High Tonnage Harvesting and Skidding for
Loblolly Pine Energy Plantations

by

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Abstract

The need for alternative and renewable energy sources is evident in the United States to ensure that the nation's energy appetite is fulfilled. The southeastern United States has a very promising source for this renewable energy in the form of woody biomass. To meet the energy needs, energy plantations will likely be utilized. These plantations will contain a high density of small stem pine trees. Since the stems are relatively small when compared to current products, the harvesting costs will be increased. The purpose of this research was to evaluate specialized harvesting and skidding equipment that would be able to harvest these small stems cost efficiently. The feller-buncher utilized was a Tigercat 845D with a specialized biomass shear head. The skidder was a Tigercat 630D equipped with an oversized grapple. This equipment was evaluated in a stand with similar characteristics of a southern pine energy plantation. During the study, the feller-buncher achieved an average productivity rate of 52 green tons/PMH and the skidder had an average productivity rate of 123 green tons/PMH. A before tax cash flow model was used to determine a cost per ton for each machine. The feller-buncher costs were $3.48/ton over a 10 year lifespan while the skidder costs were $1.78/ton over the same 10 year life. The results proved that the current system working in a southern pine energy plantation could harvest and skid small stems for approximately $5.26 per ton. After evaluating the operation, several recommendations to benefit the operation were developed. The overall combined cost could be decreased if recommendations for the feller-buncher are successfully implemented.

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

AEC	Annual Equivalent Cost
DBH	Diameter at Breast Height
Gt	Green ton
Lbs	Pounds
PMH	Productive Machine Hour
PMTI	Payments made to Interest
PMTP	Payments made to Principle
OE	Operating Expenses
SMH	Scheduled Machine Hour

I. Introduction

The topic of declining fossil fuels and the need for renewable energy sources is evident in today's society. Because of this necessity, researchers and politicians have assembled different ideas in which renewable fuels will be a major part of the United States energy portfolio. Some of the framed ideas include the Billion Ton Report (U.S. Billion Ton Update 2011), "25 by 25" (25x'25), and the Energy Independence and Security Act of 2007. The Billion Ton Report (2011) illustrates how different areas of biomass feedstock are allocated to the renewable fuel portfolio in a sustainable manner. Another policy that shows promise is the "25 by 25" idea. This states that 25% of our energy consumed must come from renewables by the year 2025. The one policy that has been enacted is the Energy Independence and Security Act of 2007 (EISA). Included in the Act are standards in which bio-fuels will play a major role in ensuring national energy security and the reduction of green-house gases. One of the main goals of the Act is to have 36 billion gallons of bio-fuels produced each year by 2022. The common attributes of all of these ideas are that they require a tremendous amount of biomass in a relatively short time period. A great deal of this biomass will be allocated to woody biomass.

Woody biomass is available in such forms as urban residues, mill residues, dedicated energy crops, and logging residues. Currently, mill and logging residues supply the woody biomass market, but they are not sufficient to meet the large scale quantities set forth. Eventually, dedicated energy crops will likely be utilized by the United States requirements for biomass feedstocks. Short-rotation woody crop (SRWC) supply systems were first described in the late-1960s and early 1970s as a means of rapidly producing lignocellulosic fiber for use in the wood products industry and for energy (Tuskan 1998). Studies have been accomplished to determine optimum species, silvicultural techniques, fertilization, genetics, and irrigation to make the crop successful (Tuskan 1998). The barrier with short-rotation woody crops is the immense amount of inputs needed for high growth rates. This poses economic and environmental issues that hinder the introduction of a biofuel market. These two issues happen to be very important considerations when choosing a crop for biomass production. Another aspect that should be taken into account is the volatile risk associated with the biofuel market. The need for biomass feedstocks for energy has not been constant in the past. To mitigate risk, the biomass feedstock crop should be flexible in its ability to produce different products in order for the landowner to make a profit from his/her initial investment. Correspondingly, the crop should be well known in different areas such as management, nursery management, and disease/pest control.

Southern pine stands have the potential to provide significant feedstocks for the biomass energy market (Scott and Tiarks 2008). Pine plantations have played a major role in the success of the forest products industry in the United States but specifically in the southeast United States. The Southeast produces more industrial timber products than any other region in the world (Allen et al. 2005). This can be attributed to the Southeast climate and knowledge of intensive southern pine plantation management. The stands proposed for the energy plantations will predominately be composed of loblolly pine (*Pinus taeda*) planted at a density between 1000 and 1200 trees per acre (TPA). Stands will be grown for 10-15 years then harvested by the clearcut method. Stands at this age are not merchantable in today's market because of the small stem dimensions at this young age. The shorter rotations will be attractive to landowners looking for a quicker return on investment when compared to other timber product types that require much longer rotations.

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

In the Southeast, conventional whole-tree harvesting systems incorporate a feller-buncher to fell and bunch the trees while a rubber-tired grapple skidder drags the bundle of trees to the loading deck (Soloman and Luzadis 2009, Wilkerson et al. 2008). These two machines are essential to the operation and must be productive for profitability. The stems are processed (de-limbed and bucked) at the loading deck into logs, tree-length material, or chips. In treelength systems, the residues such as foliage, limbs, bark, and tops are typically left on the loading deck or the skidder distributes the slash back into the harvested stand. These residues, along with the main bole of the tree, provide a large amount of low-cost biomass and potentially hinder future operations such as site preparation (Visser et al. 2009). One high productive application in forestry harvesting is the use of portable whole tree chipping systems (Klepac and Rummer 2000). The development and implementation of portable in-woods chippers has increased utilization and allowed recovery of small diameter, low-quality trees at an acceptable cost (Stokes and Watson 1988). In an energy plantation setting, the conventional whole-tree harvesting system configuration will follow traditional harvesting techniques and the whole-tree will be chipped. It is essential that the harvesting system be composed of as few machines as possible to save money in maintenance and labor costs, moving costs, and reduced interference delays (Klepac and Rummer 2000). When chipping, the equipment should be utilized to maintain wood flow for the highly productive chipping application. Using a whole-tree chipping system aids the harvesting process in several areas. One improvement is the recovery of large amounts of biomass that would otherwise be left on site (Watson et. al 1986). The other enhancement is the elimination of time consuming subsequent operations to distribute the slash in the stand, while focusing equipment operations on extraction activities (or production).

Investment in harvesting productivity research studies have been minimal since the late 1980's because the low interest in biomass feedstocks, resulting in a gap in the understanding of production potential of modern harvesting machines. Based on an unpublished benchmarking study of a current harvesting system operating in south Alabama, the USDA Forest Service found that current felling and skidding costs range from $6.00 to $9.05 per green ton. The use of more specialized and technologically advanced equipment could lower the cost per unit. These systems do not need to be capital intensive to lower costs and have the capability to be used for conventional round wood production in case of a market collapse. Because of the high volume and low product value, a highly productive operation must be developed to mitigate the low value of the material. High production rates lower the fixed costs by spreading the costs over more volume harvested. The system designed for this study is a high-speed, high-accumulation feller-buncher and a modified high capacity rubber tired skidder. A field study was performed on this new equipment to analyze productivity and costs associated with owning/operating the machines.

II. Objectives

The objective of this study was to develop and evaluate a prototype feller-buncher in conjunction with a high capacity skidder operating in a pine stand similar to that projected for a southern pine energy plantation.

The scope of this project will encompass the following specific objectives:

1. Evaluate the productivity of the Tigercat 845D feller-buncher and the Tigercat 630D skidder in the study area.

2. Estimate individual machine cost on a per unit basis when operating in an energywood plantation setting.

III. Literature Review

3.1 Mechanized Logging

Any harvesting system is driven by cost and productivity (Bolding 2002). In order for the system to be competitive for market demands, the system must meet volume demands set by the mill as well as be profitable. With the downsizing of the logging force and increase in need for raw materials, logging crews became more mechanized to meet demands. The increase in mechanization of logging has increased production and safety which leads to greater adoption of mechanized logging systems in different settings (Wang et. al 2004a). With this increase in mechanization, an increase in capital cost is also expected (Blinn et al. 1986). To maintain cost efficiency, the contractor must be able to match equipment to the harvest technique and parameters associated with the harvest region.

Wang et al. 2004b investigated the introduction of mechanized logging into Appalachian hardwoods. The system evaluated was a Timbco 445C hydro-buncher tracked feller-buncher and Timberjack 460 grapple skidder. The goals were to create accurate production estimates, cost estimates, and models for the machines in the new stand parameters. The tracked feller-buncher was chosen because of the steep terrain that would be encountered in the region and its ability to maneuver within this terrain. Also the limited area boom could reach trees while the machine remained stationary. The tracked feller-buncher for the proposed energywood plantation harvesting system comes equipped with a boom that extends far into the stand. This enables the machine to travel in a straight path while extending its boom to the maximum length to sever trees, thus increasing productivity when compared to drive-to-tree feller-bunchers (Winsauer 1980). When harvesting trees planted at a high density, the advantage of a boom type machine is even more pronounced because of the decrease in carrier movement. The machine used in the Wang study utilized a chain and bar type felling head that was not capable of accumulating stems. This type of head was effective since the hardwood species were large in diameter and crown size. The general thought of designing or choosing equipment based on stand characteristics can be used to pick machines that are more applicable to southern pine energy plantations. Productivity of the feller-buncher in the Wang study averaged 1,267 ft^3/PMH. It was most affected by DBH, species, merchantable height, and distance between trees. These results aid in selecting equipment specifications and dependent variables for systems working in different stand parameters.

3.2 Small Stem Felling

Based on conclusions from past research, the productivity of feller-bunchers decreases with stem size (Holtzcher and Lanford 1997, Kärhä 2006, Akay et al. 2004, Woodfin et al. 1987, Bolding et al. 2009). Most logging equipment is designed to fell and extract merchantable stems (Bolding et al. 2009). The harvesting of small trees with conventional equipment tends to be more costly and is a disadvantage in the energywood plantation industry. Conventional equipment is typically built large and rugged to fell trees of diverse sizes and has not been developed to efficiently harvest and utilize forest biomass used for energywood (Karsky 1992, Tuskan 1998). The challenge surrounds modifying conventional forestry equipment to remain highly productive and be more specialized towards smaller size stems without drastically increasing upfront capital costs and maintenance costs. Any improvements in the harvesting of small diameter material could aid in the emergence of the bioenergy market by making the field profitable for loggers, consumers, and landowners.

