was initiated until the time the pressure spiked to the relief setting (above 275 bar), along with the number of observations. The beginning of the cut was taken to be the time at which the grabbing arm/shear actuation button was pressed. The number of observed readings varied with the size of the tree and its position in the shear, but was typically on the order of 20 readings. Experiments were repeated at three different locations and data for a total of 50 trees were sampled.

Elemental Time Study

Time studies were carried out on the feller over three periods of about 10 to 15 minutes each using both the VDAS system and manual data collection. Manual time study was carried out in two forms: recording of times using a stopwatch, and also with a video camera. Work cycle elements timed were simply when trees were cut or piled. Physical locations of events were not measured for this study.

The VDAS collected data while the manual time studies were carried out. The data were analyzed using custom procedures to extract tree cut and bunch dump times, and these were compared to those derived manually.

8.2a.4 Results

Tree Size

An early test indicated there was some reason to suspect shear cylinder hydraulic pressure was correlated with tree size. To more formally confirm this suspicion, four trees were selected - two relatively large, one moderately sized, and one smaller tree - and cut while shear pressure was recorded. Tree selection was carried out while sitting in the cab of the feller and actual DBHs were not measured, but the four stems represented about the entire range of variation in the stand. Figure 8.2.5 shows a graph of cylinder pressure over time while cutting the trees. There were three distinct phases in the cutting cycle for each tree: 1) a period of low cylinder pressure before the tree was contacted by the blades, 2) a larger, slightly increasing pressure while the tree was cut, and 3) a pressure increase to near the relief setting as the blades made contact. The pressure during severing of the tree clearly followed relative tree size. Based on these results, a more comprehensive test was carried out.

From the preliminary data in Figure 8.2.5 there seemed to be two factors indicative of tree size present in the data. The first was magnitude of pressure, which was clearly the larger effect. But there also seemed to be an effect of time – larger trees took slightly longer to sever than smaller trees. To capture both of these effects in the data, the DBH tests measured a cumulative pressure. That is, the sum of all pressure readings from the initiation of the shear blade travel until a single observation above 275 bar was seen was used as the tree size measure.

Figure 8.2.6 shows results of these tests, with the graph being the plot of the cumulative pressure, as defined above, with tree DBH. There was a significant linear relationship observed ($p < 0.001$) with $R^2 = 0.63$. This result indicated at least an indication of tree size is observable by measuring shear cylinder pressure. The data were for trees sampled at two different sites, both loblolly pine, and both having relatively young trees - the range in tree size was small (largest trees were on the order of 25 cm DBH). Applying this same technique in other species and larger trees would likely not work as well, but with the more or less uniform conditions of these tests, the tree size prediction was reasonably good.

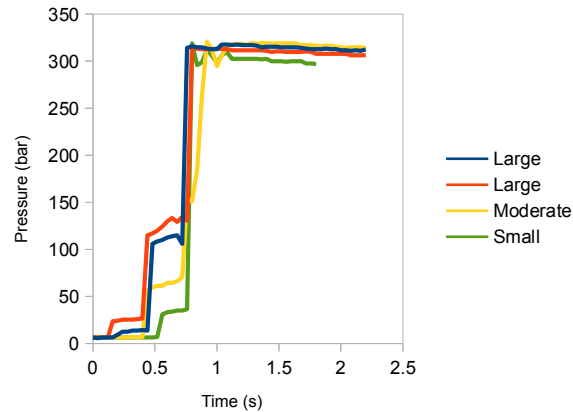


Figure 8.2.5 Shear cylinder hydraulic pressure readings for four various sizes of tree. It was concluded from these preliminary data that pressure during shear was related to tree size.

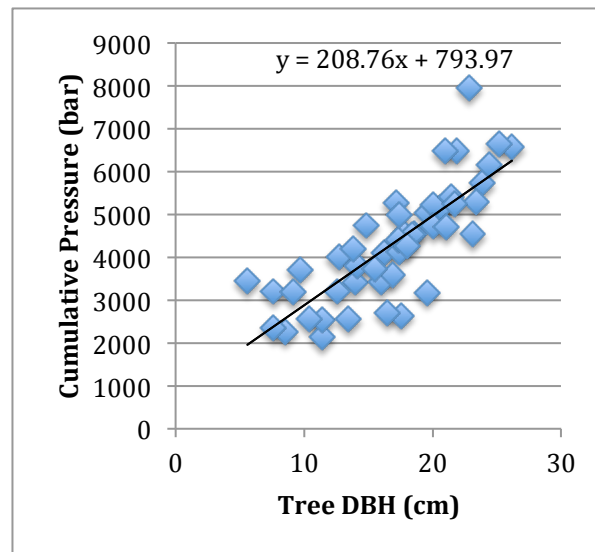


Figure 8.2.6 Graph of cumulative shear cylinder pressure versus DBH. Cumulative pressure was the sum of readings (taken every 40 ms) between the initiation of shear closure and the point at which the reading went above 275 bar.

Elemental Time Study Results

The VDAS collected what were considered raw data, operator input events without any context. For example, in the first time study in Table 8.2.2, there were a total of 57 trees observed being cut. Each cut had to be initiated by the operator pressing the Hold Arm Close button, which simultaneously began closing the shear. The VDAS data file over the same time period recorded 77 Hold Arm Close events. Also over the same time period, there were 69 instances of the Pressure Max event, so there must have been cases where the Hold Arm Close button was pushed without explicit intent of cutting a tree. The VDAS data were, therefore, filtered to extract those instances in which both events happened in sequence, first the arm closure, then the pressure exceeding 275 bar. Using this as the trigger to indicate a tree-cutting event reduced the number in the first trial listed to 59. In some instances, however, there were successive cut events that were quite close together in time and this was felt to be a practical impossibility. A second filtering was therefore imposed to remove tree cut events following a previous cut by less than three seconds. Similarly, there were cases in which multiple successive head dump events were identified with no intervening tree cuts. These were combined into a single event. The event counts filtered in this manner are those reported in Table 8.2.2.

To more clearly identify the nature of errors in the filtered VDAS time study data, the misrepresentations were characterized as being one of two types. A Type I error occurred when the VDAS reported a cut or dump event but none was observed manually. The Type II error was the reverse, or the VDAS failed to report an event when one was observed.

Absolute differences between the VDAS-estimated and observed total numbers of tree cuts were within 10% in all three tests, which was considered reasonable. In two of the three tests the number of trees reported cut was greater than the number observed. In most cases, these phantom cuts were observed just before or after a head dump event. This seemed to imply the operator did something out of the ordinary in those cases. For example, if the head were dumped and the arms returned to a closed position for travel to the next tree, that sequence would be recorded as an extra cut. This type of event sequence was not easily observed from the video records and their frequency of occurrence could not be verified.

These types of occurrences, however, point out the difficulty in extracting from a sequence of events with very little context what was actually happening, more specifically, dealing with event situations that were not common, or were particular to a given operator. For example, each of the above tests were in pine thinnings and the feller was not particularly suited for those conditions, especially when the understory was thick. The operator was quite skilled in dealing with brush and small trees impeding his progress, but his actions in cleaning often involved using the arms and shear on the cutter head. These operations, in particular, tended to cause erroneous event hits, or Type I errors.

As it currently exists, the VDAS approach is not entirely suitable for replacing manual time study. Errors in simple event detection were less than 10% for the conditions tested and, over time, the VDAS results should provide reasonably good estimates for gross time study of the feller. Elemental time study, however, would be less accurate as evidenced by the higher Type I and Type II error rates. If time to cut an individual tree, for example, were the item of interest the presence of Type I and Type II errors in the analysis would bias its estimation. The individual element detection error rates were on the order of 15 to 30%, but the net difference in numbers of events was small. Durations for single events, therefore, might be off by a significant amount, but over time the cumulative differences could go to zero. Further testing is required to determine the magnitude of any bias that might be introduced.

It was certain, however, that VDAS estimates of feller productivity were much better than those gleaned from the machine itself. The machine information system on the 845D reported a nominal tree count. In every case, this number was at least twice the value estimated using VDAS. For the second test in Table 8.2.2, for example, the tree count from the machine was 157, while the true count was 60.

Table 8.2.2 Comparison of VDAS- and manually-derived time study data.

Trees Cut				Head Dump			
Observed	VDAS (error, %)	Type I Error (rate, %)	Type II Error (rate, %)	Observed	VDAS (error, %)	Type I Error (rate, %)	Type II Error (rate, %)
57	53 (-7)	2 (3.5)	7 (12.3)	9	10 (11)	1 (11)	0
60	61 (2)	9 (15)	8 (13)	13	16 (23)	3 (23)	0
45	48 (7)	5 (11)	2 (4)	8	13 (63)	5 (63)	0
96	92 (-4)	4 (4)	8 (8)	12	16 (33)	4 (33)	0
88	73 (-17)	4 (5)	19 (22)	10	12 (20)	3 (30)	0
50	45 (-10)	1 (2)	6 (12)	6	6 (0)	0 (0)	0

8.2a.5 Summary

Automating time- and production-studies of a feller required modifications to the software running the machine to enable access to operator inputs, particularly those involving manipulation of the felling head. Engineers from Tigercat made the changes that included outputting status of various hydraulic functions onto the feller's CAN bus. These data were picked up using a commercial CAN bus interface and read, interpreted, and stored using a custom program. With this system in place, it was possible to track machine position and state over time, allowing the development of methods to interpret that information and extract time study data.

Tests were conducted of the performance of the system relative to a traditional time study approach. Results indicated the automated approach was within 10% of human-derived estimates of time study elements, but there were conditions under which it did not function well. Overall, the system would provide realistic estimates of gross machine time productivity and their accuracy would improve with the number of cycles observed.

The automated system improved on manual time study in that it could be deployed for long periods of time in diverse conditions and could, with proper tuning of the data reduction algorithms, give results of sufficient accuracy to replace the necessity for manual data collection. It had the additional advantage of allowing data on tree size to be collected in real time (based on shear pressure), which could lead to fully automated production studies and the chance to map timber yield across sites.

8.2a.6 Output

McDonald, Tim; Fulton, John; Gallagher, Tom; Smidt, Mathew. 2014. Correlation between tree size and disc saw speed during felling using a wheel-mounted feller-buncher. COFE Annual Meeting, Moline, IL: 23-25 June. 7pp.

McDonald, Tim; Corley, Frank; Hindman, Nick. 2013. Performance of a prototype eLoad Sheet for monitoring timber hauling operations. COFE Annual Meeting, Missoula, MT: 8-10 July. 4 pp.

McDonald, Timothy; Fulton, John; Pan, Pengmin. 2012. Mapping machine productivity and tree size of a feller-buncher harvesting biomass in pine plantations. COFE Annual Meeting, New Bern, NC: 10-12 September. 10 pp.

8.2b Skidder Productivity Monitoring

8.2b.1 Objectives

Objectives of this subtask were: a) to work with Tigercat, as far as possible, to integrate data collection functions into the skidder itself, b) develop cost-effective means of accessing, processing, and storing the data, and c) verify that the information tracked could be used to duplicate a human-derived time study.

8.2b.2 Methods

Identifying the elements of the work cycle of skidder operations is an initial step in designing the data acquisition system. For example, a skidder leaves a deck area and locates a bundle of cut trees, grabs the trees and returns to the deck area. The skidder can pick up one or more bunches to make a full load and returns to the deck. One simple set of elemental times selected to describe this work cycle might consist of “travel empty”, “grapple time”, “intermediate time” and “travel loaded”.

Automated Time Study Methods

The vehicle data acquisition system (VDAS) described previously in Section 8.2a was used to monitor multiple data inputs on the on-board CAN system. The VDAS recorded data extracted from the skidder CAN bus, plus an external GPS input, and then stored the information in two databases: one for periodic data, and one for event-driven (aperiodic) information.

The general approach for automated elemental time study is described in the following text:

1. Data acquisition during skidder operation.
 - a. At regular intervals (one sample every two seconds), sample and record:
 - i. Position (using GPS input)
 - ii. Fuel consumption rate
 - iii. Throttle position
 - iv. Ground speed
 - b. As events occur, record operator machine inputs:
 - i. Open or close of grapple
 - ii. Constant pressure actuation
 - iii. Extend/retract arch and boom cylinders
2. Analyze, by post-processing or real-time processing, recorded data to extract elemental time study information.

Manual Time Study Methods

In this study, the Continuous Time Method (Fenner, 2002) was used to determine the time required for each element. This timing method has the advantage that the partial activities are recorded in the sequence in which they occur, i.e. chronologically. The time study was conducted by using a stopwatch and recording event times. In addition, a POV HD 1080p video camera to record operations for subsequent laboratory analysis with Timer Pro video analysis software. Physical location of bunches was determined by manual GPS mapping operations.

Data Analysis Methods

Analysis of the data was a multi-step procedure that first combined the periodic and aperiodic data streams, producing a sequence of ‘important’ events (primarily those related to grappling or un-grappling a load, plus starting and stopping motion) along with their position and time. These data were then filtered to define work cycle elements. The filtering consisted mainly of distinguishing particular sequences of events (for example, opening followed by closing of the grapple) and the time intervals between them. Specific event sequences close together in time were used as markers to identify the beginning or ending of time study elements. As an example, the sequence of observed events might contain (along with other extraneous information) an opening of the grapple followed by the skidder stopping. If this sequence were followed closely by a closure of the grapple and the skidder moving again, this signaled a grappling operation. The grapple opening might also, if preceded by some kind of deck operations, be identified as the end of the travel loaded phase.

The original goal in developing the system was to identify a set of rules and procedures that could perform the analysis without any additional data supplied. Achieving this goal, however, proved difficult, primarily because some type of context was needed to determine, for example, the difference between travel loaded and travel empty. In this study, distinguishing these elements was done using information about where the skidder was, in particular, whether or not the machine was on or off the deck. Making this distinction required the deck area be defined prior to performing the analysis. This requirement limits this type of time study analysis to a post-processing situation.

8.2b.3 Results

The representative data reported here for the time study were collected on two different days. On the first day 13 work cycles were collected for the skidder for the video camera, manual and automated methods. On the second day, 18 work cycles were collected for the manual and automated methods.

Figures 8.2.7 and 8.2.8 in the following text show three things: position, events and the deck boundary. Positions are the black markers, and the height of the stick is the observed speed of the skidder at that point. Events are the red crosses, height shows what kind of event, like the grapple open or close button. The green trees are the deck boundary used in the data analysis.

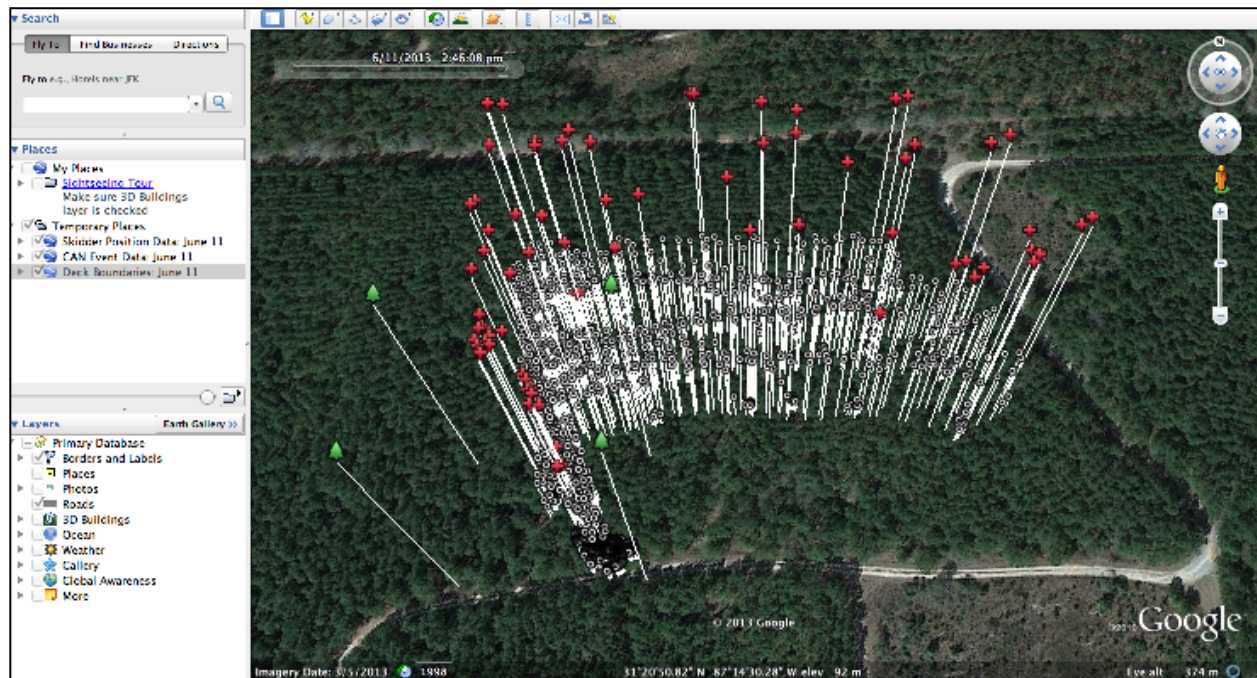


Figure 8.2.7 Map representation of the skidder data in the first day of data collection.

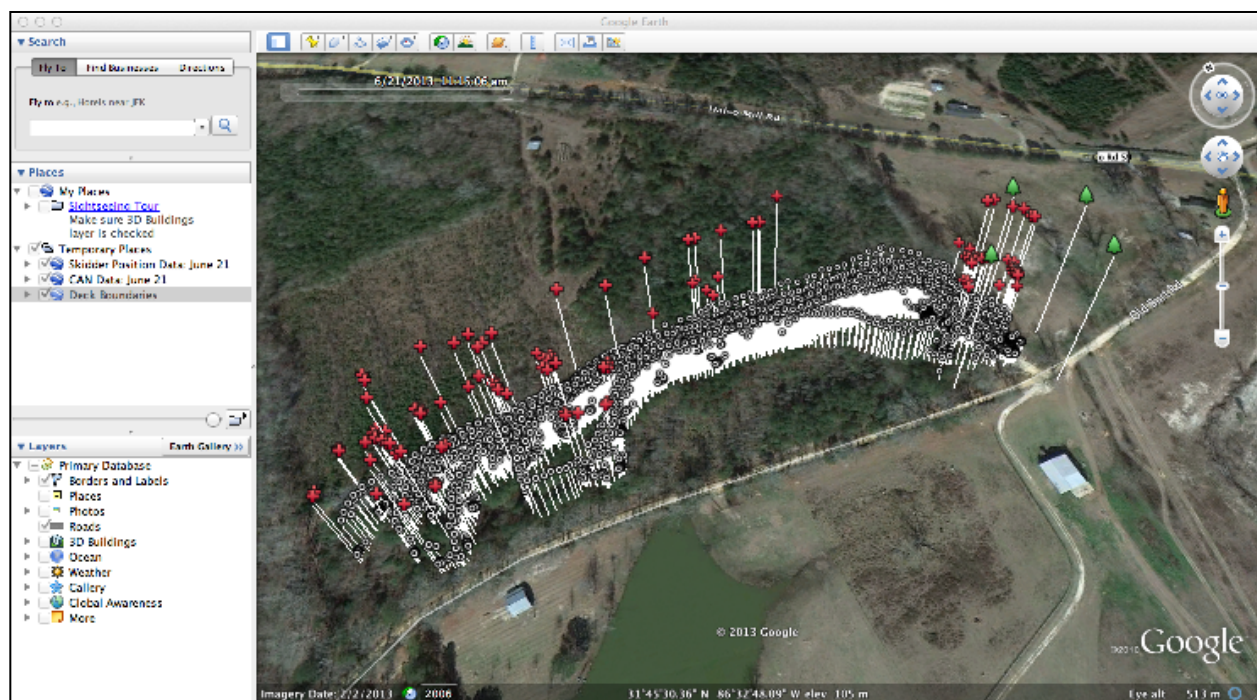


Figure 8.2.8 Map representation of the skidder data in the second day of data collection.

For the data collected in the first day, the video camera method was the control. For the data collected on the second day, the manual time was the control. Tables 8.2.3 and 8.2.4 show the duration, in seconds, of each cycle element of the skidder and the total time.

Results from the data collection for Day one are shown in Table 8.2.3. No statistically significant differences were found among any of the elemental times relative to the video time study method. For this study, the automated time study system was equivalent, averaged over all cycles, to both manual and video methods. Individual element times, however, could vary by up to nearly 100%. The largest differences in elemental times were in the travel empty portion of the skid cycle, with manual and automated methods over- and under-estimating by about 5 seconds relative to video. Standard deviations for the travel empty estimate were also about double that for the other elements.

The results for this initial portion of the study tended to support the conclusion that the automated analysis method could be used for accurate time study analysis of skidders. The data from 21 June, summarized in Table 8.2.4, however, was less positive. Because there were no video data available, comparisons were made between the manual and automated methods only. No statistically significant differences in element durations were found for the grapple and travel loaded phases. Travel empty estimates were about 50 seconds longer than found from manual analysis and were statistically different. Intermediate travel was rarely detected from the automated analysis and the estimated mean duration was also statistically significant from the manual method. Total cycle duration estimates, however, were not statistically different and means were within about 8 seconds. This portion of the study seemed to indicate the automated skidder time study was useful for gross time study of skidders in clearcuts, but perhaps not as useful if elemental times were required.

Table 8.2.3 Duration of skid cycle elements, by turn, for time study carried out on Day one. All values are in seconds and are cumulative times for each element during a single cycle.

Turn	Travel Empty			Travel Loaded			Intermediate Travel			Grapple			Total Cycle		
	V	M	A	V	M	A	V	M	A	V	M	A	V	M	A
1	35	67	38	33	65	12	20	19	11	28	32	37	116	182	98
2	57	54	48	42	39	43	10	16	7	40	32	42	148	141	140
3	73	53	131	54	55	54	28	25	0	60	57	25	215	191	210
4	45	22	31	32	20	55	13	0	26	32	51	39	122	93	151
5	41	27	30	35	35	44	11	12	22	30	30	24	117	103	120
6	75	76	66	61	67	64	11	14	10	34	29	35	180	187	175
7	84	46	71	71	76	71	11	27	20	51	42	57	217	189	219
8	27	63	23	36	36	33	0	0	0	14	8	23	77	107	79
9	52	54	40	60	62	59	22	19	20	52	57	56	187	191	175
10	81	78	76	70	73	68	14	17	0	29	23	46	195	191	190
11	92	67	96	85	86	82	21	33	11	53	43	65	251	230	254
12	56	52	48	43	42	67	11	16	10	36	30	39	147	140	164
13	99	100	178	57	57	57	48	60	10	89	70	54	292	287	299
-															
Mean ¹		-4.5	4.5		2.6	2.3		2.8	-5.7		3.3	-0.4		-2.4	0.7
Std Dev		21.1	29.3		9.7	11.5		7.6	14.5		9.2	16.2		26.2	12.4
-															
t-value ²		-0.7	0.5		0.9	0.7		1.3	-1.4		1.2	-0.1		-0.3	0.2
P-value		0.5	0.6		0.4	0.5		0.2	0.2		0.2	0.9		0.8	0.8

1 – Means are for differences between the manual or automated time study analysis methods and the video method.

2 – The t-value is for $H_0: \mu_i = 0$, where μ_i is the difference in elemental time between manual or automated estimates and the value derived from video analysis.

It was unclear why the results from Day 2 derived from the automated analysis method were so poor relative to the manual time study, particularly regarding the inability to detect the intermediate travel portion of the skid cycle. The failure to find that element may have been due to a change in behavior by the skidder operator, some change in procedures that confounded the rule-based interpretation of the results. The operator did change his typical operating activities between the two sites, using a more random approach to bunch selection and being less inclined to choose the most direct route back to the landing when hauling wood. However, these changes should not have caused the interpretation of the results using automated analysis to fail as they did. The failure does illustrate, however, the sensitivity of the analysis procedure to the operator following a predictable sequence of events when doing his job. It might be more effective to switch from a rule-based interpretation of the data, as employed here, to one that employs a statistical approach, which might be less sensitive to subtle changes in behavior by the operator.

It was also unexpected that, despite large differences in individual element times, the overall skid cycle length for Day 2 data was the same between methods. This suggested the automated analysis worked well in general, but probably tended to shift time between elements when confronted with situations outside the range of its ability to interpret. This was fortunate in that, although individual elements might be incorrect, the total cycle times were still accurate and some, albeit incomplete, information would be recovered from its application. It was also important that the automated analysis in both cases found the same number of skid cycles as manual time study. This suggested the method could be used over long periods of time to summarize production information without missing potentially significant events.

Table 8.2.4 Duration of skid cycle elements, by turn, for time study of 21 June. All values are in seconds.

Turn	Travel Empty		Grapple		Intermediate Travel		Travel Loaded		Total Cycle	
	M	A	M	A	M	A	M	A	M	A
1	119	166	51	50	4	0	119	123	293	339
2	79	98	17	20	0	0	120	119	216	237
3	137	184	45	66	15	0	155	156	351	406
4	148	140	42	50	8	0	137	138	336	328
5	160	271	40	49	27	0	160	131	388	451
6	147	142	28	16	0	0	14	168	189	326
7	163	192	55	76	23	0	184	193	424	461
8	269	210	49	88	282	12	925	958	1525	1268
9	148	458	52	24	226	0	131	136	558	618
10	163	362	65	28	147	0	150	-23	524	367
11	170	160	85	100	63	46	287	382	605	688
12	146	204	66	40	18	0	568	-37	798	207
13	131	197	26	11	27	0	17	669	201	877
14	130	184	46	80	46	12	153	151	375	427
15	156	121	7	19	0	0	1030	996	1193	1136
16	163	245	47	25	39	0	103	106	351	376
17	132	158	48	26	47	0	127	163	353	347
18	111	144	33		34	0	255	257	433	401
Mean ¹		-53.7		1.9		52.0		-8.5		-8.2
Std Dev		86.0		23.3		79.0		224.4		235.5
t-value ¹		-2.6		0.3		2.7		-0.2		-0.1
P-value		0.020		0.745		0.015		0.878		0.884

1 – Means are for differences between the manual and automated time study analysis.

2 – The t-value is for $H_0: \mu = 0$, where μ is the difference in elemental time between manual and automated estimates.

8.2b.4 Summary

An evaluation of an automated skidder time study system was undertaken. Its performance was tested relative to video- and GPS-based manual systems. Results showed there was close correspondence between the automated and manual approaches on one site, but there were large differences in elemental times on another. There was always high correlation, however, between total cycle times between all time study methods. The results indicated the automated system was feasible to apply in practice, but further refinement of data analysis methods was necessary.

8.2b.5 Output

Maza, Camila; Seixas, Fernando; McDonald, Tim. 2013. Comparação entre métodos de estudo de tempo: uma aplicação a operação de arraste florestal com uso de “Skidder”. Submitted to: Revista Scientia Forestalis.

8.2b.6 References

Fenner, P. T. 2002. Métodos de cronometragem e a obtenção de rendimentos para as atividades de colheita de madeira. Botucatu: UNESP, Faculdade de Ciências Agrônomicas. 14 p. Notas de aula da Disciplina de Exploração Florestal.

Seixas, F.; Barbosa, R. F.; Rummer, R. 2004. Colheita de madeira de eucalipto. Revista da Madeira, Curitiba, n.82.

McDonald, T.P., Fulton J. 2012. Mapping machine productivity and tree size of a Feller- Buncher harvesting biomass in pine plantations. In: 35th Council on Forest Engineering Annual Meeting. COFE, Morgantown, WV.

McDonald, T.P., Fulton J. 2005. Automated time study of skidders using global positioning system data. In: Computers and Electronics in Agriculture 48(2005):19-37.

8.2c Sensor Development to Measure Mass Flow of Biomass from Chipper

8.2c.1 Background

An important aspect of the project has been to develop technological solutions to solve problems limiting productivity or impeding quality assurance in the procurement process. Variation in moisture content has been identified as a potential problem in sourcing biomass for a conversion facility, particularly if in-field drying is used to increase transport efficiency. Some biomass-consuming mills, particularly those using thermochemical processes, would prefer to pay for raw material on an energy basis, rather than wet weight, to favor those suppliers bringing the driest wood. Practical moisture sensing systems on both ends of the procurement chain were felt to be an essential element in such a payment scheme in order to foster trust between suppliers and consumers. The work at Auburn has been aimed at development of such a moisture content measurement system for use on a chipper to sense water content of chips as they are blown into a van.

An essential precursor to such a moisture measurement system is the ability to measure mass flow rate of chips as they exit the chipper chute. We developed and tested such a device for this project, one that was practical, fairly simple, inexpensive, and relatively robust. This section of the report will provide details of the design along with some preliminary testing results.

8.2c.2 Objective

The objective of this subtask was to develop a mass flow sensor for measuring flow rate of chips leaving the chipping machine.

8.2c.3 Methods

Mass flow sensors are common on agricultural combines for a variety of applications. Many use an impact method of sensing flow rate (*Birrell and others, 1996*). In this approach, the stream of material is directed onto a force transducer that senses a change in momentum as it impacts a plate. The resulting force is used to predict mass flow. A similar approach has been used in the chipper mass flow system. A hinged element was added to the end of a chipper (*Precision Husky Corporation¹ model 3084 WTC*) chute as Figure 8.2.9. A fixture mounted between the fixed and movable portions of the chute held a dynamic mass flow sensor (*Omega Engineering, INC model DLC101-50*) that was loaded in compression when chips impacted the hinged plate. The output from the sensor was a voltage signal proportional to force and was read using a National Instruments USB-6210 data acquisition module. The data were sampled at 10 kHz and recorded using a program written in Labview (*National Instruments Corporation*).

¹ The use of trade names is for information purposes only and does not apply any endorsement by Auburn University.



Figure 8.2.9 The mass flow sensor (including force transducer) mounted on the chipper (left) and a close-up photo (right) showing the mechanism used to transmit impact force from the hinged plate to the transducer.

No independent measure of wood chip mass flow was found to be practically feasible, so experiments were instead conducted to correlate sensor output with tree DBH. Data collected by partners in the study consortium indicated DBH and weight were highly correlated for the types of stands being harvested, specifically, relatively young loblolly pine plantations. Figure 8.2.10 is a plot of the relationship between weight and DBH for a range of typical tree sizes found in the stands. A linear regression of DBH on weight was found to be significant ($P < 0.001$) with R-square in excess of 0.9.

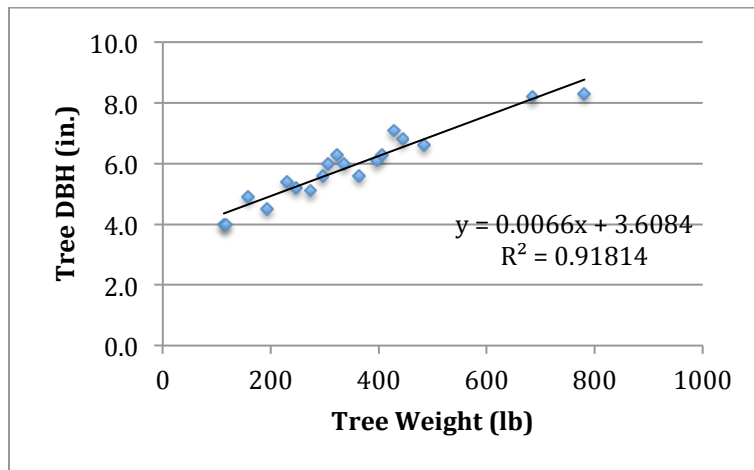


Figure 8.2.10 Regression result between tree DBH and weight.

Experiments consisted of measuring sensor output over the entire duration of a single tree being chipped. The time period used (33 seconds) was fixed. Figure 8.2.11 shows a plot of the typical force response while chipping a single stem. The 33-s duration was sufficient, in most cases, to record force while the entire stem was chipped. Problems with sampling the entire tree were sometimes encountered when, for example, the stem became hung in the debarker prior to entering the chipper. Stems in groups of about 10 were laid out on the logging deck near the chipper and measured for DBH and total height. Stems were then fed individually into the debarker and the chipper. Force response was measured and stored for each stem. Valid data for a total of 98 stems were measured sampling in this manner.

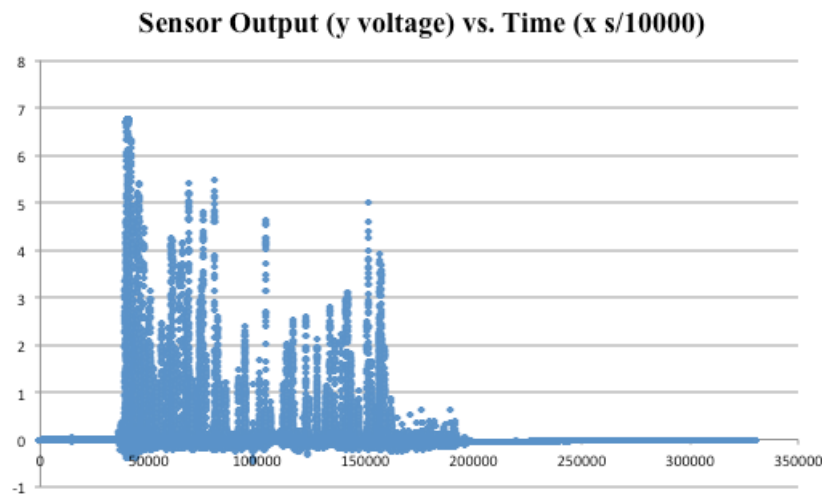


Figure 8.2.11 Force response example during chipping

Two types of measures were calculated on each force record for correlation with tree DBH. These measures consisted of the following:

- Response sum. This was simply a sum of all force observations from beginning to end of the sampling period.
- Power spectral density (PSD). The power spectrum of a signal describes the power per unit frequency it carries. PSD were calculated for each force response in Matlab2010a (*The MathWorks, Inc.*) using the Welch method with Hanning windows at length of 4096. This resulted in a relative power value at numerous (4096) discrete frequencies, only some of which were assumed related to size of the tree.

A principle components analysis (PCA) was used to determine smaller groups of frequencies most closely correlated with tree size. The ten principal components most highly correlated with DBH were then selected and used in a stepwise regression analysis to determine the smallest set of values most closely predicting tree size. A random selection of eight force records was reserved and the prediction model built from the remaining 90 observations. Finally, predictions for the eight reserved trees based on the completed model were compared to actual DBH measurements.

8.2c.4 Results

There was no correlation observed between the summed force response and tree DBH. Figure 8.2.12a shows a graph of DBH versus force sum for the 90 observations. It was surprising how completely unrelated the two were. We had originally thought a larger tree would produce a bigger force over the same length of time since the chipper fed at a constant rate and the trees were about the same height regardless of diameter. The sum should, therefore, have been greater for a larger tree, but this was not the case.

The PSD approach, however, proved more effective at capturing diameter information. The stepwise regression process resulted in a model having five total independent variables, four of which had p-values < 0.002 , the fifth with $p < 0.1$. Using these variables, the relationship between predicted and actual DBH was as seen in Figure 8.2.12b. The R-square value in this case was 0.69. This result perhaps indicated that, although the chips were striking the impact plate as they exited the chute, their path was not changed a great deal and, therefore, force measurements were relatively low. This was intentional in that we did not want to alter the flow of chips into the van and cause problems filling its volume. Though the

magnitude of the impact force of chips was not altogether different for larger trees, the rate at which they struck the plate seemed to be changed and this put higher frequency variations into the force signal. These higher frequency components were more pronounced for larger trees, indicating a more rapid rate of chip impact, and this was detected in the spectral analysis of the signal.

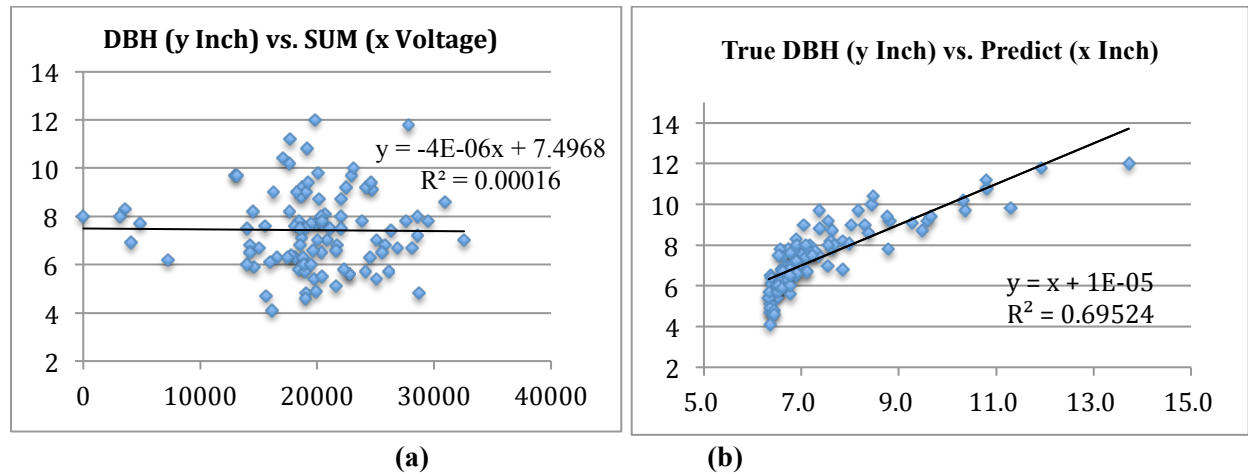
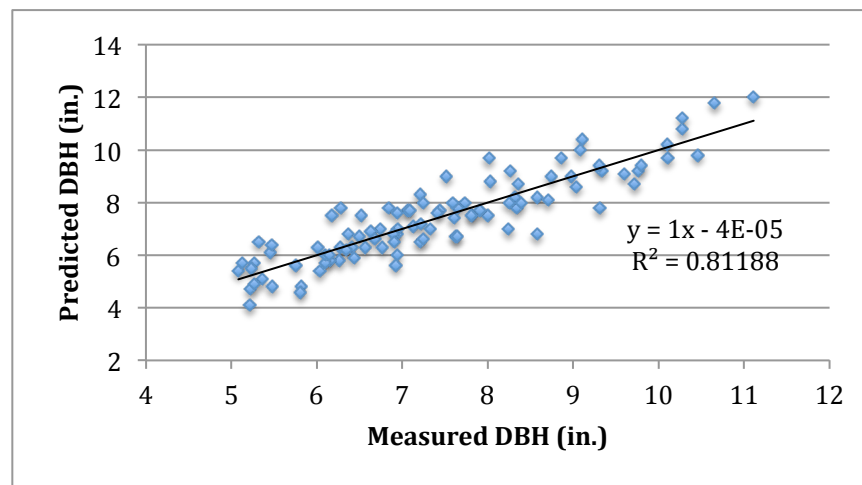


Figure 8.2.12 Regression model for direct sum (a) and PSD (b)

The model was used to estimate DBH for the eight reserved trees and results were summarized in Table 8.2.5 (marked as Lin for linear). For trees larger than about 6 inches DBH, the size estimates were typically within 10% of the actual value. For smaller trees, however, the prediction was inaccurate, with size being overestimated. The poor results for smaller trees could have been the result of background noise. Impact forces were relatively small for even large trees and shaking of the chute could easily have overwhelmed the response for smaller stems. This effect was visible in the results shown in Figure 4b mainly as a significant nonlinearity at low DBH. A log-transformation was applied to the regression data in an attempt to counteract the nonlinearity at low DBH. The regression of predicted to actual DBH for the transformed data are shown in Figure 8.2.13. A good linear relationship between true DBH and predicted value was obtained with higher R-square. The eight reserved trees were also tested using the log-transformed model and results were listed in Table 8.2.5 (marked as Log). Clearly the log-transformation method improved the prediction accuracy significantly for small DBH trees, average error decreasing from 7.90% to 5.77%. Interestingly, the prediction accuracy for larger trees seemed to go down slightly.

Table 8.2.5. True stem diameter vs. predicted value for PC regression.

TREE NO.		1	2	3	4	5	6	7	8	Average
Predicted	Lin	12.3	6.9	10.9	7.8	6.2	7.0	6.5	7.3	8.11
	Log	10.7	7.3	10.3	8.5	5.2	7.6	6.2	7.8	7.95
True DBH		11.8	7.0	10.8	8.2	4.7	7.4	5.8	7.5	7.9
Error Absolute value	Lin	4.15%	0.99%	1.05%	4.53%	31.91%	5.64%	12.55%	2.35%	7.90%
	Log	9.32%	4.29%	4.63%	3.66%	10.64%	2.70%	6.90%	4.00%	5.77%

**Figure 8.2.13. Regression model for log-transformed data.**

An experiment was conducted to test if these results calculated for individual trees might be applicable in a production situation in which multiple stems were moving through the chipper on a continuous basis. Fundamental to this analysis was the assumption that the same force response would be seen whether a single stem, or multiple stems, were being chipped as long as the total cross-sectional area were the same. The difference in the two scenarios was the lack of knowledge about when a stem might begin or end its trip through the chipper. In our original tests, data were captured while the entire tree was chipped. In a production setting, the beginning and ending points would vary for each of many stems going through at any one time and it would not be possible to calculate the PSD and subsequent prediction based on the entire, individual-stem force signal. It was felt a discontinuous sampling strategy would be most practical in this scenario, that is, making estimates of mass flow over short bursts of time and accumulating them to predict total mass flow.

Four different sampling strategies were evaluated in these experiments. For each one, the sampling process was applied to the continuous data collected for individual stems, and the resulting DBH calculated using the PC regression model for the (shorter) periods of time covered. All these DBH estimates were then averaged and compared to the global average DBH for all stems. The four sampling strategies were as follows.

1. Continuous sampling over short periods
 - a. Two second intervals
 - b. Five second intervals
2. Discontinuous sampling

- a. Sampling every other second
- b. Sampling two seconds, then waiting three seconds

Results are found in Table 8.2.6. For continuous sampling (strategies 1a. and 1b. above), all data were contained in the PSD computation and, as might be expected, the global DBH estimate was closer to the true value, differing by less than about 0.3%. For the partial sampling strategies (2a. and 2b. above), there was some loss in accuracy with global DBH estimates differing by about 1.8%, or less, from the true value. The correct approach to use in creating a production mass flow sensor would be related to the practicalities involved in developing the system itself. If the PSD calculations could be done in real time, the continuous strategy would most likely be more accurate in predicting DBH. If it were necessary to store data in order to make the PSD calculation, then the discontinuous approach would perhaps be more suitable with only a slight decrease in total accuracy.

Table 8.2.6. DBH calculation from different sampling methods

Sampling Methods	Prediction DBH on Average (inches)	True DBH (inches)
Two second intervals	7.41	7.43
Five second intervals	7.42	
Sampling every other second	7.36	
Sampling 2s then waiting 3s	7.30	

8.2c.5 Summary

An approach to measure mass flow rate of chips exiting a chipper was presented. The method used a force measurement over time to estimate mass flow. Data were correlated to tree size (and therefore weight) using a prediction model based on the force signal power spectrum. Results showed good agreement between measured and predicted individual tree DBH for the conditions used in these tests. Other experiments indicated the approach would be applicable for continuous measurement of mass flow from multiple stems, but this was not verified in practice. Further research will test the method for multiple stems and verify accuracy of predicted truckload weights.

8.2c.6 Output

Pan, Pengmin; McDonald, Timothy; Taylor, Steve; Fulton, John. 2012. Real-time monitoring mass-flow of wood chips based on force sensor. COFE Annual Meeting, New Bern, NC: 10-12 September. 7 pp.

8.2c.7 References

Birrell, S. J., K. A. Sudduth, and S. C. Borgelt. 1996. Comparison of sensors and techniques for crop yield mapping. *Computers and Electronics in Agriculture* 14(2-3): 215-233.

8.2d Sensor Development to Measure Moisture Content of Chips

8.2d.1 Background

Purchasing biomass for energy on a dry matter basis is preferable because it means the consumer is not paying for water, plus the additional expense of drying the feedstock. From the producer's standpoint, however, selling wood on a dry basis means there could be disagreement over the true moisture content of delivered material and, if that were the case, the likelihood he was being underpaid. A real-time moisture sensing system deployed at the point of production providing accurate readings might serve to resolve this conflict between buyer and seller.

8.2d.2 Objective

The objective of this subtask was to develop a moisture sensor for wood chips based on electrical capacitance.

8.2d.3 Methods and Results

It was assumed loggers would be delivering biomass in chipped form and would therefore have a chipper on their landings. It was decided to develop a moisture sensor that would affix to the exit chute of a chipper and provide readings on moisture content as the chips were being blown into a van for delivery, precluding the necessity of handling the chips for sampling purposes.

Moisture in a moving stream of wood chips was measured using a transducer sensitive to variations in permittivity of the material within its enclosure. Permittivity of biomass and water are quite different and the two can be distinguished by their composite permittivity signal given some knowledge of the total amount of material present. The sensor was built using sets of paired plates to form multiple capacitive elements each pair of which attenuated a dynamic signal by an amount related to the dielectric of the material between them. This attenuation in an input signal was measured and related back to permittivity, and hence moisture.

As noted above, the sensor required an independent measure of mass in order to distinguish water from wood. For the purposes of this study the mass flow measurement was made using an impact method similar to that used in combines to generate yield maps. A prototype chipper mass flow sensor was built and tested, a photo of which is shown in Figure 8.2.9. The arrangement consisted of a hinged plate at the end of the chipper chute that redirected the flow of material slightly. The change in momentum of the chip stream resulted in a small force that could be measured. Tests were conducted on individual stems to predict its total weight based on the force response observed as it was chipped. The tests involved recording force over the entire chipping cycle for the stem, transforming the time signal to the frequency domain, calculating principal components, and finally correlating the loadings with stem weight. Results indicated a strong linear relationship ($R^2 = 0.81$) between predictions of tree weight based on the transformed force readings and actual tree weight (Figure 8.2.13), which, because the chipper operated at a constant feed rate, should be equivalent to mass flow rate.

A prototype capacitive moisture sensing system was built and tested as seen in Figure 8.2.14. Coupled with the impact mass flow sensor, the capacitive moisture transducer was found to be linearly related ($R^2 = 0.72$) to moisture content of a stream of pine chips (Figure 8.2.15).