Studies have been completed in the area of feller-bunchers harvesting small diameter stems, some of which investigated understory removal of forest fuel to reduce wildfire hazard while also producing energy (Bolding et al. 2009, Pan et al. 2007, Holtzscher and Lanford 1997). Other studies focused on specialized biomass harvesting of short rotation woody crops (Curtin et al. 1985, Spinelli et al. 2006). These studies showed productivity variation based on different stand characteristics and machine type.

Bolding et al. (2002) performed a study concerning forest fuel reduction using a CTL operation and a small chipper for non-merchantable trees. The objective of this study was to determine the productivity and economics of the thinning system and evaluate if the system could be an economically viable solution to reducing wild fire hazard. The harvester's move time and swing time decreased as trees per acre increased (Bolding 2002). Also the harvester showed a statistically significant increase in the amount of time to fell a 6+ inch tree when compared to trees with diameters less than 6 inches. The harvester's productivity was based on two different products, merchantable trees and non-merchantable (< 4 inches). The productivity of the harvester averaged 32 tons/PMH and 10 tons/PMH for merchantable and non-merchantable, respectively. The result documented the challenges of small tree harvesting with CTL equipment. The total cost to fell and bunch trees for the machine was $4.94/ton.

Karha et al. 2006 compared harvesters and harwarders in Finland on young stands. The harwarder is a machine that performs both harvesting and extraction of stems. Based on the production of the harvester system tested, the following conclusions were drawn. First, the harvester worked best with larger stems (>20 cm). Also the machine worked well when whole-tree removal from the stand was greater than 55 m^3/ha and the stand was greater than two hectares. The results reflect several situations for the proposed energywood plantation: the stand must be large and contain high amounts of medium sized stems.

Stokes et al. 1985 investigated a continuous travel feller-buncher for short-rotation biomass harvesting. This prototype called the HYD-Mech FB-7 was fabricated for trees less than 8 inches at the stump which are not what is proposed in the current system being discussed but did offer advice on feller-buncher design. The head utilized on the machine had difficulty in the accumulating process for the small stems that led to problems laying a tight bunch on the ground (Curtin et al. 1985). This would inhibit subsequent operations, such as skidding, that would lead to a loss in the overall system productivity (Hartsough and Stokes 1997). The incorporation of an automatic accumulating arm on the felling head would help the equipment operator by providing better handling control of the severed trees.

3.3 Small Stem Skidding

Another piece of equipment that is common for a conventional harvesting operation in the southeast U.S. is the rubber-tire grapple skidder (Klepac and Rummer 2000). The skidder’s purpose is to skid the felled whole-tree material to the landing where it can be loaded onto tree-length trucks or chipped into chip vans. Various studies have been completed on skidding operations in different forest settings (Klepac and Rummer 2000, Bolding et al. 2009, Kluender et al. 1997, Miller et al. 1987). These studies found the same two variables exist as the most significant factors affecting productivity: Skid distance and payload. Emphasis on improving the skidders performance over these variables is essential.

The southern pine energy plantations will be harvested on a relatively short rotation which will entail handling small diameter, short stems. Because individual stem volume will be decreased when compared to conventional products such as pulpwood or sawtimber, standard dimensions of the grapple available on the skidder will cause an underutilization of the equipment's horsepower. The reason for this underutilization is the grapple located on the skidder can only handle a certain volume of trees. Southern pine energy plantations will be shorter than trees designated as pulp wood, but the feller-buncher operator may still create the same size diameter bundle. Kluender et al. (1997) found that the one factor that had the greatest impact on skidding productivity was stem size. The decrease in length of the short-rotation crops will lead to a decrease in volume and weight thus underutilizing the skidder's towing capacity. Incorporating a larger grapple on the same horsepower skidder will allow for a greater diameter bundle with similar weight as a conventional bundle to be efficiently pulled, thus increasing biomass volume skidded to the loading deck.

In 2000, Klepec and Rummer performed a study in central Alabama comparing a Timberjack 460 and a Timberjack 660. Both were tested in the same area with similar skid distances. The 460 had a production rate of 46.5 tonnes/PMH and the 660 showed a rate of 45.7 tonnes/PMH. The conclusions of this study were that the smaller 460 had a higher productivity due to higher utilization of the grapple. The larger 660 did not fully utilize the grapple size making its time loaded inefficient. The study also provided insight into subsequent operations that affected the efficiency of the skidders. The feller-buncher operator directly influenced the productivity of the skidders because the operator determined the bunch size set out for the skidder. This bunch size should be optimized for the skidder in order for it to meet its maximum pulling capacity. The skidder operator should also be instructed to fill the grapple while completing a cycle. Stokes et al. (1986) found that by grabbing two or more bunches during a cycle, total cycle time increased 44%. However, the payload almost doubled in size making the skidding function more productive.

3.4 Energy Recovery (ER) boom system

Conserving energy usage on the machinery is a major challenge when harvesting small diameter stems at a very high production rate. The reason for this is the machine's boom will be moving at a high pace between the densely planted trees which requires an immense amount of energy thus causing higher fuel consumption. Conventional boom carrying machines inefficiently use two different arcing motions to reach a sought after length (Tigercat Inc.). Because the inefficient use of energy results in a higher cost in conventional harvesting of large wood, the problem is magnified by the low value and number of movements needed to harvest southern pine energy plantations. Tigercat Inc. has developed an energy recovery system for its boom carrying machines that helps eliminate some of the energy usage that occurs as the boom maneuvers. The system allows the machine operator to extend and retract the boom on a horizontal plane which takes away the double arcing seen on conventional boom machines. The operator can extend and retract the boom more smoothly with a single joy stick which controls the main and stick booms simultaneously. This results in higher production based on ease of travel for the boom and a reduction in operator fatigue (Tigercat Inc.). Also the ER system transfers energy between the main and stick boom functions resulting in less energy needed to move the entire boom. Ultimately, this technology should help in reducing production costs for harvesting small diameter material.

3.5 Biomass Harvesting with a Shear

Continuous saw heads incorporated on a feller-buncher have been shown to be highly productive (Greene et al. 1987). The issue with these heads is the high capital costs and high operating costs when compared to the less expensive shear heads. Also, the use of shear heads in rough terrain leads to less mechanical problems than continuous saw heads (Wang et al. 2004b). Shear heads have been used in conventional harvesting systems for many years but previous versions of the shear head would not meet the high productivity standards needed for southern pine energy plantations. The increase in technology available today could make these shear heads far more productive.

Another positive effect of incorporating a shear-head in place of the continuous saw-head is the lower stump remaining after a tree is severed. One major benefit of this incorporation is the increased yield of wood felled when the stump is cut flush with the ground. Shear heads can be placed directly on the ground while continuous saw heads cannot achieve this result due to the deterioration of the saw-teeth when the saw-teeth meet the soil. The implementation could result in an increase of up to six inches of the largest portion of the bole of the tree being felled, increasing woody biomass recovery by 2% per acre.

3.6 Environmental Challenges

One issue with the feller-buncher is the environmental impacts that it can place on a property. The dominant feller-buncher type incorporated in southeastern logging operations is the rubber-tired drive-to-tree model. Since the energy plantations will be planted at a high density, the machine will be making several passes over the same area which could lead to soil compaction. Also, this type of feller-buncher has a tendency to cause unacceptable rutting in wet weather making it extremely weather sensitive as well as a producer of erosion. This rutting can lead to more erosion which has detrimental affects to water quality. Since southern pine energy plantations are generally clearcut, one must take into account that clearcutting generally produces more soil disturbance than thinning or select cutting (Reisinger et al. 1988, Carter et al. 2006).

Cut-to-Length systems incorporate a harvester which is similar to the tracked feller-buncher except for the severing head. The boom allows the machine to stay stationary and reach far into the stand to sever a tree which leads to less travel in the stand. The less movement of the carrier reduces the amount of soil compaction on site (Bolding et al. 2002). The machine can also handle steep terrain better than rubber-tired versions which could lead to safer working condition for the operator and will not constrain the procurement associate to buy only flat terrain stands.

3.7 Ergonomics

Ergonomics has been a major issue in the forest harvesting equipment market. The mechanization of forestry work has resulted in a sharp decline in the number of accidents (Hansson 1990). Unfortunately the mechanization has caused other long term problems for forest machinery operators due to uncomfortable positioning while operating the equipment. Despite the ergonomic and industrial hygiene improvements successively introduced, musculoskeletal complaints are still present. The occupational health services for the forestry industry have found that the symptoms mainly occur in the arms, shoulders, neck, and other parts of the cervical spine (Hannson 1990).

IV. Equipment Design

4.1 Harvesting System

The high production harvesting system used in this study was composed of the following equipment: Tigercat 845D tracked feller-buncher, Tigercat 630D rubber-tired grapple skidder, Tigercat 234 Loader, Precision Husky 2300 flail, and a Precision Husky chipper. The felling and skidding equipment was the main focus of this research while the other equipment will be investigated in subsequent studies. The product delivered to mills was clean chips for pulp and paper production. This step of the process occurs on the landing, which will allow for minimal impact on the productivity of the feller-buncher and skidder. Corley Land Services was responsible for the operation and maintenance of the system.

4.2 Tigercat 845D

The tracked feller-buncher design was oriented around the concept of using existing equipment with slight modifications. This method would aid in lowering upfront capital costs for the machine. The 845D carrier component is extremely similar to Tigercat's 845C tracked feller-buncher except for the interim Cummins QSB 6.7 liter Tier IV engine (Figure 2) which is rated at 260 hp. It is a high performance mid-sized feller-buncher that offers limited tail-swing and a clamshell style retracting roof enclosure that facilitates access to the engine compartment. The engine is a newly developed interim Tier 4i design that is EPA compliant. It also offers the state of art energy recovery boom system. In an attempt to conserve more energy, it contains an automatic variable speed cooling fan with reversing cycle for improved fuel economy and quieter operation (Tigercat Inc.) For increased operator performance, it is equipped with many ergonomic amenities such as climate control, excellent visibility, air-ride suspension seat and decreased engine noise. The weight of the feller-buncher is 57,100, the width is 10 feet 9 inches, and the other dimensions of the machine are illustrated in Figure 1.