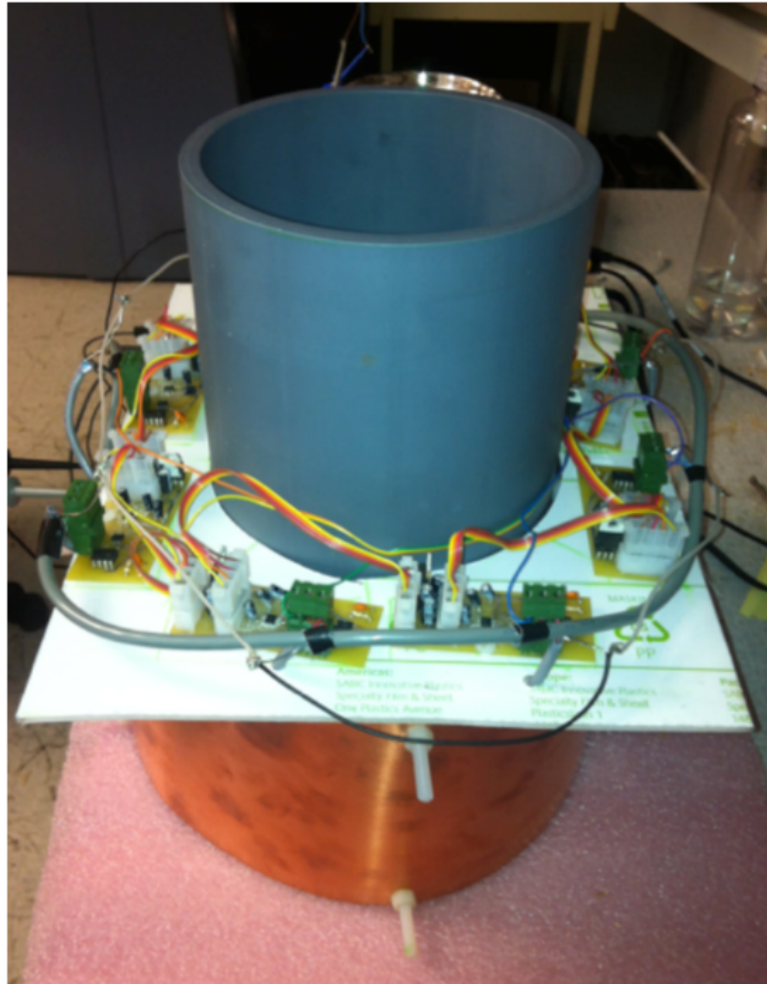


Figure 8.2.14 The prototype capacitive moisture sensor as tested in the lab consisted of a tube through which chips were conveyed, sensor electronics for measuring the time-varying capacitance changes within the tube (affixed to the white board near the middle of the tube), plus shielding for the sensor electrodes themselves (below the electronics) to eliminate problems with stray capacitances. Sensor electrodes (8 in number) were copper strips 10x2.5 cm arranged uniformly around the tube.

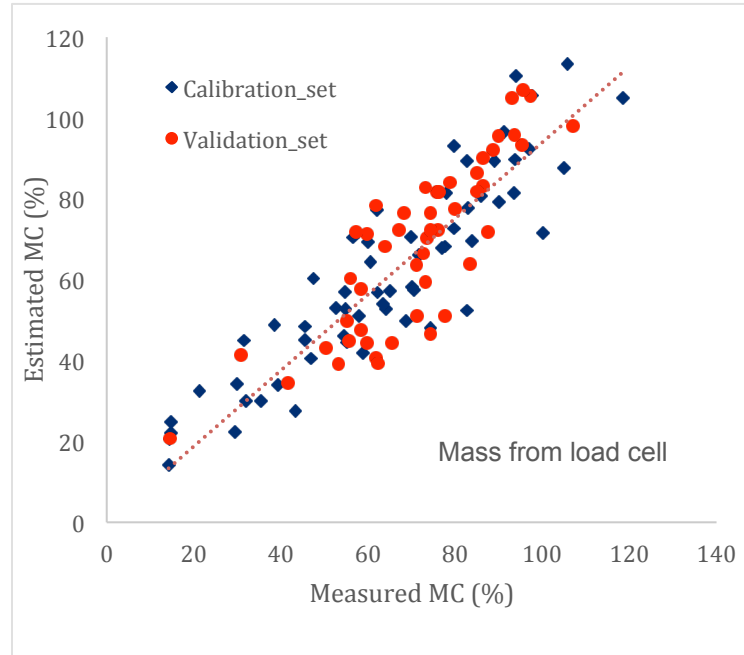


Figure 8.2.15 The measured and predicted moisture content of moving pine chips predicted using the combination of impact force sensor and the capacitive sensor of Figure 8.2.14. The coefficient of determination for the validation data set was $R^2 = 0.71$.

The capacitive sensor used multiple electrodes to provide estimates of the bulk permittivity of the material within its enclosure, but the arrangement also allowed the application of tomographic techniques to also measure the permittivity distribution. With the assumption of uniform bulk density of the material, this distribution in permittivity could also be used to image the variation in moisture content and mass of the material under test (Figure 8.2.16). Using this approach, the sensor could provide simultaneous estimates of both moisture and mass flow (using an imaging technique) and eliminate the need for the impact force mass flow sensor.

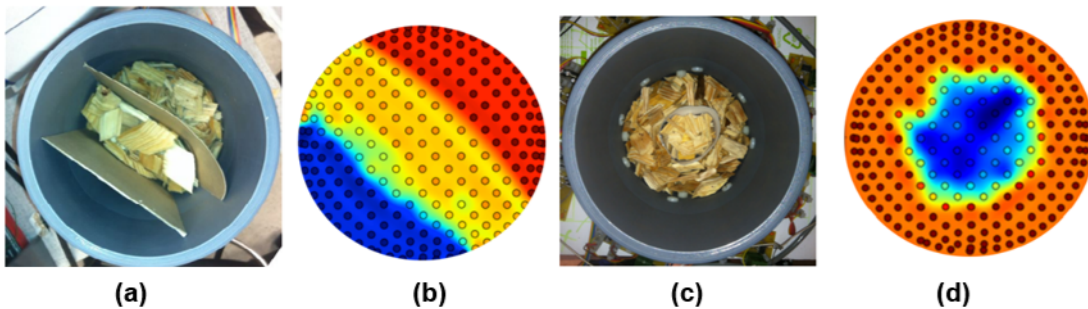


Figure 8.2.16 Two sets of images showing actual contents of the sensor enclosure ((a) and (c)) along with estimated moisture distribution based on the capacitance sensor in tomographic mode. Image (b) illustrates pine chips at two different moisture levels separated by a partition, plus an area with no chips present. Image (d) also shows the enclosure with chips at two moisture levels, but without the empty component and with the dryer chips surrounding wetter chips in the center.

Accuracy of the imaging approach to estimate mass flow was limited by several factors, the most critical of which was sampling rate sufficient to observe the material passing through the sensor enclosure. Although in the prototype system this sampling rate was limited to about 10 frames per second, it was still possible to estimate both mass and moisture using a single sensor. The relationship between measured

and predicted moisture content for various samples of pine chips flowing through the sensor is shown in Figure 8.2.17. The accuracy of the method was not sufficient for use as a tool for most production settings, but could be improved with faster data acquisition hardware.

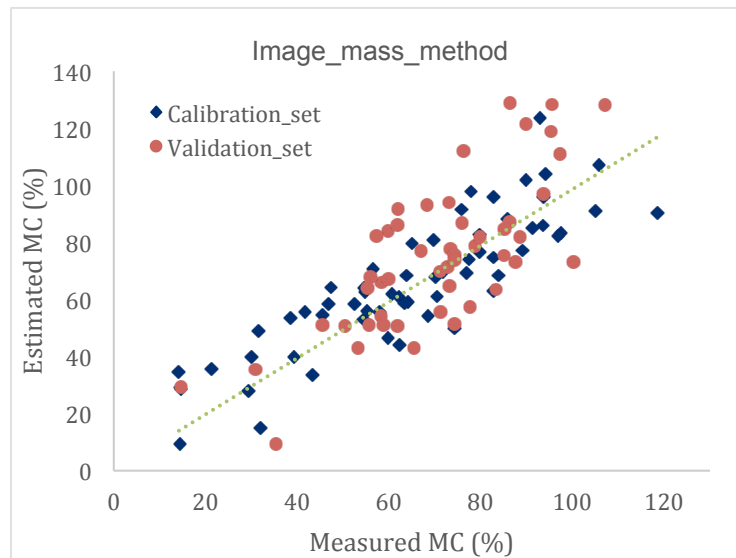


Figure 8.2.17 Measured and predicted moisture content of a stream of pine chips flowing through the capacitive sensor based on tomographic reconstruction of permittivity variations. Coefficient of determination for the validation data set was 0.57.

8.2d.4 Summary

A prototype sensor was developed to measure moisture content of chips flowing through a chute or pipe. This capacitive sensor used tomographic reconstruction of permittivity variations to estimate moisture content. The sensor shows promise for measuring moisture content if high-speed data acquisition hardware can be used for the system.

8.2d.5 Output

Pan, Pengmin. 2014. Monitoring Moisture Content and Mass Flow of Wood Chips Using Electrical Capacitance Tomography. PhD dissertation, Auburn University, Biosystems Engineering Department. Auburn, AL.

8.3 Feedstock Characteristics

The text for this subtask contains two subsections: Section 8.3a describes properties of southern pine trees; and Section 8.3b describes properties of chipped biomass from numerous tracts.

8.3a Tree Properties

8.3a.1 Objective

The objective of this subtask was to evaluate properties of trees being harvested from the study sites in terms of weight by diameter class, field moisture content of wood and bark, moisture content of limbs and foliage, density of wood and bark, and ash content. An additional objective was to develop regression relationships to predict tree weight (whole-tree, total stem inside and outside bark, and stem to a 2-inch top inside and outside bark) as a function of tree size.

8.3a.2 Methods

Trees were selected from several study sites to represent a range of diameter classes. Plantation stands were sampled during the months of April, May, and December. A natural stand was sampled during the month of October. Sample trees were felled with a chainsaw at ground level. After felling, sample trees were measured for butt diameter and DBH in addition to total length, length to a 2-inch top, and length to the first live limb. Trees were then suspended by a chain attached to the forks of a tractor and a digital load cell was used to measure tree weights. After trees were weighed whole-tree they were delimbed with a chainsaw to determine total stem weight and weight of limbs and foliage. Trees were then topped at 2 inches and weighed. Sample disks were cut from each tree at butt, DBH, 10 feet and then every 5 feet along the entire stem. Disks were placed in sealable plastic bags and labeled. Limbs and foliage were sampled by selecting one limb from each whirl. Sample limbs were cut into manageable pieces and placed in a container and weighed in the field. Pieces were then placed in a large plastic bag and labeled. In the lab, disks were measured with a D-tape for outside diameter. Bark was then removed with a wood chisel and inside diameter measured. Green weight of bark and wood of each disks were measured on a digital scale. Moisture content was assessed through loss in drying, as prescribed in European Standard EN 14774-2 (2009). Samples were placed in pans and heated in a drying oven at $105 \pm 2^\circ\text{C}$ until total mass loss differed by less than 0.2% between measurements taken one hour apart. The wet basis moisture content was calculated by dividing the difference between initial and oven-dry sample mass by the initial sample mass.

Dry density of wood and bark was measured by displacement in water. A beaker of water was placed on a digital scale and zeroed for tare. Samples were then coated with paraffin wax to inhibit absorption of water and then submerged in the beaker and the reading on the scale was recorded. The reading on the scale in grams directly translates to cubic centimeters to give volume displaced by the sample.

8.3a.3 Results

Twenty-eight trees were sampled from plantation sites and ten trees were sampled from the natural stand. Of the twenty-eight plantation trees, twenty-five were weighed. Mean DBH of sampled trees from plantations was 6.2 inches and 6.3 inches for trees from the natural stand. Whole-tree weight of plantation trees averaged 378 lbs. compared to 430 lbs. for the natural stand. Total stem and bark accounted for 82.4% of the whole-tree weight for natural pine and 84.3% for plantation pine. Moisture content of wood was nearly the same between the two stand types (54.9% for natural and 56.0% for plantation). Similarly, the moisture contents of wood and bark based on a weighted average were nearly identical (55.1% for natural and 55.3% for plantation). A summary of data for both stand types is shown in Table 8.3.1. Density of wood and bark based on a weighted average were the same between the two stand types at 28.4 lb/ft^3 . Also, the specific gravity of wood was the same between the two at 0.46.

Table 8.3.1. Standing tree summary for natural and plantation loblolly pine in Butler, Covington, Crenshaw, and Monroe Counties in Alabama.

Variable	Natural			Plantation		
	n	mean	s	n	mean	s
DBH (in)	10	6.3	1.76	25	6.1	1.48
Height (ft)						
1 st live limb	9	29.4	3.81	25	26.6	8.72
2-in top	10	41.4	8.91	25	38.4	9.06
Total	10	52.9	7.38	25	48.7	8.35
Weight (lb)						
Whole-tree	10	430.0	282.23	25	378.1	234.87
Total stem outside bark	10	347.7	217.60	25	314.9	183.75
Stem to 2-in top outside bark	10	340.4	218.28	25	307.8	184.18
Limbs & foliage	10	82.3	68.70	25	63.2	58.65
Percent of whole-tree by weight						
Total stem outside bark	10	82.4	3.91	25	84.3	5.58
Total stem inside bark	10	64.8	3.38	24	71.6	7.61
Stem to 2-in top outside bark	10	79.4	3.59	25	81.7	5.49
Stem to 2-in top inside bark	10	62.4	3.42	25	69.3	7.43
Limbs & foliage	10	17.6	3.91	25	15.7	5.58
Moisture Content (% wet-basis)						
Wood	107	54.9	4.96	256	56.0	5.51
Bark	107	56.0	9.99	256	45.0	11.67
Wood & bark ¹	107	55.1	5.38	256	55.3	5.59
Limbs & foliage	10	53.2	7.13	24	57.7	6.31
Whole-tree ¹	10	54.8	2.79	23	54.9	2.44
Density (lb/ft³ dry basis)						
Wood	107	28.8	3.23	256	28.7	3.17
Bark	107	25.7	2.02	256	25.2	3.68
Wood & bark ¹	107	28.4	2.90	256	28.4	2.72
Specific Gravity						
Wood	107	0.46	0.0515	256	0.46	0.0510

¹Weighted averages.

The general practice of harvesting small diameter pine would be to acquire it from plantations, so regression analysis was used to predict component weights for plantation loblolly pine. Table 8.3.2 summarizes the different equations developed based on DBH and total height. Weight equations for whole-tree, total stem outside bark, and total stem inside bark are displayed graphically in Figure 8.3.1.

Table 8.3.2. Weight equations from trees sampled in Butler, Covington, and Crenshaw Counties in Alabama.

Component	N	Equation ¹	R ²	C.V.
Whole-tree (Stem + Limbs + Top)	25	$0.1849506 \cdot \text{DBH}^2 \cdot \text{TH}$	0.991	11.38
Total Stem (0" Top - Wood & Bark)	25	$0.1517053 \cdot \text{DBH}^2 \cdot \text{TH}$	0.993	9.90
Total Stem (0" Top - Wood Only)	24	$0.1341208 \cdot \text{DBH}^2 \cdot \text{TH}$	0.990	11.52
Stem (2" Top - Wood & Bark)	25	$0.1492390 \cdot \text{DBH}^2 \cdot \text{TH}$	0.993	9.76
Stem (2" Top - Wood Only)	24	$0.1315197 \cdot \text{DBH}^2 \cdot \text{TH}$	0.990	11.67

¹Equations predict weight in pounds; DBH = Diameter at Breast Height in inches; TH = Total height in feet.

Note: No intercept term used in equations: R-square is not corrected for the mean.

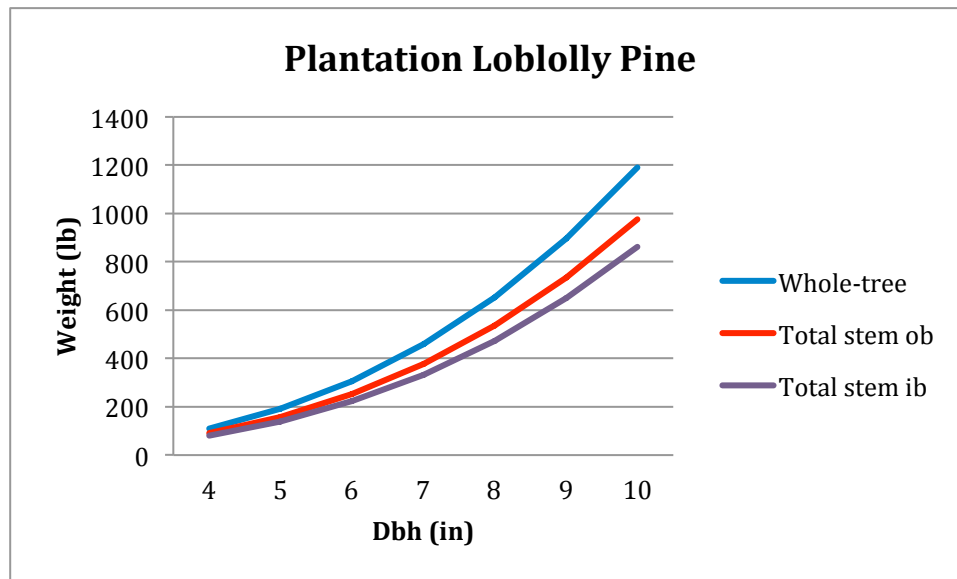


Figure 8.3.1 Weight equations for plantation loblolly pine in south Alabama.

8.3a.4 Summary

A total of twenty-eight trees from plantation sites were sampled for density and moisture content, however, only twenty-five of these were weighed. Therefore, mean DBH and heights reported in Table 8.3.1 reflect those of trees where weights were measured. Mean DBH and total height were slightly larger for trees sampled in the natural stand which resulted in a higher mean stem weight. Moisture content and density of wood and bark were the same between the two stand types. Specific gravity of wood was also the same.

The square of DBH and total height were highly correlated with tree weight and were used as independent variables in regression equations for predicting weights for whole-tree, total stem, and stem to a 2-inch top.

8.3b Chip Properties

8.3b.1 Objectives

The objective of this subtask was to quantify physical properties of southern pine biomass chips (whole tree and clean chips, green and transpirationally-dried chips) produced during the study.

8.3b.2 Methods

Composite samples representing loaded chip trailers were collected at harvest sites in southern Alabama. Each composite sample was composed of eleven or more incremental samples collected from different parts of the load of chips (CEN/TS 14778-1:2005). When equipment and working conditions allowed workers to safely sample chips from the outflow spout of the disk chipper during chipping, incremental samples were collected by diverting chips into a collection container through a pipe intermittently inserted into the outflow stream of the chipper. When chips could not be safely sampled from the moving chip stream, incremental samples were collected from different parts of the load after the chipper had been powered down.

Composite samples were thoroughly mixed in the collection container and sealed in airtight containers. To provide enough material to perform all analytical tests, the volume of each sample was 18-37 liters (5-10 gallons). Following sample collection, samples were transported to the laboratory and stored at 2-5°C while awaiting analysis to minimize biological activity.

During transport and storage stratification occurs in biomass samples. Prior to analysis, biomass samples were mixed to homogenize them and divided to obtain representative subsamples of the appropriate size for specific analyses. This was accomplished through the coning and quartering technique: the sample was poured into a cone on a clean, non-absorbent surface; returned to the sample container; poured into a cone a second time; returned to the sample container; poured into a cone a third time; flattened by pressing down on the top of the cone; and divided into quarters. Two opposing quarters were returned to the sample container and the remaining half of the sample was used in a laboratory test or further divided by repeating the coning and quartering process (but only pouring the sample into a cone one time instead of three) until a representative subsample of appropriate size was obtained.

Tests for energy content, ash content, volatiles, fixed carbon, and other material properties require that samples be milled to reduce particle size to a nominal top size of 1 mm (0.04 in.) or less. Subsamples of suitable size were dried to a moisture content of approximately 10-15% at 50°C or less to minimize losses of volatiles during drying. Dried subsamples were then milled in a clean hammermill equipped with a 3.2 mm (0.125 in.) screen and then milled in a clean cutting mill equipped with a 1 mm screen to achieve the required particle size. Milled subsamples were then sealed in an airtight sample container.

Moisture Content

Laboratory tests of biomass moisture content measure the percentage of sample mass contributed by water in the sample. The moisture content of live loblolly pine trees fluctuates in response to climate and soil moisture conditions, and may exceed 60% of the wet tree mass. After a tree is cut the moisture content of the tree decreases as moisture losses to continuing transpiration from leaves and evaporation exceed moisture gained from precipitation and absorption. When trees are processed and delivered shortly after felling the moisture content of the trees remains high. The transpirational drying component of the High Tonnage Forest Biomass Production Systems from Southern Pine Energy Plantations project was intended to improve the efficiency of biomass transportation and conversion to fuel products at biorefineries. The target moisture content for transpirationally dried wood chips was 30%.

Moisture content was assessed through loss on drying, as prescribed in European Standard EN 14774-2 (2009). For each sample, a representative subsample of a minimum of 300 g was obtained and spread in a

thin layer in a clean drying dish of known mass. The sample and pan are heated in a drying oven at $105 \pm 2^\circ\text{C}$ until total mass loss differed by less than 0.2% between measurements taken one hour apart. The wet basis moisture content was calculated by dividing the difference between initial and oven-dry sample mass by the initial sample mass.

Bulk Density

The bulk density of a particulate material is the mass of a collection of particles divided by the volume of space the collection of particles occupies. The bulk density of comminuted forest biomass depends on the density of the particles that constitute the solid fraction of the material, physical characteristics of the particles, and material handling. Differences in one or more of these variables between materials lead to a wide range in bulk densities among forest-derived biomass products.

Bulk density testing was guided by European Standard EN 15103 (2009). Two test cylinders were used in bulk density tests: one cylinder with a capacity of 5 L (1.3 gallon) and another with a capacity of 20 L (5.3 gallon). The 5 L cylinder allows efficient analysis of bulk density for samples with piece sizes similar to those of conventional chips or smaller, but the larger piece sizes of the transpirationally dried chips necessitated a larger cylinder.

A representative subsample approximately 30-50% greater in volume than the test cylinder was obtained and poured into the test cylinder from a height of 15 cm (6 in.) above the rim of the cylinder until a cone formed at the top of the cylinder and additional material poured onto the cylinder fell away to the sides. As the chips formed a cone above the cylinder rim the pouring height of 15 cm above the level of the cone was maintained. The filled cylinder was dropped from a height of 15 cm onto a clean solid wooden board three times, refilled in the same manner as at first, excess material above the cylinder rim was removed by passing a wooden scraper-board across the cylinder rim, and the mass of the filled cylinder was recorded. The test was repeated three to five times for each sample, and the bulk density of the sample was calculated for each repetition by dividing the mass of the sample in the cylinder by the volume of the cylinder. The bulk density values of the repetitions were averaged to obtain the wet-basis bulk density estimate for the sample. The dry-basis bulk density value of each sample was calculated by multiplying the wet-basis bulk density value by the difference between one and the decimal-form moisture content of the sample.

Particle Size

Industrial-scale forest biomass comminution equipment produces particles that span a range of sizes. The particle size distribution of comminuted biomass affects material handling and the economic and technical suitability of the material for use in energy conversion processes.

A representative subsample of approximate 8 L was obtained for each sample for particle size analysis. Prior to analysis, samples were dried to allow free movement of particles. Particle size was assessed using a chip classifier (TMI Chip Class™) set to shake samples for 10 minutes and equipped with 45 mm, 13 mm, 7 mm, and 3 mm round-hole screens and a bottom pan to catch material passing the 3 mm screen. The fraction of the subsample retained on each screen and the bottom pan was weighed, and the percent of the subsample in each fraction was calculated by dividing the mass of each fraction by the total subsample mass.

Bark Content

Bark makes up a fraction of comminuted forest biomass. Debarking equipment does not remove all bark from trees, and even clean chips contain some bark.

Bark content was assessed by manually separating bark from wood in the fraction of dried biomass samples not passing a 3 mm round-hole screen. Bark content was calculated by dividing the mass of bark in the screened sample by the combined mass of wood and bark in the subsample.

Energy Value

The energy stored in forest biomass makes it valuable as a fuel for direct combustion and as a feedstock for the production of biofuels.

The laboratory test for energy content was conducted using milled sample material. The moisture content of milled samples was determined and the energy released during the bomb calorimeter combustion of three replicate samples of 0.65 g each was recorded.

Ash Content

The solid material remaining after the combustion of a biomass sample is ash. While the majority of moisture-free mass of live forest biomass is made up of cellulose, hemicelluloses, lignin, and extractives, trace amounts of silicon, phosphorus, potassium, calcium, sodium, and other plant micronutrients remain as ash when forest biomass combusts. Soil deposited on forest biomass during growth and harvesting also contributes to the ash content of forest biomass. The ash content of bark and foliage is higher than the ash content of wood, and wood chips produced from delimbed and debarked trees have lower ash content than whole-tree chips.

Ash in biomass creates problems in biomass processing, conversion, and combustion processes. Among the problems associated with ash are waste accumulation, abrasion and mechanical wear of equipment, fouling of boilers and other equipment, and reduced energy content.

To assess ash content, a 1 g subsample of milled biomass was placed into a crucible and heated to 575°C as specified in NREL/TP-510-42622. For each sample three replicate measurements of ash content were made. Ash content was calculated for each replicate by dividing the mass of ash by the initial moisture-free mass of the ash test sample. The estimate of sample ash content is made by averaging the ash estimates for the three replicate measures of ash content.

Volatiles

When heated, components of biomass separate into moisture, volatiles, fixed carbon, and ash. Volatiles content influences the amount of producer or synthesis gas that can be produced from the biomass.

Volatiles content is assessed with a thermogravimetric analyzer as a 10 mg subsample of milled biomass is weighed as it is heated to above 900°C.

Fixed Carbon

When heated, components of biomass separate into moisture, volatiles, fixed carbon, and ash. Fixed carbon influences the amount of char that can be produced from the biomass.

Fixed carbon content is assessed with a thermogravimetric analyzer as a 10 mg subsample of milled biomass is weighed as it is heated to above 900°C.

8.3b.3 Results

Moisture Content

A total of 63 samples, each representing a loaded chip trailer, were analyzed for moisture content. The maximum measured moisture value was 59.8%, and the minimum was 34.0%. The average measured moisture content for all samples was 49.4%, with a standard deviation of 7.7. Summary statistics for each of the material types produced in the project are presented in Table 8.3.3, and complete moisture content results are presented in Appendix B.1.

The transpirational drying treatment included in this project did result in average moisture content values more than fifteen percentage points lower than values calculated for conventional chips and microchips produced from freshly harvested trees.

Table 8.3.3 Moisture content of wood chips produced at sites in southern Alabama.

MOISTURE CONTENT (% Wet Basis)			
Material	n	mean	s
<u>Pine, Freshly Cut:</u>			
Clean Conventional	24	55.9	2.2
Clean Microchips	2	58.0	1.5
WT ¹ Microchips	4	55.1	1.0
<u>Pine, Transpirationally Dried:</u>			
TD ² Clean Conventional	15	39.3	3.1
TD WT Microchips	2	38.8	2.5
<u>Pine, Roadside Storage:</u>			
RS ³ Clean Microchips	2	49.1	1.4
<u>Mixed Species, Freshly Cut:</u>			
MS ⁴ WT Conventional	5	47.4	4.6
MS WT Microchips	7	49.2	2.2
<u>Hardwoods, Roadside Storage:</u>			
HW ⁵ RS Clean Microchips	2	42.8	9.1

¹Whole Tree, ²Transpirationally Dried, ³Roadside Storage, ⁴Mixed Species, ⁵Hardwoods

Bulk Density

A total of 34 samples were analyzed using the 5 L test cylinder. The maximum wet-basis bulk density estimate obtained using the 5 L cylinder was 403.2 kg/m³ and the minimum was 240.6 kg/m³. The average 5 L wet-basis bulk density for all tested samples was 344.4 kg/m³, with a standard deviation of 40.0. The maximum dry-basis bulk density estimate obtained using the 5 L cylinder was 206.5 kg/m³ and the minimum was 110.6 kg/m³. The average 5 L dry-basis bulk density for all tested samples was 164.2 kg/m³, with a standard deviation of 16.0.

A total of 26 samples were analyzed using the 20 L test cylinder. The maximum wet-basis bulk density estimate obtained using the 20 L cylinder was 420.5 kg/m³ and the minimum was 258.5 kg/m³. The average 5 L wet-basis bulk density for all tested samples was 320.8 kg/m³, with a standard deviation of 57.4. The maximum dry-basis bulk density estimate obtained using the 20 L cylinder was 183.4 kg/m³ and the minimum was 162.8 kg/m³. The average 20 L dry-basis bulk density for all tested samples was 171.6 kg/m³, with a standard deviation of 5.7.

Summary bulk density statistics for each of the material types produced in the project are presented in Table 8.3.4, and complete moisture content results are presented in Appendix B.2. As expected, the average wet-basis bulk density of chips produced from transpirationally dried trees was lower than for chips produced from freshly cut trees.

Table 8.3.4 Bulk density of wood chips produced at sites in southern Alabama.

BULK DENSITY (kg/m ³)										
Material	n	5L Wet mean	s	5L Dry mean	s	n	20L Wet mean	s	20L Dry mean	s
<u>Pine, Freshly Cut:</u>										
Clean Conventional	13	377.1	12.5	169.1	4.7	7	404.0	12.7	175.2	2.6
Clean Microchips	2	385.9	4.1	161.9	4.2					
WT ¹ Microchips	4	343.9	13.4	154.6	8.9	2	363.9	1.9	165.8	2.5
<u>Pine, Transpirationally Dried:</u>										
TD ² Clean Conventional						15	283.4	12.7	171.8	5.8
TD WT Microchips						2	267.6	12.8	163.7	1.3
<u>Pine, Roadside Storage:</u>										
RS ³ Clean Microchips	2	352.3	0.8	179.2	4.6					
<u>Mixed Species, Freshly Cut:</u>										
MS ⁴ WT Conventional	4	271.7	23.6	145.8	24.5					
MS WT Microchips	7	313.6	22.2	159.5	15.9					
<u>Hardwoods, Roadside Storage:</u>										
HW ⁵ RS Clean Microchips	2	335.7	15.6	191.2	21.6					

¹Whole Tree, ²Transpirationally Dried, ³Roadside Storage, ⁴Mixed Species, ⁵Hardwoods

Particle Size

Summary particle size statistics for each of the material types produced in the project are presented in Table 8.3.5, and complete data are provided in Appendix B.3. The greatest fraction of conventional chips was retained on the 13 mm screen, and the greatest fraction of microchips was retained on the 7mm screen. The data suggest that transpirational drying causes a shift toward larger particle sizes.

Table 8.3.5 Particle size distribution of wood chips produced at sites in southern Alabama.

PARTICLE SIZE (% Retained on Screen)											
Material	n	0mm mean	s	3mm RH ¹ mean	s	7mm RH mean	s	13mm RH mean	s	45mm RH mean	s
<u>Pine, Freshly Cut:</u>											
Clean Conventional	14	2.7	1.4	12.6	5.1	32.3	5.2	52.2	11.3	0.3	0.3
Clean Microchips	2	5.2	1.2	22.0	0.3	46.4	0.9	26.6	0.1	0.0	0.0
WT ² Microchips	3	4.3	2.5	19.3	2.0	50.0	5.1	25.9	1.3	0.5	0.5
<u>Pine, Transpirationally Dried:</u>											
TD ³ Clean Conventional	15	0.7	0.3	4.3	0.9	16.0	2.1	70.1	3.6	8.9	3.9
TD WT Microchips	2	4.2	0.7	15.7	0.4	39.0	3.6	38.1	0.3	3.1	2.3
<u>Pine, Roadside Storage:</u>											
RS ⁴ Clean Microchips	2	2.9	0.8	21.2	6.9	50.8	1.6	25.2	9.2	0.0	0.0
<u>Mixed Species, Freshly Cut:</u>											
MS ⁵ WT Conventional	4	7.2	2.7	15.0	3.2	24.9	2.4	50.6	6.5	2.3	2.0
MS WT Microchips	7	9.6	2.2	23.8	2.4	41.0	4.6	25.1	4.5	0.4	0.5
<u>Hardwoods, Roadside Storage:</u>											
HW ⁶ RS Clean Microchips	2	2.3	0.6	14.1	2.8	48.3	4.5	35.0	0.6	0.5	0.4

¹Round Hole, ²Whole Tree, ³Transpirationally Dried, ⁴Roadside Storage, ⁵Mixed Species, ⁶Hardwoods

Bark Content

Seven samples of freshly harvested, clean, conventional pine chips were tested for bark content (Table 8.3.6). The maximum calculated value was 4.0% and the minimum value was 1.2%. The average bark content of the samples tested was 2.5%, with a standard deviation of 1.2.

Table 8.3.6 Bark content test results for freshly harvested conventional clean pine chips produced at a site in southern Alabama.

Sample ID	Flail	Bark Content (% dry basis)
20121023_001_USFS_Rigsby	Precision 2300	1.2
20121023_002_USFS_Rigsby	Precision 2300	1.4
20121023_003_USFS_Rigsby	Precision 2300	2.2
20121023_004_USFS_Rigsby	Precision 2300	1.5
20121023_005_USFS_Rigsby	Delimbinator	3.6
20121023_006_USFS_Rigsby	Delimbinator	3.7
20121023_007_USFS_Rigsby	Delimbinator	4.0

Energy Value

In total, the energy content of 62 samples was analyzed. The maximum energy value observed was 9051.98 British Thermal Units (BTU)/dry lb and the minimum value was 8057.22 BTU/dry lb. The average energy content for all samples was 8679.76 BTU/dry lb, with a standard deviation of 196.86. Complete energy content results are presented in Appendix B.4, and summary statistics for each of the material types produced in the project are presented in Table 8.3.7.

Table 8.3.7 Energy content of chips produced in southern Alabama.

ENERGY CONTENT (BTU/dry lb)			
Material	n	mean	s
<u>Pine, Freshly Cut:</u>			
Clean Conventional	24	8790.04	<i>67.46</i>
Clean Microchips	2	9032.73	<i>27.23</i>
WT ¹ Microchips	4	8649.96	<i>359.02</i>
<u>Pine, Transpirationally Dried:</u>			
TD ² Clean Conventional	15	8673.10	<i>61.31</i>
TD WT Microchips	2	8714.01	<i>32.94</i>
<u>Pine, Roadside Storage:</u>			
RS ³ Clean Microchips	2	8443.92	<i>9.11</i>
<u>Mixed Species, Freshly Cut:</u>			
MS ⁴ WT Conventional	4	8558.16	<i>100.22</i>
MS WT Microchips	7	8536.84	<i>159.88</i>
<u>Hardwoods, Roadside Storage:</u>			
HW ⁵ RS Clean Microchips	2	8057.87	<i>0.91</i>

¹Whole Tree, ²Transpirationally Dried, ³Roadside Storage, ⁴Mixed Species, ⁵Hardwoods

Ash Content

A total of 62 chip samples were analyzed for ash content. The maximum observed ash content was 5.44% and the minimum value was 0.14%. The average ash content for all 62 samples was 0.81% and the standard deviation was 0.91. Summary ash statistics for each of the material types produced in the project are presented in Table 8.3.8, and complete data are provided in Appendix B.5.

Table 8.3.8 Ash content of wood chips produced at sites in southern Alabama.

ASH CONTENT (% Dry Basis)			
Material	n	mean	s
<u>Pine, Freshly Cut:</u>			
Clean Conventional	24	0.39	<i>0.14</i>
Clean Microchips	2	0.54	<i>0.10</i>
WT ¹ Microchips	4	0.62	<i>0.24</i>
<u>Pine, Transpirationally Dried:</u>			
TD ² Clean Conventional	15	0.44	<i>0.08</i>
TD WT Microchips	2	0.78	<i>0.28</i>
<u>Pine, Roadside Storage:</u>			
RS ³ Clean Microchips	2	0.50	<i>0.04</i>
<u>Mixed Species, Freshly Cut:</u>			
MS ⁴ WT Conventional	4	2.74	<i>1.83</i>
MS WT Microchips	7	2.12	<i>0.97</i>
<u>Hardwoods, Roadside Storage:</u>			
HW ⁵ RS Clean Microchips	2	1.24	<i>0.25</i>

¹Whole Tree, ²Transpirationally Dried, ³Roadside Storage, ⁴Mixed Species, ⁵Hardwoods

Volatiles

A total of 56 samples were analyzed for volatiles content. The maximum volatile content observed was 86.62%, and the minimum was 76.65%. The average volatiles content of tested samples was 83.66%, and the standard deviation was 2.10. Summary volatiles content statistics for each of the material types produced in the project are presented in Table 8.3.9, and complete data are provided in Appendix B.6.

Table 8.3.9 Volatiles in wood chips produced at sites in southern Alabama.

VOLATILES (% Dry Basis)			
Material	n	mean	s
<u>Pine, Freshly Cut:</u>			
Clean Conventional	24	84.97	<i>0.85</i>
Clean Microchips	2	83.75	<i>0.03</i>
WT ¹ Microchips	2	82.55	<i>0.10</i>
<u>Pine, Transpirationally Dried:</u>			
TD ² Clean Conventional	15	84.25	<i>1.20</i>
TD WT Microchips	2	81.55	<i>1.05</i>
<u>Pine, Roadside Storage:</u>			
RS ³ Clean Microchips			
<u>Mixed Species, Freshly Cut:</u>			
MS ⁴ WT Conventional	4	80.68	<i>2.69</i>
MS WT Microchips	7	80.52	<i>1.87</i>
<u>Hardwoods, Roadside Storage:</u>			
HW ⁵ RS Clean Microchips			

¹Whole Tree, ²Transpirationally Dried, ³Roadside Storage, ⁴Mixed Species, ⁵Hardwoods

Fixed Carbon

A total of 56 samples were analyzed for fixed carbon content. The maximum fixed carbon content observed was 11.49%, and the minimum was 6.41%. The average fixed carbon content of tested samples was 9.20%, and the standard deviation was 1.14. Summary fixed carbon content statistics for each of the material types produced in the project are presented in Table 8.3.10, and complete data are provided in Appendix B.7.

Table 8.3.10 Fixed carbon in wood chips produced at sites in southern Alabama.

FIXED CARBON (% Dry Basis)			
Material	n	mean	s
<u>Pine, Freshly Cut:</u>			
Clean Conventional	24	9.11	<i>1.27</i>
Clean Microchips	2	9.48	<i>1.00</i>
WT ¹ Microchips	2	9.74	<i>0.32</i>
<u>Pine, Transpirationally Dried:</u>			
TD ² Clean Conventional	15	8.83	<i>0.90</i>
TD WT Microchips	2	10.56	<i>0.37</i>
<u>Pine, Roadside Storage:</u>			
RS ³ Clean Microchips			
<u>Mixed Species, Freshly Cut:</u>			
MS ⁴ WT Conventional	4	8.55	<i>0.74</i>
MS WT Microchips	7	10.07	<i>1.10</i>
<u>Hardwoods, Roadside Storage:</u>			
HW ⁵ RS Clean Microchips			

¹Whole Tree, ²Transpirationally Dried, ³Roadside Storage, ⁴Mixed Species, ⁵Hardwoods

8.3b.4 Summary

This subtask quantified physical properties of southern pine biomass chips. Various forms and moisture contents of chips were sampled from numerous harvesting operations in South Alabama.

The average 20 L dry-basis bulk density for all tested samples was 171.6 kg/m³, with a standard deviation of 5.7. The greatest fraction of conventional chips was retained on the 13 mm screen, and the greatest fraction of microchips was retained on the 7mm screen. The data suggest that transpirational drying causes a shift toward larger particle sizes.

The average bark content of the samples tested was 2.5%, with a standard deviation of 1.2. The average energy content for all samples was 8679.76 BTU/lb, with a standard deviation of 196.86.

The average ash content for all 62 samples was 0.81% and the standard deviation was 0.91. The maximum observed ash content was 5.44% and the minimum value was 0.14%.

The average volatiles content of tested samples was 83.66%, and the standard deviation was 2.10. The average fixed carbon content of tested samples was 9.20%, and the standard deviation was 1.14.

8.3b.5 References

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8.4 Test and Demonstrate New Feller Buncher and Skidder

8.4a New Feller Buncher and Skidder Production Rates

8.4a.1 Objective

The objective of this subtask was to establish production rates for the new machines, which included a Tigercat 845D tracked feller-buncher with a shear head and a Tigercat 630D high capacity grapple skidder. An additional objective was to determine independent variables, which have the most significant impact on machine performance and develop regression equations to predict total cycle time for each machine.

8.4a.2 Methods

Stand Description

To assess stand characteristics such as density and stocking levels, fixed radius plots were installed in each stand where time study data were collected. Within each plot DBH (Diameter at Breast Height) were measured on trees 3.6 inches and larger and species recorded. Total tree height was measured on every fifth plot tree. Tree diameters were measured to the nearest 0.1 in. using calipers while total heights were measured to the nearest 0.5 feet using an electronic hypsometer.

Feller-Buncher

Felling data were collected on all but one of the sites during the study period. Data were collected by recording on video the feller-buncher working in study areas that were installed within a stand. The machine evaluated was a Tigercat 845D tracked swing-to-tree feller-buncher equipped with a high-speed shear head. In each study area, trees were measured for DBH and species was recorded. Each plot tree was marked with a number for identification purposes while recording. On some sites, tree numbers were either printed onto heavy stock paper cards and stapled onto trees or trees were color coded by diameter class. Tree weights were calculated using local weight equations to determine productivity. A complete observation, or cycle, of a feller-buncher began after trees in the head were dumped and the machine initiated travel to cut the first tree and ended when trees in the head were dumped. Cycle elements consisted of move or swing to first tree, accumulate, move between trees, move to dump, and dump.

Skidder

Skidding data were collected on all but two of the study sites. A Tigercat 630D rubber-tired skidder with a large capacity grapple was evaluated during the study period. Productivity was measured using stopwatches and numbering bunches for identification during a cycle. For most bunches a sample of trees were measured for DBH and total stem count was recorded. On some sites, trees placed in bunches from the feller-buncher were tracked which provided more detailed data related to bundle weight. For bunches where measurements could not be obtained a total stem count was taken. A complete observation, or cycle, began when the skidder left the landing and ended when the skidder returned to the landing and dropped its load. Cycle elements included empty travel, position and grapple, intermediate travel, loaded travel, empty landing travel, loaded landing travel and ungrapple. Normally, when a skidder enters a landing from the woods with a load or leaves the location where the load is ungrappled, normally at the loader, and starts traveling across the landing back to the woods, travel speeds can vary significantly between traveling on a skid trail and traveling across a landing. Therefore, empty landing travel and loaded landing travel were elements used to help reduce variability in empty travel and loaded travel times. Distances traversed by the skidder for the travel elements were measured using a Garmin GPS unit.

8.4a.3 Results and Discussion

Stand Description

Inventory data were collected at each study site. All of the sties except one were plantation pine. Stand density of pine trees in the 4-inch diameter class and larger averaged 488 TPA (trees per acre). Of the total density, 81% of trees were in the 4 to 8-inch diameter classes. Stocking levels in whole-tree green tons averaged 129 gt/ac. Of the total stocking level, 54% was contained in the 7 to 9-inch diameter classes. Stand summaries by diameter class for all plantation sites combined and the natural stand are displayed in Tables 8.4.1 and 8.4.2, respectively.

Table 8.4.1. Stand summary for plantation sites.

STAND AND STOCK TABLE FOR LOBLOLLY PINE		
DBH Class (in)	TPA	Tons/Ac ¹
4	48	2.8
5	70	7.0
6	101	16.1
7	99	22.9
8	77	25.3
9	50	22.2
10	26	15.7
11	6	5.0
12	5	5.4
13	6	6.8
Total	488	129.2

For the natural stand loblolly pine ranged up to 20 inches in diameter and totaled 330 TPA in the 4-inch and larger diameter classes. Compared to the plantation sites, 58% of trees were contained in the 4 to 8-inch diameter classes. Only 6% of the total stand density was in the 14-inch and larger diameter classes.

Stocking level in whole-tree green tons totaled 150.2 gt/ac. Of the total stocking level, the 8 to 12-inch diameter classes represented 55% of the tonnage.

Table 8.4.2. Stand summary for natural site.

STAND AND STOCK TABLE FOR LOBLOLLY PINE		
DBH Class (in)	TPA	Tons/Ac ¹
4	29	1.6
5	46	4.6
6	37	5.8
7	43	10.3
8	38	12.9
9	32	14.5
10	30	18.0
11	25	19.7
12	19	18.1
13	11	13.0
14	7	8.9
15	6	10.4
16	3	5.4
17	2	4.1
18	1	1.5
20	1	1.4
Total	330	150.2

Feller-Buncher

For felling, productivity averaged 99.2 gt/PMH for the Tigercat 845D feller-buncher performing plantation clearcut operations and 119 gt/PMH while clearcutting a natural stand. Trees in the natural stand were 1-inch larger in diameter on average, which was one factor that contributed to the higher productivity rate. Felling summaries for both stand types are shown in Table 8.4.3.

Regression analysis showed that the number of trees per accumulation was the most significant variable for predicting cycle time ($p < 0.000$) for the feller-buncher while plantation clearcutting. The square of the mean tree DBH per accumulation was also significant ($p = 0.0151$).

Plantation:

$$\text{Total cycle time (min)} = 6.7837002 * \text{NoTrees} + 0.1571190 * \text{MDBH}^2 + 7.1358877$$

NoTrees = number of trees per accumulation

MDBH = mean DBH of trees per accumulation

$$R^2 = 0.57; \text{C.V.} = 16.50; n = 271$$

Feller-buncher cycle time while working in the natural stand was also dependent on the number of trees per accumulation ($p < 0.000$) and the square of the mean DBH per accumulation ($p = 0.0044$).

Natural:

$$\text{Total cycle time (min)} = 7.4534403 * \text{NoTrees} + 0.0706839 * \text{MDBH}^2 + 9.6879350$$

NoTrees = number of trees per accumulation

MDBH = mean DBH of trees per accumulation

$$R^2 = 0.79; \text{C.V.} = 16.37; n = 49$$

Table 8.4.3. Felling summary for both plantation and natural sites.

CLEARCUT FELLING (Tigercat 845D Feller-Buncher)			
Variable	N	mean	s
Plantation			
Total time (sec)	271	64.0	16.06
Trees/cycle	271	7.3	1.92
Tons/cycle ¹	271	1.7	0.43
Tons/PMH	271	99.2	27.59
Trees/min	271	6.9	1.20
Mean DBH/cycle (in)	271	6.7	0.83
Natural			
Total time (sec)	49	62.7	21.94
Trees/cycle	49	6.4	3.06
Tons/cycle ¹	49	1.9	0.71
Tons/PMH	49	118.7	62.88
Trees/min	49	6.0	1.85
Mean DBH/cycle (in)	49	7.7	3.62

¹Whole-tree green tons.