Figure 1: Feller-buncher dimensions.

The boom can reach to a maximum of 26 feet 5 inches or 8.05 meters. Fuel capacity for the machine is 257 gallons for less stoppage time to refuel. The top speed in low range is 1.2 mph and high range 2.6 mph. The track width for the machine is 28 inches.

The machine carries a Prototype DT1802 Biomass Harvesting High Speed Shear (Figure 3). This shear head was designed with a thinner blade to aid in severing the smaller trees at a higher speed. This will hinder the machine in its ability to harvest larger diameter stems but the hydraulic system set up allows for interchangeable head replacement. The hydraulic component of the head itself has been modified for a higher pump flow which will be pertinent to achieve the desired severing time. This shear-head contains a proprietary component that assists with stem handling. An automatic accumulating arm was developed and implemented on the new felling-head with the idea that the operator would only press one button to fell and bunch a stem. The bunching capability of a feller-buncher is increasingly important with decreasing stem size. The mass holding of stems dampens the effect of decreasing stem size and allows for sustained productivity (Spinelli et. al 2006). The feature can theoretically decrease cycle time and lessen operator fatigue since he/she only presses one button instead of multiple movements.

Figure 2: Tigercat 845D equipped with specialized biomass shear head.

Figure 3: DT1802 Biomass Harvesting High Speed Shear.

4.3 Tigercat 630D

Like the feller-buncher, the skidder was not a completely newly designed machine but was slightly modified for skidding smaller trees. The 630D model is Tigercat's largest four wheeled model (Figure 5). Like all current skidder models made by Tigercat, it has Turnaround™ seating to allow the operator to spin to either direction the skidder travels. The skidder incorporates a unique hydrostatic drive system which allows the 630D to operate at variable engine rpm, automatically increasing engine speed when additional horsepower is demanded (Tigercat Inc.). The skidder weighs 37,250 lbs, the width is 11 feet 9 inches, and the other dimensions of the machine are as illustrated in Figure 4:

Figure 4: Skidder dimensions.

The engine on the skidder is a Cummins QSB6.7 Tier III which operates at 194 kW (260 hp) at 2,200 rpm. It has a fuel capacity of 155 gallons with a top speed of 12 mph. The difference between this modified machine and standard equipment offered by Tigercat is the grapple size. The grapple located on this prototype is the same available for Tigercat's 635D 6-wheeled skidder. The maximum opening of the grapple is 151 inches and when closed tip to tip has 21 ft^2 of area. This available area will theoretically hold 98 six inch diameter trees.

Figure 5: Tigercat 630D skidder with oversized grapple.

V. Materials and Methods

5.1 Site Description

To test the newly manufactured equipment, Corley Land Services procured tracts of timber that were similar to the projected energy wood plantations (i.e. 700 trees per acre and average DBH of 6 inches). Since southern pine energy plantations has not yet developed, stands with the exact parameters discussed for energy plantations were scarce. While the machines were operated on many sites, we selected one stand which was similar to the specifications of the proposed southern pine energy plantations.

The plantation where the equipment was tested was in Monroe County, AL about 5 miles east of Monroeville. The site was relatively flat with approximately 10.8 acres of 11 year old loblolly pine (*Pinus taeda*) with a minimal hardwood component. A systematic grid style cruise was applied to the tract and 20th acre plots were used to sample the stand. All trees located on the plots were measured for DBH using one inch classes. Three random trees per plot were also measured for total height. From the sample of three trees per plot, regression equations were developed to better estimate height of different diameter trees in the stand. A total of 10 plots were taken on the tract which allow for achieving descriptive elements of the stand.

5.2 Production Study

Corley Land Services moved to the stand on January 3, 2012 and finished at noon on January 6, 2012. During the study period, the feller-buncher began harvesting trees approximately 5 hours before the skidder began operations. The feller-buncher operator's responsibility was to harvest all stems located on the study site and place the stems in bunches for the skidder. The operator was instructed to cut and travel down a center row and harvest 2 adjacent rows on each side of the travel row. This would allow the feller-buncher to utilize the boom extension length to harvest 5 rows in one pass and minimize carrier travel. By limiting carrier travel, the machine would be better utilized based on its design and soil impacts from trafficking would be minimized.

The skidder operator began operation on the study site after the chipper had been moved to the new deck. He transported the bunches made by the feller-buncher to the landing. During the study, two individuals operated the skidder. This was recorded to identify potential differences between the operators.

To measure the productivity of the individual machines, three forms of data collection methods were utilized on the skidder and feller-buncher. MultiDAT data recorders (geneq.com) were installed on both machines for the experiment. These apparatus contain a vibration sensor to measure productive time for the machine. The vibration threshold was set on each machine to determine operating times. Once the vibration threshold was exceeded, the MultiDAT recorded the machine was active and stopped recording when the vibration level decreased. Also the MultiDAT contains a GPS receiver and Garmin 15 antennae which was mounted on the outside of the skidder for better reception. The MultiDAT recorded the location of the machine every three seconds. The coordinates were time stamped. The GPS was not used on the feller-buncher.

Video cameras were mounted on the machines to monitor specific operations for use in the elemental time study analysis. The feller-buncher camera was mounted inside the cab near the front door where it recorded the operation of the felling head. The skidder camera was mounted on the back of the cab and recorded grapple operations. These cameras contained a memory card that had a capacity of approximately 4 hours of memory per use. For this reason, the cameras were downloaded when the operator paused for lunch.

Along with the MultiDATs and video cameras, data was taken by hand in the field during the harvest operation. For the feller-buncher, the machine was followed by a worker periodically throughout each day where trees per accumulation, accumulations per bunch, and total time were all recorded. The data was used for both feller-buncher productivity and to identify average bunch size skidded by the skidder. The skidder was followed by a separate worker throughout the entire study period where arrival time to each bundle was recorded and the number of bundles grappled was recorded.

5.3 Data Analysis

5.3.1 Stand Parameters

To calculate production rates for the machines, the stand conditions had to be analyzed from the cruise data. From the 10 plots, information such as average tree size, trees per acre, and volume per acre was estimated. A model for height was formed from the three sample trees located on each plot. This was accomplished using Statistical Analysis Software (SAS 9.2). An equation was generated to estimate height for each diameter class. Clark and Saucier (1990) contains a weight equation for total pine biomass in the coastal plain region. This equation combined with diameters and heights estimated total weight per stem.

Plot level data were analyzed by determining the key statistics for parameters such as trees per plot, basal area per plot, and weight per plot. By averaging the plot level data and multiplying by a factor of 20, trees per acre, weight per acre (tons), and basal area (ft^2) per acre was calculated. From average weight per acre and average trees per acre by diameter class, an average weight per tree on the stand was determined for use in production equations.

To verify the cruise information, load sheets from the tract were acquired from Corley Land Service. The load sheets contained the number of loads and the respective weight for each load. The crew harvested clean chips. Therefore, the total biomass on the tract could not be determined from the load sheets. To compare the tonnage delivered at the mill and the cruise information, the merchantable green weight equation from Bullock and Burkhart (2003) was used to determine clean chip volume on the tract.

5.3.2 Feller-buncher

Productivity rates for machines are one of the major calculations used to determine the viability of new systems. The productivity of the feller-buncher was developed by sampling cycles throughout the study period. A cycle for the feller-buncher was defined as the harvest of one accumulation of trees. The cycle started when the last accumulation was placed in a bunch and ended when the current accumulation was placed in a bunch. To utilize this method, the video tapes were reviewed. For each cycle, total time, trees per accumulation and accumulations per bunch were recorded. A bunch can be described as a pile of accumulations made by the feller-buncher for the skidder to drag to the landing. Delays were noted if they occurred for more than one minute. By recording this information and the time for each cycle, an accurate estimate of trees per minute could be calculated. Trees per minute was then multiplied by the average tree size formed in the stand analysis to estimate the productivity for the feller-buncher. A linear regression equation was developed to reflect the time needed to complete one cycle where the number of trees severed per cycle was the dependent variable.

5.3.3 Skidder

Skidding productivity was determined by bunch size and the use of the MultiDAT data recorders. Prior studies have resulted in skid distance and payload as the most significant variables that affect skidding productivity (Wang et al. 2004a, Miller et al. 1987, Bolding et al. 2009, Kluender et al. 1997). Because of this, the productivity analysis focused on these two areas. A cycle was the time needed to leave the landing and return to the landing to drop a new bunch of trees. Average bunch size was estimated from the data collected by the workers in the field. The workers recorded the number of trees placed in each bunch made by the feller-buncher. This combined with average tree size estimated from the stand inventory gave an estimated weight per bunch. Another worker recorded the skidder arrival time and number of bundles grabbed by the skidder in each cycle. This information was compared to the MultiDAT information which also gave a precise travel distance and time. The data collected in the MultiDAT was downloaded into ArcGIS 10 to develop skidding distances and time. These variables were then used to develop a regression model to better describe productivity.

5.4 Economic Analysis

One of the main goals of the study was to perform an economic analysis on both machines that could be used to estimate costs. By calculating total costs for the machines, they can be compared to other equipment operating in similar conditions. The method used for this analysis was a discounted cash flow model (Tufts and Mills 1982). This method calculates the before and after tax cash flow cost of individual machines as well as an entire system by taking into account stand characteristics, machine types, and productivity. For the purpose of this study, both before and after tax costs were estimated. The model separates total cost into fixed and variable costs. Fixed costs used in the analysis are purchase price, depreciation, insurance, and taxes (Tufts and Mills 1982). Variable costs used in the analysis include fuel and lube, maintenance, and repair. The average labor rate for U.S. loggers was used. Fuel consumption and productive hours for each machine were recorded by the crew members. Repair and maintenance cost information was acquired from the Caterpillar Performance Handbook. Also major replacements such as replacing tracks, wheels, and engines were placed in the expected year of replacement for the economic analysis.

The model reports costs for equipment in dollars per ton and dollars per SMH. Utilization rates were applied to the machines to develop costs in dollars per PMH. Productivity for each machine was estimated during the study, which eliminates the need for the stand and productivity calculation portion of the spreadsheet.

The benefit of using this type of analysis is the incorporation of taxes and annual equivalent cost (AEC) for the machines. The AEC illustrates the annual cost for owning and operating a machine throughout its expected life. It can be used to determine the optimum economic life of the machine (Tufts and Mills 1982). Costs from the model can be extremely beneficial when estimating the economic life of the machines and when a replacement is needed (Tufts and Mills 1982).

VI. Results and Discussion

6.1 Stand Parameters

For this study, all pine 3 inches at DBH and greater were considered merchantable since the entire tree would be theoretically chipped into a van. The results of these regressions were used in calculations of stem weight which was determined through volume equations (Clarke and Saucier 1990, Bullock and Burkhart 2003). The regression equation developed for height is as follows.

Ht=Total height in feet
D=Diameter at breast height

This equation was proven to be significant at $\alpha = 0.05$ level (p-value = $3.14*10^{-11}$) and had a R^2 value of 0.79. Mean square error was calculated to be 9.44. This indicates that DBH explains 79% of variation in total height of the trees.

To further illustrate stand parameters, a diameter distribution of each DBH class was developed. This parameter is important to discuss because the study site's qualities are relative to that of the proposed energy plantations. By having a diameter distribution similar to the proposed plantations, the machines could be accurately evaluated while working in small stem situations. The diameter distribution of the stand was calculated in percentages. The illustration of the trend of DBH distribution and the respective percentages are shown in Figure 6.

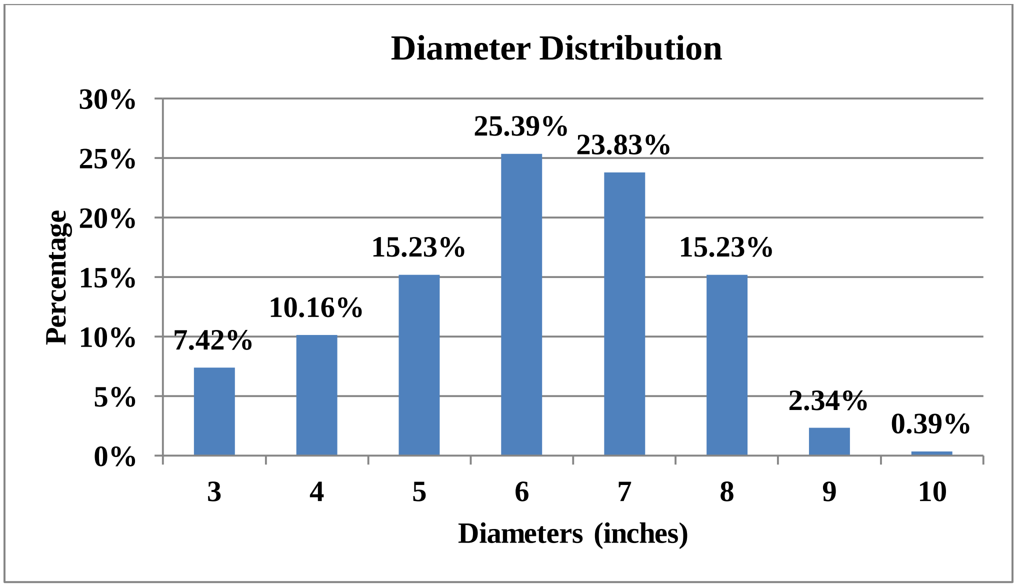

Figure 6: Bar graph illustrating the percentage of each diameter class in the study area.

Plot level descriptive statistics for standing merchantable pine can be seen in Table 1. Confidence intervals were developed for the weight per plot variable. The 95% confidence interval resulted in 7947 lbs as the lower limit and 9510 lbs as the upper limit. This range in weight can be attributed to variation of trees per acre and size of trees across the stand.

Table 1: Plot level density and weight statistics for pine.

	N	Max	Min	Mean	Standard Deviation
Basal Area/Plot[1]	10	6.69	4.78	6.02	0.58
Trees/Plot	10	33.00	24.00	28.80	2.74
Weight/Plot[2]	10	9815	6692	8729	1014

[1]Basal Area/Plot=measured in ft^2
[2]Weight/Plot=measured in pounds

Average total pine biomass was 87.29 tons/acre. Stand density was measured by trees per acre and basal area. Average trees per acre was 576 while the basal area was 120.32 ft^2/acre. Other key statistics can be seen in Table 2.

Table 2: Per acre density and weight statistics for pine.

	Max	Min	Mean	Standard Deviation	95% lower	95% upper
Basal Area/acre[1]	133.84	95.55	120.32	11.63	111.99	128.64
Trees/acre	660	480	576	54.81	536.79	615.21
Weight/acre[2]	98.15	66.92	87.29	10.15	80.03	94.55

[1]Basal Area/acre=measured in ft^2
[2]Weight/acre=measured in tons

From TPA and tons per acre, average tree size was formulated. Based on the data, average tree size resulted in 303.10 lbs or 0.15 tons. This value was utilized in productivity calculations for the feller-buncher and grapple skidder.

To verify the cruise information, load sheets containing actual tonnage taken to the mill were acquired. As stated earlier, the final product of the operation was clean chips which would not be the same tonnage as total biomass. From the load sheets, total clean chip output harvested off the 10.8 acre study site was found to be 549.21 tons. This tonnage was delivered to the mill in a total of 21 loads of clean chips. From the Bullock and Burkhart (2003) equation and the cruise information, the total volume of clean chips located on the stand prior to harvest was calculated to be 549.7 tons or 54.4 tons per acre. The very small difference between the two numbers confirms the stand data collection portion of the study.

6.2 Feller-buncher Production

The feller-buncher productivity was estimated by developing a linear regression model. The dependent variable was cycle time which was the time to harvest and release one accumulation of trees. The independent variable was the number of trees harvested for one accumulation. During the study period, a total of 186 cycles were measured and recorded which consisted of the harvest of 1,404 trees. Descriptive statistics for the study on feller-buncher cycle time are listed in Table 3.

Table 3: Key statistics for feller-buncher cycles.

	N	Min	Max	Mean	Standard Deviation
Acc time[1]	186	0.22	3.48	1.36	0.33
Trees/acc[2]	186	1	15	7.55	2.19
Time/tree[2]	186	0.11	2.35	0.19	0.17

[1]Acc = Accumulation
[2]Acc time, Time/tree = measured in minutes

The mean estimate for time per accumulation was 1.36 minutes. To acquire a range of cycle times, 95% confidence intervals were formulated for this measure (upper=1.42, lower=1.30). A scatterplot shows the relationship between the number of trees harvested and cycle time (Figure 7). The figure illustrates a trend of increasing cycle time with the increase in trees harvested per accumulation. The average payload per accumulation was estimated as 1.13 tons.

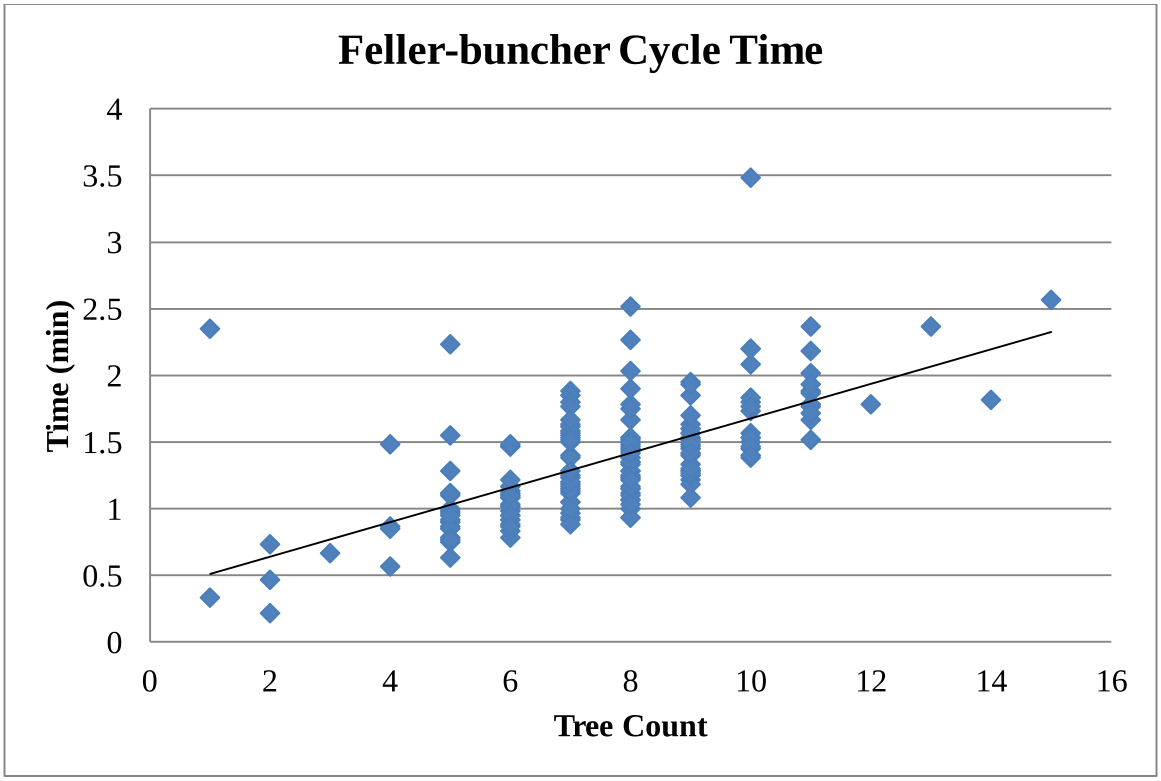

Figure 7: Scatterplot of feller-buncher cycle time versus trees per accumulation.