Skidder

Skidder productivity averaged 156 gt/PMH while operating in clearcut plantations with freshly cut green trees (Table 8.4.4). The skidder was not observed while operating in the natural stand. A unique feature of the Tigercat 630D grapple skidder included an operator's seat with the ability to rotate 360 degrees. Using joysticks coupled with the rotating seat made it possible for the skidder operator to travel from the landing to the woods facing rearward. This eliminated the need to stop and back-up to a bundle and enabled the skidder to travel continuously to a bundle, therefore eliminating positioning time and reducing cycle time.

To model skidder cycle time General Linear Models Procedure (SAS, 1988) was used. Empty travel and loaded travel distances were used as independent variables to model the dependent variables of empty travel and loaded travel times. Intermediate travel distance was used to model intermediate travel time. Position and grapple time was correlated with the number of bunches per cycle. Ungrapple times were constant and 95% confidence limits ($t=2$) were calculated for estimation purposes. Empty landing and loaded landing distances were used as independent variables for predicting landing travel times.

Data analysis showed there was a 4.7% difference between empty travel speed and empty landing speed. There was a 17.1% difference between loaded travel speed and loaded landing speed. Regression analysis for empty travel and loaded travel with landing travel not included did not significantly improve the model of these two elements as compared to models where landing travel was combined with empty and loaded travel. Therefore, the models below for predicting empty and loaded travel times represent total travel time where landing travel is combined into the models.

Regression analysis showed that total empty travel distance was the most significant independent variable for predicting empty travel time ($p < 0.0001$).

$$\begin{aligned}\text{Empty travel time (min)} &= 0.00149655 * \text{TEDist} + 0.25723468 \\ \text{TEDist} &= \text{empty travel distance (ft)} \\ R^2 &= 0.83; \text{C.V.} = 18.31; n = 193\end{aligned}$$

Independent variables tested to model position and grapple (PG) time included the number of bunches grappled, position of the skidder during empty travel (forward or grapple first), and type of wood skidded (green or dry). The number of bunches per cycle was the most significant variable ($p < 0.0001$), followed by position of the skidder during travel empty ($p = 0.0073$), and type of wood skidded ($p = 0.0320$). Skidding dry wood had a significant effect on position and grapple time. Due to its lighter weight, the operator spent more time trying to grapple more stems to make a payload. This is reflected in the data summary where position and grapple time averaged 0.40 min. while skidding green wood compared to 0.97 min. for dry wood, or a 142.5% increase. The number of stems per cycle averaged 25.4 for green wood compared to 41.9 for dry wood.

$$\begin{aligned}\text{PG time (min)} &= 0.76297625 * \text{NBunches} - 0.1538388 * \text{TEPos} - \text{TWood} * 0.15148068 - 0.40564928 \\ \text{NBunches} &= \text{number of bunches per cycle} \\ \text{TEPos} &= \text{empty travel position (0=forward; 1 = grapple first)} \\ \text{TWood} &= \text{type of wood (0=green; 1=dry)} \\ R^2 &= 0.55; \text{C.V.} = 66.15; n = 193\end{aligned}$$

Intermediate travel time was dependent on intermediate travel distance ($p < 0.0001$).

$$\begin{aligned}\text{Intermediate travel time (min)} &= 0.00237175 * \text{IntDist} + 0.12771499 \\ \text{IntDist} &= \text{intermediate travel distance (ft)} \\ R^2 &= 0.75; \text{C.V.} = 36.82; n = 49\end{aligned}$$

Regression analysis showed that total loaded travel distance was the most significant independent variable for predicting loaded travel time ($p < 0.0001$).

$$\begin{aligned}\text{Loaded travel time (min)} &= 0.00183151 * \text{TLDist} + 0.26785967 \\ \text{TLDist} &= \text{loaded travel distance (ft)} \\ R^2 &= 0.81; \text{C.V.} = 20.17; n = 193\end{aligned}$$

Ungrapple time averaged 0.195 min. Confidence interval limits at the 95% level ($t=2$) were calculated and ranged from 0.186 to 0.203 min. Therefore, the true value for ungrapple time has a 95% chance of residing within this confidence interval.

Table 8.4.4. Skidding summary for plantation and natural sites.

CLEARCUT SKIDDING (Tigercat 630D Grapple Skidder)			
Variable	n	mean	s
Plantation, Green			
Total time (min)	148	3.1	1.53
Trees/cycle	148	25.4	8.31
Tons/cycle ¹	148	7.0	2.35
Tons/PMH	148	155.8	76.43
Bunches/cycle	148	1.1	0.34
Mean DBH/cycle (in)	148	6.7	0.53
Total distance (ft)	148	1152	630.9
Plantation, Dry			
Total time (min)	45	4.1	1.39
Trees/cycle	45	41.9	10.85
Tons/cycle ¹	45	5.4	1.40
Tons/PMH	45	87.0	30.19
Bunches/cycle	45	1.6	0.49
Total distance (ft)	45	1311	488.0

¹Whole-tree green tons.

8.4a.4 Summary

Productivity of the Tigercat 845D feller-buncher averaged 99.2 gt/PMH while clearcutting plantation loblolly pine and 118.7 gt/PMH while clearcutting in a natural stand. The best independent variable for predicting felling cycle time was the number of trees accumulated per cycle.

The Tigercat 630D grapple skidder was very productive in clearcut operations and averaged 155.8 gt/PMH. Travel distance was the most significant independent variable for predicting travel times for each travel element. Position and grapple time was mostly correlated with the number of bunches grappled per cycle, position of the skidder during empty travel, and the type of wood being skidded. Ungrapple time was best estimated using 95% confidence limits which ranged from 0.186 to 0.203min.

8.4a.5 Outputs

Klepac, J. 2013. Performance of a tracked feller-buncher with a shear head operating in small-diameter pine. In: Proceedings of the 36th annual meeting of the Council on Forest Engineering. July 7-10, 2013. Missoula, Montana: University of Montana. 9p.

8.4b Comparison of New Feller Buncher and Skidder with Traditional Machines

8.4b.1 Objective

The focus of this study was to evaluate and compare the performance and cost of four harvesting systems while operating in a pine plantation. The four systems evaluated included: 1) a tracked feller-buncher with a conventional skidder (TFB/CS); 2) a rubber-tired feller-buncher with a large capacity skidder (RTFB/LS); 3) a tracked feller-buncher with a large capacity skidder (TFB/LS), and 4) a rubber-tired feller-buncher with a conventional skidder (RTFB/CS).

8.4b.2 Methods

Felling was accomplished using either a Tigercat 845D tracked swing-to-tree feller-buncher or a TimberKing 340 rubber-tired drive-to-tree feller-buncher. The Tigercat 845D utilized a shear head and was powered by a 260-hp Tier 4 engine with a boom reach of 26.5 feet and was approximately two years old. The TimberKing 340 was equipped with a 175-hp engine and a circular sawhead and was approximately seven years old.

Trees were skidded whole-tree using either a Tigercat 630D rubber-tired grapple skidder or a Caterpillar 525B rubber-tired grapple skidder. The Tigercat 630D was powered by a 260-hp engine and utilized a 25 ft² grapple. The machine was mounted on Firestone Forestry Special DH 35.5L-B32 tires and was approximately three years old. In addition to the large grapple on the Tigercat 630D, another unique feature included the ability for the operator to rotate the seat 180 degrees and drive facing rearward of the machine. This allowed the operator to drive directly to a bundle for grapple without having to turn, stop, and back-up to grapple. The Caterpillar 525B was powered by a Cat 3126 DITA 160-hp diesel engine and utilized a 12.5 ft² bunching capacity grapple. The machine was mounted on 30.5L x 32 Firestone tires.

At the landing, a Tigercat 240 tracked loader processed trees into longwood using a Chambers Delimbinator and loaded them onto trailers. Loads hauled from the site ranged from 8 to 10 per day.

Study site

The study site was a 14-year old loblolly pine plantation located in Crenshaw County, Alabama. The study area consisted of approximately 12 acres of a 52-acre tract. Soil type was an Arundel-Halso, which are gently sloping to moderately steep, moderately deep, well drained soils and deep, moderately well drained soils that have a loamy surface layer and a clayey subsoil (USDA Natural Resources Conservation Service. 2007. Soil Survey of Crenshaw County, Alabama).

A line-plot cruise over the 52-acre tract was used to determine stand density and volume per acre. A 12-acre contiguous area on the south side of the tract was divided into four units which measured approximately 3 acres each. This area was selected due to similar stand composition and tree size as revealed from cruise data. The web tool ArcGIS Explorer Online (<http://www.arcgis.com/explorer>) was used to locate waypoints and create boundaries for the four units. These waypoints were entered into a Garmin GPSmap 62s handheld device and located on the ground. Unit boundaries were identified using flagging. Treatments were randomly assigned to each unit without replication (Figure 8.4.1).

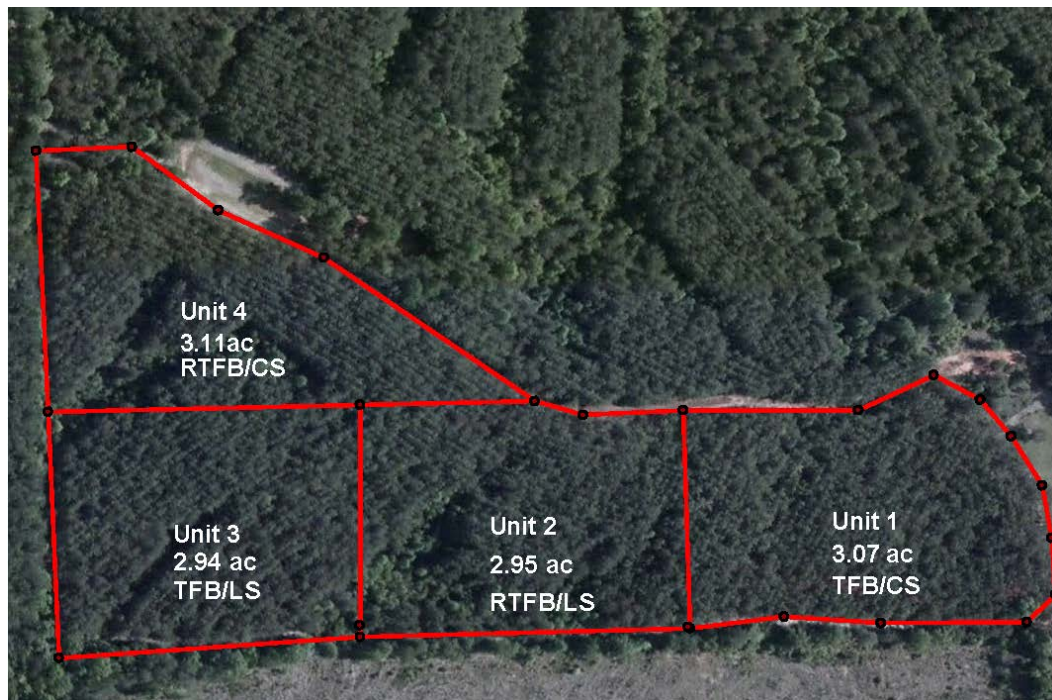


Figure 8.4.1 Treatment assignments for the paired feller buncher and skidder study.

Felling

Within each unit, a plot was installed and all trees within the plot were color coded with paint based on 1-inch DBH classes so that trees could be identified by size as they were being cut. Only trees 3.6 inches DBH (Diameter at Breast Height) and larger were marked. Feller-bunchers were recorded on digital video as they worked within each plot and the color code of each tree was recorded.

Each feller-buncher had its own experienced operator throughout the study. Operators worked within each marked plot and placed trees in bunches for skidding. Bundle size was determined by the skidder being used for a particular unit, so operators built large bunches for the large capacity skidder and smaller bunches for the conventional skidder. Each bundle containing trees from within the felling plot was numbered so the size of each tree within a bundle would be known for calculating green tons per bundle. For bunches that contained trees from within the unit but were outside the felling plot, a stem count was made and bunches numbered consecutively. Tree weights were calculated using a regression equation developed using trees from the study site and other nearby counties. Sampled trees were felled, measured for DBH, height to a 2-inch top, total height, and whole-tree weight. For trees in the 11-inch class and larger, weights were calculated using an equation for planted pine in the Southeast (Clark and Saucier, 1990) because these stems were beyond the parameters of the regression equation.

Video of the feller-bunchers was reviewed and analyzed using the time study analysis software program TimerPro. Elements for the Tigercat 845D feller-buncher included move-to-first tree, reach-to-first-tree, accumulate, move between trees, move-to-dump, and dump. For the TimberKing 340 elements included move-to-first-tree, accumulate, move-to-dump, and dump.

Move-to-first tree included travel time from the point where trees were dumped from the head to the first tree to be cut in a cycle. The element started at the end of dumping and ended when the sawhead made contact with the tree or the machine stopped moving.

Reach-to-first tree was the time required to extend the boom and make contact with the first tree to be cut in a cycle. The element began either at the end of dumping where the feller-buncher extended the boom to the first tree without having to move or at the end of move-to-first tree. It ended when the sawhead made contact with the tree.

Accumulate was the time required to cut and gather trees into the head. For the Tigercat 845D this included reaching to and cutting trees. The element started when the shear made contact with the tree and ended when the boom began movement to cut the next tree. For the TimberKing 340 accumulate time included traveling to and cutting trees. The element started when the sawhead made contact with a tree, and ended when the tires began to move.

Move between trees was associated with the Tigercat 845D and included time required to travel during a cycle to reach additional trees to cut. The element began after a tree was cut during accumulating and the tracks started moving and ended when the tracks stopped.

Move-to-dump was the time required to travel to the location where trees were being placed to create a bundle. The element began when the last tree in a cycle was cut and the tracks or tires started moving and ended when the tracks or tires stopped.

Dump was the time required to release trees accumulated in the head onto the ground or bundle being built. For the Tigercat 845D the element began when the last tree was cut and rotation of the cab toward the dumping location began and ended when all trees were out of the head. For the TimberKing 340 the element began with forward rotation of the head and ended when all trees were out of the head.

Skidding

An elemental time and motion study was performed on each skidder using stopwatches as they harvested each study unit. Machine elements evaluated included landing empty, travel empty, position, grapple, intermediate travel, travel loaded, landing loaded and ungrapple. Total weight of bunches built from trees cut from felling plots was determined using felling data. Bunches created from unmarked trees within a unit but outside the felling plot were estimated using a stem count and an average tree weight of 520 lb. The landing empty element included travel across the landing to a common point at the landing boundary after ungrappling a load. The element started at the end of ungrappling and ended when the skidder reached the intersection of the landing boundary and the primary skid trail.

Travel empty included travel to the woods to obtain a load and included all travel after landing empty to the point in the woods where the skidder made its initial stop. The element began at the end of landing empty and ended when the skidder stopped to prepare for positioning.

Position time included travel while the skidder backed up to grapple a bundle. The element began at the end of travel empty and ended when the skidder stopped at a bundle to prepare for grapping. Occasionally, this element did not occur with the Tigercat 630D, since it sometimes traveled to the woods grapple first and stopped at a bundle without positioning.

Grapple time included lowering the grapple, closing the grapple around a bundle, and lifting the grappled bundle in preparation for travel to another bundle location or to the landing. The element began at the end of positioning, or in some cases with the Tigercat 630D, at the end of travel empty, and ended when the load was secured in the grapple and forward travel began.

Intermediate travel included travel between bunches when the skidder picked up more than one bundle for a load. The element began at the end of the grapple element and ended when the skidder stopped to prepare to grapple an additional bundle.

Travel loaded included travel from the woods once the skidder obtained a full load to the landing boundary. The element began at the end of the grapple element once a full load was obtained and ended at the intersection of the primary skid trail and the landing boundary.

Landing loaded included travel from the landing boundary across the landing to the point where the load was dropped near the loader. The element began at the end of travel loaded and ended when the skidder stopped to prepare to ungrapple.

Ungrapple included the time required to drop the load on the landing near the loader. The element started at the end of landing loaded and ended when the load was dropped and the skidder began landing empty travel.

A Garmin GPSmap 62s was mounted in each skidder during the time study period to obtain skid distances. Distances obtained included landing empty travel, travel empty, intermediate travel, travel loaded and landing loaded.

8.4b.3 Results

Felling

The tracked (Tigercat 845D) feller-buncher cut 575 trees, which resulted in a total of 72 observations while building bunches for the conventional (CAT 525B) skidder (TFB/CS system). The number of trees per accumulation averaged 7.5 with a maximum of 11 trees. The number of accumulations per bundle averaged 2.4 with a maximum of 4 accumulations. The conventional (TimberKing 340) feller-buncher cut 385 trees which resulted in a total of 85 observations while building bunches for the large skidder (RTFB/LS system). The number of trees per accumulation averaged 4.5 with a maximum of 9 trees. The number of accumulations per bundle averaged 5.9 with a maximum of 7 accumulations. While building large bunches for the large capacity skidder (TFB/LS system) the tracked feller-buncher cut 387 trees for a total of 52 observations. The number of trees per accumulation averaged 7.2 with a maximum of 12 trees. The number of accumulations per bundle averaged 3.1 with a maximum of 4 accumulations. A total of 343 trees were cut by the conventional feller-buncher while building bunches for the conventional skidder (RTFB/CS) for a total of 101 observations. The number of trees per accumulation averaged 3.4 with a maximum of 7 trees. The number of accumulations per bundle averaged 4.4 with a maximum of 7 accumulations. Percent of total cycle time for each feller buncher time study element for the four study areas is displayed in Figures 8.4.2 through 8.4.5.

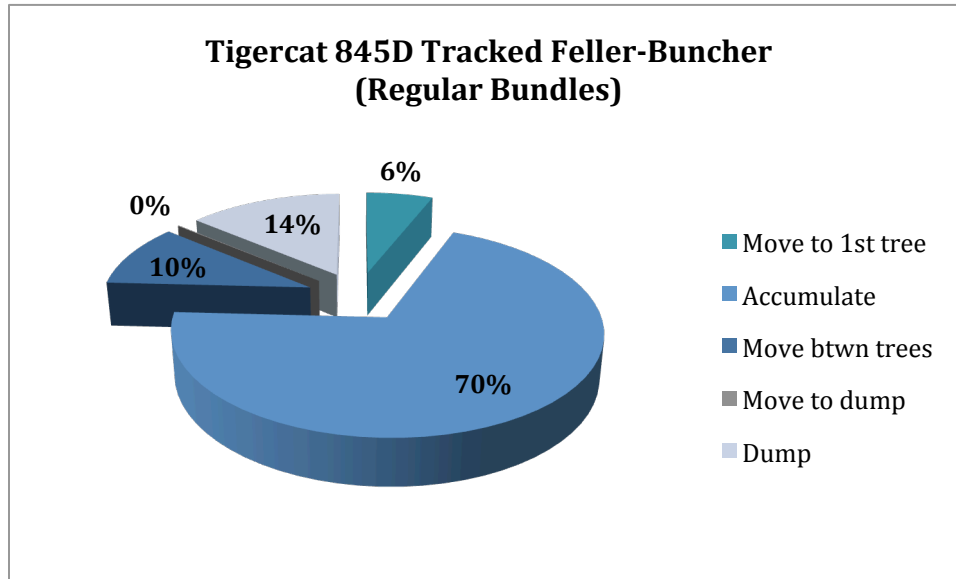


Figure 8.4.2 Percent of total cycle time for the tracked feller-buncher building regular size bundles.

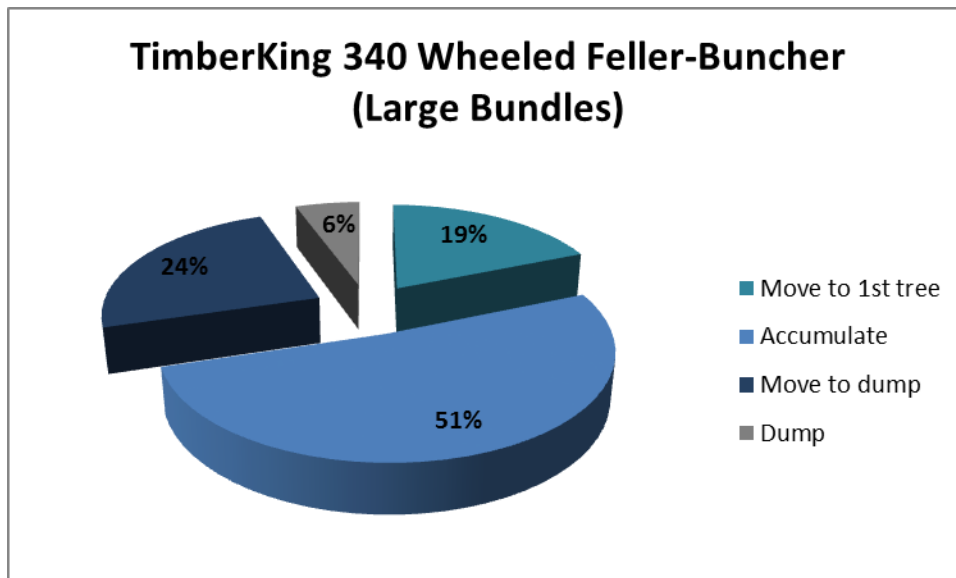


Figure 8.4.3. Percent of total cycle time for the conventional feller-buncher building large size bundles.

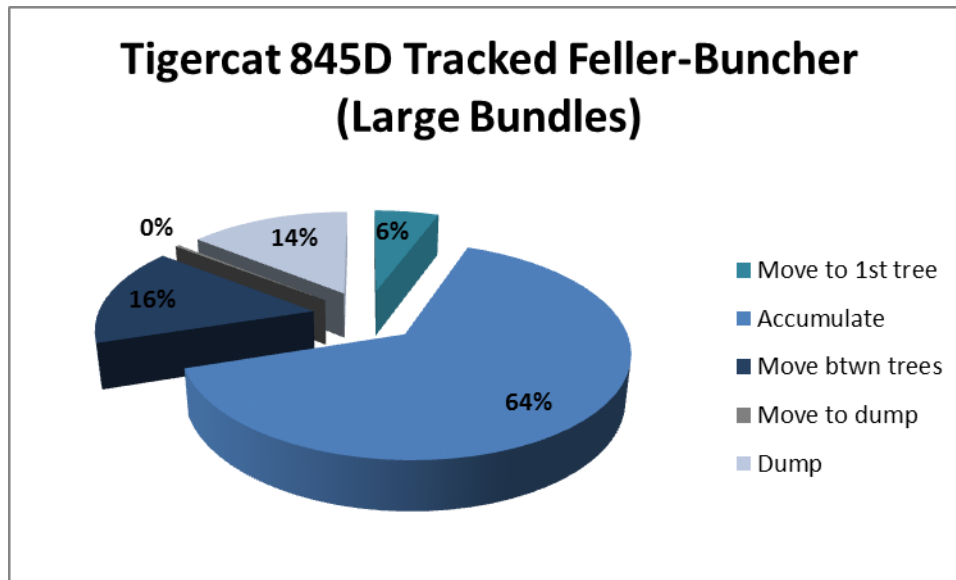


Figure 8.4.4. Percent of total cycle time for the tracked feller buncher building large size bundles.

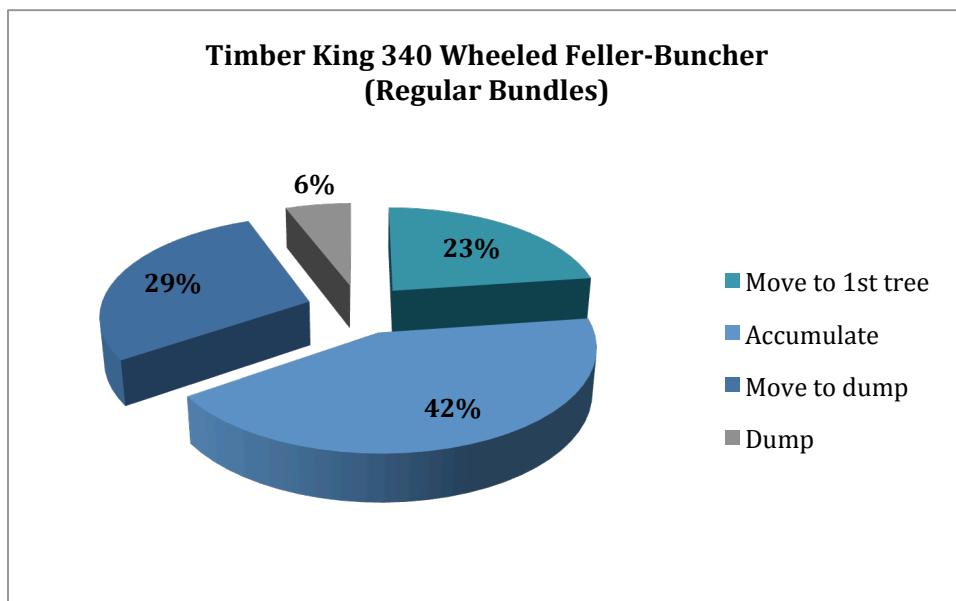


Figure 8.4.5. Percent of total cycle time for the conventional feller-buncher building regular size bundles.

Skidding

Production rates for the skidders are based on a standardized cycle time to account for unequal distances of each study area from the landing. A standardized one-way distance of 677 feet was used in the comparison analysis.

The conventional grapple skidder averaged 72 gt/PMH while skidding bunches built by the tracked feller-buncher. The number of bunches skidded per cycle averaged 1.1 with a maximum of two bunches. The number of stems per cycle averaged 19.6 with a maximum of 32 stems. The large capacity grapple skidder averaged 143 gt/PMH while skidding bunches built by the conventional feller-buncher. The number of bunches skidded per cycle averaged 1.1 with a maximum of two bunches. The number of stems per cycle averaged 25.2 with a maximum of 43 stems. The large capacity grapple skidder averaged 129 gt/PMH while skidding bunches built by the tracked feller-buncher. The number of bunches skidded per cycle averaged 1.2 with a maximum of two bunches. The number of stems per cycle averaged 27.2 with a maximum of 42 stems. While skidding bunches built by the conventional feller-buncher, the conventional grapple skidder averaged 48 gt/PMH. The number of bunches skidded per cycle averaged 1.1 with a maximum of two bunches. The number of stems per cycle averaged 19.6 with a maximum of 21 stems. Percent of total cycle time for each time study element for the four study areas is displayed in Figures 8.4.6 through 8.4.9.

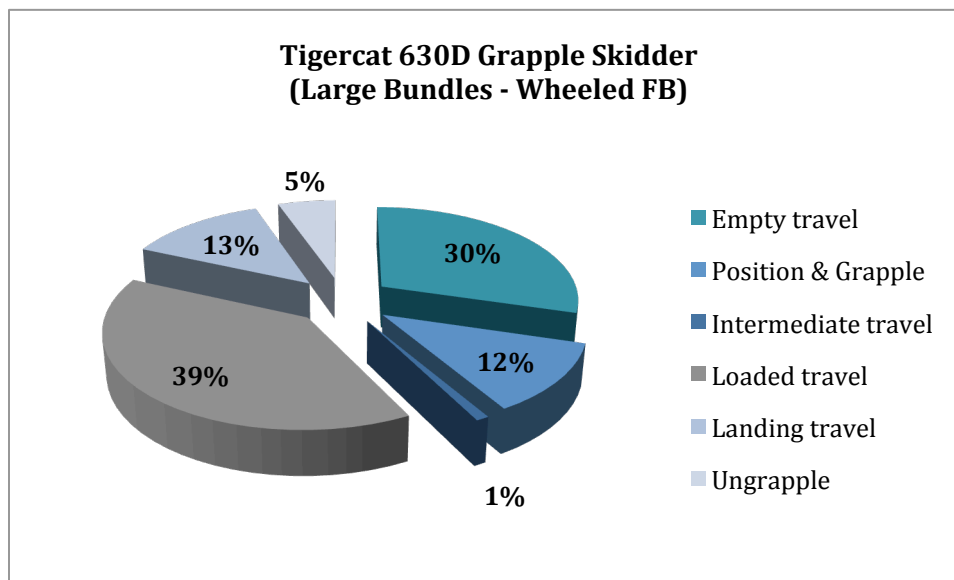


Figure 8.4.6. Percent of total cycle time for the conventional skidder skidding bundles built by the tracked feller-buncher.

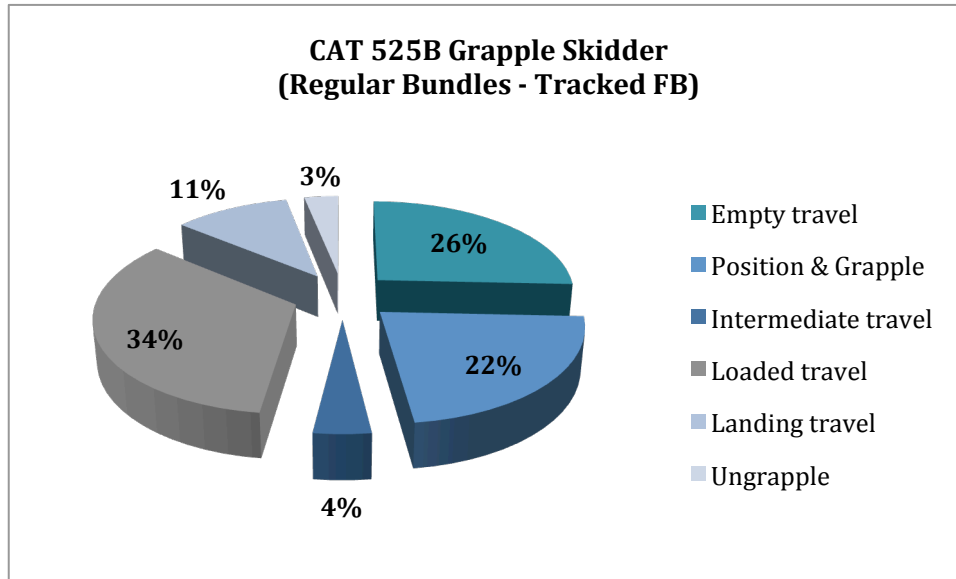


Figure 8.4.7. Percent of total cycle time for the large capacity skidder skidding bundles built by the conventional feller-buncher.

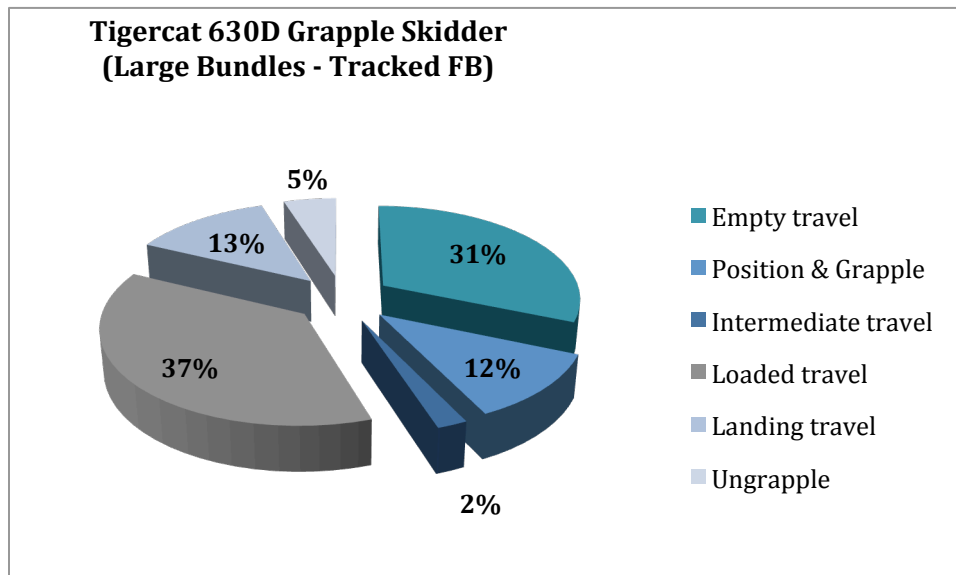


Figure 8.4.8. Percent of total cycle time for the large capacity skidder skidding bundles built by the tracked feller-buncher.

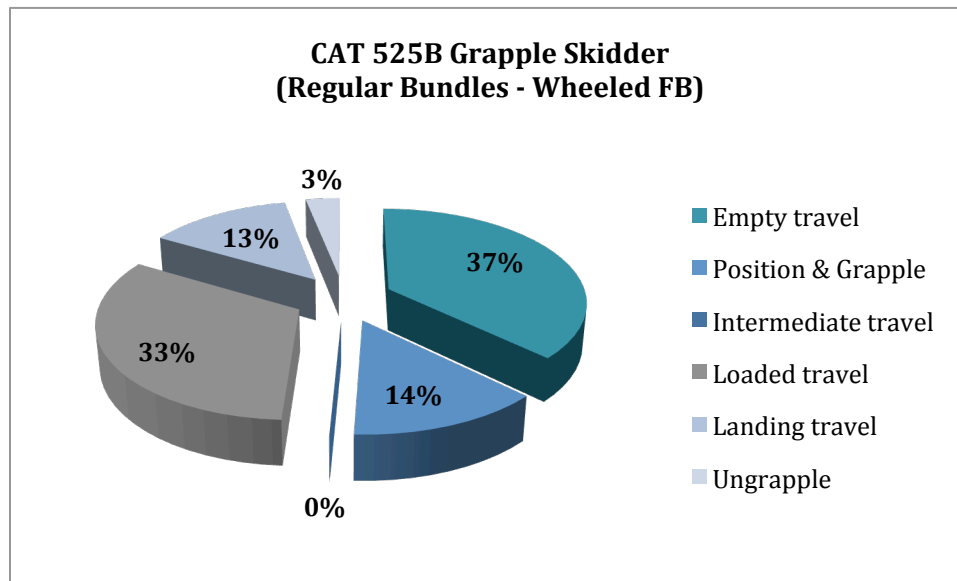


Figure 8.4.9. Percent of total cycle time for the conventional skidder skidding bundles built by the conventional feller-buncher.

A machine rate analysis was performed for each machine studied. Productive hours were observed during the field study, and a utilization rate of 85% was applied to both machine types to calculate scheduled machine hours (SMH). A fuel cost of \$3.50 per gallon for off-road diesel fuel was used. System costs for each of the four systems was then developed (Table 8.4.1). When inequities in production warranted, additional machines were added to balance the systems. The goal in balancing systems was to maximize system production, not individual machine production.

System production rates and costs are summarized in Table 8.4.1. Production rates in gt/SMH for the Tigercat 845D tracked feller buncher paired with the conventional Cat 525 skidder (TFB/CS) were fairly well balanced (83.1 and 61.5 gt/SMH, respectively), which resulted in one machine of each type being required in that system. This system configuration resulted in a cost of \$3.10/gt to the landing for the system. Production rates for the rubber-tired feller buncher paired with the large (Tigercat 630D) skidder (RTFB/LS) were unbalanced since the large-capacity skidder could haul more (121.3 gt/SMH) than one rubber-tired feller buncher could produce (75.9 gt/SMH). To balance the system, a second feller buncher was added and resulted in a cost to the landing of \$2.31/gt. Production rates for the Tigercat 845D tracked feller buncher paired with the Tigercat 630D large-capacity skidder (TFB/LS) were the most closely balanced (97.1 and 109.9 gt/SMH, respectively), which resulted in one machine of each type being used for the system. This TFBLS system had a unit cost to the landing of \$2.31/gt. The rubber-tired feller buncher paired with the conventional skidder (RTFB/CS) had unbalanced production rates (67.7 and 40.7 gt/SMH, respectively) and was limited by the skidder productivity. To balance that system, two skidders were required to match the productivity of the feller buncher, which increased skidding productivity to 81.4 gt/SMH. This resulted in the RTFB/CS system being the most expensive at \$3.72/gt.

Table 8.4.1. Balanced harvesting system productivities and costs.

System	Machine	No. of Machines	All (gt/SMH)	System		
				(gt/SMH)	(\$/SMH)	(\$/gt)
TFB/CS	Tigercat 845D	1	83.13	61.54	190.73	3.10
	Cat 525B	1	61.54			
RTFB/LS	TimberKing 340	2	151.81	121.30	280.64	2.31
	Tigercat 630D	1	121.30			
TFB/LS	Tigercat 845D	1	97.07	97.07	223.92	2.31
	Tigercat 630D	1	109.91			
RTFB/CS	TimberKing 340	1	67.75	67.75	252.12	3.72
	Cat 525B	2	81.43			

8.4b.4 Summary

Four machines were paired into four systems to evaluate the resulting differences. The feller-bunchers operated differently based on the skidder pairing. Feller-buncher production rates were higher when building larger bunches. When the feller-bunchers were paired with the conventional skidder, smaller bunches were built and production rates were lower. The Tigercat 845D accumulated approximately 7.35 stems per accumulation and the accumulation size was not significantly affected by skidder pairing. The TimberKing operator accumulated 45% more stems per accumulation when building bunches for the large capacity skidder as compared to building bunches for the conventional skidder. The felling plots were designed to have a similar size distribution, so this difference in trees per accumulation may be an operator effect rather than a pairing effect.

Balanced systems that used the large capacity skidder had the lowest overall system costs. These lowest cost systems also had the highest production rates (gt/SMH). The conventional system (RTFB/CS) required two skidders to balance the system and had the highest cost, \$3.72/gt. The high tonnage system (TFB/LS) and the RTFB/LS had the lowest costs per ton, \$2.31/gt.

8.4b.5 References

USDA Natural Resources Conservation Service. 2007. Soil Survey of Crenshaw County, Alabama.

8.4c Discussion of New Feller Buncher and Skidder Commercialization Pathway

Both the 845D feller buncher and the 630D skidder performed exceptionally well during the testing and demonstration phase. Both machines met or exceeded the productivity goals set out during the design phase and performed well as discussed in the previous sections.

Both machines experienced routine downtime and maintenance items that are to be expected on any new machine. The feller buncher did not experience any major mechanical issues; however, there were challenges with the implementation of the new emissions systems. After a few months of operation, the machine experienced a period of frequent exhaust system “regeneration” cycles (this is where the diesel particulate filter is heated to burn off particulates that have accumulated in the filter). During the regeneration cycle, the machine operator would have to move the machine to an area (like a road) where there were no woody debris that could catch fire. Consequently, this activity affected productivity on a short term basis. This problem was resolved by engineers with Tigercat and the machine functioned well throughout the remainder of the study. The machine also experienced a fire from pine straw that had dropped into the area at the base of the boom. After cleaning up the fire suppression chemicals and replacing some burned wiring, the machine went back into service and did not experience any further problems like this.

The skidder experienced one mechanical breakdown in the failure of the differential in the rear axle. This was a rather unusual mechanical failure, but one that was repaired without major delays and the machine functioned well otherwise. As is frequently the case with skidders, the seat in the skidder needed some repair during the study. This is a common occurrence in wheeled skidders due to the rough terrain on which they operate and the resulting heavy forces on the seat. Also, as one would expect, the tires were replaced on the skidder after approximately 4000 hours of operation.

At the start of the study, the 630D skidder was commercially available in Tigercat’s line of equipment. This machine is still available and marketed heavily by Tigercat. The larger capacity grapple is available for order on the skidder.

The 845D track feller buncher was developed as a new prototype just for this research and demonstration project. However, an 845D production model is now available for purchase and is being marketed by Tigercat. This production version of the 845D is shown in Figure 8.4.15. The product literature for the new 845D is included in Appendix A. The production version of the 845D includes several upgrades over the prototype version tested in this project. The primary difference is a change in engines from the Cummins QSB 6.7 to a Tigercat FPT NEF 6.7 US EPA Tier 4 Final 272 hp. This new engine has higher horsepower and its emission system uses a diesel exhaust fluid (DEF) injection system. With the new engine, there was a need to revise wiring and software to support the final Tier 4 requirements. The engine enclosure was modified to provide improved service access. The fuel tank was modified to accommodate an additional DEF tank and the main frame turntable of the machine was upgraded.

As currently marketed, the production 845D is configured for operation of a disk saw felling head. With this change, the energy recovery swing system is not offered on the production model 845D at this time. However, the other energy saving feature of the ER Boom is included in the production 845D. The DT1802 shear felling head is not currently in production, but it is available as the market develops for high tonnage harvests of small diameter material.



Figure 8.4.15 Production version of the 845D track feller buncher.

8.5 Chipping and Debarking Machines

8.5.1 Background

In-woods chipping of trees has been a component of forest harvesting for decades (Stokes et al 1987). These chipping operations produced either clean chips for the pulp and paper industry or whole tree (dirty) chips for energy production. Emerging biomass markets have increased the interest in producing a microchip in the woods. Wood pellet manufacturers as well as woody biomass ethanol and biodiesel startups have expressed interest in in-woods produced microchips.

A microchip has been defined as a chip between 1/4 and 3/8 inches in length (Steiner and Robinson 2011). A traditional pulp and paper chip is generally 1 ¼ inches in length. Microchips potentially offer several advantages to traditional pulp chips. Steiner and Robinson (2011) list multiple advantages. These include; lower overall total system energy requirements, faster processing times, smaller equipment sizes and fewer processing steps. Whitelaw (2009) also suggests that microchipping can eliminate front end grinding in the pellet process and reduce the horsepower requirement for regrounding after the drying process.

Hein (2011), quotes several industry sources, that also contend that microchips may reduce the required mill chipping and grinding capacity and offer better material characteristics. These include less variability in moisture content, faster drying and easier chemical conversions.

Microchips can be produced with either drum chippers or disk chippers (Hein 2011), Steiner and Robinson (2011) and Whitelaw (2009). Drum chippers are more commonly used to produce microchips due to their screening capabilities. Examples of chipper characteristics that may be modified to change chip characteristics include spout angle, knife angle, knife length, number of knives and disc/drum speed (Smith and Javid 1997) Watson and Stevenson (2007).

8.5.2 Objective

The objective of this subtask was to quantify the performance and cost of a microchipping operation in southern pine energy plantations.

8.5.3 Methods

A Precision Husky WTC-2675² disc chipper was modified in an effort to produce microchips in the field. The chipper was equipped with an 8 knife disc rather than the traditional 3 or 4 knife disc. Over the course of the trial, knife length, knife and counter knife angle, as well as number of chip breakers and paddles were modified in an effort to produce microchips. This paper documents just two of the microchipper trials. For chip comparison, conventional chips were produced with this same chipper and disc, but with only 4 knives installed.

The desired specification was for 90% of chips produced to pass a ½ inch round-hole screen. This specification was established based on conversations with various biomass end users located in the southeastern United States.

² The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

Due to a low demand for in-woods pulp chips and whole tree chips during the time of the study, the number of loads produced was small. Each load produced was timed with a stopwatch and mill load tickets were used to determine tons produced. Fuel consumption was recorded on a sample of loads. Fuel use was measured by topping the tank before and after individual loads and from the chipper's on-board computer.

Chip samples were taken from the spout of the chipper multiple times (minimum of 11) during each load to produce a sample representative of a whole van load of chips. Chip analysis included particle size analysis, moisture content and bulk density measurements. Particle size was measured by passing the samples through a stack of round-hole sieves.

8.5.4 Results

Seventeen loads were sampled. Table 8.5.1 shows the results of producing whole tree conventional chips and two trials of whole tree microchips. The average number of stems per load and average tons per load were similar for conventional chips compared to the first trial of microchips, but the conventional chips averaged approximately 10 gt/PMH more than the microchipping. For the second trial of microchipping, the number of stems per load was less and the tons per load was higher, but the microchip production (8.79 gt/PMH) remained lower than the conventional chips. These two trials showed that microchipping production was 12.8% and 11.1% less on average than producing conventional chips with the same chipper.

Table 8.5.1 Productivity data for a disc chipper producing whole tree conventional and microchips.

Conventional Chips				
	Time (min)	# Stems	Tons	Tons/PMH
Min	16.59	278	21.05	76.14
Max	18.47	350	24.86	82.89
Avg.	17.59	320	23.33	79.52
Count	4			
Micro Chips 1				
Min	15.21	177	19.25	54.77
Max	24.92	425	25.03	84.16
Avg.	19.73	312	22.41	69.37
Count	8			
Micro Chips 2				
Min	20.65	76	26.68	58.91
Max	27.20	143	29.18	84.78
Avg.	23.96	121	27.81	70.73
Count	5			

Fuel consumption was not measured on every load. Table 8.5.2 shows the results for the fuel consumption as measured for the whole tree conventional chipping and the whole tree microchipping. Not enough data was collected to look for statistically significant differences in the results. The data indicates that the fuel

consumption for microchipping was higher than that of conventional chipping with the same chipper. A difference of 0.62 gt/gal represents a 14.8% increase in fuel consumption to produce microchips.

Table 8.5.2 Fuel consumption for a disc chipper producing whole tree conventional and microchips.

	Conventional Chips	Micro Chips
Gallons	26	39
Tons	108.82	139.07
Gal/ton	0.24	0.28
gt/gal	4.19	3.57
Gal/hr.	18.76	19.53

In terms of chip particle size, the chipper did not meet the goal of 90% passing a ½ inch round-hole screen (actual screen size was 13 mm, which equates to 0.51 inches). Table 8.5.3 shows the results of the chip analysis. On average, 74% of the microchips produced passed the ½ inch screen. This compares to 47% of conventional chips passing the ½ inch screen, resulting in a difference of 36.7%. The average moisture content difference between the two chip sizes was 3%.

Table 8.5.3 Chip characteristics of whole tree conventional and microchips produced with a disc chipper.

	Conventional Chips	
	MC	% Passing
	(WB)	(13 mm rd.)
Min	0.44	38.4
Max	0.54	55.8
Avg.	0.47	47.1
Count	5	4
	Microchips	
Min	0.46	68.1
Max	0.56	82.1
Avg.	0.50	74.4
Count	8	7

The machine rate method was used to calculate the owning and operating cost for the chipper (Brinker, et al, 2004). The calculations assumed an off-road diesel cost of \$3.50/gallon, 2000 scheduled hours per year and a utilization rate of 50%. The purchase price of the Precision Husky WTC 2675 disc chipper was \$490,000. Using the chipping production rates measured during the study, a ton of conventional chips made from whole trees would cost \$3.08/ ton to produce at road side. The cost of producing microchips was \$3.82/ton. A difference of \$0.74/ton was observed. This represents the cost associated only with the chipper.

8.5.5 Summary

Results indicate that the disc chipper can produce microchips, but currently cannot meet the narrow specification of 90% passing a ½ inch round-hole screen. On average 74% of the chips produced did meet the required size. Future adjustments to the chipper have the potential to further increase the percent of

acceptable microchips produced. The study also indicated that producing microchips with the disc chipper reduced the chipping production rate by 10 gt/PMH an approximately 12% reduction in productivity. This reduction in productivity was also accompanied by an approximately 15% increase in fuel consumption.