When evaluating the regression developed, the model was proven to be statistically significant at $\alpha = 0.05$ significance level. The ANOVA table (Table 4) shows that the variability in the response variable (cycle time) is significantly related to the predictor variable (number of trees).

Table 4: Analysis of variance for feller-buncher cycle time.

	df	SS	MS	F	Significance F
Regression	1	18.7861	18.7861	67.3571	3.76157E^{-14}
Residual	185	51.5971	0.2789		
Total	186	70.3833			

The regressor or the number of trees was proven to be significant using the t-test approach. The following table represents the regression equation details.

Table 5: Regression equation details for the feller-buncher cycle.

	Coefficients	Standard Error	t Stat	P-value	Lower 95%
Intercept	0.300	0.138	2.16	0.031	0.027
Trees	0.144	0.018	8.21	$3.8E^{-14}$	0.109

R^2=0.26

From the table, the p-value exhibited for the tree variability is statistically significant because it is less than the threshold of 0.05. This indicates that the number of trees harvested is statistically important and explains variability in the feller-buncher cycle time. This relationship is illustrated with a scatterplot showing actual cycle time and predicted cycle time (Figure 8).

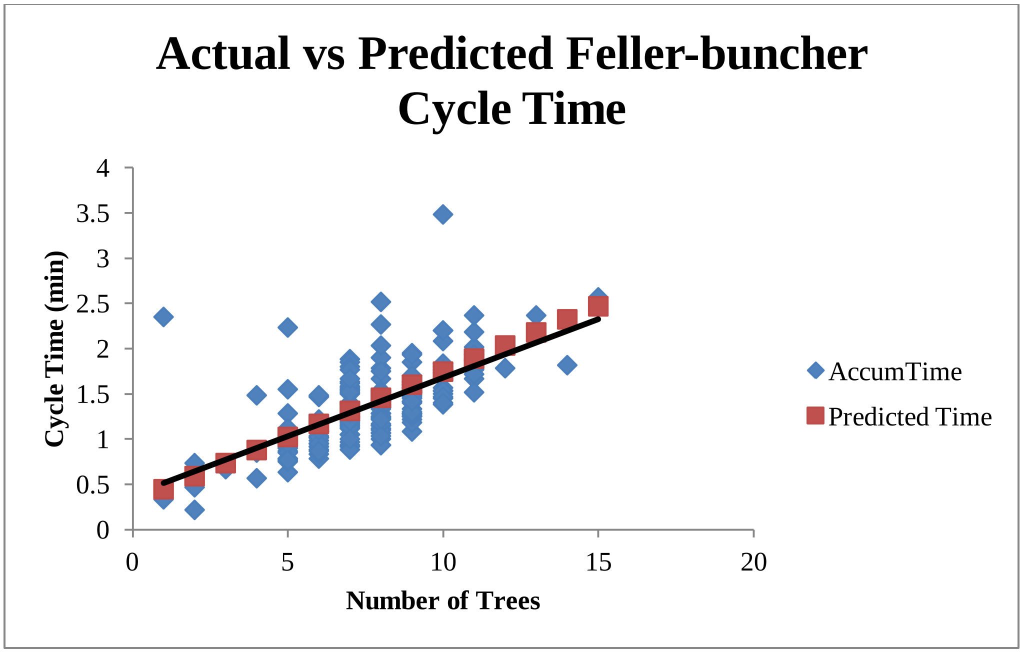

Figure 8: Scatterplot illustrating actual felling time and predicted felling time based on the model.

As expected, there is a definite trend of increasing cycle time as more trees are harvested per accumulation. A majority of the data points occur between 5 and 10 trees harvested per accumulation and variation is evident for cycle time. This is due to several factors including operator delay, irregular patterns of harvest, trees not properly grasped, and irregular tree shape. Operator delays included time to stretch or answer a phone call; these were typically no longer than 30 seconds. Irregular patterns of harvest consistently occurred. The operator did not follow a consistent harvest scheme and would skip trees nearest to the machine in order to reach another tree. If a consistent pattern of harvesting trees nearest to the felling head was followed by the operator, productivity could increase. Trees not properly grasped by the accumulating arm also occurred throughout the harvest. This happened when stems began to fall out of the harvesting head. The falling of trees caused delay when the operator attempted to correct the problem. The issue consistently limited the accumulation of more trees during the cycle. One characteristic of the stand that would not be found on most plantations was the crook and sweep of some trees. In several locations across the tract, trees contained significant amounts of sweep which inhibited the operator's ability to fill the head. This anomaly also led to trees falling out of the head which caused more delay.

Figure 9: Tigercat 845D with a full accumulation of pine stems.

Throughout the study period, only one mechanical delay was observed. The delay in machine operability was a result of slash blocking the cooling system located on the carrier. To correct the problem, the filter was pulled and cleaned which took approximately 5 minutes. The scheduled hours for the feller-buncher were 10 hours per day with a 30 minute lunch and two 15 minute breaks. Total observed/recorded scheduled time for the study period was 22.5 hours. The feller-buncher finished 2.5 hours into the last day of work. From the MultiDAT, productive time was measured for the scope of the study period. The productive hours for feller-buncher by day were 7.78 hours, 8.89 hours, and 2.19 hours respectively. This resulted in total productive hours of 18.87. A utilization rate of 83.8% was calculated. Moving time and repairs were not observed in the study period which resulted in the high utilization rate.

The productivity of the feller-buncher was a measure of how many tons the machine could fell and bunch in an hour (PMH or SMH). From the 186 cycles recorded, the feller-buncher averaged a productivity of 52.34 tons/PMH. The 95% confidence interval for this mean resulted in the upper being 54.03 tons/PMH and the lower being 50.64 tons/PMH. By multiplying the PMH productivity found in the cycle analysis by the utilization rate, the machine produced 43.86 tons/SMH. Other key statistics concerning productivity can be viewed in Table 6.

Table 6: Descriptive statistics of productivity of the feller-buncher based on PMH and SMH.

	PMH (tons)	SMH (tons)
10^{th} Percentile	38.01	31.85
90^{th} Percentile	66.07	55.37
Mean	52.34	43.86
STD	11.69	9.79

The number of accumulations per bunch was another variable investigated in the feller-buncher study. The first method of this analysis utilized the video of the feller-buncher to measure bunch characteristics. A total of 22 bunches were sampled for accumulations per bunch. From the samples, a mean of 3.77 accumulations were used to form each bunch. On average, each bunch contained approximately 30 trees. An example of a typical bunch is shown in Figure 10. Key statistics for bunch characteristics can be viewed in Table 7.

Table 7: Descriptive statistics of bunch size made by the feller-buncher.

	N	Min	Max	Mean	Standard Deviation
Acc/Bunch	22	2	5	3.77	0.79
Trees/Bunch	22	19	39	29.73	6.26

Figure 10: Typical bunch made by the feller-buncher in the young stand.

The results for bunch size by viewing the video was verified with data collected in the field. While evaluating the feller-buncher in the field, a total of 130 bunches were sampled for accumulations per bunch and trees per bunch. For this data collection method, accumulations per bunch resulted in an average of 3.67 which is very similar to the result of the prior method. Also the 130 bunches averaged 28 trees per bunch which confirms the cycle results.

6.3 Skidder Production

Figure 11: Tigercat 630D traveling towards the landing with a full payload.

The Tigercat 630 was the only skidder utilized to skid wood from the stand to the loading deck during the 3 day period (Figure 11). On the first day of the study, the operator who usually operates the skidder was absent. This forced the crew to use an operator who was unfamiliar with the machine (Operator A). Field data was collected for this operator to compare production rates to the experienced operator (Operator B). Unfortunately, the MultiDAT was disconnected and distance values could not be obtained for this day's work. To compare the two, only the data collected in the field were used. Based on the feller-buncher analysis, bunch size averaged 4.54 tons. All cycles that did not involve delay from subsequent operations were used. From the data collected in the field, 33 cycles were measured for the operator A and 63 for the operator B. Operator A averaged 1.30 bunches per cycle and approximately 6.18 minutes per cycle. Operator B achieved an average of 1.60 bunches per cycle and approximately 3.79 minutes per cycle. Based on these results, the operator A could only reach a productivity of 53.66 tons/PMH while Operator B reached a productivity of 123 tons/PMH (Figure 12).

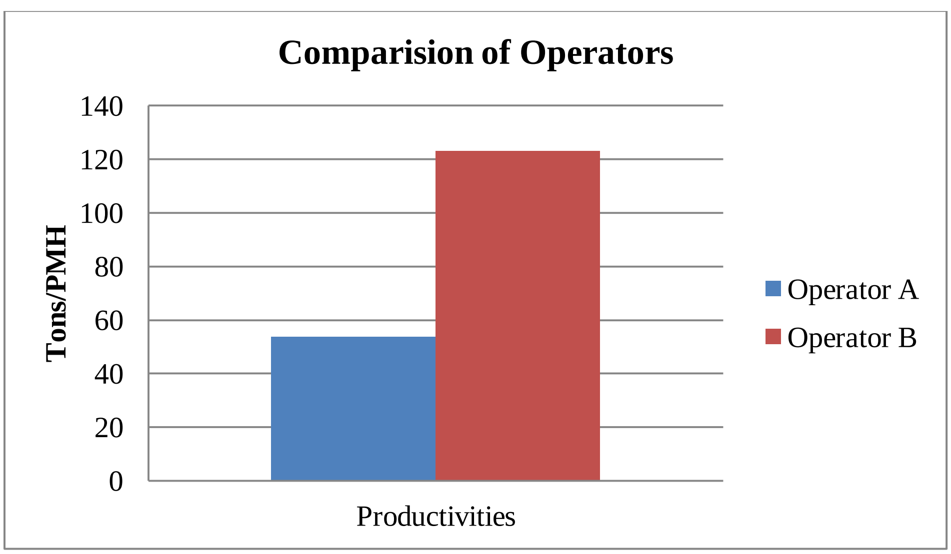

Figure 12: Graph illustrating the difference in production capabilities between the fill-in operator and the experienced operator.

This difference can be attributed to training and experience on the modified skidder for Operator B. Unfamiliarity with the machine controls led to slower travel speed and higher grappling time for Operator A. Also, the efficient use of the turn-around seat was more evident with Operator B which led to a higher productivity. These results show the importance of operator training to obtain high productivities. The results of this analysis and the failure of the MultiDAT forced the scope of this project to concentrate on the time that Operator B worked on the skidder. Total scheduled operating time for the experienced operator (B) on the skidder was 17.7 hours.

The skidder productivity was also evaluated by forming a linear regression model. Cycle time was the dependent variable and the independent variables used for the analysis were total cycle distance and the number of bunches grappled. The distance variable was measured in meters and was for a round trip. Throughout the study period, each skidder cycle was recorded which resulted in a total of 97 cycles. This total includes all delay and non-delay cycles. During the cycles, the operator averaged a payload of 7.13 tons. Other information concerning this step of the skidder evaluation is shown in Table 8.

Table 8: Key statistics for skidder cycles which contain delay and delay free cycles.

	N	Max	Min	Mean	Standard Deviation
Cycle Time[1]	97	3:37:36	0:01:06	0:09:48	0:27:32
Bundle #	97	3	1	2	1
Distance[2]	97	2246	65	478	351

1Cycle Time in hours, minutes, seconds
[2]Distance in meters

Three times during the study period, a mechanical issue with the flail limited skidder activity. This caused the extreme maximum time shown in Table 8. The scatterplot of the data illustrates cycle time versus skid distance and how the mechanical delays of the flail relate to normal functions (Figure 13). The red dots indicate outliers because of subsequent operation mechanical delays. Also, some delay can be attributed to a lack of trucks. On some occasions during the study, the operation came to a standstill due to no trucks. With no available chip van, there would be a surplus of wood on the deck which inhibited the skidder to bring more stems. Since these types of delays occurred on almost half of the skidder cycles, delay free cycles were used to estimate the productivity of the skidder and form the regression model.

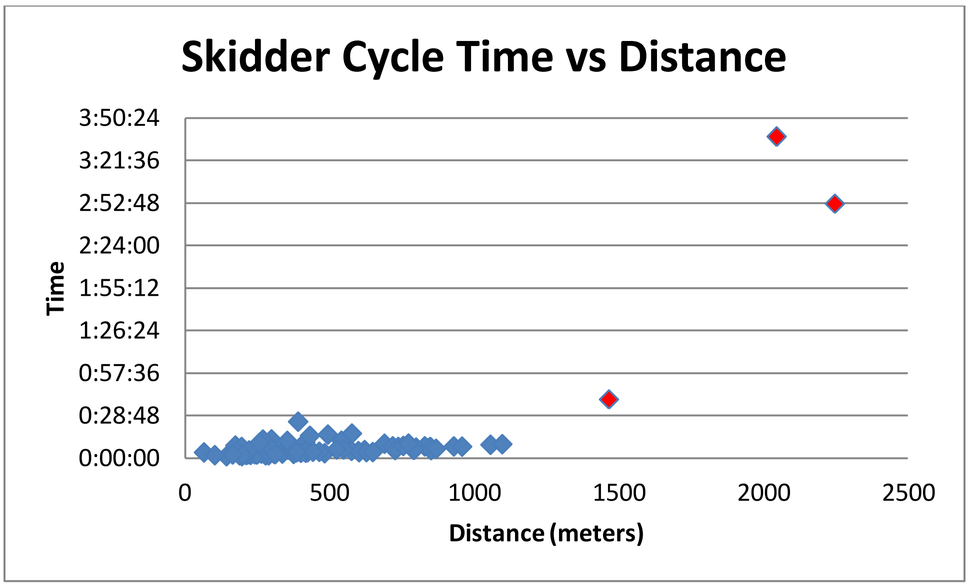

Figure 13: Scatterplot of skidder cycle time, showing several cycles impacted by chipper repairs.

Of the total cycles, the worker in the field recorded a total of 59 delay free cycles. The average payload for the delay free cycles was calculated to be 7.55 tons. Further information concerning delay free cycles is illustrated in Table 9. The relationship between distance, bunches grappled and cycle time is much better in the delay free analysis of the skidder (Figure 14). This graph shows that there is a strong linear relationship between the two variables.

Table 9: Descriptive statistics for skidder delay free cycles.

	N	Max	Min	Mean	Standard Deviation
[1]Cycle Time	59	0:09:15	0:01:06	0:03:55	0:01:53
Bunch #	59	3	1	1.68	0.502
[2]Distance	59	1096	103	459	251

[1]Cycle time in hours, minutes, seconds
[2]Distance in meters

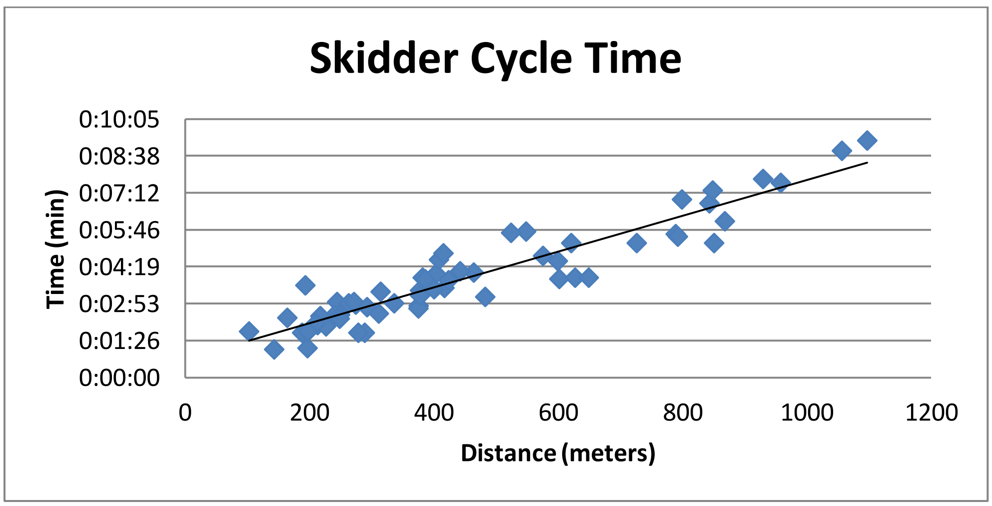

Figure14: Scatterplot showing delay free cycle time and distance for 59 skidder cycles and trend line.

From the 59 cycles, a linear regression model was developed for the independent variable cycle time. The regression was proven to be statistically significant at the α =

0.05 level (F-value = 217.9, p-value = $3.8*10^{-27}$). The analysis revealed a high R^2 value of 0.886 and an adjusted R^2 value of 0.882. Thus, distance and the number of bundles explain 88% of variation in cycle time. The ANOVA returned a MSE of $2.04x10^{-7}$. Both independent variables were also proven to be statistically significant at the α = 0.05 level. Indicators for this conclusion are highlighted in red on Table 9. The distance variable was the more significant of the two as shown in the respective p-values calculated (Table 10) and therefore accounts for more of the variance.

Table 10: Regression coefficients and statistical information for the skidder cycle model.

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.0001405	0.000198	0.71	0.4804	-0.00026	0.000537
Distance	$4.44437E^{-06}$	$2.97E^{-07}$	14.97	$3.13E^{-21}$	$3.85E^{-06}$	$5.04E^{-06}$
Bunch #	0.000317	0.000141	2.24	0.0286	3.43E-05	0.0006

[1]Cycle time decimal days
[2]Distance in meters
[3]Bunch in number of bunches

R^2=0.88

Productivity was calculated for each delay-free cycle. Average productivity for the skidder resulted in 123.73 green tons/PMH. The high productivity can be attributed to multiple factors in the study. First, the modified skidder has the oversized grapple which gives it the ability to grapple larger payloads. Since the skidder can acquire more tonnage with each skid without increasing cycle time, the productivity is increased. Also, the tract offered many short skids which minimize time. This is confirmed by the regression developed which showed that distance was the most significant variable. The maximum productivities achieved were when the skidder grappled multiple bunches near the landing. In these cases, the skidder could produce 282 green tons/PMH. This unusually high productivity was not typical in the study. In other situations, long skids reduced the productivity to 55 green tons/PMH.

Based on the average productivity of the skidder, it is only utilized 32% because of the limitations of the feller-buncher. However, the skidder was also affected by the loading deck congestion because it directly affects where wood can be placed. If the loader cannot move wood fast enough through the chipper, the skidder is forced to wait near the deck which increases variable costs/ton. This low rate is almost unavoidable without scheduling less working hours for the skidder. The recommendation would be to park the skidder when the deck is full and avoid unnecessary travel. The operator could then assist with other jobs in the logging operation. This would allow some of the operator's labor costs to be applied to other machines. Changing deck orientation could allow for more room for wood storage, therefore reducing delay time.

6.4 Economic Analysis

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

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

All variable costs associated with operating the feller-buncher and skidder were used in the cash flow model. Fuel use was determined based on the detailed records maintained by Corley Land Services. The feller-buncher used approximately 9.9 gallons of off-road diesel per productive/operating hour. The skidder consumed an average of 6 gallons per productive machine hour. Off-Road diesel was priced at $3.80/gallon. Lube cost was determined as a percentage of fuel usage (Brinker et al. 2002). These costs were combined in the analysis for a resulting figure of $54.10/PMH for the feller-buncher and $39.16/PMH for the skidder. Repair and maintenance costs were formed using the Caterpillar Performance Handbook. Total repair and maintenance cost for the feller-buncher was estimated at $16.00/PMH. The maintenance and repair rate used for the skidder was $10.00/PMH. If the assumption error is 50%, the overall AEC of the machine had a minimal change (<1%). Major repairs or replacements were also included into the analysis. The two main components that would need to be replaced during the feller-buncher's life span would be the undercarriage and engine. Tires (at $8,000 every 3 years) would be the main component with a replacement schedule for the skidder. According to Cummins, the feller-buncher engine would need to be rebuilt at year 5 at a cost of approximately $15,000. The undercarriage would have a low rebuild at ages 3 and 9. Also, it would have a major rebuild of the undercarriage at age 6. Both rebuilds include track replacement. The labor rate was set at $15.00 per hour with 33% fringe benefits for the operator. An inflation rate of 3% was used on labor, maintenance, and fuel. A utilization rate of 75% was used for the analysis for the feller-buncher instead of the measured 84%. This is the maximum that could be seen for the machine due to expected operational delays. However, the skidder utilization rate of 32% was used because it was limited by the feller-buncher and deck delays.