The study results show the cost, in lost production and increased fuel consumption, of producing microchips in the field with a disc chipper. These costs may be feasible based on some of the potential advantages of processing cost savings that may be realized by the end-user after delivery of microchips.

8.5.6 Output

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8.5.7 References

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Stokes, B.J., W.F. Watson, and D.L. Sirois. 1987. Factors affecting power requirements for chipping whole trees. In Proc. of conf. *American Society of Agricultural Engineers Summer Meeting*, Baltimore, Maryland, June 28-July 1, 1987.

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8.6 Truck Transport Operations

8.6.1 Objective

The objective of this subtask was to evaluate the cost and productivity of the processing and transportation operations for transpirationally dried wood chips.

8.6.2 Methods

A 30-acre stand of loblolly pine plantation in southeast Alabama was felled and bunched. The trees were left to dry in place for approximately six weeks. The trees were then skidded and chipped on site with a mobile disk chipper. The chips were blown into the trailers. An additional 7 acres of green trees from the stand were felled, skidded and processed following the chipping of the transpirationally dried trees.

In anticipation of transporting drier (lighter) chips, larger capacity chip trailers were added to the trucking fleet. The larger trailers were 123 yd³ (large), while the existing trailers were 100 yd³ (regular) and 88 yd³ (small). The goal of using the larger trailers was to maintain as close to a legal payload as possible with the drier chips.

Drier chips potentially have a higher value to end users due to the higher net energy content (BTU) gained by removing moisture. Moisture content was calculated for green and dried trees during the study. It was found that green trees had an average moisture content of 54% and the dried trees had an average moisture content of 39%, resulting in an average weight loss was 15%. The load tickets for the tract were used to analyze load data.

8.6.3 Results

Overall, transpirational drying has the potential to reduce transportation costs for forest biomass. Table 8.6.1 shows an analysis of trucking costs at various moisture contents and haul distances. This analysis is based on an example contract trucking rate of \$0.14 per net ton per one-way mile (assuming that the truck is fully loaded with a 28.5 net ton load). This is equivalent to a contract trucking rate of \$3.99 per one-way mile for a fully loaded truck. Industry practice for contract trucking in Alabama is to charge that rate of \$3.99 per one-way mile regardless of how heavily the truck is loaded. Table 8.6.4 shows that trucking costs for woody biomass at 56% MC will be \$15.91 per dry ton for a 50 mile haul distance. If the wood is transpirationally dried to a moisture content of 30%, the trucking cost can be reduced to \$10.00 per dry ton (assuming a full 28.5 net ton payload), resulting in a savings of \$5.91 per ton compared to green material. This table also shows that when the haul distance is increased, the savings from transpirational drying also increase. For example, for a 100-mile haul distance, the savings in trucking cost is \$11.82 per dry ton when the wood is dried to 30% MC. These results show that it may be possible to increase the procurement radius for a given biofuel operation by using transpirational drying to reduce trucking costs at those long haul distances. Figure 8.6.1 shows those same trucking costs over a range of moisture contents for various haul distances. Figure 8.6.2 shows the net savings in trucking costs by drying the biomass from 56% to different levels, by one-way haul distance.

Table 8.6.1 Illustration of biomass trucking costs at various biomass moisture contents and one-way haul distances. Costs are based on contract trucking rates of \$0.14 per net ton per mile, or \$3.99 per one-way mile (assuming 28.5 net tons per load).

			One-way Haul Distance					
			25 miles	50 miles	75 miles	100 miles	125 miles	150 miles
Moisture Content	Net Tons Per Load	Dry Tons Per Load	Cost Per Dry Ton					
56%	28.5	12.5	\$7.95	\$15.91	\$23.86	\$31.82	\$39.77	\$47.73
50%	28.5	14.3	\$7.00	\$14.00	\$21.00	\$28.00	\$35.00	\$42.00
45%	28.5	15.7	\$6.36	\$12.73	\$19.09	\$25.45	\$31.82	\$38.18
40%	28.5	17.1	\$5.83	\$11.67	\$17.50	\$23.33	\$29.17	\$35.00
35%	28.5	18.5	\$5.38	\$10.77	\$16.15	\$21.54	\$26.92	\$32.31
30%	28.5	20.0	\$5.00	\$10.00	\$15.00	\$20.00	\$25.00	\$30.00
25%	28.5	21.4	\$4.67	\$9.33	\$14.00	\$18.67	\$23.33	\$28.00

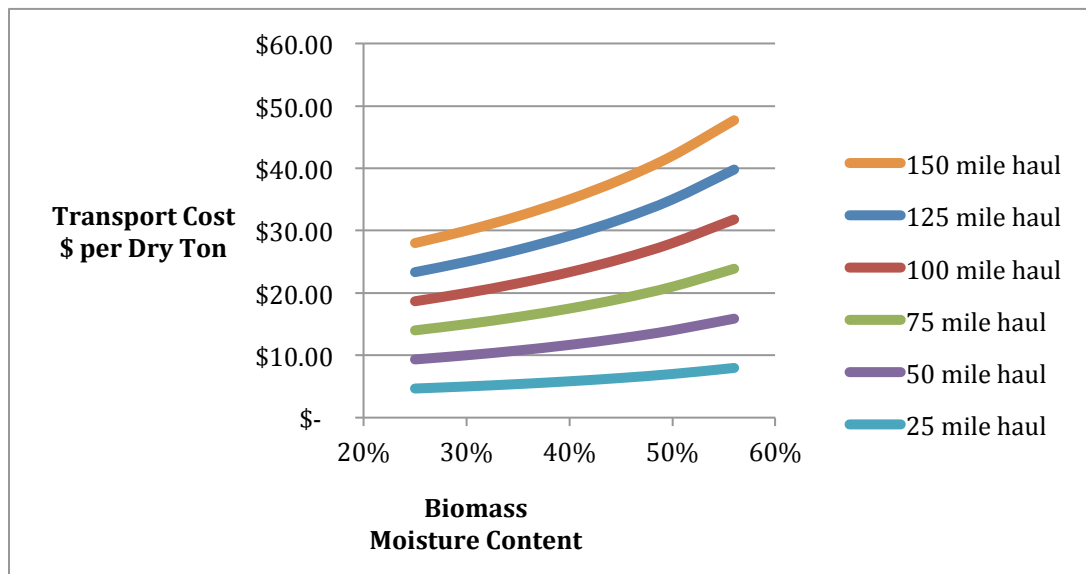


Figure 8.6.1 Trucking cost by moisture content and one-way haul distance. Costs are based on contract trucking rates of \$0.14 per net ton per mile, or \$3.99 per one-way mile (assuming 28.5 net tons per load).

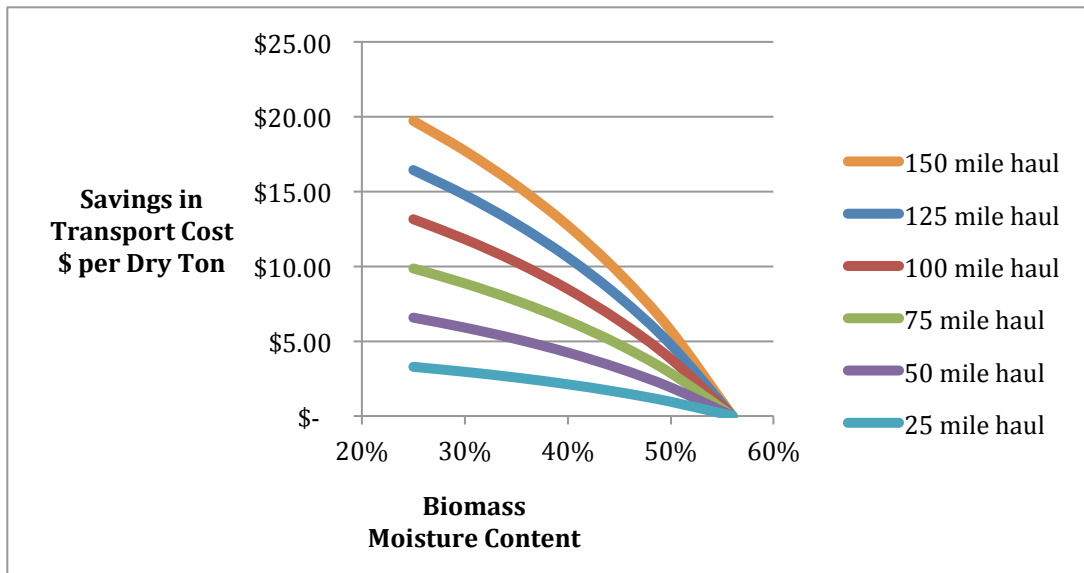


Figure 8.6.2 Savings in trucking costs due to transpirational drying by moisture content and one-way haul distance. Costs are based on contract trucking rates of \$0.14 per net ton per mile, or \$3.99 per one-way mile (assuming 28.5 net tons per load).

In the field experimental work, a total of 1393 “dry” tons (dt) in 61 truck loads were processed from the transpirationally dried trees. Table 8.6.2 shows the results of the load analysis. The large trailers were used to transport 934 dt on 39 loads. The regular and small trailers were used to transport 344 dt (16 loads) and 115 dt (6 loads), respectively. The large trailers averaged a net payload of 23.96 tons, while the regular and small trailers averaged 21.51 dt and 19.24 dt, respectively. The maximum legal load, using a tare weight of 15.5 tons, was calculated at 28.5 tons. With an average of 23.96 dt/load the large trailers were 16% below the legal payload and the regular and small trailers were 24.5% and 32.5% below the legal limit, respectively. These results show that there are additional opportunities to reduce transportation cost due to lost payload capacity.

Table 8.6.2 Truck load data for transpirationally dried wood chips.

	Large-Dry	Regular-Dry	Small-Dry
Capacity (yd ³)	123	100	88
# Loads	39	16	6
Avg. Wt. (tons)	23.96	21.51	19.24
Min Wt. (tons)	20.67	20.11	17.72
Max Wt. (tons)	29.03	22.83	20.78
Avg. Tare Wt. (tons)	15.38	15.24	15.01
Avg. Density (lbs/ft ³)	14.42	16.00	16.23

A bulk density for each load was calculated by dividing the net weight of the load by the volume of the trailer. The void formed at the back of the trailer from the chips sloping down to the trailer gate was subtracted from the trailer volume. Otherwise, it was assumed the trailer was completely full. The calculated load density for the large trailer was the lowest of the three at 14.42 lbs/ft³, which is 10% less than the density of the regular trailer. The regular trailer and small trailers averaged 16 and 16.23 lbs/ft³, respectively. A paired t-test procedure was used to test for significant differences between the calculated

load densities. It was found that the large load density was significantly ($<.0001$) different than the regular load density. The t-test also indicated that there was no significant difference ($<.0001$) between the densities of the regular and small trailer densities. These results indicate that a physical characteristic of the large trailer, chips, loading method or a combination of these is affecting load density. Possible reasons are that the large trailer is too long and the chips are too light and cannot be blown far enough. To achieve the legal payload with the large trailer would have required a load density of 17 lbs/ft³. This exceeds the density achieved with the smaller two trailers and suggests that it is not feasible as the system is configured now. A net load of 26.6 dt could be realized if the load density of the large trailer could be increased to that of the regular trailer (16 lbs/ft³). At a density of 14.42 lbs/ft³ a trailer with a capacity of 146 yd³ would be required to reach maximum payload.

The green chips transported from the tract were also analyzed (Table 8.6.3). On-board scales were not installed on any of the truck/trailer combinations used on the study. The large trailers were not filled to capacity in order to avoid surpassing the legal limit (44 tons gross). Therefore, these data are presented but are not included in the overall analysis of the results. The data from the regular and small trailers represent fully loaded trailers.

Table 8.6.3 Truck load data for green wood chips.

	Large-Green	Regular-Green	Small-Green
Capacity (yd ³)	123	100	88
# Loads	7	7	3
Avg. Wt. (tons)	24.94	25.81	25.20
Min Wt. (tons)	21.6	23.1	24.13
Max Wt. (tons)	28.46	28.47	26.3
Avg. Tare Wt. (tons)	15.49	15.16	14.13
Avg. Density (lbs/ft ³)	15.00	19.20	21.26

A total of 429 gt were produced from the green trees during the study. The regular trailers were used to transport 180 gt on 7 loads and the small trailers transported 75 gt on 3 loads. The resulting average load density was 19.2 lbs/ft³ and 21.3 lbs/ft³, for the regular and small trailers, respectively. A paired t-test was performed to determine if the density of the green loads (19.2 lbs/ft³) was different than that for the dry loads (16.00 lbs/ft³) on the regular trailer. The results showed that there was a significant difference ($<.0001$) between the densities. This result is expected considering the 15% weight difference between the green and dry chips. The results from a paired t-test procedure between the load densities of the regular and small trailers were found to be significant (0.047).

The analysis of trucking costs depicted in Table 8.6.1 and Figures 8.6.1 and 8.6.2 was repeated using information gathered from the field experiments. Realizing that the field experiments showed a lower bulk density was achieved in the transpirationally dried loads, the lower bulk densities and net weights were used in this revised analysis. The net weights used for the loads at lower moisture contents were based on using actual field data for the maximum and minimum moisture contents and truck weights, then using a linear relationship to estimate the weight between the maximum and minimum moisture contents. The results from this additional analysis are shown in Table 8.6.4 and Figures 8.6.3 and 8.6.4. This revised analysis reveals that transporting 30% MC biomass 50 miles will cost \$11.88 per dry ton (with the less-than-full payload), which still results in a savings of \$4.03 per dry ton when compared to the green biomass transport cost. When the less-than-full payload costs are compared to the full-payload costs, the less-than-full load costs \$1.88 per dry ton more to transport 50 miles. The project team feels that it is possible to overcome the issue where the full payload was not reached with the transpirationally dried wood chips.

Table 8.6.4 Illustration of biomass trucking costs at various biomass moisture contents and one-way haul distances using less-than-full loads at reduced moisture contents. Costs are based on contract trucking rates of \$0.14 per net ton per mile, or \$3.99 per one-way mile (assuming 28.5 net tons per load).

			One-way Haul Distance					
			25 miles	50 miles	75 miles	100 miles	125 miles	150 miles
Moisture Content	Net Tons Per Load	Dry Tons Per Load	Cost Per Dry Ton					
56%	28.5	12.5	\$7.95	\$15.91	\$23.86	\$31.82	\$39.77	\$47.73
50%	27.5	13.7	\$7.26	\$14.53	\$21.79	\$29.06	\$36.32	\$43.59
45%	26.6	14.6	\$6.82	\$13.64	\$20.46	\$27.28	\$34.10	\$40.92
40%	25.7	15.4	\$6.46	\$12.92	\$19.38	\$25.84	\$32.31	\$38.77
35%	24.9	16.2	\$6.17	\$12.34	\$18.52	\$24.69	\$30.86	\$37.03
30%	24.0	16.8	\$5.94	\$11.88	\$17.81	\$23.75	\$29.69	\$35.63
25%	23.1	17.4	\$5.75	\$11.50	\$17.25	\$23.00	\$28.75	\$34.49

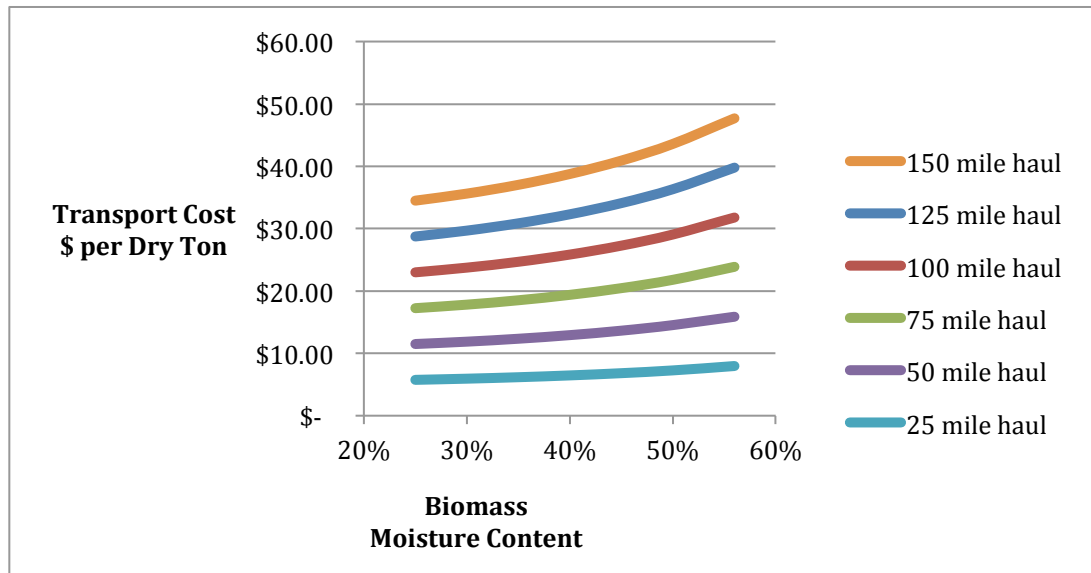


Figure 8.6.3 Trucking cost by moisture content and one-way haul distance with less-than-full loads. Costs are based on contract trucking rates of \$0.14 per net ton per mile, or \$3.99 per one-way mile (assuming 28.5 net tons per load).

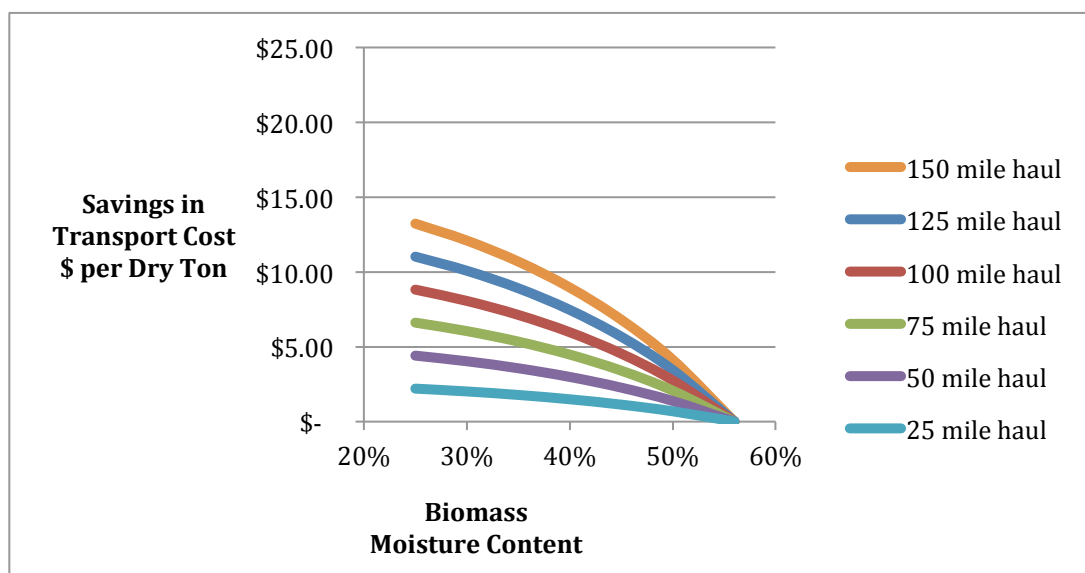


Figure 8.6.4 Savings in trucking costs for less-than-full loads due to transpirational drying by moisture content and one-way haul distance. Costs are based on contract trucking rates of \$0.14 per net ton per mile, or \$3.99 per one-way mile (assuming 28.5 net tons per load).

8.6.4 Summary

Transpirational drying has been shown as a method that can significantly reduce trucking costs for woody biomass. By drying wood to 30% moisture content and insuring a full legal payload, trucking costs can be reduced by \$5.91 per dry ton for a 50-mile haul distance. When hauling biomass longer distances, the savings from transpirational drying are greater. At a haul distance of 100 miles, the savings in trucking costs are \$11.82 per dry ton with 30% MC biomass. These results show that the procurement radius for a biofuel plant can be effectively increased by using transpirational drying, especially at those outer distances from the plant.

Transpirational drying is effective only if the size of the chip trailers or log trailers can be increased to account for the reduced bulk density and allow for full legal payloads. In this study, the use of larger trailers to haul transpirationally dried chips increased payload 10% over the regular chip trailers used by the contractor. The number of loads required to transport all chips from the site could have been reduced by 6 if the larger trailers had been used exclusively. This gain, however, was still 16% below the maximum legal load.

There was a significant difference between the bulk densities of the large trailer and the regular trailer when hauling dry chips. Although all trailers appeared to be completely full before departing, this cannot be confirmed. The lower density suggests that a characteristic of the trailer or a material property of dry chips is contributing to the reduced load density. The large trailer may be too long for the lighter chips to be blown and packed into the front of the trailer. This would indicate that a different trailer configuration or loading method might be required to achieve maximum density. Possible solutions include low profile tires that would allow for an increase in trailer height or top loading the trailers. The number of loads could have been further reduced by 12 if the large trailers could be loaded at a density of 16 lbs/ft³. This equates to an increase in load size of 19% over the regular trailers.

When the less-than-full payloads were analyzed for overall trucking costs, there is still a reduction in trucking cost due to transpirational drying. Even with a 4.5-ton reduction in the payload on the truck, the

biomass can be transported with a cost of \$11.88 per dry ton for a 50-mile haul distance. This is \$1.88 more than if the truck could have been fully loaded. Further work to refine the trailer, or loading techniques will overcome this challenge of completely filling the trailer and achieving the full legal payload.

8.7 Transpirational Drying

8.7.1 Objective

The objective of this subtask was to evaluate the effectiveness of transpirational or field drying of pine trees under different seasons and under different field storage conditions.

8.7.2 Methods

This task felled whole-tree loblolly pine and left them in the woods to transpirationally dry for several weeks until a target moisture content of about 35% was reached. Moisture content, ash content and bulk density was measured for samples of disks removed from the trees as well as clean conventional chips and micro-chips. Also, productivity studies evaluated the effect of dried wood on skidder productivity. Trees were felled and dried during two conditions (summer and winter) in central and south Alabama. Trees were stored in the field in two locations (the original feller buncher bunches or in piles near the road side). Two separate studies are described in the following text.

Study 1 – Covington County, AL – Whole Trees

A 37-acre loblolly pine plantation in Covington County, Alabama was felled and left in-woods to transpirationally dry. Fixed radius plots (0.1-acre) were installed across the stand to assess tree size, density and stocking level. A total of ten plots were installed in a line-plot cruise. Within each plot, DBH was measured on each tree 3.6 inches in DBH and larger. Total heights were sub-sampled and measured on every fifth plot tree.

Trees were felled April 2, 2012 and were allowed to dry until May 22, 2012 (Figure 8.7.1). Moisture content was monitored in three ways: 1) cutting disks from trees at the butt, DBH, and in 10-ft intervals up the stem; 2) repeated weighing of whole-trees; and 3) collecting chip samples during harvesting. Both clean conventional chips and whole-tree micro-chips were collected during the study.

The Tigercat 630D grapple skidder was evaluated using time-and-motion to determine the effect of skidding dry wood on productivity. Productivity was measured using stopwatches and numbering bunches for identification during a cycle. A stem count was done on each bundle skidded during the time study and an average tree size that was adjusted for moisture content was applied to estimate tons contained in each bundle. A complete observation, or cycle, began when the skidder left the landing and ended when the skidder returned to the landing and dropped its load. Cycle elements included empty travel, position and grapple, intermediate travel, loaded travel, empty landing travel, loaded landing travel and ungrapple. Distances traversed by the skidder for the travel elements were measured using a Garmin GPS unit.

Climatological data during the drying period were obtained online from a station located in Andalusia, Alabama (Weather Underground, Inc. 2014). Climate data obtained included temperature, dew point, relative humidity, wind speed, and precipitation. Average daily temperature, humidity, and dew point were calculated by summing the maximum and minimum values and dividing by two times the number of days (Stokes et.al. 1987).



Figure 8.7.1 Felled trees during transpirational drying tests in Covington, County, AL

Study 2 – Butler County, AL - Delimbed Trees

Drying of delimbed trees in one large pile at a landing was conducted on a site located in Butler County, Alabama from October 31, 2012 thru January 23, 2013. Both pine and hardwood trees were delimbed and debarked using a Chambers Deliminator and placed in a large pile at the landing. At the end of the drying period three pine trees were selected from the bottom and middle of the pile and four from the outside for moisture content determination. For hardwoods, two trees were selected from each of the three pile locations. Disks were cut with a chainsaw at the butt, DBH, mid-stem, and top on each selected tree. Each disk was placed in a plastic bag which was sealed and labeled. Two trees were felled during data collection and disks cut at butt and DBH to determine green moisture content.

Climatological data during the drying period were obtained online from a station located in Red Level, Alabama (Weather Underground, Inc. 2014). Climate data obtained included temperature, dew point, relative humidity, wind speed, and precipitation. Average daily temperature, humidity, and dew point were calculated by summing the maximum and minimum values and dividing by two times the number of days (Stokes et.al. 1987).

In the lab, moisture content was assessed through loss on drying, as prescribed in European Standard EN 14774-2 (2009). Each sample was weighed to obtain field weight. Weighed samples were then placed in aluminum pans and put in a drying oven at $105 \pm 2^{\circ}\text{C}$ until total mass loss differed by less than 0.2% between measurements taken one hour apart. The wet basis moisture content was calculated by dividing the difference between initial and oven-dry sample mass by the initial sample mass.

Study 3 – Monroe County, AL – Whole Trees

In-woods drying of whole-trees was investigated on a site in Monroe County, Alabama from August 21, 2013 thru October 31, 2013. The site encompassed an area of approximately 5 acres. The stand was divided in half and two drying methods were evaluated; drying in small skidder bunches left in the stand (Figure 8.7.2) and drying in one large pile at the landing (Figure 8.7.3). To determine green moisture content, four trees were felled and disks were cut at DBH, mid-stem, and a 2-inch top (Figure 8.7.4). For the small bunches, trees were felled and placed in bunches which averaged 23 trees each and left in the stand. For the large pile trees were skidded to the landing the same day they were felled and stacked in one pile. After the drying period, three locations or zones of bottom, middle, and outer were identified for

both small bunches and the large pile. Three small bunches were selected and three trees from each zone were marked for sampling of moisture content. For the large pile, nine trees were selected from each zone for moisture content determination. Selected trees were transported by the skidder to a sampling area near the landing where disks were cut from the butt, DBH, mid-stem, and a 2-inch top. For trees with broken tops below 2 inches, samples were cut below the break. Sample disks were placed in paper bags, labeled, and weighed the same day to determine field weight.



Figure 8.7.2 Example of bunches left in the field for drying in Monroe County, AL.



Figure 8.7.3 Large pile used for transpirational drying in Monroe County, AL.



Figure 8.7.4 Example of collecting disks from trees for moisture content determination.

Climatological data during the drying period were obtained online from a station located in Evergreen, Alabama (Weather Underground, Inc. 2014). Climate data obtained included temperature, dew point, relative humidity, wind speed, and precipitation. Average daily temperature, humidity, and dew point were calculated by summing the maximum and minimum values and dividing by two times the number of days (Stokes et.al. 1987).

In the lab, moisture content was assessed through loss on drying, as prescribed in European Standard EN 14774-2 (2009). Each sample was weighed to obtain field weight. Weighed samples were then placed in aluminum pans and put in a drying oven at $105 \pm 2^{\circ}\text{C}$ until total mass loss differed by less than 0.2% between measurements taken one hour apart. The wet basis moisture content was calculated by dividing the difference between initial and oven-dry sample mass by the initial sample mass.

8.7.3 Results

Study 1 - Covington County, AL – Whole Trees

The stand had a QMD (Quadratic Mean Diameter) of 6.0 inches for loblolly pine. Total height averaged 42.0 feet. Density totaled 574 TPA with a stocking level of 95.28 whole-tree green tons per acre in the 4 to 10-inch diameter range. Table 8.7.1 shows a summary of the stand information by DBH class.

Table 8.7.1. Stand summary for transpirational drying site in Covington County, Alabama.

STAND AND STOCK TABLE FOR LOBLOLLY PINE (Transpirationally Dried Site)		
DBH Class (in)	TPA	Tons/Ac
4	93	5.31
5	125	12.89
6	163	25.64
7	124	27.66
8	51	15.95
9	14	5.45
10	4	2.38
Total	574	95.28

A summary of the moisture content analysis during the study is displayed in Table 8.7.2 and Figure 8.7.5. For solid wood disk samples, disks were cut from five trees at four different times during the drying period. Five different trees were sampled at each visit. For solid wood tree samples, twenty whole-trees were weighed twice during the drying period to determine weight loss. Weighing of trees occurred on April 26 and May 16. A total of 15 loads were sampled for clean conventional chips and two loads were sampled for whole-tree micro-chips.

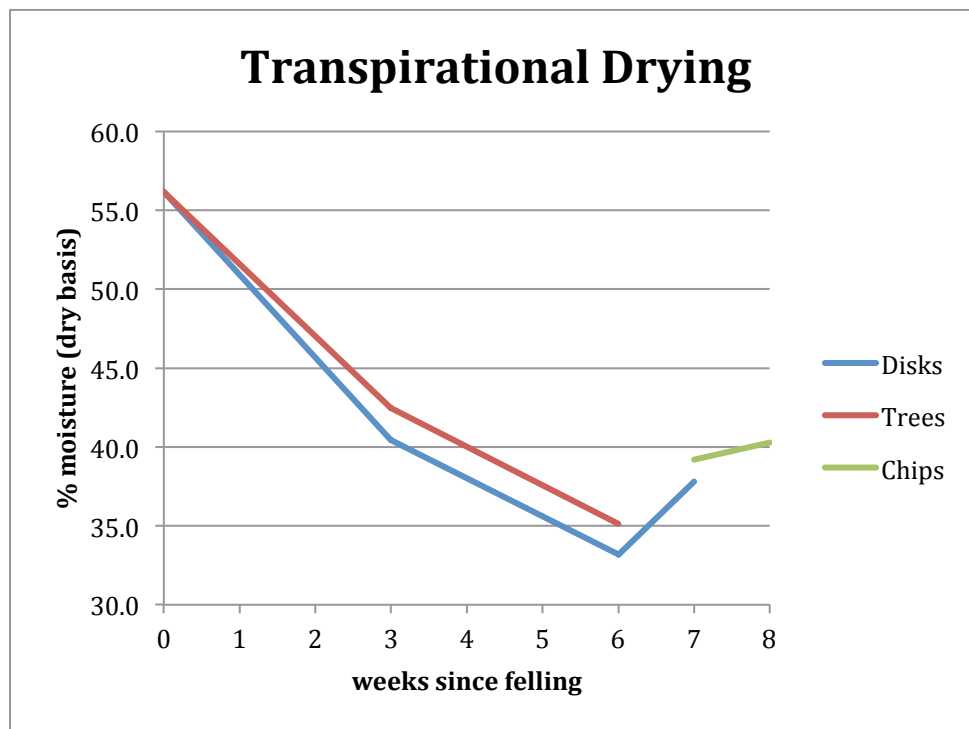


Figure 8.7.5 Drying trends for different measurement techniques in Covington County, AL.

Table 8.7.2 Mean moisture content (% wet-basis) of loblolly pine for the transpirational drying site in Covington County, Alabama.

Time of Observation	Sample Type			
	Solid Wood		Chips	
	Disks ¹	Trees ²	Clean ³	WT Micro ⁴
Week 0	56.2	56.2	56.2	56.2
Week 3	40.4	42.5	-	-
Week 6	33.2	35.1	-	-
Week 7	37.8	-	-	38.8
Week 8	-	-	40.3	-
% change				
Week 0	-	-	-	-
Week 3	28.1	24.4	-	-
Week 6	17.8	17.4	-	-
Week 7	+13.8	-	-	31.0
Week 8	-	-	28.3	-
Total % change from green	32.7	37.5	28.3	31.0

For the climate data in Table 8.7.3, high and low values for temperature, humidity, and dew point are averages over the course of the drying period. Mean values for temperature, humidity, and dew point were calculated by summing all high and low values and dividing by two times the number of drying days. For precipitation, high and low values reflect the maximum and minimum rainfall recorded on a particular day. Values for high wind speed and gust reflect averages over the drying period. A total of 4.89 inches of rainfall was recorded at the weather station in Andalusia, Alabama during the study. During the last three days of the drying period 0.36 inches of rainfall was recorded. Although, a rain event totaling 1.59 inches was recorded on May 13th, nine days before the end of the drying period.

Table 8.7.3 Climatological data for drying of loblolly pine during April and May in Covington County, Alabama.

Variable	High	Mean	Low	Gust	Total
Temperature (F)	83.4	72.1	60.7	-	-
Humidity (%)	86.2	62.6	39.0	-	-
Dew Point (F)	62.3	57.5	52.6	-	-
Precipitation (in)	1.59	0.098	0.0	-	4.89
Wind Speed (mph)	11.5	3.5	-	22.6	-

Skidding transpirationally dried wood had a significant impact on payload size and productivity. The number of stems skidded per cycle for dry wood averaged 41.9, compared to 25.4 while skidding green wood, an increase of 65%. Average payload while skidding dry wood decreased 23% to 5.4 net tons. When just considering the net tons, this appears to be a 44% reduction in productivity while skidding transpirationally dried material. Productivity averaged 87 dt/PMH (at 35% MC) while skidding dry wood compared to 155.8 gt/PMH while skidding green wood.

Study 2 – Butler County, AL - Delimbed Trees

Trees dried for 85 days from October 31, 2012 to January 23, 2013. Analysis of moisture content showed trees located in the outer zone of the pile had the most significant amount of drying. Hardwood trees sampled from the bottom and middle of the pile had nearly the same moisture content, while hardwood trees from the outer zone exhibited the lowest moisture content of both species. A summary of moisture contents for each species and zone is shown in Table 8.7.4, where n represents the number of disks sampled. Climate data for the drying period is summarized in Table 8.7.5.

Table 8.7.4 Moisture content summary of piled delimbed loblolly pine and hardwood trees after drying in Butler County, Alabama.

MOISTURE CONTENT (% wet-basis)						
Zone	Pine			Hardwood		
	n	mean	s	n	mean	s
Bottom	12	40.14	9.881	8	38.46	4.69
Middle	12	45.96	9.201	8	36.99	4.36
Outer	15	31.90	8.998	8	30.31	6.43
Green	4	51.40	8.544			

For the climate data in Table 8.7.5, high and low values for temperature, humidity, and dew point are averages over the course of the drying period. Mean values for temperature, humidity, and dew point were calculated by summing all high and low values and dividing by two times the number of drying days. For precipitation, high and low values reflect the maximum and minimum rainfall recorded on a particular day. Values for high wind speed and gust reflect averages over the drying period. A total of 10.98 inches of rainfall was recorded at the weather station in Red Level, Alabama during the drying period. No rainfall was recorded during the last three days of the drying period. Only 0.06 inches of rainfall was recorded during the last seven days of the drying period. Although, a rain event totaling 1.55 inches was recorded on January 16th, eight days before the end of the drying period.

Table 8.7.5 Climatological data for drying period of piled delimbed loblolly pine trees in Butler County, Alabama.

Variable	High	Mean	Low	Gust	Total
Temperature (F)	65.7	54.3	42.8	-	-
Humidity (%)	96.4	76.1	55.9	-	-
Dew Point (F)	53.3	46.8	40.2	-	-
Precipitation (in)	1.97	0.13	0.0	-	10.98
Wind Speed (mph)	6.2	1.2	-	10.4	-

Study 3 – Monroe County, AL – Whole Trees

Trees in small skidder bunches dried for 72 days while trees in the large pile dried for 70 days. Sampled trees ranged in size from 3.6 to 10.5 inches DBH and averaged 7.0 inches for the large pile and 7.3 inches for the skidder bunches. Mean moisture content of green trees, calculated by averaging disks sampled at DBH, mid-stem, and top, was 58.4%. Analysis of moisture content of disks sampled from the butt, DBH, mid-stem, and top of each tree showed moisture content of trees in skidder bunches averaged 25.6% while trees in the large pile averaged 39.3%. Differences in moisture content by zone were more pronounced for the large pile as compared to the skidder bunches. In the large pile moisture contents ranged from 28.6% for the outer zone to 48.9% at the bottom, compared to 23.8% to 29.2% for the skidder bunches. A summary of moisture contents is displayed in Table 8.7.6, where n represents the number of disks sampled.

Table 8.7.6 Moisture content summary of bundled and piled loblolly pine whole-trees after drying in Monroe County, Alabama.

MOISTURE CONTENT (% wet-basis)						
Zone	Skidder Bunches			Large Pile		
	n	mean	s	n	mean	s
Bottom	36	29.2	15.7	37	48.9	14.0
Middle	42	24.3	13.0	40	40.5	17.3
Outer	40	23.8	11.8	39	28.4	17.0
Overall	118	25.6	13.6	116	39.1	18.1

Moisture content at the different locations along the stem varied considerably as summarized in Table 8.7.7. These means reflect overall moisture content by stem location regardless of zone. The highest variability occurred in the top samples of trees for both pile types as indicated by their standard deviations. Locations which were least variable were DBH and mid-stem for the large pile and Butt and DBH for the skidder bunches (Klepac et.al., 2014).

Table 8.7.7 Moisture content summary for loblolly pine by location along stems for each pile type.

MOISTURE CONTENT (% wet-basis)						
Location	Skidder Bunches			Large Pile		
	n	mean	s	n	mean	s
Butt	52	15.4	3.70	50	26.8	13.72
DBH	14	25.3	5.62	14	38.5	9.50
Mid	26	44.0	10.94	26	55.1	8.50
Top	26	27.7	11.51	25	48.2	19.33

8.7.4 Summary

Analysis of disk samples from Study 1 from week seven showed that moisture content of felled trees dropped to the target range of 35 to 40% after approximately seven weeks of drying. Micro-chip samples collected during the same week were also close to the target at 38.8%. Samples of clean conventional chips collected during week eight were slightly wetter with a moisture content of 40.3%.

From Studies 2 and 3, for loblolly pine trees in the outer zone of the two large piles, whole-trees had a lower final moisture content (28.4%) after drying when compared to delimbed trees (31.9%), which resulted in a 11.6% difference. These results should be expected since cut trees continue to transpire through the foliage and these moisture losses exceed that which evaporates from the stem of delimbed trees. Although the whole-trees dried during a different time of year than the delimbed trees, they had a drying time that was 15 days shorter. Also, the whole-trees initially had a higher green moisture content, assuming they started at 58%, compared to 51% for the delimbed trees.

Allowing whole-trees to dry in skidder bunches was more effective at reducing moisture content of trees than drying them in a large pile. Overall, there was a 41.7% difference in the final moisture content between the two pile sizes.

8.7.5 Output

Klepac, J., D. Mitchell and J. Thompson. 2014. The effect of pile size on the moisture content of loblolly pine while field drying. In: Proceedings of the 37th annual meeting of the Council on Forest Engineering. June 15-18, 2014. COFE. Morgantown, WV.

8.7.6 References

Stokes, B.J., W.F. Watson, and D.E. Miller. 1987. Transpirational drying of energywood. ASABE Paper No. 87-1530. American Society of Agricultural and Biological Engineers. St. Joseph, MI.

Weather Underground, Inc. 2014. Historical weather data. Available online at <http://www.wunderground.com/history>.

8.8 Extended Work Schedules

8.8.1 Background

The use of extended working hours in the US is not widespread. Those that implement extended working hours cite a variety of considerations that impact their choice of work schedules. Some operate up to 24 hours per day during the winter months to maximize production while the ground is frozen and operable. Cold winter conditions encourage others to schedule more work hours in a day to avoid unproductive time warming engines and fluids. These are two practical responses for addressing environmental conditions through the use of extended working hours.

Extended working hours are also implemented to reduce equipment costs or to increase production. Increasing the scheduled number of working hours should result in increased daily production. Therefore, the cost per ton produced should decrease when these fixed costs are spread over a larger daily production amount.

The daily production increase may not directly reflect the increased scheduled work hours. In other words, the tons per hour produced during the nighttime hours may not be the same as the production rate observed during daytime hours. Ample evidence exists in literature that indicates that there are psychological, physiological and social impacts associated with working longer shifts, or at night (Mitchell et al, 2008). These impacts can result in decreased night shift production, but also in increased safety risks, higher employee turnover, and even increased health risks.

Production after dark is typically less than the production obtained during daylight hours. In their recent literature review, Murphy and Vanderberg (2007) found that night shift productivity is approximately 10% less than that of the day shift. Nicholls et al (2004) measured a 22% night shift production reduction for in harvester production in first thinnings. In this Australian study, different operators were assigned to each shift, and each shift included hours of daylight and darkness. In a more recent study, Petersons (2010) measured the productivity of a harvester operating in daylight and darkness in first commercial thinnings in Latvia. He found a 12% reduction in the production between daytime and nighttime hours. The harvester performed functions of felling, processing and sorting. The stands contained a mixture of species and trees were not in rows.

8.8.2 Objective

The objective of this study was to quantify the productivity difference of a single feller-buncher operator working both daytime and nighttime hours in a planted southern pine plantation.

8.8.3 Methods

Study Site

The study site was located in Pike County, Alabama, approximately 18 miles from Troy, AL. The 125-acre bedded and planted loblolly pine (*Pinus taeda*) stand was owned by a large timber landowner. The stand was 15 years old at the time of harvest, and the prescription was a first thinning. To prepare for a nighttime harvest, the contractor chose to fell every fourth row during daylight hours and thin between these rows during the observation periods (day and night). Productivity was compared between day and night conditions with the operator performing the same thinning task.

Harvest Data Collection

Data were collected, using 0.10 acre plots, to determine the average DBH and height of the trees in the study area. These data were used to determine the descriptive statistics for the study site. A biometric regression equation developed from similar stand data (Klepac, unpublished data) was used to determine the average stem weight based on stem data collected on the site. The study was installed on September 6, 2012. Sunset occurred at 7:02 pm Central Daylight Time (CDT).

Production data were collected on the felling operation during both daylight and dark hours. Data collected included stems per accumulation, accumulations per bunch, and stems per bunch. A stopwatch was used to gather time per accumulation data.

8.8.4 Results

The average stem was 8-inches DBH with a height of 55-feet. The average stem weight was estimated to be 668.26 lbs/tree. The operator had over a year of experience on the feller-buncher and 24 years of operator experience. The TigerCat 845D was equipped with a standard lighting package with lights mounted on the front and sides of the cab. The cutting head was a shear.

The feller-buncher was observed for a total of 57 accumulation cycles for each shift type (day and night). A cycle was identified as the time it took for the boom to begin to ascend from setting down an accumulation until the boom began to ascend from the next accumulation. Day shift data collection began at 3:35 pm (CDT), and night shift data collection began at 7:56 pm (CDT). Gross time (including short delays) for the day observations was 2 hours, 10 minutes. Gross time for the night observations was 2 hours, 9 minutes. The average accumulation cycle time during the day shift was 2.29 minutes. The average cycle time per accumulation during the night shift was 2.26 minutes. There was no significant difference in the cycle time per accumulation by shift ($\alpha=.05$, p-value = 0.9363).

The average stems per accumulation by shift differed by an average of 0.72 (Table 8.8.1). This difference was not statistically significant ($\alpha=.05$, p-value = 0.146). The average accumulations per bunch, however, differed by 0.5 (Table 8.8.2). This difference was significant ($\alpha=.05$, p-value = 0.0032).

Table 8.8.1 Stems per accumulation per shift.

Shift	N	Mean	Standard Deviation
Day	57	7.1	3.1
Night	57	6.4	2.0

Table 8.8.2 Accumulations per bunch by shift.

Shift	N	Mean	Standard Deviation
Day	28	2.0	0.7
Night	38	1.5	0.6

The operator created 28 bunches during the day shift and 38 during the night shift. The average number of stems per bunch during the day shift was 14.3, while the average during the night shift was 9.5. This difference in the number of stems per bunch was statistically significant ($\alpha=.05$, p-value < 0.0001). This equates to the night shift operation placing 33.5% fewer stems per bunch than during the day shift. Using the calculated average stem weight, the night shift produced 121 tons compared to 134 tons produced during the day shift. This translates to 61.55 gt/hr (green tons/hour) for the day shift, and 56.37 gt/hr for the night shift. Overall, findings indicate a shift difference of 8.4% fewer gt/hr produced during the night shift.

While the entire harvesting system was not observed during this short study, we can make some inferences about the impacts of night logging on system productivity. The smaller bunches created during the night shift would potentially negatively impact the production of the skidder. The skidder may have to grapple more bunches to make a full payload, thus increasing the average intermediate travel time between bunches.

The silvicultural prescription of removing every fourth row was not a common prescription for this operator to implement. Removing every fourth row meant that there were three rows to thin between each removal row. The operator was familiar with odd-numbered row thinnings. With even-numbered thinning, the operator thinned two rows on one side and one on other side. While this awkward movement was the same during the day as after dark, it may result in lower overall production as compared to production in odd-numbered row thinnings. During both shifts, the operator would reach out to two rows on either side of the removal row to remove trees that may have been missed while working down the previous removal row.

The feller-buncher used in this study measures 11.1 feet wide. The counter-weight extends beyond the tracks, making it difficult to turn and maneuver in the row (Figure 8.8.1). Operationally, the steps required to turn the machine around with a full accumulation to place bunches behind were complex. The operator would set the full accumulator head between the residual trees, walk the track forward, then retract the head and swing the boom around to place the accumulation in a bunch behind the forward rate of progress. The machine was designed for clearcut harvesting, so the production observed in this study may have been negatively impacted by the silvicultural prescription and planting spacing.



Figure 8.8.1. Maneuvering is difficult in narrow rows.

The machine did not have an additional lighting package nor any aftermarket lighting added (Figure 8.8.2). The operator suggested that lights pointing upward from the cab would have been useful during night felling to avoid hanging accumulated stems in the canopy of the residual stand. Upward pointing lights would have also aided in tree selection for form, as many of the trees in the stand were forked.

The cutting contract required low stumps. The design of the shear allowed the operator to ‘bump’ the head on the ground before shearing to keep stump heights low. This was made more difficult due to the bedding in the stand. However, the operator stated that he used the same technique to cut low stumps during both shifts.

In discussions with the operator at the end of the night shift, he mentioned that he would not want to work a night shift on a permanent basis. He often arrives to work before sunrise and works in the dark, but that is only on a personal-request situational basis and is not an assigned work schedule. When asked about the isolation of working at night, he responded that he prefers having another equipment operator on site. Even though he doesn’t work closely with the skidder operator, they are aware of each other’s presence



Figure 8.8.2. Night logging with a standard lighting equipment package.

and would check on each other for safety if they had not had recent visual contact. In terms of safety, the operator mentioned that he prefers to stay within the safety of the equipment cab at night.