The annual equivalent cost (AEC) is the cost to own and operate a piece of equipment over its entire lifespan while taking into account the time value of money (Tufts and Mills 1982). For the purpose of this study, the feller-buncher and skidder were placed on a 10 year or 20,000 SMH lifespan. Assuming this ten year span, the feller-buncher has an AEC of $275,066.94. By applying the 52 tons/PMH found in the study to the economic analysis, the feller-buncher could produce a ton of wood for $3.48/green ton (Table 11). The skidder cost analysis model returned an AEC of $141,323 over the ten year lifespan. By applying the productivity of 123 tons/PMH and an utilization rate of 32% achieved by the skidder, the 630D can skid wood for $1.78/green ton (Table 12). Thus, the two machines combined can harvest and skid wood for $5.26/green ton before tax in an energy plantation setting.

Table 11: Feller-buncher economics.

DISCOUNTED BEFORE-TAX CASH FLOW COST ANALYSIS

Tigercat 845D feller-buncher

Purchase price	$495,080.00		Discount rate	7%
Trade-in	0		Finance APR	7%
BV of trade-in	0		Marginal tax rate	0
Down payment	$50,000.00		Amount financed	$445,080.00
Number of payments	60		Monthly payment	$8,813.12
Expense Option	0		Adjusted basis	$495,080.00
Hours per day	9		Expected life, years	10
Days per year	225		Residual value end of life	5%
Fuel & Lube	$54.19		Inflate F&L	3%
Maint & Repair	$16.00		Inflate M&R	3%
Labor rate	$15.00		Inflate labor	3%
Fringe benefit %	33%		Utilization	75%
Insurance & taxes	6%		Production (tons/PMH)	52

AEC	($296,677.77)	($289,253.96)	($288,607.75)	($280,875.90)	($276,832.01)
Cost per ton	($3.76)	($3.66)	($3.65)	($3.56)	($3.51)
	Year 1	Year 2	Year 3	Year 4	Year 5
Salvage value	$409,566.18	$332,603.75	$264,192.69	$204,333.02	$153,024.73
ACRS Dep	$85,513.82	$76,962.44	$68,411.05	$59,859.67	$51,308.29
Book value	$409,566.18	$332,603.75	$264,192.69	$204,333.02	$153,024.73
Fuel & Lub	$82,301.06	$84,770.09	$87,313.20	$89,932.59	$92,630.57
Repair & Maint.	$24,300.00	$25,029.00	$25,779.87	$26,553.27	$27,349.86
Addl. Maintenance			$20,000.00		$15,000.00
Labor	$42,643.13	$43,922.42	$45,240.09	$46,597.29	$47,995.21
Insurance	$29,704.80	$24,573.97	$19,956.22	$15,851.56	$12,259.98
Total Expenses	178948.9875	178295.484	198289.3832	178934.7147	195235.629

AEC	($275,589.83)	($272,721.12)	($271,664.14)	($274,064.47)	($275,066.94)
Cost per ton	($3.49)	($3.45)	($3.44)	($3.47)	($3.48)
	Year 6	Year 7	Year 8	Year 9	Year 10
Salvage value	$110,267.82	$76,062.29	$50,408.15	$33,305.38	$24,754.00
ACRS Dep	$42,756.91	$34,205.53	$25,654.15	$17,102.76	$8,551.38
Book value	$110,267.82	$76,062.29	$50,408.15	$33,305.38	$24,754.00
Fuel & Lub	$95,409.49	$98,271.77	$101,219.93	$104,256.52	$107,384.22
Repair & Maint.	$28,170.36	$29,015.47	$29,885.93	$30,782.51	$31,705.99
Addl. Maintenance	$40,000.00			$20,000.00	
Labor	$49,435.07	$50,918.12	$52,445.66	$54,019.03	$55,639.61
Insurance	$9,181.48	$6,616.07	$4,563.74	$3,024.49	$1,998.32
Total Expenses	$222,196.40	$184,821.43	$188,115.26	$212,082.56	$196,728.14

Table 12: Skidder economics.

DISCOUNTED BEFORE-TAX CASH FLOW COST ANALYSIS Tigercat 630D Skidder				
Purchase price	$330,019		Discount rate	7.00%
Trade-in	$0		Finance APR	7.00%
BV of trade-in	$0		Marginal tax rate	0.00%
Down payment	$50,000		Amount financed	$280,019
Number of payments	60		Monthly payment	$5,545
Expense Option	$0		Adjusted basis	$330,019
Hours per day	9.00		Expected life, years	10
Days per year	225		Residual value end of life	5.00%
Fuel & Lube	$31.16		Inflate F&L	3.00%
Maint & Repair	$10.00		Inflate M&R	3.00%
Labor rate	$15.00		Inflate labor	3.00%
Fringe benefit %	33.00%		Utilization	32%
Insurance & taxes	6.00%		Production (tons/PMH)	123.00

AEC	($167,610.04)	($162,226.19)	($159,703.58)	($154,491.81)	($149,851.91)
Cost per ton	($2.11)	($2.04)	($2.01)	($1.94)	($1.89)
	Year 1	Year 2	Year 3	Year 4	Year 5
Salvage value	$273,015.72	$221,712.76	$176,110.14	$136,207.84	$102,005.87
ACRS Dep	$57,003.28	$51,302.95	$45,602.63	$39,902.30	$34,201.97
Book value	$273,015.72	$221,712.76	$176,110.14	$136,207.84	$102,005.87
Fuel & Lub	$20,134.89	$20,738.94	$21,361.11	$22,001.94	$22,662.00
Repair & Maint.	$6,461.78	$6,655.63	$6,855.30	$7,060.96	$7,272.78
Addl. Maintenance			$8,000.00		
Labor	$42,643.13	$43,922.42	$45,240.09	$46,597.29	$47,995.21
Insurance	$19,801.14	$16,380.94	$13,302.77	$10,566.61	$8,172.47
Total Expenses	$89,040.93	$87,697.93	$94,759.26	$86,226.80	$86,102.47

AEC	($146,361.64)	($143,986.86)	($142,525.76)	($141,693.56)	($141,322.95)
Cost per ton	($1.84)	($1.81)	($1.79)	($1.78)	($1.78)
	Year 6	Year 7	Year 8	Year 9	Year 10
Salvage value	$73,504.23	$50,702.92	$33,601.93	$22,201.28	$16,500.95
ACRS Dep	$28,501.64	$22,801.31	$17,100.98	$11,400.66	$5,700.33
Book value	$73,504.23	$50,702.92	$33,601.93	$22,201.28	$16,500.95
Fuel & Lub	$23,341.86	$24,042.11	$24,763.38	$25,506.28	$26,271.47
Repair & Maint.	$7,490.97	$7,715.70	$7,947.17	$8,185.58	$8,431.15
Addl. Maintenance	$8,000.00				
Labor	$49,435.07	$50,918.12	$52,445.66	$54,019.03	$55,639.61
Insurance	$6,120.35	$4,410.25	$3,042.18	$2,016.12	$1,332.08
Total Expenses	$94,388.25	$87,086.19	$88,198.38	$89,727.01	$91,674.30

To better understand the system under government tax rates, an after tax analysis was performed while assuming the same parameters. The marginal tax rate used in the analysis was 25% which was for a married sole proprietor owner filing and having a joint income of $70,700 to 142,700 (CCH 2011). This rate was used because the logger must net this amount of income to pay for the machinery. After applying the federal tax rate, the feller-buncher has an AEC of $206,984 and a cost per ton of $2.62. The skidder's AEC decreased to $106,559 and cost per ton to $1.34. The decrease in cost for both machines reflects a reduction in tax liability due to expenses. These deductions are applied to expenses and interest payments.

To complement the AEC analysis, a separate expense method was performed to illustrate actual cash payments for years one through ten. This analysis took all payments made to principle (PMTP), payments made to interest (PMTI), and operating expenses (OE) expected for each year and determined a cost per ton without salvage value or depreciation. The analysis would be beneficial in illustrating to loggers what they would actually pay out of pocket before any tax deductions and/or the selling of the machine. These numbers are much higher than the AEC because they do not include the salvage value of the machine at year's end (Table 13 and Table 14). These estimates are reported in today's dollars and have no inflation consideration. Both cost rates drop significantly after year 5 because machine payments are completed.

Table 13: Feller-buncher cash inputs by year.

	year 1	year 2	year 3	year 4	year 5
Expenses	$340,392.15	$289,909.22	$310,078.80	$290,905.10	$307,392.40
Tonnage	78,975	78,975	78,975	78,975	78,975
Cost/Ton	$4.31	$3.67	$3.93	$3.68	$3.89
	year 6	year 7	year 8	year 9	year 10
Expenses	$228,787.74	$191,610.52	$195,108.02	$219,285.10	$204,146.75
Tonnage	78,975	78,975	78,975	78,975	78,975
Cost/Ton	$2.90	$2.43	$2.47	$2.78	$2.58

Table 14: Skidder cash inputs by year.

	year 1	year 2	year 3	year 4	year 5
Expenses	$205,577.47	$154,234.47	$161,295.80	$152,763.34	$152,639.01
Tonnage	78,975	78,975	78,975	78,975	78,975
Cost/Ton	$2.60	$1.95	$2.04	$1.93	$1.93
	year 6	year 7	year 8	year 9	year 10
Expenses	$102,205.16	$95,137.60	$96,491.34	$98,268.76	$100,472.30
Tonnage	78,975	78,975	78,975	78,975	78,975
Cost/Ton	$1.29	$1.20	$1.22	$1.24	$1.27

6.5 Comparison Analysis

In hot logging, all jobs are affected by subsequent operations. To have an efficient logging system, the entire operation should be balanced. Having a balanced system is critical to maintaining production and achieving lower total costs. Minimizing interactions between machines and the number of each type of machine in a system are two important aspects of balancing a harvesting system.