8.8.5 Summary

In this study, the production rate of the feller-buncher during the night shift was 8.4% lower than that of the day shift. However, the production differences were not similar for all feller-buncher functions. The average accumulation cycle time was not different between shifts. In addition, the average number of stems per accumulation did not differ based on shift. The number of accumulations per bunch was found to be significantly different between shifts, which resulted in smaller bunches created during the night shift. These smaller bunches may impact the productivity of the skidding component which was not included in this study.

This short study provides some insight into the impacts of felling trees after dark. Further research is needed on a whole harvesting system to determine machine interactions and system performance when implementing shift schedules.

8.8.6 Outputs

Mitchell, D. 2012. Ups and Downs Associated with Implementing Shift Schedules on a Southern Harvesting Operation. In Engineering New Solutions for Energy Supply and Demand. 35th Council on Forest Engineering Annual Meeting. Council on Forest Engineering. Morgantown, WV.

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Mitchell, D.L., T. V. Gallagher and R. E. Thomas. 2008 The Human Factors of Implementing Shift Work in Logging Operations. JASH 14(4): 391-404.

Murphy, G. and M. Vanderberg. 2007. Modelling the economics of extended shift and 24/7 forest harvesting. NZ Journal of Forestry, August 2007, pp 15-19.

J. Petersons. 2010. Factors affecting harvester productivity in forest thinning in Latvia. In: 16th Annual International Scientific Conference: Research for Rural Development, Jelgava Latvia, May 19-21, 2010: p. 183-187.

8.9 Environmental Impacts

8.9a Quantifying Residue after Biomass Harvest

8.9a.1 Objective

The objective of this evaluation was quantification of forest residues as a result of biomass harvests and nutrient pools associated with residue components.

8.9a.2 Methods

Three operational-scale harvesting treatments were inventoried for post-harvest forest residue content. They consisted of a 24-year-old stand (Butler) and 13-year-old stand (Covington) subjected to clearcutting and a 13-year-old tract subjected to a thinning operation (Estate). All sites were loblolly pine (*Pinus taeda* L.) plantations subjected to biomass harvesting systems.

An inventory of standing woody biomass (alive and dead) was determined through utilization of inventory plots and final volumes estimated by volume/yield equations. A representative sample of trees (10 – 20) was then weighed to validate volume estimations.

Within study stands, five 23.9 foot fixed radius plots ($1.8 \times 10^3 \text{ ft}^2$) were located within treatment areas and 5 subplots (3.28 foot fixed radius/ 33.4 ft^2) were located within each plot. All biomass was collected within each sampling plot, sorted by size, and quantified. Biomass residues were quantified using the line transect method to determine Down Woody Material (DWM). A subset of biomass samples was subjected to nutrient analyses.

8.9a.3 Results

All Study Sites

General information on biomass characteristics of study sites indicated differences in number of trees per acre and basal area (Table 8.9.1).

Table 8.9.1 Study site stand information, Alabama.

LOCATION	AGE	TREATMENT	TOTAL AREA (ac)	TREES/AC (tpa)	BASAL AREA (ft^2/ac)
ESTATE	13	THINNING	121	950	ND
COVINGTON	13	CLEARCUT	37	660	142.5
BUTLER	25	CLEARCUT	45	850	181.3

Butler and Covington

Standing biomass was estimated for stands subjected to clearcut harvesting: 190 green tons/ac in Butler and 95 green tons/ac in Covington. Of those totals, 160 and 83 green tons/ac was estimated to be merchantable for the Butler and Covington tracts, respectively (Figure 8.9.1). Recovery efficiencies were estimated to be 87.5 and 90% for Butler and Covington sites, respectively.

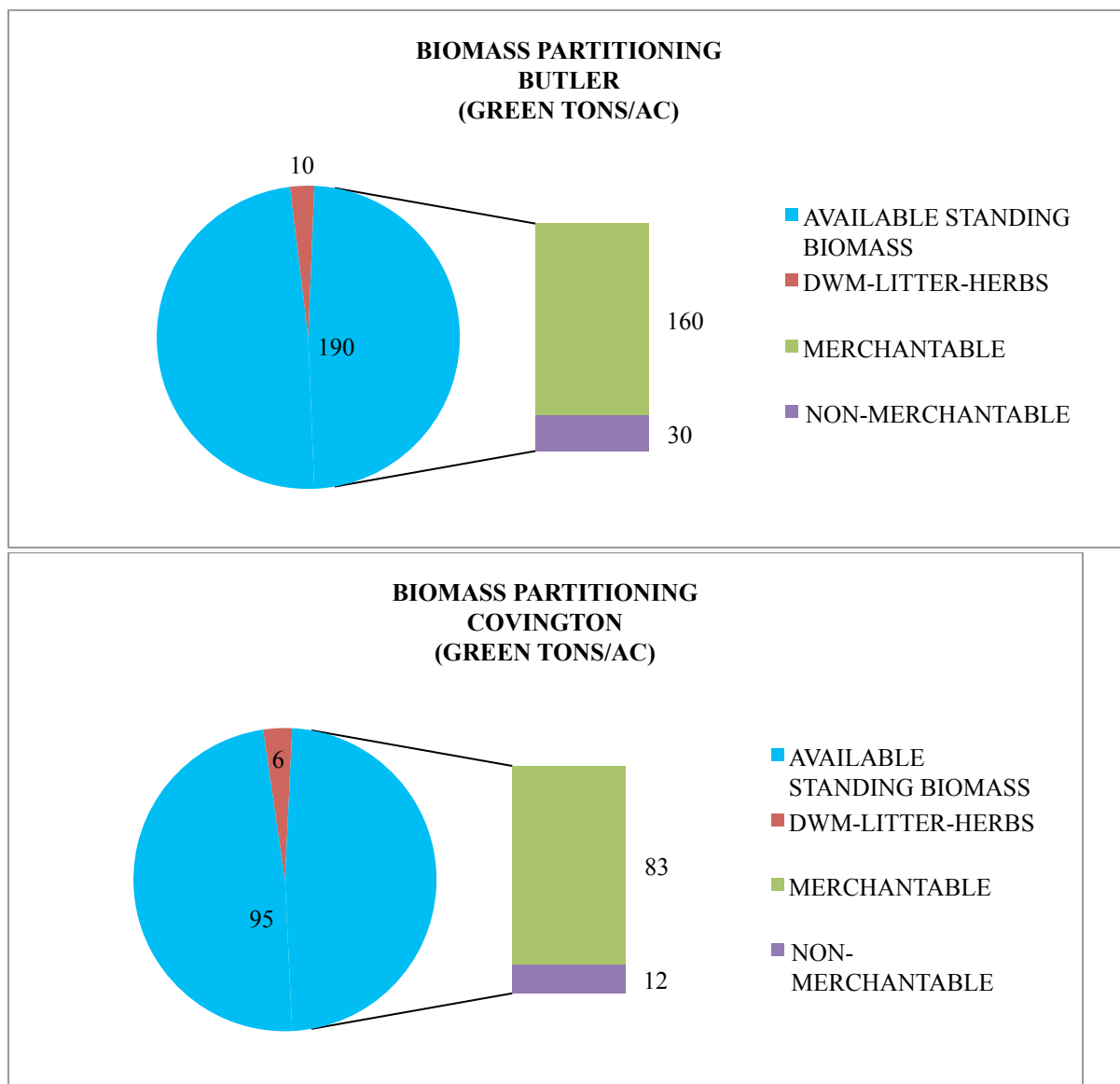


Figure 8.9.1 Biomass partitioning in select tracts, Alabama.

For each study site, forest residues that remained on site were estimated to be 10 and 6 green tons/ac in Butler and Covington tracts, respectively. Downed woody material (DWM) was separated into 2 classes that reflected size and length of remaining biomass: Coarse Woody Debris (CWD) defined as having a diameter ≥ 3 inches and Fine Woody Debris (FWD) with a diameter of ≤ 3 inches; a minimum length of > 2.95 feet was required for each class. Results of pre- and post-harvest residue distribution are included in Table 8.9.2.

Table 8.9.2 Summary of biomass residue composition, Alabama.

SITE	BIOMASS COMPONENT (tons/ acre)								
	± CWD			FWD			DWM		
	PRE	POST	DIFF	PRE	POST	DIFF	PRE	POST	DIFF
BUTLER	1.8	4.9	+3.1	6.1	10.2	+4.2	7.9	14.1	+6.2
COVINGTON	0.0	1.1	+1.1	6.1	3.8	-2.3	6.1	4.9	-1.2

± CWD – Coarse Woody Debris; FWD – Fine Woody Debris; DWM – Down Woody Material.

Downed wood material was higher in Butler compared to Covington which reflected the degree of biomass availability due to stand age differences.

Nutrient content of biomass components from select sampling locations are indicated in Table 8.9.3. Nutrient contents were measured in several components including bole and remaining biomass (DWM). Differences were noted between the two sites by TYPE and LOCATION in terms of nutrient content with higher contents associated with Covington for a majority of nutrients evaluated. DWM classes included CWD and FWD with the latter partitioned into 3 classes based on size: large fine wood (LFW)(2-3”), medium fine wood (MFW)(1-2”), and small fine wood (SFW)(<1”).

Table 8.9.3 Summary of nutrient contents by TYPE and LOCATION, Alabama.

TYPE	LOCATION	C	N	CA	MG	K	NA	AL	P	MN
		(----- % -----)		(----- ppm -----)						
BOLE	BUTLER	51.4	0.08	764.2	241.7	545.1	94.6	275.2	59.0	56.8
	COVINGTON	52.0	0.12	714.9	268.0	649.7	18.5	421.8	112.5	61.4
DWM	BUTLER	48.6	0.34	2812.6	387.7	848.0	51.1	258.3	119.1	94.5
	COVINGTON	48.5	0.38	3441.2	452.7	707.7	21.5	412.1	221.0	160.0

Needle nutrient contents were typically higher in samples from Covington (Figure 8.9.2). Nutrient concentrations of DWM classes indicated differences among the classes by location (Figure 8.9.3). Carbon and nitrogen levels appeared to be higher in Butler, potentially indicating the influence of age in C and N accumulations. Among base cations, nutrient accumulations were higher in smaller size material for both locations while accumulations of Al, Mn, and P saw differences by location with higher concentrations in Covington.

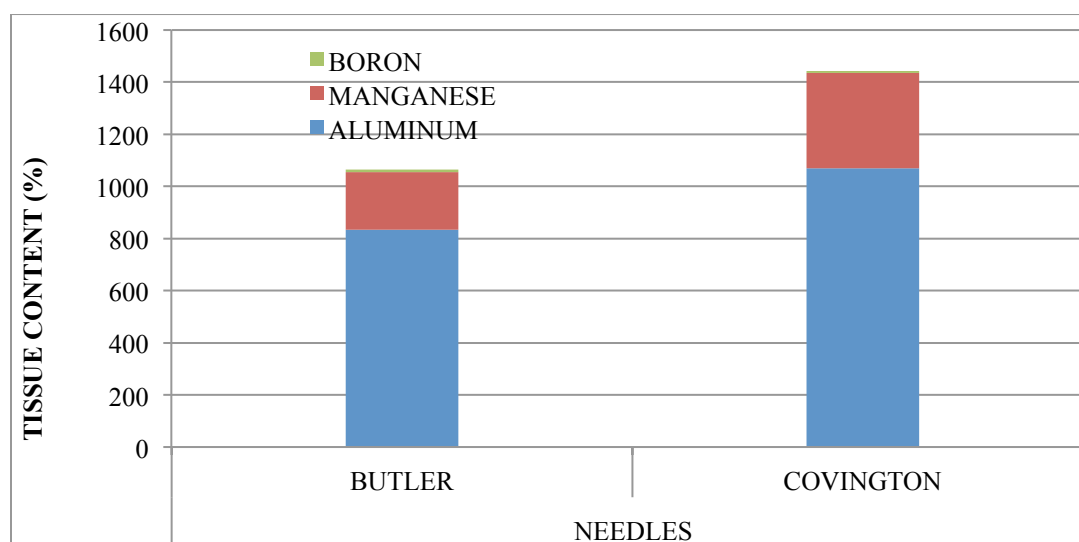
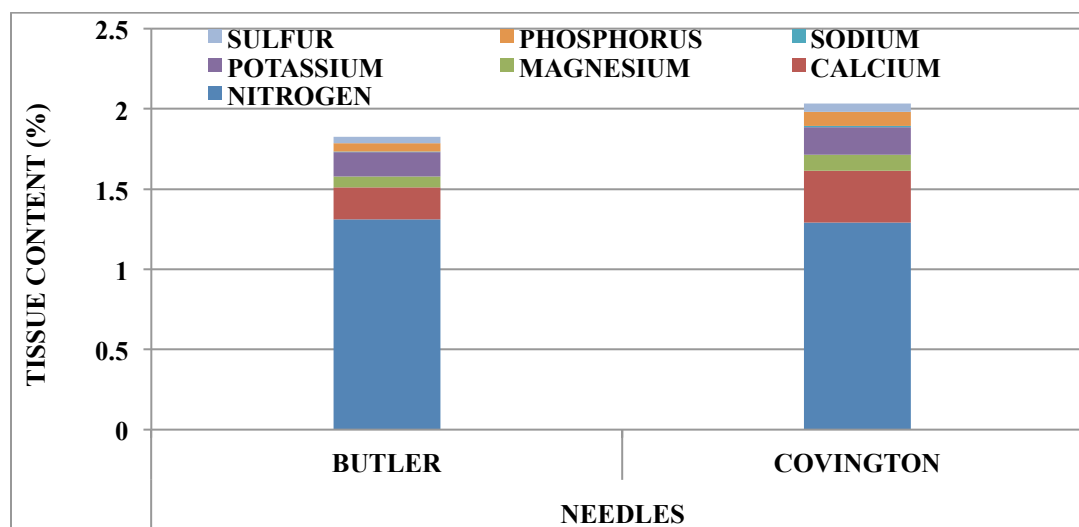


Figure 8.9.2 Tissue nutrient concentrations of pine needle samples, Alabama.

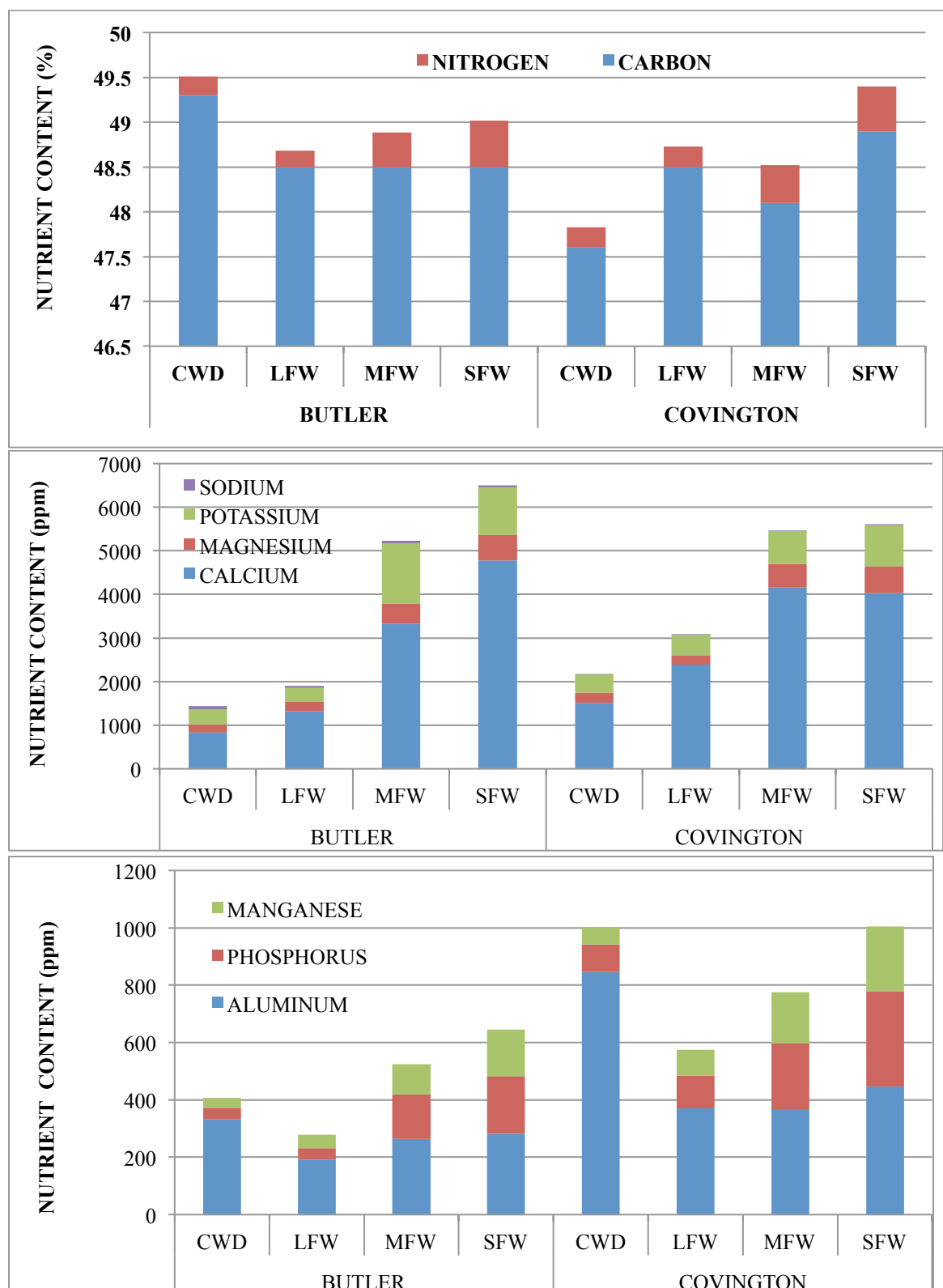


Figure 8.9.3 Nutrient concentrations of DWM classes, Alabama.

Estate

The Estate tract was a 13 year old loblolly pine stand that was subjected to a thinning operation. Standing biomass was estimated to be 103 green tons/ac of which 90 green tons/ac was determined to be merchantable material; approximately 13 green tons/acre was classified as non-merchantable (Figure 8.9.5).

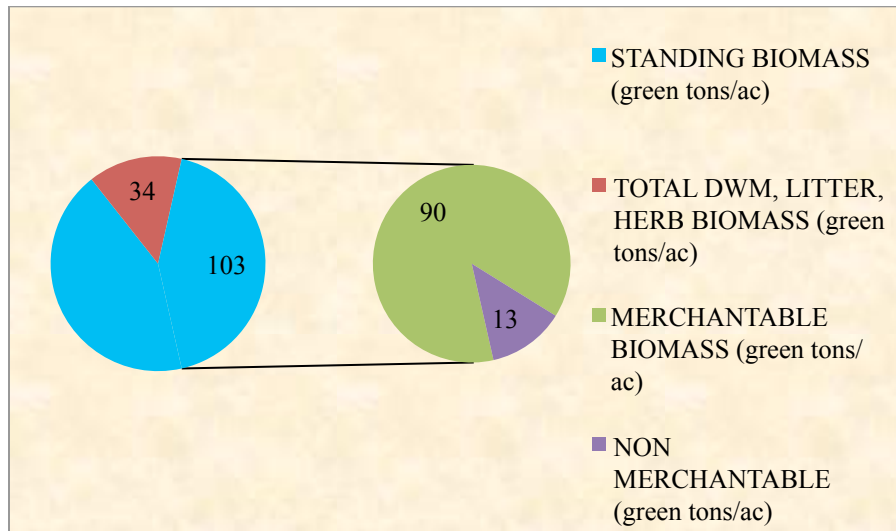


Figure 8.9.5 Biomass Partitioning in Estate Tract, Alabama.

In regards to nutrient content of DWM, three classes of FWD were available for analysis; CWD samples were absent from sampled plots (Table 8.9.3). Overall, C and N reflected results associated with Covington, levels similar in younger age stands. Calcium levels exceeded all other nutrients and overall nutrient levels in DWM were similar to Covington. Needle tissue content in Estate samples were lower in select elements including N, K, P, and S compared to Butler and Covington (Table 8.9.4).

Table 8.9.4 Nutrient composition of DWM and DWM classes, Alabama

TYPE	LOCATION	[±] C	N	CA	MG	K	NA	AL	P	MN	S
		(-----%-----)		(-----ppm-----)							
DWM	ESTATE	50.8	0.41	3622.6	470.8	378.6	20.5	346.9	117.5	101.8	309.0
LFW		52.3	0.31	3601.3	600.9	423.4	24.0	394.2	94.9	89.7	276.2
MFW		49.9	0.37	3881.3	407.8	316.8	18.8	378.7	116.5	112.1	311.9
SFW		50.4	0.54	3383.0	416.8	400.0	19.0	272.4	138.7	102.6	335.5

[±] Nutrients were previously identified except S – sulfur.

Table 8.9.5 Nutrient composition of needles samples, Alabama

TYPE	LOCATION	[±] N	CA	MG	K	NA	P	S	AL	MN	B
		(----- % -----)							(----- mg/kg -----)		
NEEDLES	ESTATE	0.63	0.32	0.11	0.08	0.005	0.02	0.02	810.6	233.7	9.4

[±] Nutrients were previously identified except B – boron.

8.9a.4 Summary

Three sites in Alabama were evaluated for biomass content under pre-and post harvest conditions. Two sites were subjected to clear cut harvesting (Butler and Covington) and a third was subjected to a thinning operation (Estate). Age classes of the sites included two 13 year old stands: Covington and Estate and one 25 year old stand (Butler). Each stand was evaluated for standing biomass and merchantable and non-merchantable residues and the amount of DWM. Assessment of nutrient contents of post harvest material revealed differences in select nutrients by location. Nutrient concentrations of DWM classes indicated differences among the classes by location. Carbon and nitrogen levels appeared to be higher in Butler, potentially indicating the influence of age in C and N accumulations. Among base cations, nutrient accumulations were higher in smaller size material for both locations while accumulations of Al, Mn, and P saw differences by location with higher concentrations in Covington. Needle nutrient contents were typically higher in samples from Covington. The results for Estate nutrients indicated C and N levels similar to Covington underscoring the influence of age. Calcium levels exceeded all other nutrients and overall nutrient levels in DWM were similar to Covington. Needle tissue content in Estate samples were lower in select elements including N, K, P, and S compared to Butler and Covington .

8.9b Air Quality Around Biomass Harvesting Operations

8.9b.1 Background

It is widely accepted that logging operations are a dusty work environment. This is clearly evident from accumulated dust in cabs and on machine surfaces. However, air quality on biomass harvesting operations is not well understood, nor documented in existing literature. A variety of activities occur on the landing and each may contribute to poor air quality.

Soil type and moisture content may impact air quality and ash content in processed biomass. When soil moisture content is high, fewer particles may become airborne as a result of equipment movements. Particle sizes associated with different soil types may impact the amount of dust that becomes airborne. Soils with smaller particles, <0.1 mm diameter, that rise more than 30 cm into the air may stay suspended for longer periods than larger particles (White 2006). Larger particles (>0.1 mm) do not usually rise over 30 cm, and usually fall back to the ground.

The impact of dust concentrations on air quality of the work environment of forest workers on biomass harvesting operations is unknown. Although personal exposure to dust can be measured, it may be highly variable due to differences in operational characteristics between logging sites, site differences, and a host of other variables. Dust concentration measurements on biomass harvesting operations are needed to quantify air quality and determine the impact that it may have on the health of forest workers.

Chippers and grinders may change the air flow on a landing, and the volume of air flow varies between machines. In a dusty working environment, dust will also be present in the air flow and may get deposited on processed biomass. The impact of dust concentrations on biomass feedstock qualities is also not documented in existing literature.

This introduction provides a brief summary of air quality as it relates to the working environment and human health. It also examines the potential impact of air quality on biomass feedstock quality.

Human Health

Standards for air quality in the working environment are regulated by the United States Department of Labor, Occupational Safety and Health Administration (OSHA). The Occupational Safety and Health Administration (OSHA) was created to ensure safe and healthful working conditions for working men and women by setting and enforcing standards and by providing training, outreach, education and assistance. "Standard" means a standard which requires conditions, or the adoption or use of one or more practices, means, methods, operations, or processes, reasonably necessary or appropriate to provide safe or healthful employment and places of employment' (OSHA 2011). As such, air quality standards are addressed by OSHA (1910.1000, Air Contaminants). OSHA sets enforceable permissible exposure limits (PELs) to protect workers against the health effects of exposure to hazardous substances. PELs are regulatory limits on the amount or concentration of a substance in the air. Forestry does not have any industry-specific PELs, however some other industries do. The general air quality standards for all inert or nuisance dusts (whether mineral, inorganic, or organic) not listed specifically by substance name are covered by the limits set for Particulates Not Otherwise Regulated (PNOR). The limits for PNOR are 15 mg/m³ for total dust, and 5 mg/m³ for the respirable fraction (OSHA 2011).

There are health issues related to nuisance dust in the working environment. Potential symptoms from exposure to nuisance dust include irritation to skin, throat, or upper respiratory systems. Dust may also cause irritation to the eye, and in severe cases, may scratch the cornea. Exposure to wood or inorganic dusts may also cause allergic respiratory reactions, especially in people who suffer from asthma. However, not all dusts pose the same level of health hazards. OSHA (2011) lists the following factors that can make inorganic dust particles harmful:

- Dust composition
 - Chemical
 - Mineralogical
- Dust concentration
 - On a weight basis: milligrams of dust per cubic meter of air (mg/m³)
 - On a quantity basis: million particles per cubic foot of air (mppcf)
- Particle size and shape
 - The particulate size distribution within the respirable range
 - Fibrous or spherical
- Exposure time

Forest workers on biomass harvesting operations can be exposed to nuisance dust in many ways. On a whole tree chipping operation, most workers operate in enclosed machine cabs. Windows and doors are often opened during normal operations. One of the primary reasons to open doors or windows is to communicate with other workers on the job site. These communications are considered administrative delays in productive environments, so operators do not allow the ‘dust to settle’ prior to opening a window or door. Modern equipment cabs have a positive pressure which keeps dust out, but open windows bypass the machine’s cab air filtration system and may negatively impact the interior air quality.

Truck drivers are also in the landing area during active operations and exposed to nuisance dust. If a chip van has an open top, the truck driver often exits the truck’s cab to watch the operation and move the truck/trailer forward to achieve a full payload. If the chip van is loaded from the rear, chips are ‘blown’ in and fine airborne particles exit the trailer through screened openings in the van. Nuisance dust that becomes airborne due to machine activity near the chipping operation may affect the work environment for truck drivers.

Many of the other workers on biomass harvesting operations are exposed to nuisance dust. Measurements of dust concentrations are needed on a variety of biomass operations.

Ash Content/Biomass Quality

Inorganic elements in wood are often referred to as ash content in biomass. Some of these elements occur naturally in trees because they are brought into the tree from the soil through the root system and sap stream (Koch 1972). In processed biomass, inorganic soil particles that adhere to the tree are included in ash content.

Ash generally constitutes less than 0.5% of oven-dry loblolly (*Pinus taeda*) or longleaf pine (*Pinus palustris*) stemwood (Koch 1972). Needles of loblolly pine have been found to have an ash content of 2% (Metz and Wells 1965). Although this amount seems very small, it results in a residue after energy conversion processes. When biomass is burned in a boiler, everything that doesn’t completely combust can fuse together. This non-combusted material includes impurities, such as metal, sand and plastic; and the inorganic substances from biomass. This fused material can block the burning ports in a boiler so that the boiler doesn’t heat evenly or efficiently. Ash content is also very important when pelletizing woody biomass. The ash in biomass can cause wear on pellet die, reducing die life. In addition, residential pellet customers want premium pellets with low ash content to reduce the maintenance of removing ash from their wood stoves.

Ash content is often measured through destructive analysis by grinding the material very finely, then drying it in a muffle furnace (ASTM D-1102 2007). In the furnace, the organic material in the biomass burns off and the inorganic components are left in the bottom of the crucible. Ash content is usually

reported as a percentage of the oven-dry weight of wood. The resultant ash can be further analyzed for mineral content.

In 2006, pulp mills in Alabama were beginning to add limits to the ash content in their biomass delivery specifications (Mitchell 2006). Later, in 2008, biomass deliveries from land clearing operations were blocked from a mill using biomass as boiler fuel due to the high levels of ash in the material. The land clearing operation included pulling the stumps and grinding them along with other biomass material from a land clearing operation. Samples from this land clearing operation were found to contain an ash content range of 1 to 36% (Mitchell unpublished data). In another study, a front-end loader was used to feed biomass into a tub grinder and resulted in high ash percentages ranging from 20 to 65% (Rummer unpublished data). In these examples, equipment selection impacted the ash content in processed biomass.

Other sources of inorganic elements (ash) may occur as a result of the harvesting system. A variety of research is currently being conducted in the Research Work Unit to quantify the impacts of harvesting on feedstock characteristics. Researchers are studying whether the process of skidding whole trees from the stump to the landing increases the ash content in processed whole-tree biomass as opposed to trees that were forwarded or fully suspended during the extraction phase of harvesting. Another research topic related to ash content is quantifying the amount of ash in bark, stemwood, limbs and needles of sampled trees. These topics and more can provide information that can lead to improved harvesting techniques to increase the quality of biomass by reducing the ash content.

8.9b.2 Objective

The objective of this subtask was to quantify nuisance dust in the area around a biomass harvesting operation. Specifically, this subtask addressed safety issues (human health) related to air quality on landings of biomass harvesting operations. These dust measurements were compared to the OSHA standards to determine whether they are within the defined PEL. This subtask also analyzed the impact of air quality on processed biomass by measuring ash content, which may negatively affect the value of the forest product.

8.9b.3 Methods

Site Location/Logging Operation

Data were collected for two days on a logging operation in Butler County, Alabama. Equipment on the landing consisted of a Precision Husky WTC-2366 used in combination with a ForestPro flail. A TigerCat 240 tracked loader fed the flail machine and removed residues from between the flail and the chipper. A rubber-tired HydroAx 411E with a brush blade was used to pile flail and chipper rejects at the edge of the cleared landing. The study was installed in April, 2011. The text summarizes data from a clean chipping operation.

Air Sampling and Analysis Methods

An air sampler was used to measure the volume of particulate matter (mg m^{-3}) in the working environment during active chipping operations. One air sample was collected for each load, resulting in one observation per load of chips. The sampler was located close to the chipper in order to get a base line, or worst case, measurement (Figure 8.9.6). Exposure time for individual workers was not collected in this study.

Methodology outlined in NIOSH (2003) was followed for determining total dust using an Airchek model 224-PCXR7 air sampling system. Sampling was performed during the processing of nine loads of chips from a single clean chipping operation.

Airborne particles were collected in cartridges attached to an Airchek model 224-PCXR7 sampler. Each cartridge contained a polyvinyl chloride (PVC) filter (37 mm diameter, 5.0µm pore size) and was sealed to protect against external contamination. Filters were exposed on the sampler for the duration of time that it took to process one load of chips. Once an observation was completed, the sample cartridge was sealed (plugged) and stored upright in a cooler for transport to the laboratory.

Sampler airflow was measured and calibrated at the beginning and end of every observation using a Bios DryCal primary flow meter air calibrator. Any air flow differences in the calibration readings between the start and end of each observation were used for corrections. Due to the filter's sensitivity to oils and dust, some prepared cartridges were exposed on the landing to quantify any handling and storage of the prepared cartridges that could have impacted the results of the observations. These blank cartridges were used to determine if a correction factor was needed for the filter weights.



Figure 8.9.6. The air sampler was placed near the throat of the chipper.

Soil moisture content testing followed the methods outlined for standard bulk density testing methods (Grossman and Reinsch 2002). A soil sample was collected during each air sampling observation. Core soil samples were collected by driving 50 mm diameter metal corers into the soil. The samples were cut to 25 mm depth, labeled, sealed and stored in a cooler for transportation to the laboratory. The samples were cut to only include the top 25 mm depth of soil to better characterize the soil moisture on the soil surface. Samples were dried at 105°C for 24 hours, then reweighed. Soil type information was obtained using USGS soil maps.

Wood chips were collected to determine if there were any relationships between dust concentration, soil moisture content, and ash content in processed chips. Samples were collected in accordance with laboratory analysis procedures outlined by the National Renewable Energy Lab (Sluiter 2005). Chip moisture content was determined using methodology described in ASTM (2006) standard E-871 (standard test method for moisture analysis of particulate wood fuels). Ash content of the wood chip samples was determined using ASTM standard D-1102 (standard test method for ash in wood).

8.9b.4 Results

The basic descriptive statistics shown in Table 8.9.5 were calculated from the data collected. The current dataset was limited to nine observations because of the small tract size and limited delivery quota during the study period.

Table 8.9.5 Descriptive statistics for biomass and soil.

	N	Mean	Standard Deviation
Biomass ash content (%)	8	0.305	0.146
Biomass moisture content (%)	9	56.9	2.4
Soil moisture (%)	9	19.4	2.2
PNOR-area (mg/m³)	8	1.3	1.34

Air Quality

Exposure levels of the 9 air quality samples ranged in value from 0 to 11 mg m⁻³. The exposure level measured for load 5 was higher than the rest, and may be attributed to a blown hydraulic hose that sprayed fluid onto the air sampler. Removal of load 5 from the analysis resulted in an average exposure level of 1.3 mg m⁻³ for the remaining 8 observations, as shown in Table 1. These remaining 8 observations had exposure levels ranging from 0 to 4 mg m⁻³ (95% CI = 0.264 to 2.329 mg m⁻³). Exposure levels measured during this test are well within the PEL of 15 mg m⁻³ (OSHA 2011) for a working area, or less than 1% of allowable PNOR. Accuracy of these exposure levels could be increased in the future by using a 5-place balance as opposed to the 4-place balance used in this study.

Temperatures during the study ranged from 21 to 24 °C (70 to 76 °F). Relative humidity ranged from 40 to 73%. Relative humidity is usually low (<70%) during dust storms (Hagen and Woodruff 1973), therefore it is expected that dust levels would have been low during the field study.

Ash

The mean ash content analysis for 8 samples of clean chips (chip samples were not collected for load 5) was 0.31percent (95% CI = 24.7 – 36.2%). Low ash content was expected since the chips were processed through a flail prior to chipping (minimal bark and needles).

Since this field study includes only limited data, and was collected on a clean chipping operation, a simple analysis was performed to determine how much dust concentration would be necessary to impact the ash content in a load of biomass chips. An assumption of this analysis is that the total dust on the sampling filter is inorganic and considered ash. During data collection, processing times ranged from 39 to 81 minutes with an average time of 52 minutes. Therefore, the analysis includes a variety of processing times. Longer observation times may impact the amount of dust particles captured on the sampling filters.

The sensitivity analysis began by considering three levels of ash content acceptable in the delivered load. Pellet mills are sensitive to ash, so the lower limit for the analysis was set at 2%. Additional amounts of 5 and 10% ash were also included. Assumptions necessary for the analysis were that a load of biomass weighed 23.6 tonnes (26 tons) and contained 50% moisture. Ash is calculated on a dry biomass basis. At 2% ash, the load would contain 236 kg (520 lbs.) of ash. At 5 and 10%, the ash in a load would be 590 kg. (1,300 lbs.) and 179 kg. (2,600 lbs.), respectively. The Precision Husky WTC-2366 has an air flow rate of 311.485 m³ min⁻¹ (11,000 ft³ min⁻¹) and at various loading time periods, different total volumes of air would be blown through the chipper. Table 8.9.6 displays the dust concentrations that would have to

be sampled in order to reach various ash concentrations from accumulated total dust in the working environment, and without consideration of the ash in and on the biomass.

Table 8.9.6 Total accumulated ash (percent) based on dust concentrations and loading times.

Dust Concentration (mg m⁻³)	Processing Time					
	15	30	45	60	75	90
2	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0
17000	0.7	1.3	2.0	2.7	3.4	4.0
42000	1.7	3.3	5.0	6.7	8.3	10.0
84000	3.3	6.7	10.0	13.3	16.6	20.0

Longer loading times may contribute to higher ash contents solely based on the dust concentration in the working environment and the volume of air moved. However, the PEL for total dust concentration (OSHA 2011) is much lower than would be required to attribute 2% of ash content to nuisance dust. Based on this analysis, a load of chips should not have any discernable ash content due to dust in the working environment.

Soil

The soil type on this first test site was Luverne, sandy loam, on 5-8% slopes. This is a well drained soil type. Sandy loam soil types usually contain more sand than clay or silt. Sand particles are larger than clay or silt and could possibly explain the lack of ash collected on the air sampling filters.

Approximately 3.8 cm (1.5-inches) of rain fell on the test site the day before data collection began. Rainfall data were estimated using NOAA rainfall maps and the nearest weather station data. The Luverne soil type is characterized as being well-drained, and there was no standing water present on the site during chipping operations. The landing area had been cleared a week earlier in preparation of moving onto the site during the morning of the first day of data collection. Laboratory testing revealed that the average soil moisture on the site during data collection was fairly low, 19.4%. However, when equipment trafficked in the landing area, there were no visible signs of soil lifting into the air. One would expect clouds of dry matter to rise into the air with such low soil moisture. This may be partially explained by the type of chipping operation. Flail residues coupled with the chipper overs and unders created a layer of material that formed a mat on the operational area of the landing. This mat may have reduced the aerial soil dispersion.

8.9b.5 Summary

Analysis during somewhat favorable conditions had levels that were less than one percent of allowable nuisance dust for a working area. Future studies on a variety of soil types may indicate whether soil particle size has an impact on the air quality on biomass chipping operations. The mat of residues on the landing of this clean chipping operation may have helped the air quality on this study site by limiting airborne particles. Further testing on a variety of sites should also provide further insight into the relationship between soil type and biomass ash content.

Dust in the air sampler filters could be further analyzed using an ash test. This test would determine whether the source of the nuisance dust was organic or inorganic. The inorganic component would be

considered an impurity in the biomass, whereas the organic component could include wood dust and other particles that would not negatively impact the quality of the biomass produced.

The results of this analysis of air quality on biomass chipping operations are expected to be useful to land managers, loggers, and the biomass industry. Land managers could use the results of this study to determine whether dust abatement techniques would be warranted on their land during logging operations. Loggers, and their employees, could benefit by understanding the health exposure risks associated with biomass chipping operations. The biomass industry could benefit from the knowledge gained about the impact of air quality (nuisance dust) on biomass feedstock quality. Further analysis is needed to fully address the objectives of this study.

8.9b.5 Outputs

Mitchell, D. 2011. Air Quality on Biomass Harvesting Operations. In Proceedings of 34th International Meeting of the Council on Forest Engineering. Council on Forest Engineering, Morgantown, WV.

8.9b.6 References

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Task 9 – Data Analysis and Processing

9.1 Objective

The objective of this task was to develop harvest productivities and costs and system productivities and costs as a function of system configuration, forest stand characteristics, and feedstock characteristics. An analysis tool was developed to predict harvest costs given user-specified constraints.

9.2 Modeling Methods and Results

To summarize the findings of individual task studies, the group developed a model to predict costs FOB (i.e. biomass loaded on the truck at the landing) for the systems tested in this study. The model estimated productivity of in-woods operations using a stand density table and an estimate of either tree weight or total weight per acre, both based on DBH class, and estimates of skidding distance. The predicted machine productivities as a function of stand density and stand characteristics were based on the elemental time studies conducted on various stands in this overall project. The terrain on which the high tonnage system was tested did not vary enough to detect any productivity differences by terrain; therefore, the model does not account for any terrain effects.

Machine operating costs, or machine rates were calculated using the approach of Brinker and others (2002). Assumptions in the calculations common to all machines are shown in Table 9.1 and machine specific values are shown in Table 9.2

Table 9.1 Basic assumptions for machine rate calculations common to all machines.

Parameter	Value
Scheduled Hours per Year	2500
Interest Rate	10%
Fuel Cost, \$/gal	3.50
Insurance Rate, % of value	1.0
Property Tax Rate, % of value	0.1
Service Life, years	5
Lubrication Cost, % of fuel consumption cost	37

Table 9.2 Machine-specific assumptions for machine rate calculations. Conventional and high tonnage system options are shown.

Category		Machine				
		Conventional		High Tonnage		Chipper + Loader
		Feller Buncher	Skidder	Feller Buncher	Skidder	
Purchase Price		\$241,070	\$240,192	\$490,000	\$318,552	\$770,000
Salvage Value, % of purchase		20	25	50	25	20
HP		175	175	260	260	925
Fuel consumption (gal/HP-hour)		0.028	0.028	0.028	0.028	0.02292
Repair and Maintenance, % of depreciation		100	90	90	90	100
Tires (or tracks), \$ per set		\$12,000	\$12,000	\$22,000	\$24,000	\$23,000
	SMH per set	4,000	4,000	4,000	5,000	6,000
Consumable, \$ per (set)		\$1,000 (teeth)				\$1,000 (knives)
	Replacement interval, SMH	425				150
Consumable, \$ per (set)		\$8,500 (saw disk)				
	Replacement Interval, SMH	5,100				
Operator Pay, \$/hr		15	15	15	15	20
	Benefits, % hourly rate	30	30	30	30	40
Machine Rate, \$/SMH		\$88.38	\$81.05	\$121.48	\$105.70	\$262.67

Felling Productivity

Productivity of felling operations was modeled using two variables, (1) an average tree size for the stand, and (2) information about the machine itself related principally to the felling head. The second variable, which we have named the feller buncher ‘capacity’, is calculated using a relationship derived from production study data taken for the study. The model was developed using the following steps, first for the Tigercat 845D machine.

The data in Figure 9.1 show the number of trees collected by the machine in a cycle as a function of timber volume, which is represented using the natural log of the average stem DBH squared. The data show a great deal of variability, but there is also evident a threshold in average stem volume above which another tree seemingly could not be collected. This frontier was extracted from the plot and a nonlinear regression fit. Results are seen in Figure 9.2.

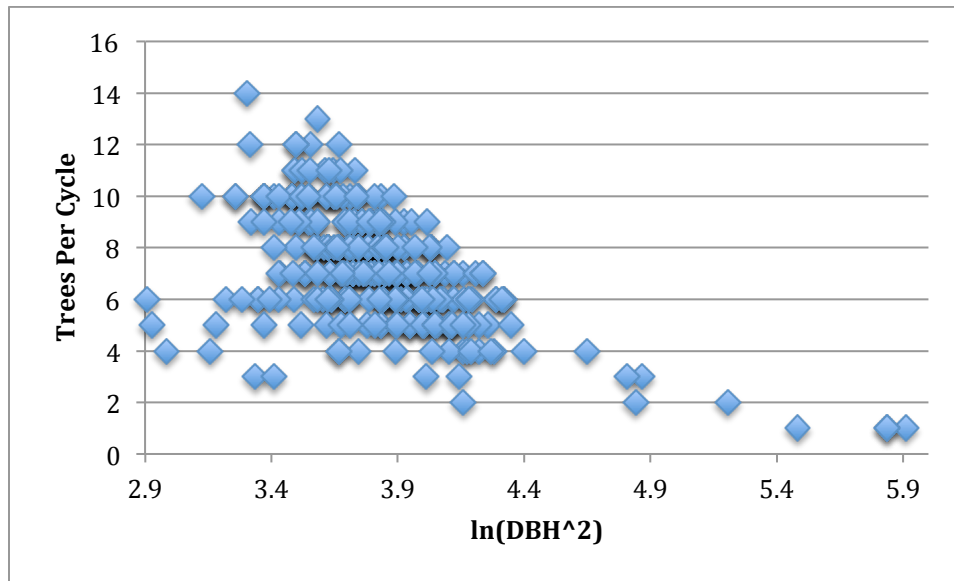


Figure 9. 1 Number of trees accumulated by the feller buncher in a cycle as a function of timber volume.

We suspected the capacity value would be representative of several operating characteristics related to the machine, including how the operator worked. And, because it could be predicted based only on the average tree size, it was a straightforward calculation.

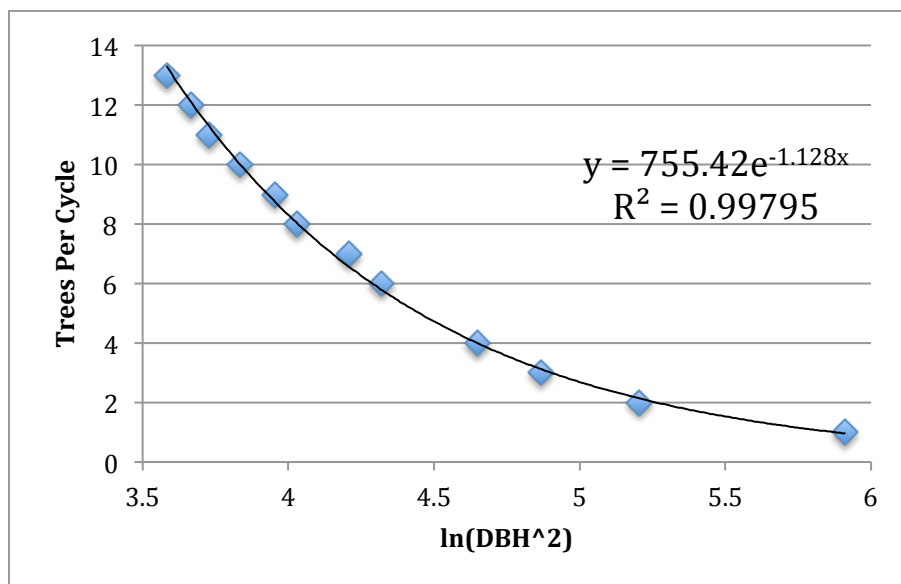


Figure 9. 2 Felling head capacity as a function of tree size.

Using the capacity value and average tree size to predict felling cycle time worked reasonably well (Figure 9.3), with a linear model including the two variables ($P < 0.001$ for both) explaining about 54% of the variability observed in the data. This was comparable to the typical approach of using the number of trees collected per cycle to predict cycle time. That relationship, shown in Figure 9.4, had $R^2 = 0.6$, somewhat higher than the method we used, but requiring someone to estimate an average number of trees cut per cycle, which may not be intuitively obvious when using the model for predictive purposes. Our approach substituted a single parameter, the average tree size, and did almost as well in predicting cycle times.

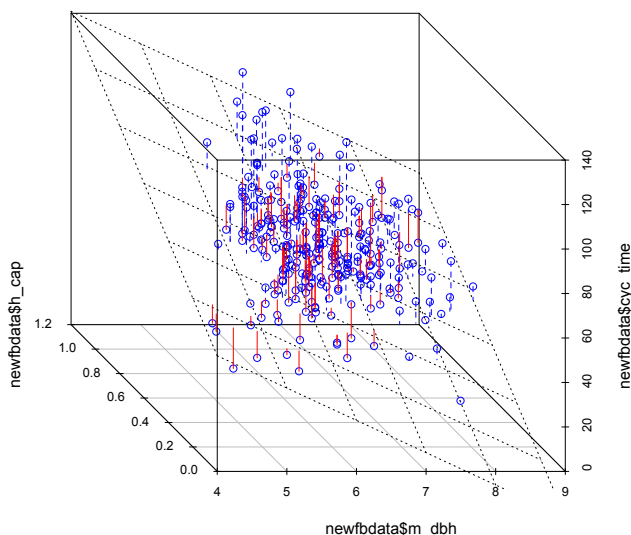


Figure 9. 3 Predicted felling cycle time as a function of tree size and capacity.

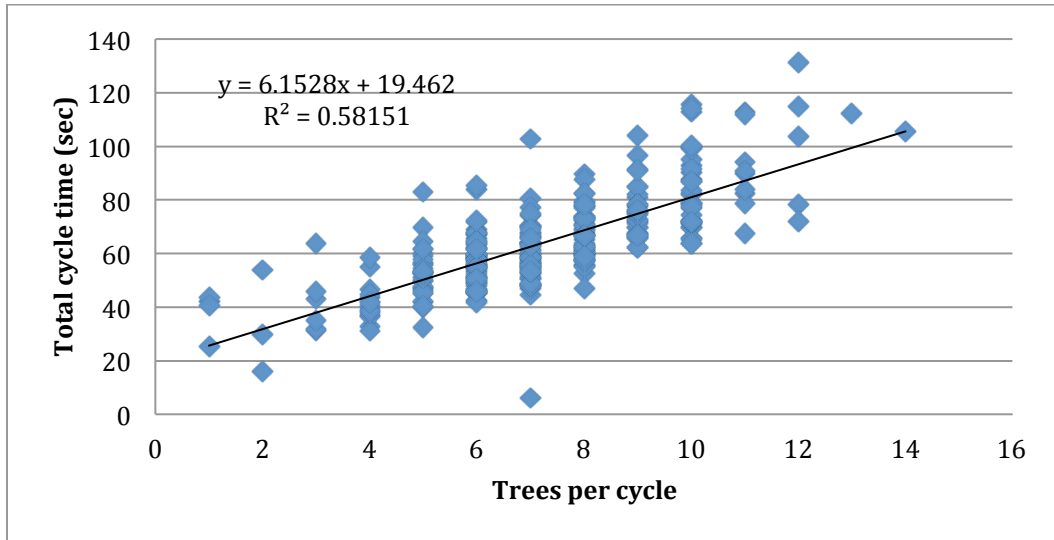


Figure 9. 4 Predicted felling cycle time of the Tigercat 845D based on number of trees per cycle.

The trees per accumulation vs. total stem volume relationship for the benchmark feller bunchers displayed a frontier similar to the Tigercat, except the nonlinearity was not evident (Figure 9.5) and the relationship was modeled using a linear regression instead of an exponential function.

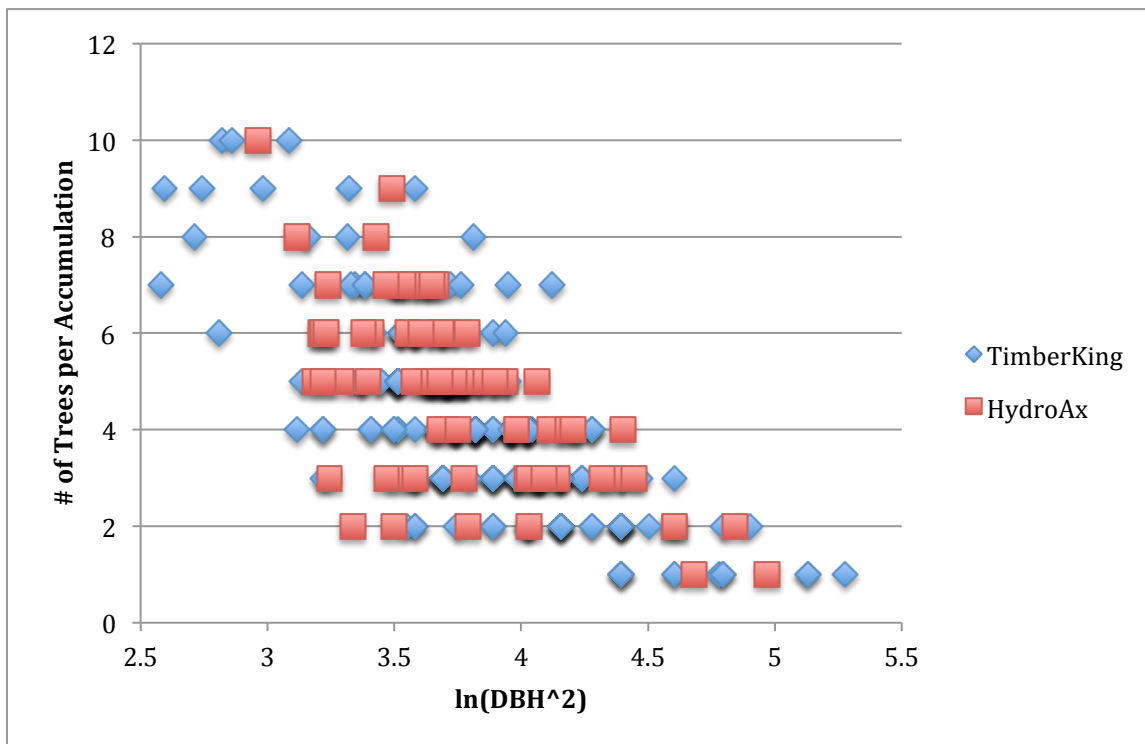


Figure 9. 5 Relationship between trees per accumulation in the felling head versus tree size for two conventional machines.

The predictive relationship between head capacity, tree size, and feller cycle time was also significant ($R^2 = 0.47$, Figure 9.6).

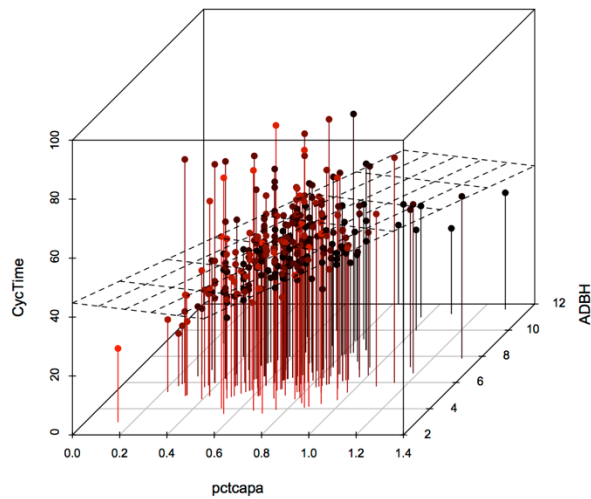


Figure 9. 6 Relationship between head capacity, tree size, and feller buncher cycle time.

The models were used in developing a spreadsheet tool for evaluating the effect of tree size on feller productivity. Results showed productivity of the Tigercat machine did not reduce as rapidly with average DBH below six in. as did the benchmark tree-length feller bunchers. Figures 9.7 and 9.8 show productivity and costs (per productive hour) estimated using the model. Productivity for the new feller buncher dropped by a factor of 2 when average DBH decreased from 10 to 4 in., but, for the benchmark systems, the predicted drop in felling productivity was nearly a factor of 10. For trees smaller than 6 inch DBH, however, the model predicted lower costs for the Tigercat 845D feller buncher and, above that threshold, costs remained similar for both machines. The largest difference in cost per ton between the two systems above six inch DBH was less than 30%.

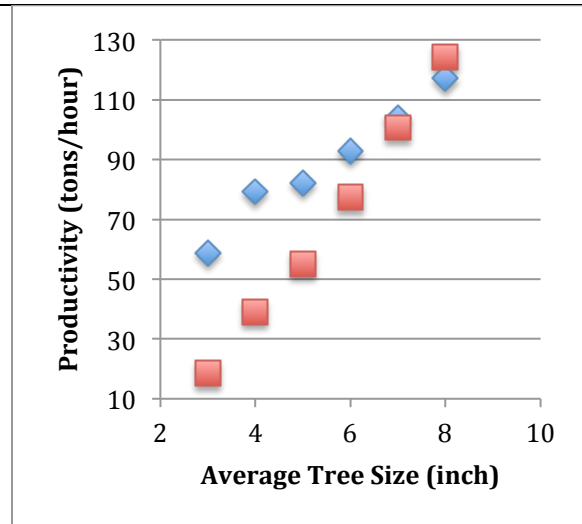


Figure 9. 7 Predicted productivity for the prototype Tigercat 845D (blue) and the Timber King wheeled (red) feller buncher as a function of tree size.

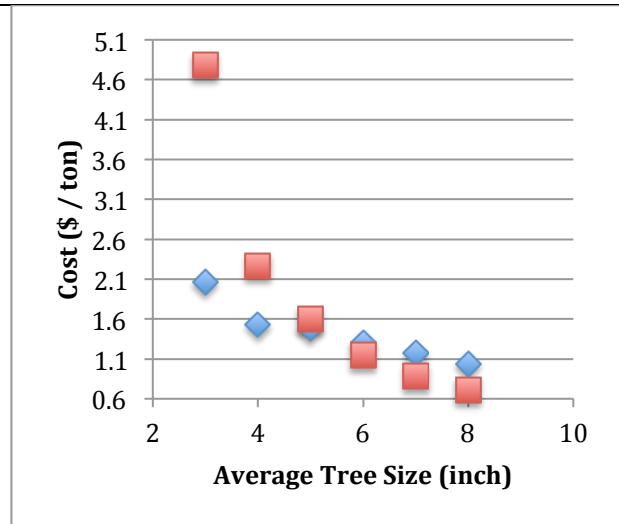


Figure 9. 8 Predicted felling cost for the prototype Tigercat 845D (blue) and the Timber King wheeled feller buncher (red) as a function of tree size.

Skidding Productivity

Models developed for skidding cycle times in all cases were based on elemental time study, with cycle elements including: travel empty, position and grapple, travel loaded, and deck operations. Travel time models were based on skid distances, and are summarized by machine type in table 9.3. All models were linear with the slope representing speed of travel and it was observed that both types of machines traveled at roughly the same speeds, loaded or empty, with the newer machine traveling slightly faster. Position and grapple times for both machine types were similar, but deck operations for the Tigercat system were over four times longer than the conventional systems (Table 9.3). We attributed this discrepancy to an inconsistent definition of time spent performing deck operations between the field studies.

Table 9.3 Linear regression model parameters for prediction of skidding productivity.

Cycle Element (all in minutes)	Machine System			
	Conventional		High Tonnage	
	Slope (Distance Factor, ft)	Intercept/Average	Slope (Distance Factor, ft)	Intercept/Average
Deck Operations		0.162		0.707
Travel Empty	0.0015743	0.30595	0.00146369	0.266562265
Position & Grapple		0.811		0.530
Travel Loaded	0.00191925	0.020625277	0.001864752	0.197372153

The largest difference in productivity between the skidder systems was not time-related, therefore, but almost exclusively due to payload. The new skidder averaged nearly twice the number of tons per trip compared to the conventional machine (6.6 vs 3.8), and costs per ton based on skidding alone were lower for the high tonnage machine down to skid distances of only 100 feet (Figure 9.9).

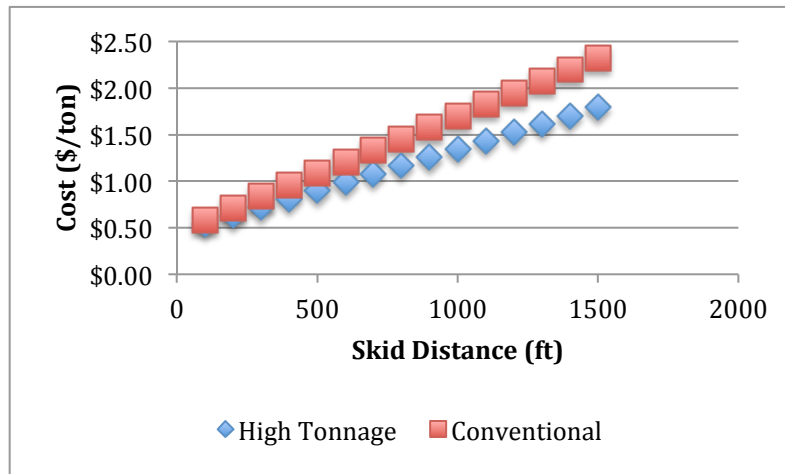


Figure 9.9 Predicted skidding cost as a function of skid distance for the high tonnage and conventional skidders.

Chipping Productivity

Elemental time study on the chipper was performed, but results did not reveal a significant relationship with tree size on productivity. The system model, therefore, used averages for production based on type of product. Table 9.4 summarizes observed productivities.

Table 9.4 Chipper productivity and cost based on machine rate calculations.

Product	Production Rate (gt/PMH)	Cost (\$/PMH)
Whole-tree microchips	70.7	3.71
Clean pulp chips	72.1	3.64
Whole-tree pulp chips	79.5	3.30

We observed about a 10% drop in productivity when using the flail, and about a 12% drop when producing microchips, compared to whole-tree regular chips.

Harvesting System Costs

The cost model sets a system-wide utilization rate based on a single machine then calculates productivity for each machine using that assumed value. It arrives at a limiting production rate, then uses that limiting value to set costs for the entire system.

The limiting production capacity in the observed systems was nearly always that of the chipper. Production of the chipper, in turn, was nearly always truck limited but, if trucks were always available for loading, the maximum utilization of the chipper would be about 80% given 5 minutes to swap an unloaded for a loaded van. That value was much higher utilization than observed in actual operation, but will be used in the following comparisons.

The cost comparison will be made between two different stands: a) an average of all the stands measured during the study, and b) a more densely planted stand cut at an earlier age. Characteristics of the stands are summarized in Table 9.5. The alternate stand was derived from estimates from the PTAeda growth model and corresponded to a spacing of approximately 7X8. The observed stand was an amalgamation of data from numerous tracts and represented an approximate spacing of 8X12.

Table 9.5 Stand characteristics for both stands used in system analyses.

DBH Class	Stand			
	Average Observed		Alternate	
	# Stems per Acre	Tons per Acre	# Stems per Acre	Tons per Acre
2	0	0	25	0.3
3	0	0	65	1.7
4	48	3	74	3.7
5	70	7	105	8.5
6	101	16	160	20
7	99	23	153	27
8	77	25	118	30
9	50	22	27	9
10	26	16	0	0
Sum	471	112	727	100

In-woods productivities and costs for each machine system are shown in Table 9.6. For these data, machine utilization was held constant at 80% and average skid distance was 530 feet on a 20-acre setting. The values shown by machine are independent of any other operation, so they are not representative of an operational scenario. They can, however, be used to evaluate the effect of stand characteristics and the difference between the conventional and high-tonnage systems. Production of both systems was lower on the stand with smaller trees. The drop in felling productivity between the observed and alternate stands was about 37% and 27% for the conventional and high-tonnage fellers, respectively. This was about what was expected given the lower sensitivity of the new feller to average tree size, but the difference in average DBH between the two stands was only about 1 inch (6.7 vs 5.9 inch, respectively for the observed and

alternate stands). Neither stand had average DBH that might result in a distinct advantage in productivity for the new feller.

Felling productivity was calculated based on skidder capacity, meaning time to fell included intermediate travel to build bunches targeting a nominal maximum skidder bunch size. Skidding productivity and costs, therefore, did not drop significantly between the two stands since bunch size remained near optimal. The slight increase observed in the conventional skidder between the two stands was an artifact of the bunch size calculations, which could only assume integer values for numbers of accumulations per bunch.

Table 9.6 In-woods model-derived productivity and cost for various functions in the conventional and high tonnage systems. Stand type refers to planting density, with the Observed data being an average all those stands harvested for the study for which data were available, and the Energy stand built using PTAeda at an initial stand density of 8x7 feet.

Stand	Conventional				High Tonnage			
	Felling		Skidding		Felling		Skidding	
	Productivity (gt/PMH)	Cost (\$/ton)	Productivity (gt/PMH)	Cost (\$/ton)	Productivity (gt/PMH)	Cost (\$/ton)	Productivity (gt/PMH)	Cost (\$/ton)
Observed	69.4	1.27	52.1	1.56	74.6	1.63	94.8	1.11
Alternate	43.5	2.03	58.8	1.38	54.1	2.25	92.6	1.14

System-level costs included chipping, which was assumed independent of average stem size. Chipping productivity was, therefore, 63.6 tons per scheduled machine hour regardless of stand type (79.5 gt/PMH at 80% utilization) and was the limiting operation in the observed stand for the high-tonnage system. For the alternate stand, felling was limiting, about 15% lower than the chipping operation. In the conventional system, on the other hand, skidding was the limiting operation in the observed stand, and felling for the alternate stand. The cost summary based on these limiting productivities is shown in Table 9.7. Total costs per green ton were slightly lower for the high-tonnage system in the observed stand (7.7%) and lower still in the alternate stand (9.5%), again illustrating the productivity advantage of the new system in trees with smaller average DBH.

Table 9.7 System cost summary based on a maximum single-machine utilization of 80%.

Operation	Stand Type			
	Observed		Alternate	
	Conventional Cost (\$/gt)	High Tonnage Cost (\$/gt)	Conventional Cost (\$/gt)	High Tonnage Cost (\$/gt)
Felling	1.69	1.91	2.03	2.25
Skidding	1.55	1.66	1.86	1.95
Chipping	5.04	4.13	6.03	4.86
Total	8.29	7.70	9.92	9.06

Since the chipping function limited the overall productivity of each of the systems listed in Table 9.7, a modified production system was proposed to determine if additional productivity gains and cost reductions could be achieved with the high productivity feller buncher and skidder by changing the chipping and overall operational model. The modified system used two chippers and skidders and it altered scheduled hours to decouple the felling operation. It was assumed the two chippers would operate on separate tracts at 50 scheduled hours per week, along with their respective skidders, and the single feller buncher would be run 7 days per week at maximum capacity (90 scheduled hours = 5 days double-shifted, + 1 weekend 10-hour shift, 80% utilization). This modified system operates in a mode where the feller buncher would now run closer to its full potential productivity. Also, by decoupling felling and skidding, the modified system should be more suited to a transpirational drying scheme. System productivity on the observed average stand for the above configuration would be limited by the chipping operation and costs to the chip van would be lower than the system as-tested (\$7.16/gt, 7% reduction). Table 9.8 contains a summary of the cost projections for this modified high tonnage system. No allowance was made in this analysis, however, for losses in productivity associated with the assumed double shifting of the feller. The feller, however, had 6% higher productivity than the chipper and could sustain some drop in productivity at night and not limit the system's productivity. This reserve in productivity was close to the drop observed in night operations during this study.

Table 9.8 Predicted productivity and cost for the modified high tonnage harvest system.

	Number of Machines	Scheduled Hours per Week	Productivity, (gt/SMH)	Green Tons per Week	Cost (\$/gt)
Felling	1	90	74.6	6718	\$1.37
Skidding	2	50	94.8	9484	\$1.66
Chipping	2	50	63.6	6362	\$4.13
Total					\$7.16

Another alteration in system configuration was simulated using the cost analyzer, this time changing the delivered product from biomass chips to green whole trees. This modified scheme could be used to maximize in-woods operational productivity, but would shift the cost of

chipping to the consumer. This may be an effective means of lowering overall cost provided there were some advantage gained in productivity using centralized, rather than dispersed, in-woods chipping. The centralized chipping approach would likely result in higher overall recovery of biomass, given trailers could be modified to haul the trees whole with minimal losses, but capital costs would be significantly higher for a central woodyard facility. Such systems have been used successfully for many years, however, in specific areas in the southern US to capture advantages inherent with the predominant feedstock species (slash pine).

Costs for the system are summarized in Table 9.9 for the two types of stands (Observed, and the more heavily stocked Alternate). The primary assumption made in the analysis was that the loading operation would never limit in-woods productivity. The productivity estimates available tended to support the idea that, without the need to delimb and stack, loading production was about 25% higher than that of both the high tonnage feller and skidder. The machine rate used in cost calculations for the loading operation was based on a tracked carrier costing \$250,000 and 200 HP. Results indicated much lower FOB costs than delivering chips, with the high tonnage system lower in both types of stands. Because the felling operation was limiting in the Alternate stand for both systems, costs per machine were not lowered, the additional advantages came strictly from the difference between loading whole tree and chipping. The same was true for the Observed stand in the conventional harvest system, except skidding had been limiting in that case. Costs per machine were lower in the high tonnage system and Observed stand, however, because it had been chipping limited in that scenario.

Table 9.9 Predicted productivity and cost for the high tonnage and conventional harvest systems loading whole trees.

Operation	Stand Type			
	Observed		Alternate	
	Conventional Cost (\$/gt)	High Tonnage Cost (\$/gt)	Conventional Cost (\$/gt)	High Tonnage Cost (\$/gt)
Felling	1.69	1.63	2.25	2.25
Skidding	1.55	1.42	1.86	1.95
Loading WT	1.82	1.27	2.18	1.76
Total	5.07	4.32	6.07	5.96

Transportation and Other Costs

Previous discussion in Section 8.6 showed that transportation costs can be reduced significantly through transpirational drying. When moisture content of the biomass is reduced to 35%, trucking costs of pulp size or micro chips can be reduced to \$10.77 per dry ton from \$15.91 per dry ton for green chips (at a representative 50-mile haul distance).

Other costs experienced by the logger include: 1) procurement costs, 2) mobilization costs, 3) overhead costs, 4) profit, and 5) stumpage or landowner payment. These costs will vary by the

individual logger and by the individual timber tract and therefore have not been included in these analyses.

Overall Harvest and Transport Costs

Overall harvest and transport costs are summarized in Table 9.10 on a dry ton basis for functions of felling, skidding, loading and chipping, and trucking using the alternate modeled stands. The conventional or traditional system costs are based on the assumption that transpirational drying is not conducted. The high tonnage system costs are based on the assumption that transpirational drying is utilized.

Table 9.10 System cost summary for conventional, high tonnage, and modified high tonnage systems with transpirational drying and trucking included. The high tonnage systems are using transpirational drying in this analysis.

Operation	Conventional Cost (\$/dt)	High Tonnage Cost (\$/dt)	Modified High Tonnage (\$/dt)	HighTonnage – Whole Tree (No Chipping) (\$/dt)
Felling	\$4.06	\$4.50	\$2.74	\$4.50
Skidding	\$3.72	\$3.90	\$3.32	\$3.90
Loading and Chipping	\$12.06	\$9.72	\$8.26	\$3.52
Trucking	\$15.91	\$10.77	\$10.77	\$10.77
Total	\$35.75	\$28.89	\$25.09	\$22.69

9.4 Discussion

The high tonnage felling and skidding system achieved significantly higher productivities than their traditional system counterparts. In the high tonnage system, the productivities of the feller buncher and skidder are relatively closely matched. However, in the actual system tested, the feller buncher and skidder can produce more biomass than the chipper can process. Therefore, the chipping function sets the overall system productivity at a lower level. Setting the system productivity at a lower level than the maximum potential of the feller buncher and skidder results in effectively lowering the utilization rate for both machines. When these lower utilization rates are coupled with the higher initial costs of the machines, the cost per ton of biomass produced is very near or slightly above the cost of the conventional system.

Achieving a more balanced system can be accomplished through at least two methods: 1) identify a higher capacity chipper to match the high productivity of the feller buncher and skidder, or 2) reconfigure the system to allow the feller buncher to work alone at its full productivity and fell trees for two crews; with each crew having one high productivity skidder and one loader and chipper. The option of using a larger chipper is possible, but in most forest situations in the U.S., the limiting factor will then become availability of trucks. For a chipper to

produce nearly 100 gt/hr, this would require loading about four trucks per hour. Such a high rate of trucks will require more area for staging the trucks at the deck and it will require a higher volume road to be able to move the trucks into and out of the forest. Frequently, the higher volume road, or larger truck staging area is not available. Therefore, the option of identifying a higher capacity chipper may be not be practical.

The second option of developing a modified high tonnage harvest system appears more feasible when considering the transportation system constraints. This system requires fewer trucks in and out of a given tract, which will lead to reduced truck interaction and more efficient operations. In the modified high tonnage system (with one feller buncher serving two crews, each with one skidder, loader, and chipper), the overall system cost, with transpirational drying, was reduced to an estimated \$23.99 per dry ton (delivered cost for a 50-mile haul distance). This system results in the lowest overall delivered cost when compared to the traditional system, or the original high tonnage system.

9.5 Summary

A spreadsheet model was developed to predict individual machine and overall system productivity and cost for the high tonnage system operating in various stand conditions. This modeling framework is based on the relationships developed through elemental time studies of the machines working in various stand and terrain conditions.

The model framework illustrated how the high tonnage machines were able to work in pine stands that had smaller diameter trees planted at higher densities without suffering major reductions in their productivity. These results validate the overall design of the high tonnage feller buncher with the high capacity shear felling head and the high productivity skidder.

The original high tonnage harvest system resulted in a feller buncher and skidder with higher productivities than the chipper selected for the study. This resulted in lowering the effective utilization and increasing the operating costs of the machines so that they had costs very near or slightly higher than the conventional system. When a modified high tonnage system was developed (one feller buncher serving two crews), the resulting system had a lower overall harvest cost than the traditional system. When transpirational drying was incorporated into the high tonnage and modified high tonnage systems, the final delivered costs were \$25.37/dt and \$23.99/dt, both of which were several dollars less than the \$29.89/dt for the conventional system.

9.6 References

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Appendices

Appendix A.
Equipment Information

Tigercat 845D

Tigercat 630D

Precision Husky WTC 2675



The 845D series feller bunchers are quick, agile and well suited to plantations, natural stands and small diameter/high cycle applications. The 845D also has the power and stability to handle larger timber. The L845D is equipped with a super-duty FH400 leveling undercarriage for high performance and stability on slopes.

BENEFITS AND ADVANTAGES:

Powerful, efficient Tigercat FPT Tier 4f engine

- Extremely quiet and fuel efficient
- Simple, reliable SCR emission control technology

Efficient high-capacity cooling system

- Automatic variable fan speed for improved fuel efficiency
- Automatic reversing cycle to clean the heat exchangers
- Rear cooling air intake is well away from saw discharge

ER boom technology unique to Tigercat

- Increases productivity, performance and fuel efficiency
- Smooth planar boom motion reduces operator fatigue
- ER control switch provides a boost for extra stick force
- Structural parts are well proven in high cycle applications

Quiet, climate controlled operator's station

- Full length front window for a clear view of the tracks
- High output heater/air conditioner with multiple vents
- Extreme duty air-ride suspension seat
- Generous storage space behind the seat

Tigercat-built forest duty undercarriages

- F8 non-leveling or FH400 leveling
- Long track frames for excellent stability on slopes

Super-duty leveling system

- Large pins, roller bearings eliminate wear in pivot joints
- Frames are built with thick steel sections to minimize flex
- Field-proven in over 1,000,000 hours of operation

Highly durable design and construction

- Solid steel one-piece turntable and smooth, impact resistant engine enclosure

Excellent service and component access

- Clamshell style retracting roof for excellent access to the engine, major components and service points
- The pumps and filters are housed in a separate, easily accessed compartment
- Large clean-outs underneath

SPECIFICATIONS

845D

L845D

DIMENSIONS with 610 mm (24 in) double grouser shoes

WIDTH	3 380 mm (133 in)	3 430 mm (135 in)
LENGTH less boom	4 900 mm (193 in)	4 900 mm (193 in)
HEIGHT less skylight	3 360 mm (132 in)	3 730 mm (147 in)
GROUND CLEARANCE	710 mm (28 in)	685 mm (27 in)
WEIGHT less head	25 900 kg (57,100 lb)	32 480 kg (71,600 lb)
TAIL SWING over side	990 mm (39 in)	1 040 mm (41 in)

POWER

ENGINE	Tigercat FPT N67 Tier 4f, 210 kW (282 hp) @ 2,200 rpm	Tigercat FPT N67 Tier 4f, 210 kW (282 hp) @ 2,200 rpm
COOLING	Aluminum side-by-side radiator, oil cooler and charge air cooler; Removable intake debris screen	Aluminum side-by-side radiator, oil cooler and charge air cooler; Removable intake debris screen
FAN	Hydraulically driven, automatic variable speed, reversible	Hydraulically driven, automatic variable speed, reversible
FUEL CAPACITY usable	800 L (210 US gal)	800 L (210 US gal)
DEF CAPACITY	80 L (21 US gal)	80 L (21 US gal)

HYDRAULIC SYSTEM

PUMP, MAIN	Piston	Piston
PUMP, SAW	Piston	Piston
PUMP, CLAMP/ACCUM. ARMS	Piston	Piston
PUMP, COOLING FAN	Piston	Piston
RESERVOIR	190 L (50 US gal)	190 L (50 US gal)
FILTRATION	(5) Spin-on, 7 micron full flow; (1) Water absorbing	(5) Spin-on, 7 micron full flow; (1) Water absorbing
CYLINDER, HOIST	140 mm (5.5 in) bore	140 mm (5.5 in) bore
CYLINDERS, STICK/ER	(2) 110 mm (4.3 in) bore	(2) 110 mm (4.3 in) bore
CYLINDER, TILT	120 mm (4.7 in) bore	120 mm (4.7 in) bore
CYLINDERS, LEVELING	N/A	(2) 180 mm (7 in) bore
HORSE POWER CONTROL	Electronic speed sensing; All-speed antistall	Electronic speed sensing; All-speed antistall

UNDERCARRIAGE

TRACK FRAMES	R6-140-3 heavy-duty forestry; Integral track guides, ramp angles	R7-150L-2 super-duty leveling; Integral track guides, ramp angles
TRACK CHAIN	F8/D6D 203 mm (8 in) pitch sealed and greased	FH400 215 mm (8.5 in) pitch
FINAL DRIVE	(2) Axial piston motors with brakes valves Infinitely variable speed; Infinitely variable speed	(2) Axial piston motors with brakes valves Infinitely variable speed; Infinitely variable speed
TRACTIVE EFFORT	262 kN (59,000 lbf)	367 kN (82,600 lbf)
GEARBOX	Triple reduction planetary type with brake	Triple reduction planetary type with brake
FRONT IDLER	Hydraulic track adjuster; Spring shock absorber	Hydraulic track adjuster; Spring shock absorber
SLIDES, UPPER	Replaceable, bolt-on; Optional rollers	Replaceable, bolt-on
ROLLERS, LOWER	(9) D6 single and double flange tractor type	(9) FH400 single/double flange excavator type
TRACK SHOE	610 mm (24 in) single/double grouser Optional 710 mm (28 in) single grouser tri-track 760 mm (30 in) double grouser tri-track 915 mm (36 in) triple grouser tri-track	610 mm (24 in) single grouser 710 mm (28 in) single grouser
LEVELING	N/A	20° forward; 6° rear; +/-17° side

TOP SPEED

LOW RANGE	1.9 km/h (1.2 mph)	1.8 km/h (1.1 mph)
HIGH RANGE	4.2 km/h (2.6 mph)	4.2 km/h (2.6 mph)

BRAKES

TRACK	Friction disc; Automatic spring applied, hydraulic release	Friction disc; Automatic spring applied, hydraulic release
SWING	Friction disc; Manual spring applied, hydraulic release	Friction disc; Manual spring applied, hydraulic release

ROTATING UPPER

SWING DRIVE	7 rpm variable speed; 360° continuous rotation; Double reduction, swing drive planetary gearbox with brake; Piston swing motor
SWING BEARING	1 190 mm (47 in) ball circle diameter
ENCLOSURE	Hydraulically operated, retracting roof; Hinged access doors for engine and pump stack; Rear air intake for cooling system and engine

ER BOOM SYSTEM with 5702 saw; 30° wrist

MAXIMUM CUT RADIUS	8 050 mm (317 in)	8 050 mm (317 in)
MINIMUM CUT RADIUS	4 165 mm (164 in)	4 165 mm (164 in)
BARE PIN LIFT full reach	6 215 kg (13,700 lb)	6 215 kg (13,700 lb)

SPECIFICATIONS

845D

L845D

OPERATOR'S STATION

CAB	Insulated, pressurized, isolation mounted; A/C, heater, defroster with side-mount controls; Skylight or flat hatch Full length polycarbonate windshield/entry door; Polycarbonate right-side and rear windows; Tempered glass side door window High visibility machine monitoring system with warning horns; AM/FM digital stereo with CD player; (2) Power points
CONTROLS	Hydraulic proportional for boom/travel/swing with electronic travel speed control limiter Electronic for clamp/accumulating arms/wrist/leveling; Electric switch for swing brake IQAN MD3 colour display for machine monitoring and function adjustment
SEAT	Full suspension air ride, fully adjustable with angled mounting; Armrest mounted Tigercat joysticks

ELECTRICAL

BATTERY	(2) 12 v	(2) 12 v
ALTERNATOR	140 amp, 24 v	140 amp, 24 v
SYSTEM VOLTAGE	24 v	24 v
LIGHTING	(9) Halogen; (3) Service, engine enclosure	(9) Halogen; (3) Service, engine enclosure
Optional	(7) HID; (1) Halogen; (3) Service, engine enclosure	(7) HID; (1) Halogen; (3) Service, engine enclosure

OTHER STANDARD EQUIPMENT

Power-link; Fuel suction strainer; Alarm for track movement	Power-link; Fuel suction strainer; Alarm for track movement; Toolbox
---	--

OPTIONAL EQUIPMENT

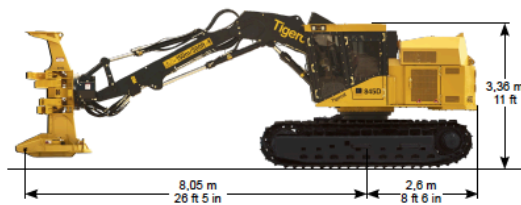
Various counterweights; High rotation wrists: 110°, 340°; Cold weather kit; Bolt-on toolbox	Cold weather kit; High rotation wrists: 110°, 340°
Ground level fueling system; R6-140-5, R6-152 undercarriages; High-flow fuel filter	Ground level fueling system; High-flow fuel filter

FELLING HEAD

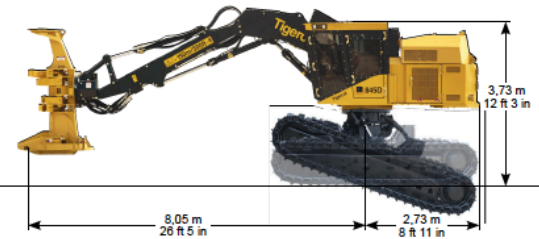
Flexible hydraulic system to accept various felling heads	Flexible hydraulic system to accept various felling heads
---	---

TIGERCAT RESERVES THE RIGHT TO AMEND THESE SPECIFICATIONS AT ANY TIME WITHOUT NOTICE

845D FELLER BUNCHER



L845D FELLER BUNCHER



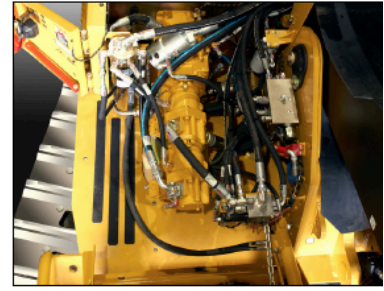
Tigercat FPT emission technology is simple and reliable, meeting Tier 4 emission standards without the complexities of a variable geometry turbocharger, EGR system, intake throttle body or diesel particulate filter. The key is the patented selective catalyst reduction (SCR) system. Tigercat FPT engines offer improved reliability and lower long-term maintenance costs.

TIGERCATPOWER.
TIGERCATSUPPORT.

High speed, high performance, high efficiency. Tigercat's patented ER technology allows the machine operator to extend and retract the boom on a horizontal plane smoothly and quickly using a single joystick. But the benefit goes beyond reducing operator fatigue.

Key to ER technology is reduced energy consumption. The ER system transfers energy back and forth between the main and the stick boom functions, reducing the total energy required to move the boom system. This reduces demands for power, pump flow and system cooling. The result is increased productivity and reduced fuel consumption per unit of production.

ER
technology



Painless maintenance routines. Excellent access to both sides of the engine and all daily service points through the swing-out doors. Hydraulic pumps are housed in a compartment separate from the engine.



Clamshell-style engine enclosure for full, easy access to all major components including the engine, cooling system and valves. Neat hose and electrical routings.



Tight-tuck boom geometry and excellent sightlines to the right side.



Efficient ER boom technology.



Rear intake is well away from the saw discharge area.



Floor to ceiling windshield.

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Tigercat



Tigercat®

620D/630D/635D SKIDDERS

The Tigercat D-series are the world's most advanced, efficient and productive skidders.

The unique drive system combines hydrostatics with electronic control technology, delivering wood to roadside at the lowest cost in a variety of terrain conditions, tree sizes and species.

The new Turnaround™ seat with rear-facing drive control is a major advancement in ergonomics and operator comfort.

TURNaround

BENEFITS AND ADVANTAGES:

- **Powerful and efficient Cummins Tier III engine**
 - Automatic variable engine speed for high fuel efficiency
 - Operator controlled maximum speed setting
- **High capacity cooling system**
 - Automatic variable pitch fan for reduced fuel consumption in cold climates
- **Enhanced hydrostatic drive system**
 - Extremely efficient driveline
 - Excellent performance in adverse terrain
- **Advanced electronic control system**
 - Enhanced for improved user interface and better fuel economy
 - Provides precise control of all machine functions
- **Standard axles are approved for flotation or dual tire configurations**
- **Designed and built for extreme duty**
 - Strength optimized frames; Strong centre section
- **Excellent service access**
 - Spacious engine enclosure
 - Tilt cab for access to pumps, motors and driveline
- **Turnaround™ equipped operator's station**
 - Two-position Turnaround™ seat with ergonomic joystick steering and full rear-facing drive controls
 - Grapple and arch functions controlled by one joystick
 - Excellent visibility to the sides of the engine house
- **Large capacity Tigercat dual cylinder grapples**
 - Choice of plate or box tongs
 - Widest tip-to-tip openings in each size class to quickly gather scattered bunches

SPECIFICATIONS 620D

630D

635D

DIMENSIONS with standard tires and arch

LENGTH.....	7 240 mm (285 in).....	7 495 mm (295 in).....	9 350 mm (368 in)
WHEELBASE.....	3 940 mm (155 in).....	4 190 mm (165 in).....	5 105 mm (201 in)
WIDTH.....	3 330 mm (131 in).....	3 330 mm (131 in).....	3 330 mm (131 in)
Narrow offset.....	3 020 mm (119 in).....	3 020 mm (119 in).....	3 125 mm (123 in)
HEIGHT.....	3 150 mm (124 in).....	3 150 mm (124 in).....	3 150 mm (124 in)
GROUND CLEARANCE.....	635 mm (25 in).....	635 mm (25 in).....	635 mm (25 in)
WEIGHT.....	16 440 kg (36,250 lb).....	16 895 kg (37,250 lb).....	21 430 kg (47,250 lb)

POWER

ENGINE.....	Cummins QSB6.7 Tier III 164 kW (220 hp) @ 2,200 rpm Preecleaner and 2-stage engine air cleaner	Cummins QSB6.7 Tier III 194 kW (260 hp) @ 2,200 rpm Preecleaner and 2-stage engine air cleaner	Cummins QSB6.7 Tier III, 194 kW (260 hp) @ 2,200 rpm Preecleaner and 2-stage engine air cleaner
TOP SPEED.....	19 km/h (12 mph).....	19 km/h (12 mph).....	14 km/h (9 mph)
COOLING.....	Side-by-side aluminum radiator, oil cooler, charge air cooler and A/C condenser	Side-by-side aluminum radiator, oil cooler, charge air cooler and A/C condenser	Side-by-side aluminum radiator, oil cooler, charge air cooler and A/C condenser
FAN.....	Fixed pitch, blower.....	Flexxaire® variable pitch, reversing.....	Flexxaire® variable pitch, reversing
Optional.....	Flexxaire® variable pitch, reversing.....	N/A.....	N/A
FUEL CAPACITY usable.....	305 L (81 US gal).....	305 L (81 US gal).....	305 L (81 US gal)
Optional.....	585 L (155 US gal).....	585 L (155 US gal).....	585 L (155 US gal)

POWER TRAIN

TRANSMISSION.....	Single-speed mechanical.....	Single-speed mechanical.....	Single-speed mechanical Variable speed hydrostatic
.....	Variable speed hydrostatic (2) variable displacement motors	Variable speed hydrostatic (2) variable displacement motors	Variable speed hydrostatic (2) Piston motors, infinitely variable
AXLE, FRONT.....	SD Inboard planetary.....	SFD, outboard planetary.....	SFD, outboard planetary
.....	+/-15° oscillation	+/-15° oscillation	+/-15° oscillation
AXLE, REAR.....	SD Inboard planetary.....	SFD, outboard planetary.....	Tigercat extreme duty tandem bogie, outboard planetary
Optional.....	SFD, outboard planetary, front and rear.....	N/A.....	N/A
DIFFERENTIAL LOCKS.....	Independent front and rear.....	Independent front and rear.....	Independent front and rear

HYDRAULIC SYSTEM

PUMP, DRIVE.....	Piston.....	Piston.....	Piston
PUMP, MAIN 1.....	Piston for all machine functions.....	Piston for all machine functions.....	Piston for all machine functions
PUMP, MAIN 2.....	Gear for cooling.....	Gear for cooling.....	Gear for cooling
FILTRATION.....	(2) spin-on, 7 micron full-flow.....	(2) spin-on, 7 micron full-flow.....	(2) Spin-on, 7 micron full-flow
CYLINDERS, ARCH.....	(2) 100 mm (4 in) bore (single function).....	(2) 100 mm (4 in) bore (single function).....	(4) 115 mm (4.5 in) bore (dual function)
.....	(4) 100 mm (4 in) bore (dual function)	(4) 100 mm (4 in) bore (dual function)	
CYLINDERS, STEER.....	(2) 85 mm (3.25 in) bore.....	(2) 85 mm (3.25 in) bore.....	(2) 85 mm (3.25 in) bore
CYLINDERS, BLADE.....	(2) 90 mm (3.5 in) bore.....	(2) 90 mm (3.5 in) bore.....	(2) 90 mm (3.5 in) bore
RESERVOIR.....	105 L (28 US gal).....	105 L (28 US gal).....	105 L (28 US gal)

BRAKES

DYNAMIC BRAKING.....	Hydrostatic.....	Hydrostatic.....	Hydrostatic
SECONDARY BRAKES.....	Enclosed, oil cooled.....	Enclosed, oil cooled.....	Enclosed, oil cooled
PARK BRAKE.....	Caliper; Spring applied/hydraulic release.....	Caliper; Spring applied, hydraulic release.....	Caliper; Spring applied, hydraulic release

TIRES

STANDARD.....	30.5Lx32,20.....	30.5Lx32,20.....	30.5Lx32,26 (front); 28Lx26,16 (rear)
OPTIONAL.....	30.5Lx32,26; 35.5x32,24; 73x44-32,16.....	30.5Lx32,26; 35.5x32,24; 73x44-32,16.....	See next page*

ARCH

STANDARD.....	Single function, continuous rotate.....	Single function, continuous rotate.....	Dual function, high lift, continuous rotate
OPTIONAL.....	Dual function, continuous rotate.....	Dual function, continuous rotate.....	N/A

GRAPPLE

STANDARD.....	Tigercat 1,39 m² (15 ft²).....	Tigercat 1,58 m² (17 ft²).....	Tigercat 1,95 m² (21 ft²)
.....	2-cylinder, plate or box tong	2-cylinder, plate or box tong	2-cylinder, plate or box tong
MAXIMUM OPENING.....	3 505 mm (138 in).....	3 630 mm (143 in).....	3 810 mm (150 in)
OPTIONAL.....	Tigercat 1,58 m² (17 ft²).....	Tigercat 1,76 m² (19 ft²).....	Tigercat 2,32 m² (25 ft²)
.....	2-cylinder, plate or box tong.....	2-cylinder, plate or box tong	2-cylinder, plate or box tong
MAXIMUM OPENING.....	3 630 mm (143 in).....	3 710 mm (146 in).....	3 835 mm (151 in)

BLADE

WIDTH.....	2 285 mm (90 in).....	2 285 mm (90 in).....	2 285 mm (90 in)
with optional extensions.....	2 920 mm (115 in).....	2 920 mm (115 in).....	2 920 mm (115 in)

ELECTRICAL

BATTERY.....	(2) 12 v.....	(2) 12 v.....	(2) 12 volt
ALTERNATOR.....	80 amp, 24 v.....	80 amp, 24 v.....	80 amp
SYSTEM VOLTAGE.....	24 v.....	24 v.....	24 v

SPECIFICATIONS	620D	630D	635D
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OTHER STANDARD EQUIPMENT

Alarm for reverse drive; Fuel suction strainer Fire extinguisher; Pressurized water system Fenders	Alarm for reverse drive; Fuel suction strainer Fire extinguisher; Pressurized water system Fenders	Alarm for reverse drive; Fuel suction strainer Fire extinguisher; Pressurized water system Fenders
--	--	--

OPTIONAL EQUIPMENT

Hydraulic winch; Halogen lighting package HID lighting package; Cold weather kit	Hydraulic winch; Halogen lighting package HID lighting package; Cold weather kit	Hydraulic winch; Halogen lighting package HID lighting package; Cold weather kit
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OPERATOR'S STATION

CAB Insulated, pressurized and isolation mounted; Air conditioner/heater/defroster; (2) doors with sliding side windows and hinged screens
Forward sloping windshield; Machine monitoring system with LCD display; AM/FM digital stereo CD, CB radio

SEAT Extreme duty Turnaround™, air ride; Fully adjustable height, seat back recline, lumbar support and armrests
2-position mechanical lock, 100° rotating for rear-facing drive

OPERATOR CONTROLS ... Electronic, joystick for arch/grapple/blade/steering; Electronic, foot pedal, front and rear with forward/reverse selector switch for drive
IQAN MD3 colour display for machine monitoring and function adjustment

TIGERCAT RESERVES THE RIGHT TO AMEND THESE SPECIFICATIONS AT ANY TIME WITHOUT NOTICE

TIGERCAT 620D SKIDDER



TIGERCAT 630D SKIDDER



TIGERCAT 635D SKIDDER



*Optional 635D front/rear tire configurations (2) 30.5Lx32,26 (4) 750/55X26.5
(2) 35.5Lx32,24 (4) 750/55X26.5
(2) 35.5Lx32,24 (4) 73/44.00x32,16PR
(2) 35.5Lx32,24 (4) 30.5Lx32,26



Clear sight line to the sides of the engine compartment



Turnaround™ provides full rear facing drive controls



Reduced neck strain when traveling in reverse or gathering a bunch



Easy access to both sides of the engine and all service points



Tilting cab to access pumps and driveline



Outboard planetary SFD (severe forest duty) axles are well guarded



Strong centre section with large pins and tapered roller bearings



High capacity dual cylinder grapples and high visibility arch



All D-series models are standard equipped for dual or flotation tires



The six-wheel drive 635D is ideal for extreme duty applications



The 620D is versatile for plantation thinning and clear fell applications

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Tigercat



KBL Unit	Model 1858	Model 2366	Model 2675	Model 3086
Height:	13'-6" [4.1m]	13'-6" [4.1m]	13'-6" [4.1m]	13'-6" [4.1m]
Width:	9'-7" [2.9m]	11'-11" [3.63m]	11'-6" [3.5m]	11'-6" [3.5m]
Length:	25'-0" [7.6m]	39' [10.9m]	45'-4" [13.8m]	45'-4" [13.8m]
Weight:	Approx. 50,400 lbs. [22909kg]	Approx. 75,400 lbs. [34,200kg]	Approx. 91,000 lbs. [41,363kg]	Approx. 96,000 lbs. [43,637kg]
Suspension:	Rocker Beam	3-Axle, Spring	3-Axle, Spring	3-Axle, Spring
Spout Opening:	18" [457mm] x 32" [813mm]	23" [584mm] x 48" [1219mm]	26" [660mm] x 48" [1219mm]	30" [762mm] x 48" [1219mm]
Feed System (Hydraulic)				
Top Roll Length:	31" [787mm]	48" [1219mm]	48" [1219mm]	48" [1219mm]
Top Roll Diameter:	21" [533mm]	21" [533mm]	21" [533mm]	21" [533mm]
Bottom Roll Length:	31" [787mm]	46" [1168mm]	N/A	N/A
Bottom Roll Diameter:	21" [533mm]	21" [533mm]	N/A	N/A
Spout Roll Length:	31" [787mm]	46" [1168mm]	N/A	N/A
Spout Roll Diameter:	21" [533mm]	21" [533mm]	N/A	N/A
Infeed Chain Conveyor	N/A	N/A	15' [4.57m] Length	15' [4.57m] Length
Power Options	500HP [373 kw] Diesel Engine	875HP [653 kw] Diesel Engine	875HP [683 kw] to 1050HP [783 kw] Diesel Engine	875HP [683 kw] to 1050HP [783 kw] Diesel Engine
Standard Equipment	58" [1473mm], 3-Knife, Left Hand Precision Chipper	66" [1676mm], 3-Knife, Left Hand Precision Chipper	75" [1905mm], 3-Knife, Left Hand Precision Chipper	86" [2185mm], 3-Knife, Left Hand Precision Chipper
	170 Gallon [644L] Hydraulic Tank	300 Gallon [1135L] Hydraulic Tank	300 Gallon [1135L] Hydraulic Tank	300 Gallon [1135L] Hydraulic Tank
	135 Gallon [511L] Fuel Tank	300 Gallon [1135L] Fuel Tank	300 Gallon [1135L] Fuel Tank	300 Gallon [1135L] Fuel Tank
	Fully Steerable Discharge Pipe Hydraulically Controlled from Operator's Cab	Fully Steerable Discharge Pipe Hydraulically Controlled from Operator's Cab	Fully Steerable Discharge Pipe Hydraulically Controlled from Operator's Cab	Fully Steerable Discharge Pipe Hydraulically Controlled from Operator's Cab
	PT Tech Hydraulic Wet Clutch	PT Tech Hydraulic Wet Clutch	PT Tech Hydraulic Wet Clutch	PT Tech Hydraulic Wet Clutch
	Rocker Beam Suspension with 255/70R22.5 Steel Belted Tires.	3-Axle Spring Suspension with 255/70R22.5 Steel Belted Tires.	3-Axle Spring Suspension with 255/70R22.5 Steel Belted Tires.	3-Axle Spring Suspension with 255/70R22.5 Steel Belted Tires.
	Hydraulic Powered Stabilizers	Hydraulic Powered Stabilizers	Hydraulic Powered Stabilizers	Hydraulic Powered Stabilizers
Also Standard for KBL Units	Husky XL-175 Knuckle Boom Log Loader	Husky XL-175 Knuckle Boom Log Loader	Husky XL-245 Knuckle Boom Log Loader	Husky XL-245 Knuckle Boom Log Loader
	Operator's Cab, with Sliding Window and Door, Hydraulically Tilts for Transport.	Operator's Cab, with Sliding Window and Door, Hydraulically Tilts for Transport.	Operator's Cab, with Sliding Window and Door, Hydraulically Tilts for Transport.	Operator's Cab, with Sliding Window and Door, Hydraulically Tilts for Transport.
	Complete Engine and Gauge Panel In Cab with Engine Start / Stop Switches	Complete Engine and Gauge Panel In Cab with Engine Start / Stop Switches	Complete Engine and Gauge Panel In Cab with Engine Start / Stop Switches	Complete Engine and Gauge Panel In Cab with Engine Start / Stop Switches

** All models available without a knuckle-boom loader. Please consult factory for more information.

Specifications given were approved at the time of initial printing and are subject to change without notice and without incurring any liability.

Appendix B.

Feedstock Property Information

Appendix B.1 Sample Information and Moisture Content Data

Sample ID	Date	Tract	Chipper	Flail
<u>Pine, Fresh</u>				
Clean Conventional				
20110406_001_USFS_Chapman	4/6/2011	Chapman	Precision WTC 2366	ForestPro
20110406_002_USFS_Chapman	4/6/2011	Chapman	Precision WTC 2366	ForestPro
20110406_003_USFS_Chapman	4/6/2011	Chapman	Precision WTC 2366	ForestPro
20110406_004_USFS_Chapman	4/6/2011	Chapman	Precision WTC 2366	ForestPro
20110407_001_USFS_Chapman	4/7/2011	Chapman	Precision WTC 2366	ForestPro
20110407_002_USFS_Chapman	4/7/2011	Chapman	Precision WTC 2366	ForestPro
20110407_003_USFS_Chapman	4/7/2011	Chapman	Precision WTC 2366	ForestPro
20110407_004_USFS_Chapman	4/7/2011	Chapman	Precision WTC 2366	ForestPro
20110407_005_USFS_Chapman	4/7/2011	Chapman	Precision WTC 2366	ForestPro
20111104_001_Corley	11/4/2011	unknown	unknown	Delimbinator
20120202_001_USFS_Coastal	2/2/2012	Coastal	Precision WTC 2675	Precision 2300
20120202_002_USFS_Coastal	2/2/2012	Coastal	Precision WTC 2675	Precision 2300
20120202_003_USFS_Coastal	2/2/2012	Coastal	Precision WTC 2675	Precision 2300
20120202_004_USFS_Coastal	2/2/2012	Coastal	Precision WTC 2675	Precision 2300
20120202_005_USFS_Coastal	2/2/2012	Coastal	Precision WTC 2675	Precision 2300
20120202_006_USFS_Coastal	2/2/2012	Coastal	Precision WTC 2675	Precision 2300
20120202_007_USFS_Coastal	2/2/2012	Coastal	Precision WTC 2675	Precision 2300
20121023_001_USFS_Rigsby	10/23/2012	Tibbett	Precision WTC 2366	Precision 2300
20121023_002_USFS_Rigsby	10/23/2012	Tibbett	Precision WTC 2366	Precision 2300
20121023_003_USFS_Rigsby	10/23/2012	Tibbett	Precision WTC 2366	Precision 2300
20121023_004_USFS_Rigsby	10/23/2012	Tibbett	Precision WTC 2366	Precision 2300
20121023_005_USFS_Rigsby	10/23/2012	Tibbett	Precision WTC 2366	Delimbinator
20121023_006_USFS_Rigsby	10/23/2012	Tibbett	Precision WTC 2366	Delimbinator
20121023_007_USFS_Rigsby	10/23/2012	Tibbett	Precision WTC 2366	Delimbinator
Clean Microchips				
20120215_001_USFS_Airport	2/15/2012	Airport	Precision WTC 2675	Precision 2300
20120215_002_USFS_Airport	2/15/2012	Airport	Precision WTC 2675	Precision 2300
WT Microchips				
20110914_008_USFS_Greenville	9/14/2011	Taylor	Precision WTC 2675	
20120215_003_USFS_Airport	2/15/2012	Airport	Precision WTC 2675	
20130423_001_USFS_Beasley	4/23/2013	Beasley	Precision WTC 2675	
20130423_002_USFS_Beasley	4/23/2013	Beasley	Precision WTC 2675	

Pine, Trans Dry

TD Clean Conventional

20120522_001_USFS_Gantt	5/22/2012	Gantt	Precision WTC 2366	Precision 2300
20120522_002_USFS_Gantt	5/22/2012	Gantt	Precision WTC 2366	Precision 2300
20120522_003_USFS_Gantt	5/22/2012	Gantt	Precision WTC 2366	Precision 2300
20120522_004_USFS_Gantt	5/22/2012	Gantt	Precision WTC 2366	Precision 2300
20120522_006_USFS_Gantt	5/22/2012	Gantt	Precision WTC 2366	Precision 2300
20120523_007_USFS_Gantt	5/23/2012	Gantt	Precision WTC 2366	Precision 2300
20120523_008_USFS_Gantt	5/23/2012	Gantt	Precision WTC 2366	Precision 2300
20120523_009_USFS_Gantt	5/23/2012	Gantt	Precision WTC 2366	Precision 2300
20120523_010_USFS_Gantt	5/23/2012	Gantt	Precision WTC 2366	Precision 2300
20120523_011_USFS_Gantt	5/23/2012	Gantt	Precision WTC 2366	Precision 2300
20120524_014_USFS_Gantt	5/24/2012	Gantt	Precision WTC 2366	Precision 2300
20120524_015_USFS_Gantt	5/24/2012	Gantt	Precision WTC 2366	Precision 2300
20120530_020_USFS_Gantt	5/30/2012	Gantt	Precision WTC 2366	Precision 2300
20120530_021_USFS_Gantt	5/30/2012	Gantt	Precision WTC 2366	Precision 2300
20120530_022_USFS_Gantt	5/30/2012	Gantt	Precision WTC 2366	Precision 2300

TD WT Microchips

20120524_012_USFS_Gantt	5/24/2012	Gantt	Precision WTC 2675
20120524_013_USFS_Gantt	5/24/2012	Gantt	Precision WTC 2675

Pine, Roadside Storage

RS Clean Microchips

20130128_002_USFS_Rigsby	1/28/2013	Tibbett	Precision WTC 2675	Delimbinator
20130128_008_USFS_Rigsby	1/28/2013	Tibbett	Precision WTC 2675	Delimbinator

Mixed Species, Fresh

MS WT Conventional

20110912_001_USFS_Greenville	9/12/2011	Taylor	Precision WTC 2675
20110912_002_USFS_Greenville	9/12/2011	Taylor	Precision WTC 2675
20110912_003_USFS_Greenville	9/12/2011	Taylor	Precision WTC 2675
20110912_004_USFS_Greenville	9/12/2011	Taylor	Precision WTC 2675
20110912_005_USFS_Greenville	9/12/2011	Taylor	Precision WTC 2675

MS WT Microchips

20110914_001_USFS_Greenville	9/14/2011	Taylor	Precision WTC 2675
20110914_002_USFS_Greenville	9/14/2011	Taylor	Precision WTC 2675
20110914_003_USFS_Greenville	9/14/2011	Taylor	Precision WTC 2675
20110914_004_USFS_Greenville	9/14/2011	Taylor	Precision WTC 2675
20110914_005_USFS_Greenville	9/14/2011	Taylor	Precision WTC 2675
20110914_006_USFS_Greenville	9/14/2011	Taylor	Precision WTC 2675
20110914_007_USFS_Greenville	9/14/2011	Taylor	Precision WTC 2675

Hardwoods, Roadside Storage

HW RS Clean Microchips

20130124_100_USFS_Rigsby	1/24/2013	Tibbett	Precision WTC 2675	Delimbinator
20130124_101_USFS_Rigsby	1/24/2013	Tibbett	Precision WTC 2675	Delimbinator

Sample ID	Moisture Content
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Pine, Fresh

Clean Conventional

20110406_001_USFS_Chapman	57.3
20110406_002_USFS_Chapman	59.8
20110406_003_USFS_Chapman	56.8
20110406_004_USFS_Chapman	55.7
20110407_001_USFS_Chapman	58.5
20110407_002_USFS_Chapman	59.8
20110407_003_USFS_Chapman	56.2
20110407_004_USFS_Chapman	55.9
20110407_005_USFS_Chapman	52.2
20111104_001_Corley	57.3
20120202_001_USFS_Coastal	53.9
20120202_002_USFS_Coastal	53.9
20120202_003_USFS_Coastal	55.7
20120202_004_USFS_Coastal	52.4
20120202_005_USFS_Coastal	54.3
20120202_006_USFS_Coastal	54.0
20120202_007_USFS_Coastal	52.7
20121023_001_USFS_Rigsby	56.5
20121023_002_USFS_Rigsby	55.2
20121023_003_USFS_Rigsby	56.7
20121023_004_USFS_Rigsby	54.1
20121023_005_USFS_Rigsby	56.3
20121023_006_USFS_Rigsby	58.1
20121023_007_USFS_Rigsby	59.3

Clean Microchips

20120215_001_USFS_Airport	59.1
20120215_002_USFS_Airport	57.0

WT Microchips

20110914_008_USFS_Greenville	56.3
20120215_003_USFS_Airport	55.1
20130423_001_USFS_Beasley	53.8
20130423_002_USFS_Beasley	55.1

Pine, Trans Dry

TD Clean Conventional

20120522_001_USFS_Gantt	40.2
20120522_002_USFS_Gantt	39.9
20120522_003_USFS_Gantt	41.7
20120522_004_USFS_Gantt	41.2
20120522_006_USFS_Gantt	38.0
20120523_007_USFS_Gantt	38.4
20120523_008_USFS_Gantt	39.8
20120523_009_USFS_Gantt	42.1
20120523_010_USFS_Gantt	36.5
20120523_011_USFS_Gantt	38.8
20120524_014_USFS_Gantt	35.8
20120524_015_USFS_Gantt	36.0
20120530_020_USFS_Gantt	46.9
20120530_021_USFS_Gantt	39.8
20120530_022_USFS_Gantt	34.0

TD WT Microchips

20120524_012_USFS_Gantt	40.5
20120524_013_USFS_Gantt	37.0

Pine, Roadside Storage

RS Clean Microchips

20130128_002_USFS_Rigsby	50.1
20130128_008_USFS_Rigsby	48.1

Mixed Species, Fresh

MS WT Conventional

20110912_001_USFS_Greenville	43.6
20110912_002_USFS_Greenville	54.0
20110912_003_USFS_Greenville	44.5
20110912_004_USFS_Greenville	44.3
20110912_005_USFS_Greenville	50.3

MS WT Microchips

20110914_001_USFS_Greenville	46.0
20110914_002_USFS_Greenville	52.3
20110914_003_USFS_Greenville	47.4
20110914_004_USFS_Greenville	49.1
20110914_005_USFS_Greenville	47.8
20110914_006_USFS_Greenville	50.7
20110914_007_USFS_Greenville	50.8

Hardwoods, Roadside Storage

HW RS Clean Microchips

20130124_100_USFS_Rigsby	36.4
20130124_101_USFS_Rigsby	49.3

Appendix B.2 Bulk Density Data

Sample ID	5L BD, wet	5L BD, dry	20 L BD, wet	20L BD, dry
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Pine, Fresh

Clean Conventional

20110406_001_USFS_Chapman				
20110406_002_USFS_Chapman				
20110406_003_USFS_Chapman				
20110406_004_USFS_Chapman				
20110407_001_USFS_Chapman				
20110407_002_USFS_Chapman	402.0	161.4		
20110407_003_USFS_Chapman				
20110407_004_USFS_Chapman				
20110407_005_USFS_Chapman				
20111104_001_Corley	403.2	172.2		
20120202_001_USFS_Coastal	374.5	172.5		
20120202_002_USFS_Coastal	372.4	171.9		
20120202_003_USFS_Coastal	378.8	167.7		
20120202_004_USFS_Coastal	363.3	173.1		
20120202_005_USFS_Coastal	376.6	172.2		
20120202_006_USFS_Coastal	374.8	172.6		
20120202_007_USFS_Coastal	371.3	175.6		
20121023_001_USFS_Rigsby	376.3	163.7	398.4	173.3
20121023_002_USFS_Rigsby	363.4	162.6	389.8	174.5
20121023_003_USFS_Rigsby	379.6	164.5	402.2	174.3
20121023_004_USFS_Rigsby	366.7	168.2	390.0	178.9
20121023_005_USFS_Rigsby			407.1	177.8
20121023_006_USFS_Rigsby			420.1	176.2
20121023_007_USFS_Rigsby			420.5	171.3

Clean Microchips

20120215_001_USFS_Airport	388.8	159.0		
20120215_002_USFS_Airport	383.0	164.9		

WT Microchips

20110914_008_USFS_Greenville	324.0	141.5		
20120215_003_USFS_Airport	352.0	158.0		
20130423_001_USFS_Beasley	349.3	161.4	362.6	167.6
20130423_002_USFS_Beasley	350.6	157.5	365.3	164.1

Pine, Trans Dry

TD Clean Conventional

20120522_001_USFS_Gantt	282.6	168.9
20120522_002_USFS_Gantt	276.1	166.0
20120522_003_USFS_Gantt	286.1	166.8
20120522_004_USFS_Gantt	278.8	164.0
20120522_006_USFS_Gantt	272.1	168.7
20120523_007_USFS_Gantt	275.8	169.9
20120523_008_USFS_Gantt	286.6	172.5
20120523_009_USFS_Gantt	290.4	168.3
20120523_010_USFS_Gantt	288.8	183.4
20120523_011_USFS_Gantt	291.2	178.1
20120524_014_USFS_Gantt	276.8	177.6
20120524_015_USFS_Gantt	280.2	179.3
20120530_020_USFS_Gantt	321.9	170.8
20120530_021_USFS_Gantt	275.8	165.9
20120530_022_USFS_Gantt	267.5	176.6

TD WT Microchips

20120524_012_USFS_Gantt	276.7	164.7
20120524_013_USFS_Gantt	258.5	162.8

Pine, Roadside Storage**RS Clean Microchips**

20130128_002_USFS_Rigsby	352.9	175.9
20130128_008_USFS_Rigsby	351.7	182.5

Mixed Species, Fresh**MS WT Conventional**

20110912_001_USFS_Greenville	283.2	159.6
20110912_002_USFS_Greenville	240.6	110.6
20110912_003_USFS_Greenville	267.6	148.5
20110912_004_USFS_Greenville	295.4	164.6
20110912_005_USFS_Greenville		

MS WT Microchips

20110914_001_USFS_Greenville	349.0	188.4
20110914_002_USFS_Greenville	324.2	154.5
20110914_003_USFS_Greenville	331.0	174.0
20110914_004_USFS_Greenville	290.3	147.7
20110914_005_USFS_Greenville	297.0	155.1
20110914_006_USFS_Greenville	311.8	153.6

20110914_007_USFS_Greenville	291.8	143.5
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Hardwoods, Roadside Storage

HW RS Clean Microchips

20130124_100_USFS_Rigsby	324.6	206.5
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20130124_101_USFS_Rigsby	346.7	175.9
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Appendix B.3 Particle Size Distribution Data

Sample ID	0mm	3mm rd	7mm rd	13mm rd	45mm rd
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Pine, Fresh

Clean Conventional

20110406_001_USFS_Chapman					
20110406_002_USFS_Chapman					
20110406_003_USFS_Chapman					
20110406_004_USFS_Chapman					
20110407_001_USFS_Chapman					
20110407_002_USFS_Chapman					
20110407_003_USFS_Chapman					
20110407_004_USFS_Chapman					
20110407_005_USFS_Chapman					
20111104_001_Corley					
20120202_001_USFS_Coastal	3.1	15.1	36.9	44.7	0.2
20120202_002_USFS_Coastal	3	17.4	35.9	43.4	0.4
20120202_003_USFS_Coastal	4.4	17.5	37.1	41	0
20120202_004_USFS_Coastal	2.9	14.4	35.3	47.4	0
20120202_005_USFS_Coastal	4.9	18.2	39	38	0
20120202_006_USFS_Coastal	4.9	20.1	38.8	36.2	0
20120202_007_USFS_Coastal	4.5	17.9	36.1	41.5	0
20121023_001_USFS_Rigsby	1.3	8.7	30.1	59.2	0.8
20121023_002_USFS_Rigsby	1.1	7.1	25.3	65.9	0.7
20121023_003_USFS_Rigsby	1.6	8.5	27.3	62.5	0
20121023_004_USFS_Rigsby	1.4	7.3	24.2	66.7	0.5
20121023_005_USFS_Rigsby	1.6	7.7	28.8	61.9	0
20121023_006_USFS_Rigsby	1.8	8.6	29.5	59.8	0.3
20121023_007_USFS_Rigsby	1.4	7.2	28.3	62.1	0.9

Clean Microchips

20120215_001_USFS_Airport	4.3	22.2	47	26.6	0
20120215_002_USFS_Airport	6	21.8	45.7	26.5	0

WT Microchips

20110914_008_USFS_Greenville					
20120215_003_USFS_Airport	7.1	21.6	44.3	26.9	0
20130423_001_USFS_Beasley	2.8	18.2	54.1	24.5	0.4
20130423_002_USFS_Beasley	2.9	18.2	51.6	26.4	1

Pine, Trans Dry

TD Clean Conventional

20120522_001_USFS_Gantt	1	4.4	15.5	68	11.1
20120522_002_USFS_Gantt	0.7	4.3	16.9	67.3	10.8
20120522_003_USFS_Gantt	0.8	5.4	18.5	71.2	4.1
20120522_004_USFS_Gantt	0.8	4.3	15.9	71.3	7.7
20120522_006_USFS_Gantt	1.5	5.9	17.7	64.6	10.3
20120523_007_USFS_Gantt	0.6	4	14.3	64.7	16.4
20120523_008_USFS_Gantt	0.5	4	13.8	69	12.7
20120523_009_USFS_Gantt	0.4	3.2	14.1	74.3	8
20120523_010_USFS_Gantt	0.6	4	16.8	75.4	3.2
20120523_011_USFS_Gantt	0.7	3.9	14.2	69.5	11.7
20120524_014_USFS_Gantt	0.8	4.2	17.2	66.7	11.1
20120524_015_USFS_Gantt	0.5	3.6	14.8	74.4	6.7
20120530_020_USFS_Gantt	0.8	5.3	19.9	72	2
20120530_021_USFS_Gantt	0.9	5	18.6	68.3	7.1
20120530_022_USFS_Gantt	0.3	2.3	12.4	75	10

TD WT Microchips

20120524_012_USFS_Gantt	3.7	15.4	41.5	37.9	1.5
20120524_013_USFS_Gantt	4.7	15.9	36.4	38.3	4.7

Pine, Roadside Storage**RS Clean Microchips**

20130128_002_USFS_Rigsby	2.3	16.3	49.6	31.7	0
20130128_008_USFS_Rigsby	3.4	26	51.9	18.7	0

Mixed Species, Fresh**MS WT Conventional**

20110912_001_USFS_Greenville	7.9	16.4	27.4	46.4	1.9
20110912_002_USFS_Greenville	5.8	12.8	24	55.9	1.5
20110912_003_USFS_Greenville	4.5	11.9	22	56.4	5.1
20110912_004_USFS_Greenville	10.6	18.9	26.3	43.6	0.6
20110912_005_USFS_Greenville					

MS WT Microchips

20110914_001_USFS_Greenville	6.9	23.2	44.4	25.4	0.1
20110914_002_USFS_Greenville	7.2	21.6	44.5	26.5	0.2
20110914_003_USFS_Greenville	9.6	26.5	46	17.9	0
20110914_004_USFS_Greenville	11.6	27.8	40.1	20.3	0.1
20110914_005_USFS_Greenville	12	23.9	35.1	27.4	1.5
20110914_006_USFS_Greenville	8.1	22	42.3	27.4	0.3

20110914_007_USFS_Greenville	11.8	21.9	34.4	31.1	0.7
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Hardwoods, Roadside Storage

HW RS Clean Microchips

20130124_100_USFS_Rigsby	2.7	16	45.1	35.4	0.7
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20130124_101_USFS_Rigsby	1.8	12.1	51.5	34.5	0.2
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Appendix B.4 Energy Content Data

Sample ID	HHV (btu/lb)
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Pine, Fresh

Clean Conventional

20110406_001_USFS_Chapman	8852.89
20110406_002_USFS_Chapman	8796.73
20110406_003_USFS_Chapman	8801.44
20110406_004_USFS_Chapman	8788.46
20110407_001_USFS_Chapman	8757.59
20110407_002_USFS_Chapman	8856.93
20110407_003_USFS_Chapman	8810.63
20110407_004_USFS_Chapman	8868.83
20110407_005_USFS_Chapman	8822.37
20111104_001_Corley	8651.55
20120202_001_USFS_Coastal	8688.86
20120202_002_USFS_Coastal	8702.57
20120202_003_USFS_Coastal	8726.57
20120202_004_USFS_Coastal	8754.99
20120202_005_USFS_Coastal	8650.19
20120202_006_USFS_Coastal	8803.23
20120202_007_USFS_Coastal	8828.85
20121023_001_USFS_Rigsby	8789.67
20121023_002_USFS_Rigsby	8868.13
20121023_003_USFS_Rigsby	8874.79
20121023_004_USFS_Rigsby	8873.88
20121023_005_USFS_Rigsby	8757.04
20121023_006_USFS_Rigsby	8838.26
20121023_007_USFS_Rigsby	8796.57

Clean Microchips

20120215_001_USFS_Airport	9051.98
20120215_002_USFS_Airport	9013.47

WT Microchips

20110914_008_USFS_Greenville	8860.49
20120215_003_USFS_Airport	9047.08
20130423_001_USFS_Beasley	8350.93
20130423_002_USFS_Beasley	8341.34

Pine, Trans Dry

TD Clean Conventional

20120522_001_USFS_Gantt	8760.36
20120522_002_USFS_Gantt	8726.19
20120522_003_USFS_Gantt	8721.75
20120522_004_USFS_Gantt	8664.96
20120522_006_USFS_Gantt	8704.25
20120523_007_USFS_Gantt	8632.46
20120523_008_USFS_Gantt	8763.01
20120523_009_USFS_Gantt	8605.61
20120523_010_USFS_Gantt	8593.32
20120523_011_USFS_Gantt	8660.33
20120524_014_USFS_Gantt	8594.77
20120524_015_USFS_Gantt	8745.45
20120530_020_USFS_Gantt	8647.81
20120530_021_USFS_Gantt	8680.12
20120530_022_USFS_Gantt	8596.17

TD WT Microchips

20120524_012_USFS_Gantt	8737.3
20120524_013_USFS_Gantt	8690.72

Pine, Roadside Storage**RS Clean Microchips**

20130128_002_USFS_Rigsby	8450.36
20130128_008_USFS_Rigsby	8437.48

Mixed Species, Fresh**MS WT Conventional**

20110912_001_USFS_Greenville	8576.38
20110912_002_USFS_Greenville	8688.7
20110912_003_USFS_Greenville	8512.88
20110912_004_USFS_Greenville	8454.68
20110912_005_USFS_Greenville	

MS WT Microchips

20110914_001_USFS_Greenville	8417.26
20110914_002_USFS_Greenville	8771.44
20110914_003_USFS_Greenville	8519.32
20110914_004_USFS_Greenville	8680.18
20110914_005_USFS_Greenville	8286.42
20110914_006_USFS_Greenville	8556.16

20110914_007_USFS_Greenville 8527.13

Hardwoods, Roadside Storage

HW RS Clean Microchips

20130124_100_USFS_Rigsby 8057.22

20130124_101_USFS_Rigsby 8058.51

Appendix B.5 Ash Content Data

Sample ID	Ash
<u>Pine, Fresh</u>	
Clean Conventional	
20110406_001_USFS_Chapman	0.44
20110406_002_USFS_Chapman	0.35
20110406_003_USFS_Chapman	0.22
20110406_004_USFS_Chapman	0.42
20110407_001_USFS_Chapman	0.33
20110407_002_USFS_Chapman	0.29
20110407_003_USFS_Chapman	0.24
20110407_004_USFS_Chapman	0.30
20110407_005_USFS_Chapman	0.14
20111104_001_Corley	0.44
20120202_001_USFS_Coastal	0.43
20120202_002_USFS_Coastal	0.46
20120202_003_USFS_Coastal	0.57
20120202_004_USFS_Coastal	0.46
20120202_005_USFS_Coastal	0.32
20120202_006_USFS_Coastal	0.57
20120202_007_USFS_Coastal	0.42
20121023_001_USFS_Rigsby	0.59
20121023_002_USFS_Rigsby	0.20
20121023_003_USFS_Rigsby	0.40
20121023_004_USFS_Rigsby	0.43
20121023_005_USFS_Rigsby	0.22
20121023_006_USFS_Rigsby	0.71
20121023_007_USFS_Rigsby	0.29
Clean Microchips	
20120215_001_USFS_Airport	0.61
20120215_002_USFS_Airport	0.47
WT Microchips	
20110914_008_USFS_Greenville	0.93
20120215_003_USFS_Airport	0.69
20130423_001_USFS_Beasley	0.45
20130423_002_USFS_Beasley	0.40

Pine, Trans Dry

TD Clean Conventional

20120522_001_USFS_Gantt	0.45
20120522_002_USFS_Gantt	0.42
20120522_003_USFS_Gantt	0.35
20120522_004_USFS_Gantt	0.45
20120522_006_USFS_Gantt	0.39
20120523_007_USFS_Gantt	0.54
20120523_008_USFS_Gantt	0.41
20120523_009_USFS_Gantt	0.31
20120523_010_USFS_Gantt	0.32
20120523_011_USFS_Gantt	0.49
20120524_014_USFS_Gantt	0.46
20120524_015_USFS_Gantt	0.49
20120530_020_USFS_Gantt	0.52
20120530_021_USFS_Gantt	0.48
20120530_022_USFS_Gantt	0.57

TD WT Microchips

20120524_012_USFS_Gantt	0.58
20120524_013_USFS_Gantt	0.98

Pine, Roadside Storage

RS Clean Microchips

20130128_002_USFS_Rigsby	0.52
20130128_008_USFS_Rigsby	0.47

Mixed Species, Fresh

MS WT Conventional

20110912_001_USFS_Greenville	1.80
20110912_002_USFS_Greenville	1.44
20110912_003_USFS_Greenville	2.27
20110912_004_USFS_Greenville	5.44
20110912_005_USFS_Greenville	

MS WT Microchips

20110914_001_USFS_Greenville	1.57
20110914_002_USFS_Greenville	2.16
20110914_003_USFS_Greenville	1.26
20110914_004_USFS_Greenville	1.63
20110914_005_USFS_Greenville	4.03
20110914_006_USFS_Greenville	1.47
20110914_007_USFS_Greenville	2.71

Hardwoods, Roadside Storage

HW RS Clean Microchips

20130124_100_USFS_Rigsby	1.41
20130124_101_USFS_Rigsby	1.06

Appendix B.6 Volatile Content Data

Sample ID	Volatile
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Pine, Fresh

Clean Conventional

20110406_001_USFS_Chapman	85.34
20110406_002_USFS_Chapman	85.15
20110406_003_USFS_Chapman	85.53
20110406_004_USFS_Chapman	85.10
20110407_001_USFS_Chapman	85.34
20110407_002_USFS_Chapman	85.44
20110407_003_USFS_Chapman	86.08
20110407_004_USFS_Chapman	85.64
20110407_005_USFS_Chapman	86.12
20111104_001_Corley	83.52
20120202_001_USFS_Coastal	84.72
20120202_002_USFS_Coastal	84.32
20120202_003_USFS_Coastal	84.68
20120202_004_USFS_Coastal	83.91
20120202_005_USFS_Coastal	84.42
20120202_006_USFS_Coastal	84.19
20120202_007_USFS_Coastal	84.54
20121023_001_USFS_Rigsby	85.28
20121023_002_USFS_Rigsby	86.29
20121023_003_USFS_Rigsby	84.16
20121023_004_USFS_Rigsby	85.11
20121023_005_USFS_Rigsby	84.06
20121023_006_USFS_Rigsby	86.62
20121023_007_USFS_Rigsby	83.65

Clean Microchips

20120215_001_USFS_Airport	83.73
20120215_002_USFS_Airport	83.77

WT Microchips

20110914_008_USFS_Greenville	82.48
20120215_003_USFS_Airport	82.62
20130423_001_USFS_Beasley	
20130423_002_USFS_Beasley	

Pine, Trans Dry

TD Clean Conventional

20120522_001_USFS_Gantt	80.75
20120522_002_USFS_Gantt	83.15
20120522_003_USFS_Gantt	83.73
20120522_004_USFS_Gantt	84.39
20120522_006_USFS_Gantt	84.22
20120523_007_USFS_Gantt	84.33
20120523_008_USFS_Gantt	84.29
20120523_009_USFS_Gantt	84.85
20120523_010_USFS_Gantt	84.40
20120523_011_USFS_Gantt	84.92
20120524_014_USFS_Gantt	85.18
20120524_015_USFS_Gantt	86.18
20120530_020_USFS_Gantt	83.83
20120530_021_USFS_Gantt	84.33
20120530_022_USFS_Gantt	85.13

TD WT Microchips

20120524_012_USFS_Gantt	80.81
20120524_013_USFS_Gantt	82.29

Pine, Roadside Storage

RS Clean Microchips

20130128_002_USFS_Rigsby	
20130128_008_USFS_Rigsby	

Mixed Species, Fresh

MS WT Conventional

20110912_001_USFS_Greenville	81.97
20110912_002_USFS_Greenville	81.81
20110912_003_USFS_Greenville	82.27
20110912_004_USFS_Greenville	76.65
20110912_005_USFS_Greenville	

MS WT Microchips

20110914_001_USFS_Greenville	82.21
20110914_002_USFS_Greenville	78.98
20110914_003_USFS_Greenville	82.74
20110914_004_USFS_Greenville	80.49
20110914_005_USFS_Greenville	78.08
20110914_006_USFS_Greenville	82.11
20110914_007_USFS_Greenville	79.00

Hardwoods, Roadside Storage

HW RS Clean Microchips

20130124_100_USFS_Rigsby

20130124_101_USFS_Rigsby

Appendix B. 7 Fixed Carbon Data

Sample ID	Fixed C
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Pine, Fresh

Clean Conventional

20110406_001_USFS_Chapman	9.13
20110406_002_USFS_Chapman	9.99
20110406_003_USFS_Chapman	10.10
20110406_004_USFS_Chapman	10.48
20110407_001_USFS_Chapman	10.17
20110407_002_USFS_Chapman	9.93
20110407_003_USFS_Chapman	9.87
20110407_004_USFS_Chapman	9.99
20110407_005_USFS_Chapman	9.65
20111104_001_Corley	10.92
20120202_001_USFS_Coastal	7.63
20120202_002_USFS_Coastal	8.61
20120202_003_USFS_Coastal	8.87
20120202_004_USFS_Coastal	8.51
20120202_005_USFS_Coastal	7.97
20120202_006_USFS_Coastal	8.69
20120202_007_USFS_Coastal	7.88
20121023_001_USFS_Rigsby	7.83
20121023_002_USFS_Rigsby	6.91
20121023_003_USFS_Rigsby	9.90
20121023_004_USFS_Rigsby	7.98
20121023_005_USFS_Rigsby	9.97
20121023_006_USFS_Rigsby	6.41
20121023_007_USFS_Rigsby	11.16

Clean Microchips

20120215_001_USFS_Airport	8.77
20120215_002_USFS_Airport	10.19

WT Microchips

20110914_008_USFS_Greenville	9.51
20120215_003_USFS_Airport	9.96
20130423_001_USFS_Beasley	
20130423_002_USFS_Beasley	

Pine, Trans Dry

TD Clean Conventional

20120522_001_USFS_Gantt	10.87
20120522_002_USFS_Gantt	9.30
20120522_003_USFS_Gantt	9.29
20120522_004_USFS_Gantt	8.63
20120522_006_USFS_Gantt	9.13
20120523_007_USFS_Gantt	8.71
20120523_008_USFS_Gantt	8.81
20120523_009_USFS_Gantt	8.83
20120523_010_USFS_Gantt	8.86
20120523_011_USFS_Gantt	7.93
20120524_014_USFS_Gantt	8.59
20120524_015_USFS_Gantt	6.63
20120530_020_USFS_Gantt	9.58
20120530_021_USFS_Gantt	8.95
20120530_022_USFS_Gantt	8.30

TD WT Microchips

20120524_012_USFS_Gantt	10.82
20120524_013_USFS_Gantt	10.29

Pine, Roadside Storage

RS Clean Microchips

20130128_002_USFS_Rigsby
20130128_008_USFS_Rigsby

Mixed Species, Fresh

MS WT Conventional

20110912_001_USFS_Greenville	8.15
20110912_002_USFS_Greenville	8.44
20110912_003_USFS_Greenville	7.99
20110912_004_USFS_Greenville	9.62
20110912_005_USFS_Greenville	

MS WT Microchips

20110914_001_USFS_Greenville	9.73
20110914_002_USFS_Greenville	10.45
20110914_003_USFS_Greenville	8.46
20110914_004_USFS_Greenville	9.52
20110914_005_USFS_Greenville	11.49
20110914_006_USFS_Greenville	9.44
20110914_007_USFS_Greenville	11.37

Hardwoods, Roadside Storage

HW RS Clean Microchips

20130124_100_USFS_Rigsby

20130124_101_USFS_Rigsby

Appendix C.

Additional Feedstock Properties Research Conducted in Conjunction with this Project

**TECHNICAL NOTE: THERMAL DECOMPOSITION BEHAVIOR OF LOBLOLLY
PINE STEMWOOD, BARK AND LIMBS/FOLIAGE**

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Abstract

A standing tree before harvest has three primary components – bark, limbs/foliage and stemwood (i.e. the center part of the tree without the bark). The typical tree harvesting operation for pulp and paper, and furniture industries involves the removal of the bark and limbs/foliage which may form up to 25% on mass basis of the tree. This large quantity of residue may be a significant quantity of feedstocks for the bioenergy industry. The goals of the study were to quantify the (a) rate and kinetics of thermal decomposition in nitrogen and air atmospheres (within heating rate range of 5°C/min to 20°C/min,) of loblolly pine bark, limb/foliage and stemwood, and (b) energy required to thermally degrade these biomass samples. The results obtained showed that significant loss in sample mass (40-60% of original mass depending on sample type) occurred within temperature of 150°C and 425°C when the samples were thermally decomposed in nitrogen atmosphere. In air atmosphere, virtually all of the non-ash component of each sample was volatilized within the temperature range of 150°C to 600°C. Stemwood had higher volatile content than bark and limb/foliage. This also resulted in the stemwood having at least 20% lower activation energy values compared to the low volatile content bark and limb/foliage. The activation energies for the samples thermally decomposition in air atmosphere were higher than the corresponding values from nitrogen atmosphere.

Keywords: thermal decomposition, kinetics, energy, thermochemical conversion

1. Introduction

The dependence of U.S. on imported crude oil is an obvious issue of national and energy security, and has significant environmental implications (Klass, 1998; Nerurkar, 2012). Several efforts are therefore being made by public and private sectors to replace a substantial part of imported crude oil with renewable resources. Biomass is the only renewable resource that can be converted into the carbon-based liquid transportation fuels, chemicals and products that are currently obtained from crude oil (Klass, 1998; Brown, 2003). According to the Energy Independence and Security Act of 2007, the goal is to produce 36 billion gallons of biofuels per year by 2022. About 50% of these projected biofuels quantity is expected to come from the Southern part of U.S. because of the vast amount of forest biomass available in this region. Forestland covers about 156 million acres (or 60 percent) of the land area in South and over 60 percent of U.S. timber production are obtained from southern forests (USDA, 2014). With the relocation of pulp and paper manufacturing industries to overseas countries, a significant amount of wood is available that can be used as biomass feedstocks for production of biopower, biofuels, and bioproducts (Frederick et al., 2008). A standing tree before harvest has three primary components – bark, limbs/foliage and stemwood (i.e. the center part of the tree without the bark). The trees after harvest are typically processed in the forest into these three components via operations such as delimbing and debarking before they are trucked out of the forest land.

The bark is the tree's natural armor that provides protection from external threats, insects and diseases, excessive heat and cold, and mechanical injuries. The limbs/foliage (including the leaves) is the tree's chemical laboratories because this is where the food for the tree is manufactured. The leaves combine carbon dioxide from air and water from the soil, in the presence of sunlight to form sugar (Young, 1980; Burton, 2008). The stemwood consists of several parts (e.g. sapwood, cambium, and heartwood). Part of the function of the stemwood is to provide strength and stiffness for the tree, produce a majority of the tree's useful wood and conduct the sap (water plus nitrogen and mineral nutrients) from roots to leaves (Grebner, 2013; Sharpe et al., 2002). Due to differences in their functions, these tree components vary widely in chemical composition (i.e. ash, energy, volatile, lignin, cellulose and hemicellulose contents) which will affect the type of products (including quantities of these products) that will be obtained from conversion (Pasangulapati et al., 2012; Bahng et al., 2009).

Thermochemical methods (e.g. pyrolysis, gasification and combustion) are commonly used to convert biomass into value-added products primarily because thermochemical processes can break down lignocellulosic biomass in a controlled manner thereby overcoming the recalcitrant problems encountered with biochemical conversion methods (NAS, 2012). In thermochemical methods, liquid or gaseous products obtained when biomass are heated to temperatures greater than 200°C (typically under controlled atmospheres) are converted into of fuels, chemicals and/or heat and power. Even though, thermogravimetric (TGA) analysis quantifies rates of thermal decomposition during the relatively slow heating process, the repeatable data obtained from TGA analysis can be used for in-depth analysis of mass loss and determination of kinetic parameters needed for design, operation and control of thermochemical conversion equipment and processes (Fasina & Littlefield, 2012). There is no documented studies that compare the thermal decomposition behavior of these three components of loblolly pine tree.

Therefore, the objectives of this study were to: (a) determine the rate and kinetics of thermal decomposition in (nitrogen and air atmospheres) of loblolly pine bark, limb/foliage and stemwood, and (b) quantify the energy required to thermally degrade these biomass samples.

2. Materials and methods

2.1. Sample preparation

The samples used in this study were obtained from trees harvested from a forestland in West Alabama. Twenty eight trees were manually harvested and carefully handled such that they did not come in contact with the soil. This approach was used to eliminate soil contamination of the samples which typically increases the ash content of forest biomass. The limbs and foliage were then separated from the rest of the trees. This was followed by manual debarking of the tree trunk. After measuring the mass of each component, the samples were transported to Auburn University and were then further processed (drying at 45°C followed by grinding by hammer mill through sets of screen until the samples passed through a 1 mm screen) before being analyzed. Heating value was obtained with an IKA C200 calorimeter (IKA Works Inc., Wilmington, NC). Ash content of samples was determined according to the National Renewable Energy Laboratory's (NREL) laboratory analytical procedure (Sluiter et al., 2005) for the determination of ash in biomass that involved ashing of samples at $575^{\circ} \pm 25^{\circ}\text{C}$ for three hours. Carbon and hydrogen contents were determined using an elemental analyzer (Model 2400 Series II Perkin-Elmer, Shelton, CT). A separate twenty eight trees were also harvested but were not separated into the three components. This portion was labelled 'whole tree' in this study. The whole tree sample was processed and analyzed as described above.

2.2. Thermogravimetric analysis

Thermal decomposition of the ground samples was carried out in a Pyris 1 TGA – thermogravimetric analyzer (Perkin-Elmer, Shelton, CT). A sample mass of about 5 mg was used for TG analysis. Heating of a sample was conducted at heating rate of 5, 10, 15, and 20°C/min within the temperature range of 30°C to 900°C in nitrogen and air atmospheres. Before use, the TGA was calibrated for temperature (alumel, nickel, perkalloys and iron) in each of the atmospheres that the experiment will be conducted, and for mass (using 100 mg weight) according to the procedure outlined by the manufacturer of the equipment.

2.3. Thermal decomposition energy

A differential scanning calorimeter (DSC) was used to quantify the energy required to thermally decompose the samples. The DSC (Model Q200, TA Instruments, New Castle, DE) was operated under nitrogen atmosphere at a flow rate of 20 ml/min. Samples (approximately 5 mg) were equilibrated at 30°C for 2 minutes, then heated to 550°C at heating rate of 20°C/min and then held at 550°C for 2 minutes. Temperature (°C), time (min), heat flow (W/g) and sample purge flow (ml/min) were all recorded by the software provided by the manufacturer of the DSC. The equipment was calibrated with indium (melting point of 429.8 K) before use according to manufacturer's specifications. To ascertain the accuracy of measurements, the latent heat of fusion (H_L) of distilled water were measured to be within 2% of published values (average H_L value of 335.9 ± 0.35 kJ/kg).

3. Results and discussion

3.1. Compositional analysis

Table 1 shows the mass fraction and composition values (heating values, ash, hydrogen and carbon contents) for the four loblolly pine samples (bark, limbs/foilage, stemwood and whole tree). About 25% (based on mass) of trees are made up of bark and limbs/foilage. This is a substantial percentage that can potentially be utilized by biorefinery plants. The challenge though is that these components (i.e. bark and limbs/foilage) inherently have higher ash contents (see Table 1) and also these are the components that interact with the soil during the currently used conventional on-site forest harvest and handling operations. Some of the analysis that we have carried out on trees that were skidded (i.e. dragged on the ground as is typically done during forest operations) indicate that the ash contents of the bark can increase by up to 6 percentage points. Table 1 also shows the bark has the lowest volatile content and therefore will produce less quantity of syngas and bio-oil, and more quantity of char during gasification and pyrolysis when compared to limbs/foilage and stemwood. The heating values of the components are however similar to that expected of biological materials that can potentially be used as biomass feedstock (Littlefield et al., 2011).

3.2. Thermogravimetric analysis – nitrogen and air atmospheres

Observed thermal behavior (TG curve) at different heating rates for the four samples during thermal decomposition in nitrogen and air atmospheres are shown in Figures 1 and 2 respectively. This response indicate that there is not a substantial effect of heating rate on mass loss for all samples thus indicating minimum thermal lag (Fasina & Littlefield, 2012). An initial mass loss (approximately 10% of initial sample mass) occurred between 30°C and 150°C which we attributed to the release of moisture from the wood samples. Thermal decomposition was therefore determined to begin after 150°C (Fang et al., 2006; Liu et al., 2008; Souza et al., 2009).

Significant loss in sample mass (40-60% of original mass depending on sample type) occurred within temperature of 150°C and 425°C when the samples were thermal decomposed in nitrogen atmosphere. It has been well documented (Vamvuka et al., 2003; Tsamba et al., 2006; Skreiberg et al., 2011) that mass loss within this temperature range is mainly due to decomposition of hemicelluloses and cellulose fractions in biomass feedstocks. Between 425°C and 900°C, the mass loss of whole, stemwood and limbs/foilage were very small (~3%) while significant mass loss of about 10% occurred with bark samples (Fig. 3). In addition, the amount of residue after thermal decomposition of bark was about 10% higher than the residue from the other samples. We attribute these responses to the higher contents of fixed carbon and ash (Table 1) and lignin content of bark. Feng et al. (2013) compared the chemical composition of bark of eight types of softwood and hardwood to their stemwood and showed that the lignin content of the bark is generally about 4% higher than those of the stemwood. Several studies have shown that even though the thermal decomposition of lignin occur over a wide temperature range, the high char residue yield of lignin is from decomposed lignin compounds that condense and form liquid intermediate fractions (Wang et al, 2009; Zhou et al., 2014).

The total percent loss in mass of the samples that were thermally decomposed in air atmosphere was greater than 95% (Fig. 2) and was significantly higher than that obtained from nitrogen atmosphere (Fig. 3). Most of the mass loss occurred within the temperature range of 150°C to 600°C with virtually all of the non-ash component of each sample being volatilized

within this temperature range. In addition, Figures 2 and 3 show there were at least two distinct phases that significant mass loss occurred in the air-atmosphere samples. The first phase of major mass loss is due to volatilization of the biomass cellulose and hemicellulose components (within the temperature range of 150°C to 425°C), while the second phase (temperature range of 425°C to 900°C) is mainly used to volatilization of the lignin components and the remaining fixed carbon (Wongsiriamnuay & Tippayawong, 2010; Fateh et al., 2013).

The fractional mass loss rate (α) was computed from the TGA mass loss data as follows.

$$\alpha = \frac{m - m_o}{m_f - m_o} \quad (1)$$

where α is the fractional mass loss (or degree of conversion) at time t ; m_o , m and m_f are the initial sample mass, the actual sample mass and the final sample mass respectively. Figures 4 and 5 (plot of the fractional mass loss rate versus temperature which is often referred to as the DTG curve) show that the fractional mass loss rate increased with increase in heating rate. As typically found in nitrogen-atmosphere biomass thermogravimetric studies, all the thermograms produced two overlapping peaks – a single peak and a shoulder peak on the left side of the single peak. Based on published studies, the shoulder at the left side corresponds to hemicelluloses decomposition while the higher temperature peak represents the decomposition of cellulose (Tsamba et al., 2006; Idris et al., 2010). However, the shoulder peaks were not prominent in the bark and limbs/foilage samples which will attribute to the higher ash contents of these samples. The temperatures at which the highest mass loss rate (corresponding to peak cellulose decomposition) and the hemicellulose decomposition peaks were obtained slightly increased with heating rate. The flat tailing section of the DTG curves at higher temperatures corresponds to the decomposition of the non-fixed carbon in lignin. The values of the mass loss rates are within the ranges that have been published for biomass feedstocks (Meszaros et al., 2004; Lee & Fasina, 2009).

Two distinct mass loss rate peaks were obtained from samples thermally decomposed in air atmosphere. These peaks increased with heating rates. Also the magnitudes of the first peak being inversely proportional to sample ash content while the temperature at which the first peak occurred was about equal to the temperature of the nitrogen atmosphere shoulder peak (for hemicellulose decomposition). It appears that both hemicellulose and cellulose decompose at the same time in air atmosphere compared to the lag in thermal decomposition of cellulose in nitrogen atmosphere. Similar response was reported by Wongsiriamnuay & Tippayawong (2010) and Li et al. (2013). We believe this is the cause for the sharper first peak and the higher magnitude of this peak in air atmosphere. The second air atmosphere peak for the samples occurred at temperatures of 475°C to 500°C. For stemwood and whole samples, the magnitude of this second major peak were about three fold lower than the first peak and about the magnitude of nitrogen atmosphere main peak. For bark and limb/foilage, the second air atmosphere peak was about the same magnitude as the first peak. Heating rate did not seem to influence the temperatures at which the first and the second peaks occurred. These mass loss rate results show that systems that are designed to thermally decompose wood in air atmosphere must be able to handle the high rate of gas release at temperatures corresponding to these peaks especially for samples with ash contents lower than 1.0%.

3.3. Kinetics of thermal decomposition

The kinetics of thermal decomposition is generally described by the equation below (Fasina & Littlefield, 2012; Dahyia et al., 2008):

$$\frac{d\alpha}{dt} = A \exp\left(-\frac{E_a}{RT}\right) f(\alpha) \quad (2)$$

T is temperature; E_a is activation energy; A is pre-exponential factor; R is universal gas constant and $f(\alpha)$ is a reaction model function that can take various mathematical forms depending on the physical mechanism (Vyazovkin 2006; Jankovic, 2008). When samples are subjected to constant heating rate of $\beta = dT/dt$, then Eqn. 1 can be rewritten as:

$$\beta \frac{d\alpha}{dT} = A \exp\left(-\frac{E_a}{RT}\right) f(\alpha) \quad (3)$$

The isoconversional method of Friedman (1964) was applied to Eqn. 3 by taking a natural logarithm of the equation resulting in Eqn. 4. Several researchers (Dahyia et al., 2008; Vyazovkin, 2006; Brown et al., 2000) have shown that this is a reliable and accurate method for estimating E_a because the method does not include any mathematical approximations and the estimated E_a is independent of the $f(\alpha)$ model.

$$\ln\left(\beta \frac{d\alpha}{dT}\right) = \ln[Af(\alpha)] - \frac{E_a}{RT} \quad (4)$$

The activation energy (E_a) values were obtained from the slope of the plot of $\ln[\beta(d\alpha/dT)]$ versus $1/T$ at constant α value (Fig. 6).

In nitrogen atmosphere (Figure 7), the activation energy values can be divided into two groups. The high volatile content samples (stemwood and whole) have at least 20% lower E_a values compared to the low volatile content samples (bark and limb/foliage). This is an indication that the presence of fixed carbon might have increased the ‘energy barrier’ that must be overcome during the nitrogen atmosphere thermal decomposition process. The fixed carbon are oxidized during air atmosphere thermal decomposition hence the air atmosphere activation energy for all the samples are essentially the same. The activation energies for the samples thermally decomposition in air atmosphere were higher than the corresponding values from nitrogen atmosphere. Munir et al. (2009) and Chandrasekaran & Hopke (2012) also reported higher values of activation energies in air atmosphere. Some of the reasons that have been given in literature for the higher activation energies in oxidizing atmosphere include the slow oxidation of char and because of the higher number of oxidizing reactions (Calvo et al., 2004; Chandrasekaran & Hopke, 2012). In air atmosphere, the activation energy increased until the conversion was about 55% due to the gradual decomposition of cellulose and hemicellulose. After the 55% conversion level, the activation energy reduced due to slow oxidation of char (Ren et al., 2013). Similar response was obtained from nitrogen atmosphere decomposition except that the peak of activation energy was at about 40% conversion and this was not followed by a dramatic reduction in activation energy (due to absence of char oxidation in inert atmosphere thermal decomposition). The activation energy values obtained in this study are similar to the values that have been reported in literature for other woody biomass (Ren et al., 2013; Shen et al., 2009; Kim et al., 2010).

3.4. Thermal decomposition energy

Fig. 8 shows the measured heat flow (W/g) during thermal decomposition of the four samples within the temperature range of 30°C to 550°C. The negative values of heat flow indicate endothermic reactions. The large endothermic peaks at temperatures around 100°C are due to moisture evaporation from the samples (He et al., 2006; Gomez et al., 2009; Park et al., 2007).

Analysis of the heat flow data was carried out by dividing the data into two zones. Zone 1 represents the energy to evaporate moisture from a sample while zone 2 depicts the energy to thermally decompose the moisture-free sample. Since the TGA study showed that thermal decomposition started at 175°C, this temperature was used to demarcate the two zones. Energy required for moisture evaporation (zone 1) was therefore obtained by integrating the heat flow curve using the software provided by the DSC manufacturer within the temperature range of 30°C to 175°C. Similarly, the software was used to obtain the energy to thermally decompose moisture-free sample within the temperature range of 170°C to 550°C.

The values of the calculated energy for the two zones are given in Table 2. The energy required (in kJ/kg of sample) to remove moisture from each sample was slightly higher than that required for thermal decomposition of the sample (Table 2). Similar results were reported by Park et al. (2007) for wood cellulose fibers, by Daugaard & Brown (2003) for oak, oat hulls, and corn stover, and by Fasina & Littlefield (2012) for pecan shells. The moisture removal energy based on the amount of water in each sample (i.e. the latent energy data in Table 2) was at least 150% higher than the latent heat of evaporation of free water. These results are consistent with other biological products and are indicative of the high interactive energies between available surface sites and moisture as the material approaches a monolayer of water molecules (Bonner and Kenney, 2013; Bahloul et al., 2008; Fasina et al., 1997). Table 2 also shows that the total energy required to thermally decompose the samples was less than 110 kJ/kg and was not significantly affected by tree component. This is less than 0.6% of the energy available in the samples (Table 1). The information presented in this section will be needed when designing and sizing equipment (e.g. pyrolyzers and gasifiers) to thermally decompose loblolly pine.

4. Conclusions

It can be concluded from this study that:

- (a) Bark and limbs/foilage respectively make up about 7% and 18% (based on mass) of loblolly pine trees. They also have lower volatile (bark – 70.4%, limbs/foilage – 79.2%) and higher ash (bark – 1.31%, limbs/foilage – 1.36%) compared to the stemwood portion (volatile - 85.6%, ash – 0.32%) of the tree.
- (b) In nitrogen atmosphere, about 40-60% of the mass of each component was volatilized between 150°C and 425°C. Beyond 425°C, the mass loss of whole, stemwood and limbs/foilage were very small (~3%) while significant mass loss of about 10% occurred with bark samples. In air atmosphere, more than 95% of the sample mass for each component was volatilized before 600°C.
- (c) The fixed carbon content of the components appear to play a role in the activation energy needed for thermal decomposition in nitrogen or air atmosphere.
- (d) Less than 2% of energy content of the tree components were needed to volatilize them.

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Table 1: Properties of loblolly pine wood components

Property	Stemwood	Bark	Limbs/foliage	Whole
Mass fraction ¹ (%)	74.6 ^b	7.2 ^c	18.2 ^d	100 ^a
Volatile content (%)	85.6 ^d	70.4 ^b	79.2 ^c	82.3 ^a
Heating value (MJ/kg)	19.1 ^a	19.8 ^b	20.3 ^c	19.1 ^a
Ash (%)	0.32 ^a	1.31 ^b	1.36 ^b	0.48 ^a
Carbon (%)	47.34 ^d	50.21 ^a	48.60 ^c	49.92 ^a
Hydrogen (%)	6.88 ^d	5.85 ^b	6.44 ^c	6.08 ^a
Nitrogen (%)	0.13 ^b	0.17 ^b	0.59 ^a	0.53 ^a
Sulfur (%)	0.05 ^b	0.01 ^c	0.01 ^c	0.25 ^a
Oxygen ² (%)	45.60 ^b	43.76 ^a	44.38 ^c	43.22 ^a

¹Based on average of 28 trees

²By difference

Values with the different letters in a row are significantly different ($P < 0.05$)

Table 2: Energy required to thermally decompose loblolly pine samples

Parameter	Stemwood	Bark	Limbs/foliage	Whole
Energy between 30°C and 175°C (kJ/kg)	137.4	169.9	159.4	151.25
Energy between 175°C and 550°C (kJ/kg)	108.8	107.7	109.5	106.3
Percent of energy content in sample ¹	1.29	1.72	1.33	1.35
Latent heat ² (kJ/kg of moisture)	3384.2	3809.4	3452.3	3725.9

¹percent ratio of thermal decomposition energy (i.e. row 3) to the energy content of the sample (row 4 of Table 1)

²also called net isosteric heat

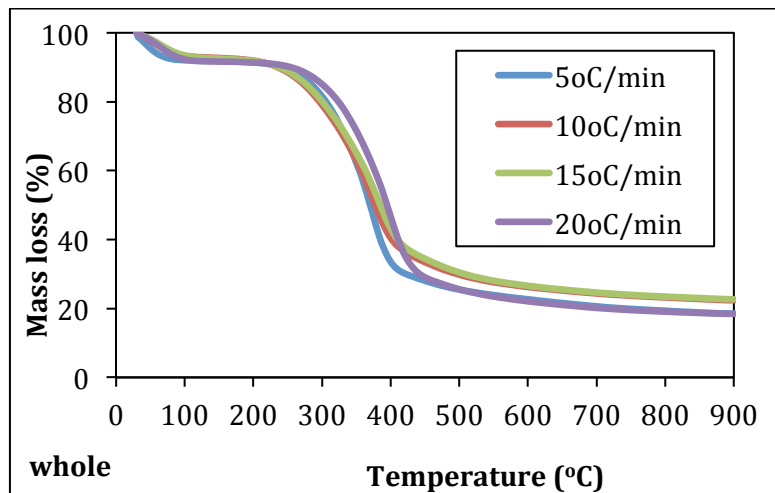
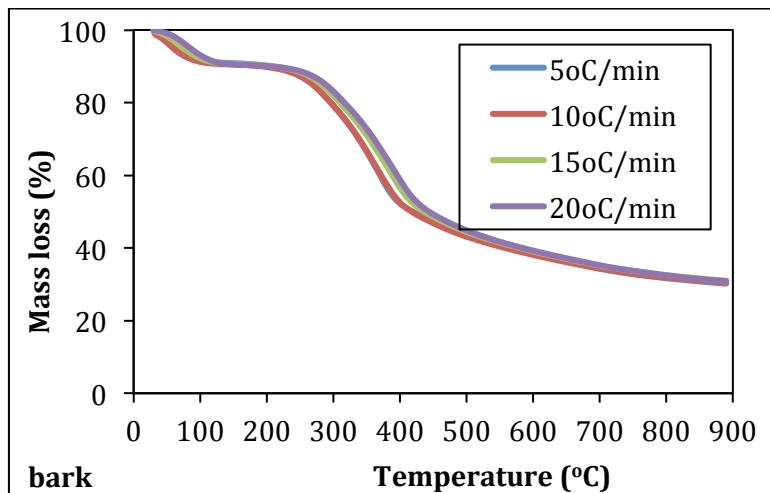
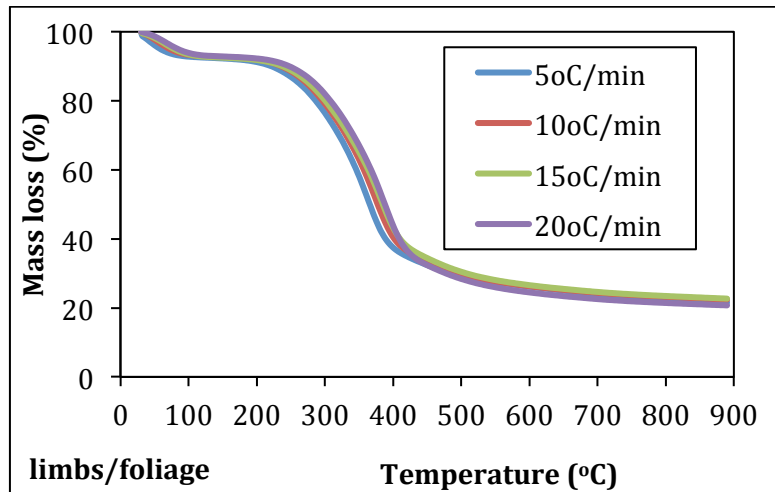
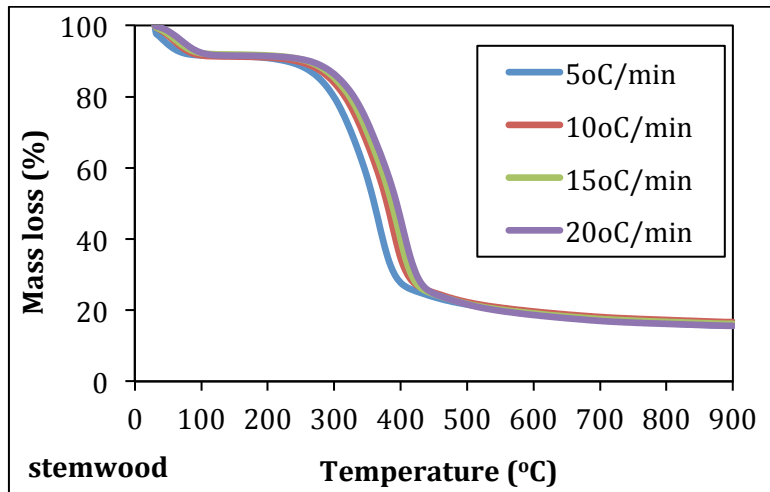


Figure 1: Percent mass loss during thermal decomposition wood samples in nitrogen atmosphere.

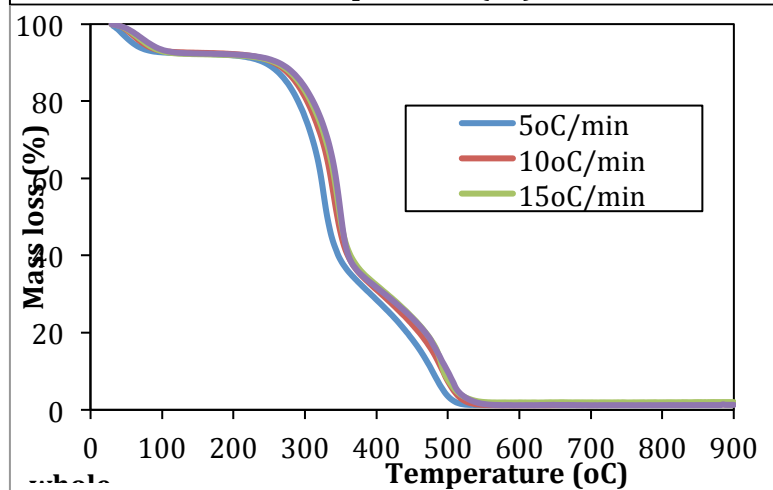
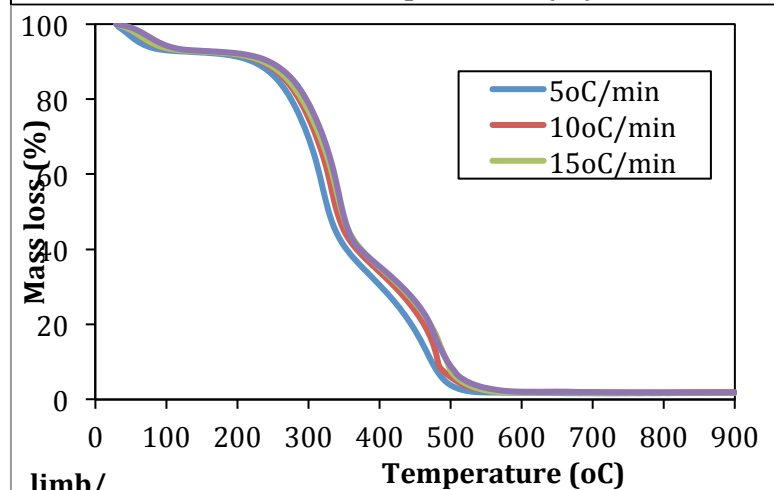
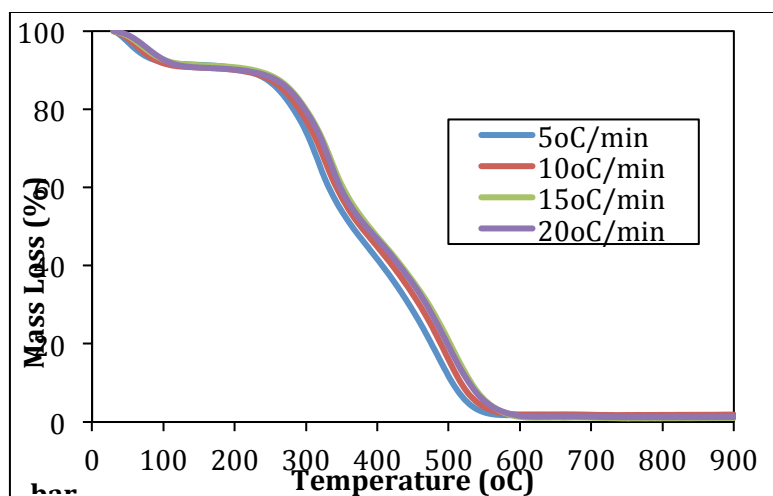
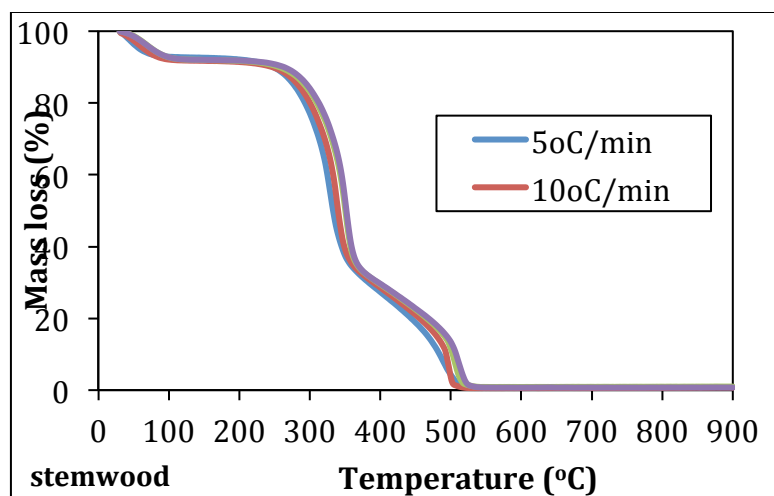


Figure 2: Percent mass loss during thermal decomposition wood samples in air atmosphere.

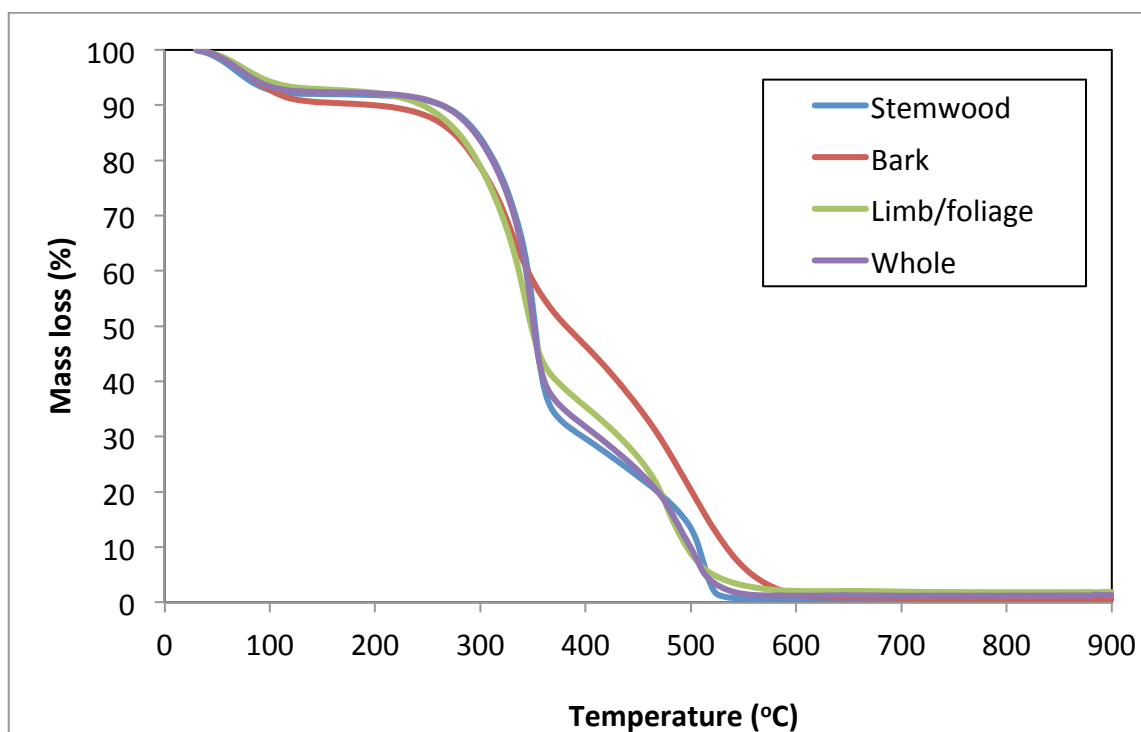
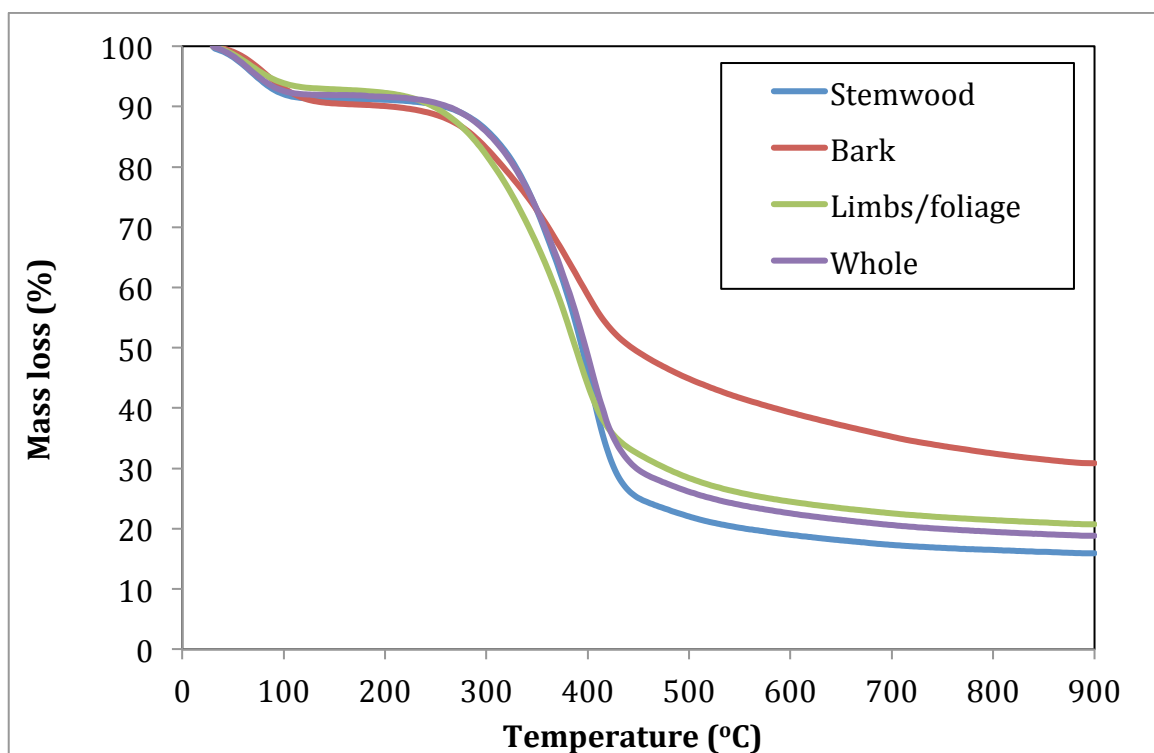


Figure 3: Comparing the thermal decomposition of the four wood samples when ther decomposed at heating rate of 20°C/min in (a) nitrogen, and (b) air atmospl

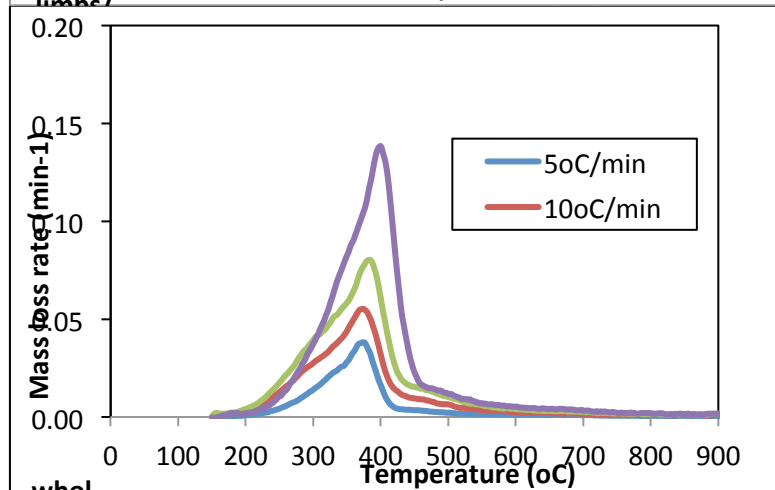
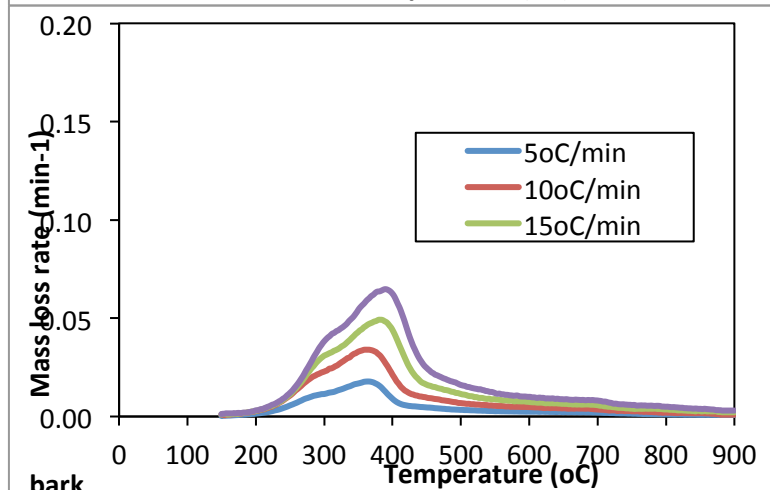
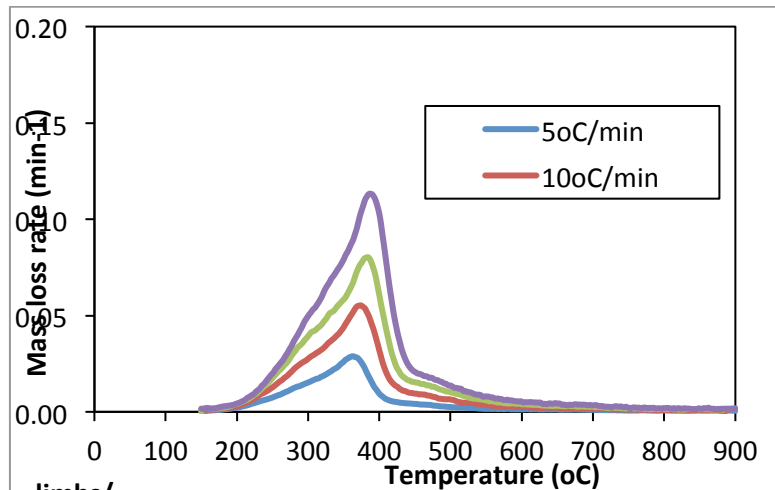
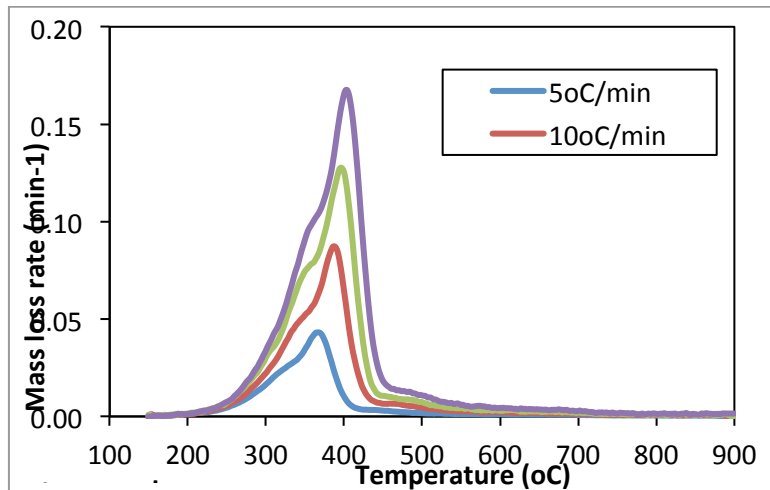


Figure 4: Mass loss rate curves for four wood samples thermal decomposed in nitrogen atmosphere and at heating rates of 5 to 20°C/min.

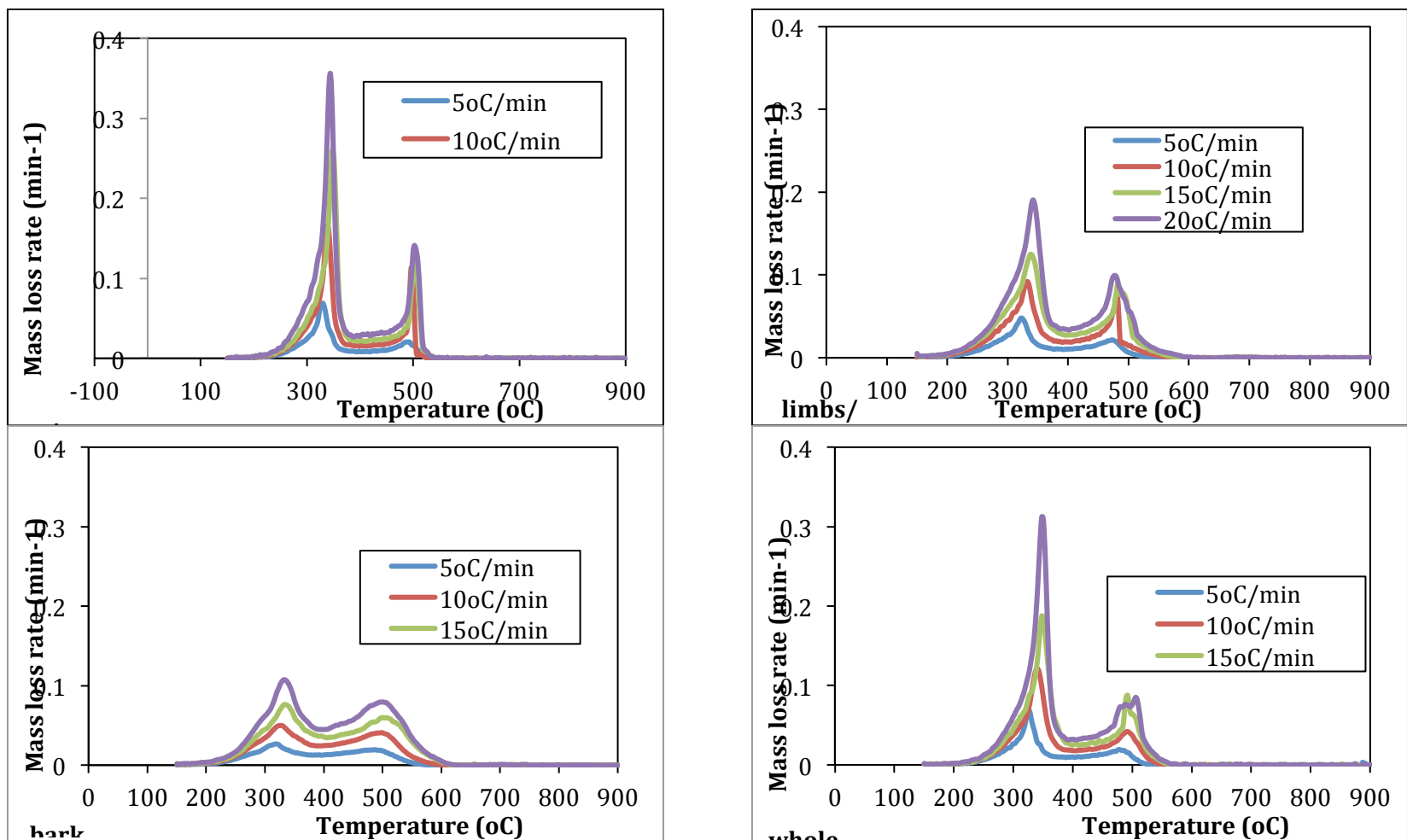


Figure 5: Mass loss rate curves for four wood samples thermal decomposed in air atmosphere and at heating rates of 5 to 20 °C/min.

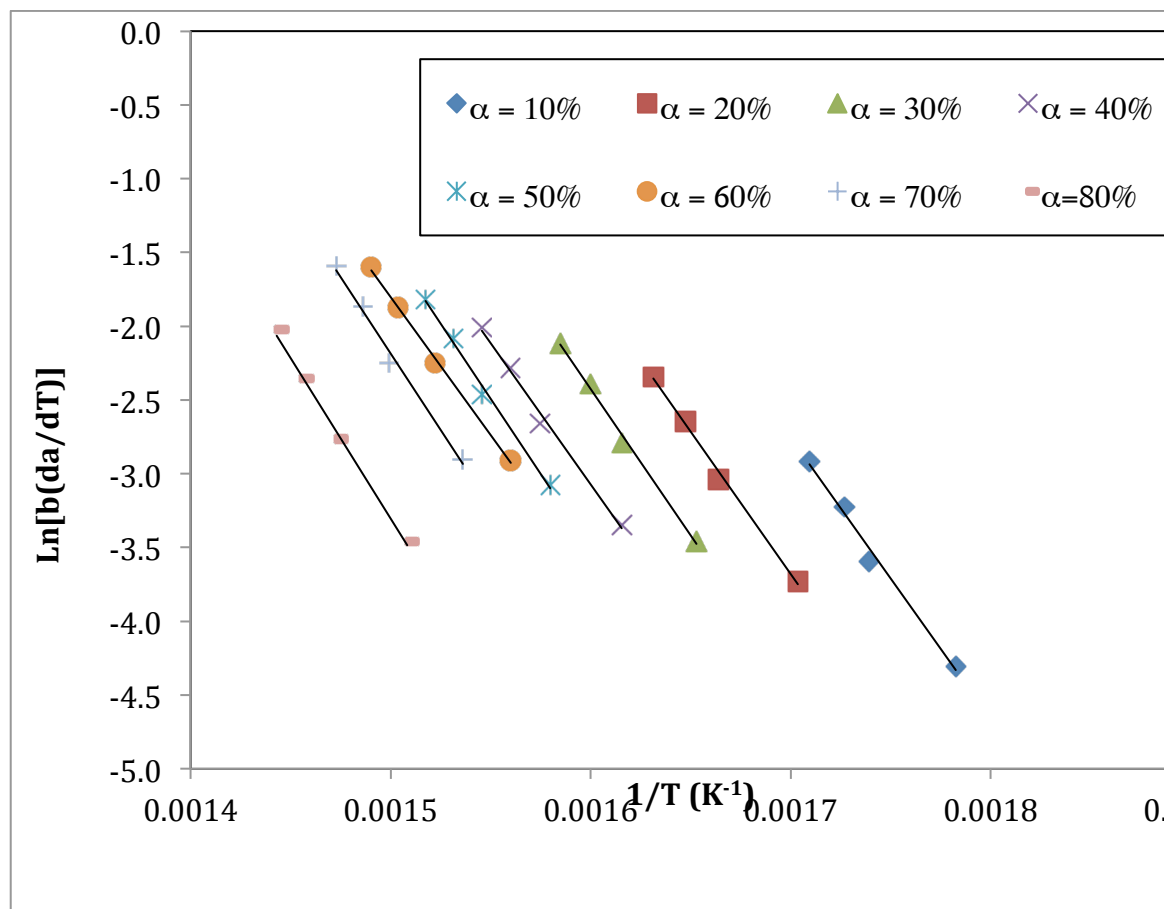


Figure 6: Example of isoconversion plots of $\text{Ln}[\beta(d\alpha/dT)]$ versus $1/T$. This graph is for a stemwood sample thermally decomposed in nitrogen atmosphere.

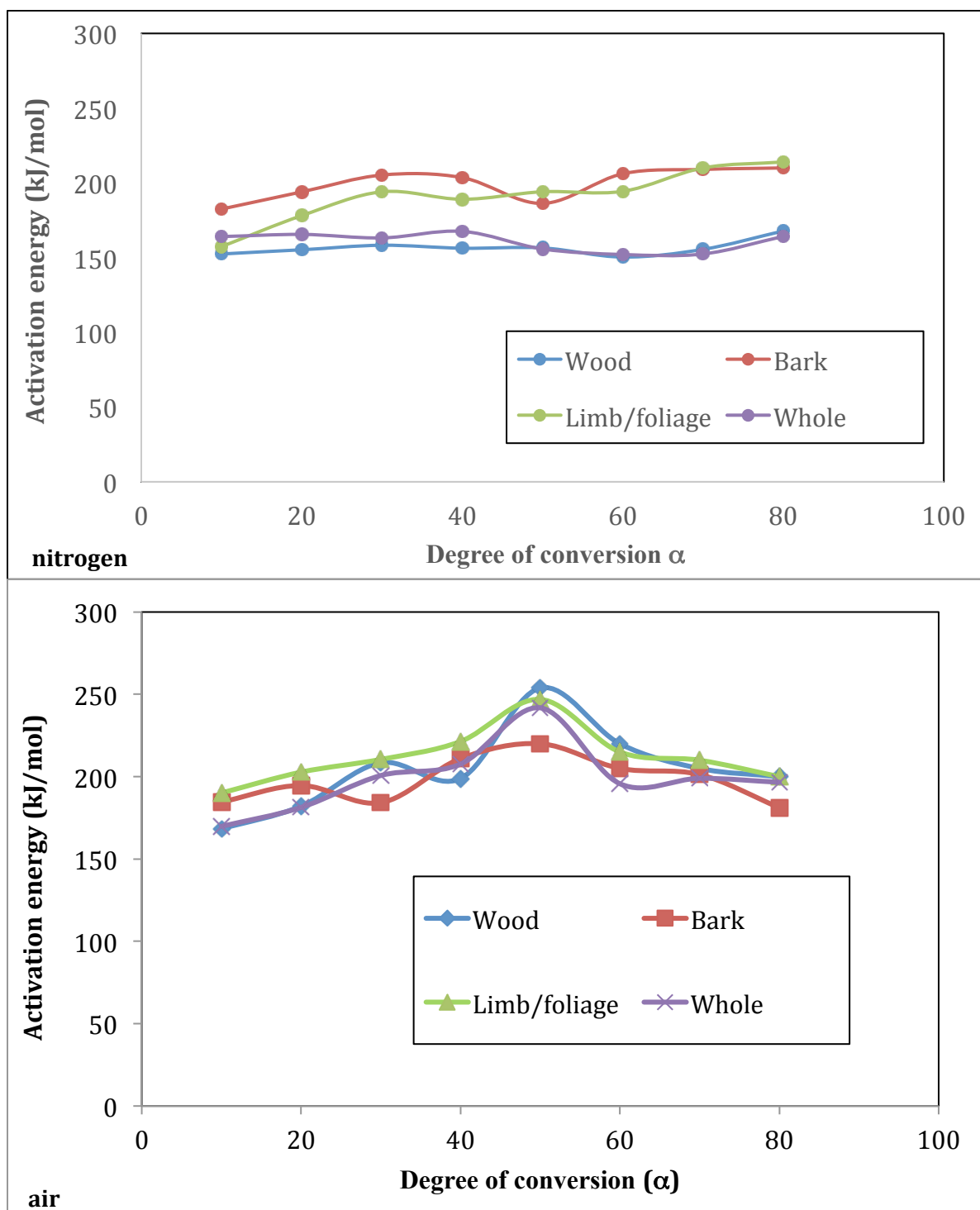


Figure 7: Relationship between apparent activation energy (E) and conversion ratio (α) for the four wood samples when thermally decomposed in nitrogen and air atmospheres.

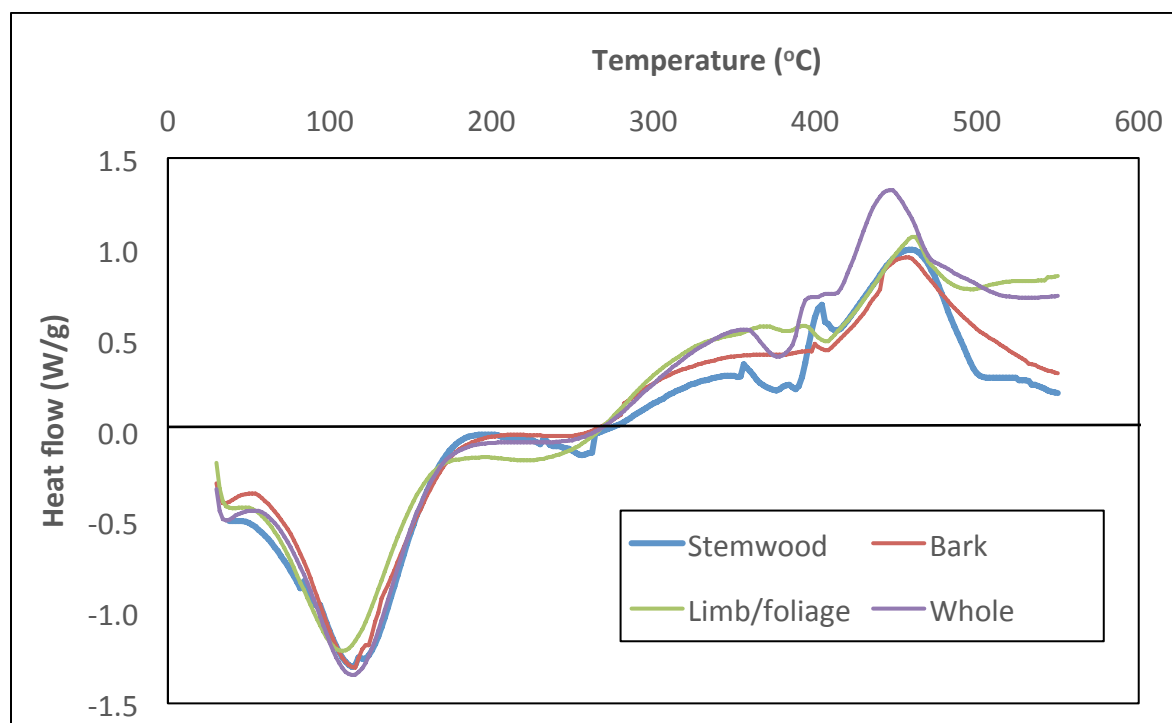


Fig. 8: Heat flow during thermal decomposition of loblolly pine samples (heating rate of 20°C/min).