Figure 15: Feller-buncher and skidder working near one another during the study.

Because of the importance of balance, the interaction between the feller-buncher and skidder was evaluated. It was evident that the feller-buncher productivity pales in comparison to the skidder productivity (Figure 16). Based on the results, the skidder could produce over double the amount the feller-buncher produced in a productive machine hour.

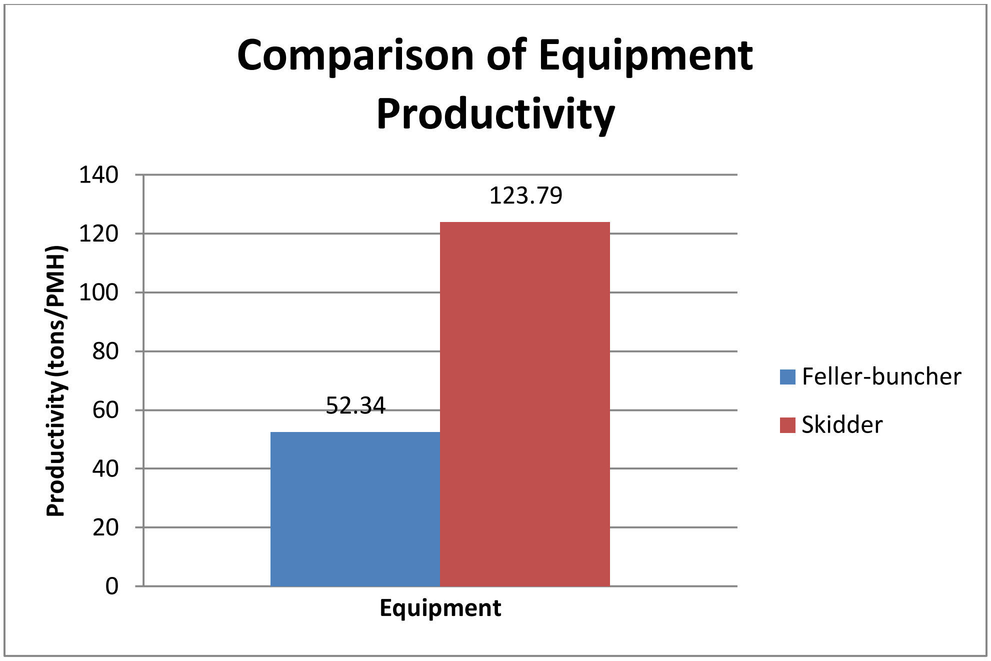

Figure 16: Illustration of the drastic difference in productivities of the skidder and feller-buncher.

Because skidding was much more productive than felling, the utilization rate for the skidder working in this situation would be very low. The poor utilization of the skidder increases downtime where no wood is being skidded. This happened frequently during the study period. When this occurred, the skidder operator either made unnecessary trips to the woods or waited with the machine running. This increases operating cost without producing any wood. To improve this relationship, a further analysis was performed. The overall hypothesis for this procedure change was to speed the feller-buncher up by changing harvest schemes while slowing the skidder down to better balance the system. The feller-buncher was evaluated by investigating productivity based on trees per accumulation and trees per bunch. We hypothesized that if the feller-buncher averaged more trees per accumulation and fewer accumulations per bunch, the overall felling productivity would be increased. The skidder was evaluated by the number of bunches grappled. By taking the additional time to grapple the new, smaller bunches made by the feller-buncher, we hypothesized that the skidding productivity would be lowered. However, we believe the more balanced system would be more productive.

6.6 Logistical Improvements

The feller-buncher was evaluated by the productivity variation between harvesting a range of 6-8 trees (group A) and a range of 9-11 (group B) trees per accumulation. The hypothesis was if the average trees per accumulation could increase from 7 to approximately 10, the feller-buncher would be more productive. The hypothesis assumes that the trees are straighter, and with less sweep, than those in the study area. The grouping was determined by assuming that some accumulations would vary because of different tree sizes in the stand. Assuming the feller-buncher harvested one abnormally large tree per accumulation would limit the felling head to 1 tree less than average. Contrastingly, if the feller-buncher harvested smaller trees, it could accumulate more trees per cycle. A total of 151 dataset cycles contained trees per accumulation in this range. The two groups were analyzed using a t-test. The p-value calculated was 0.081 which indicated that the productivities for the groups were not significantly different at the $\alpha = 0.05$ level, but were significant at the $\alpha = 0.10$ level (Table 10).

To further evaluate the productivities for each group, key statistics were formulated (Table 15). Group A contained more samples but the number of samples in group B should be sufficient to draw conclusions. The t-test indicates that there is a difference in the productivities. This also is shown in the mean results for each group's productivity. On average, harvesting 9 to 11 trees gains approximately 3 more tons per PMH. Also the variation in group B is smaller which is beneficial for maintaining a smaller range of productivity when operating. Also this can helpful for prediction purposes when scheduling harvest time.

Table 15: Key statistics for trees per accumulation based on different groups.

	N	Max	Min	Mean	Standard Deviation
Group A	97	78.17	28.99	52.55	10.73
Group B	54	75.76	26.18	55.64	8.64

The next analysis was performed on accumulations per bunch for the feller-buncher. A total of 22 bunches were sampled for the number of accumulations per bunch. A scatterplot was formed to show the trend in productivities based on accumulations per bunch (Figure 17). From the graph, a trend is not evident and an outlier is present in the 3 accumulations per bunch section.

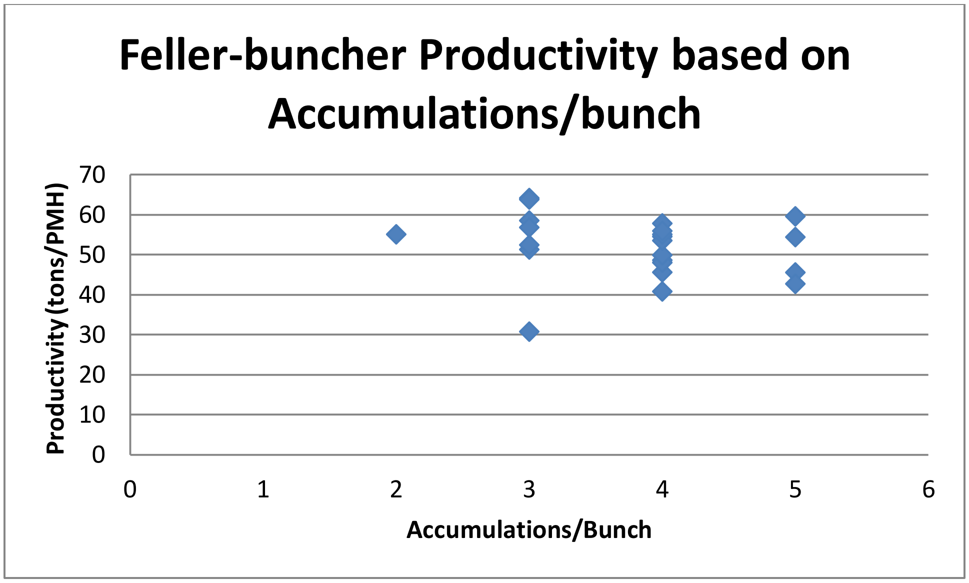

Figure 17: Scatterplot illustrating changes in feller-buncher productivity as accumulations per bunch increase.

The scatterplot did not show a trend in productivity variation versus accumulations per bunch. To further investigate, the samples were grouped in the same manner as the trees per accumulation to perform the analysis. Group A contained 2 and 3 accumulations per bunch and group B contained 4 and 5 accumulations per bunch. Descriptive statistics were formed for each group to form basic conclusions (Table 16).

Table 16: Key statistics for accumulations per bunch based on different group size.

	N	Min	Max	Mean	Standard Deviation
Group A	8	30.77	64.19	54.13	9.87
Group B	14	40.82	59.60	50.88	5.60

Group A has a higher mean productivity based on the sample but also has higher variation. The higher variation is due to the outlier shown in Figure 15. No delays were observed for this value so operator inconsistency must have been the cause of the lower productivity. There is no justification to remove this observation so we concluded that making bunches with a lower number of accumulations can be more variable.

A t-test was used to discover if there was a significant difference between the groups. From the test, the two groups were not statistically significantly different because the p-value was 0.442. Since the p-value is large, the number of accumulations per bunch is not an indicator of discrepancy in productivity. We can conclude that changing the number of accumulations per bunch will not have a significant impact on feller-buncher productivity.

Through the feller-buncher grouping analysis, productivity is not significantly affected by accumulations per bunch but can be affected by trees per accumulation. If the operator could consistently sever 10 trees per accumulation, the feller-buncher productivity can be increased. Since this is possible, the next step is to better balance the skidder's productivity to that of the feller-buncher. In order to evaluate this component of the system, the number of bunches grappled by the skidder was used as the dependent variable in productivity. During the study, the skidder typically grappled either one or two large bunches. Currently, the feller-buncher is averaging 30 trees per bunch. This means the skidder pulled approximately 60 trees to the deck during one cycle when the operator grappled two bunches. If the feller-buncher made bunches containing an average of 20 trees per bunch and the skidder grappled three bunches, the skidder would still be optimizing its pulling capability of 60 trees. To investigate this idea, the skidder cycles were separated into 1 and 2 bunch cycles while leaving distance as a variable for each cycle. By separating the two groups and keeping the distance variable, the time difference between grappling one and two bunches could be formulated. From this result, an approximate time to grapple extra bunches can be calculated.

From the model built for the skidder cycle, the dependent variable entitled bunches grappled was found to be statistically significant when predicting cycle time (*p-value* = 0.02). The model produced a coefficient for the bunch variable of 0.000317. This adds roughly 27 seconds for each additional bunch grappled during a cycle. This trend can be viewed in a scatter plot where a linear trend line is utilized (Figure 18).

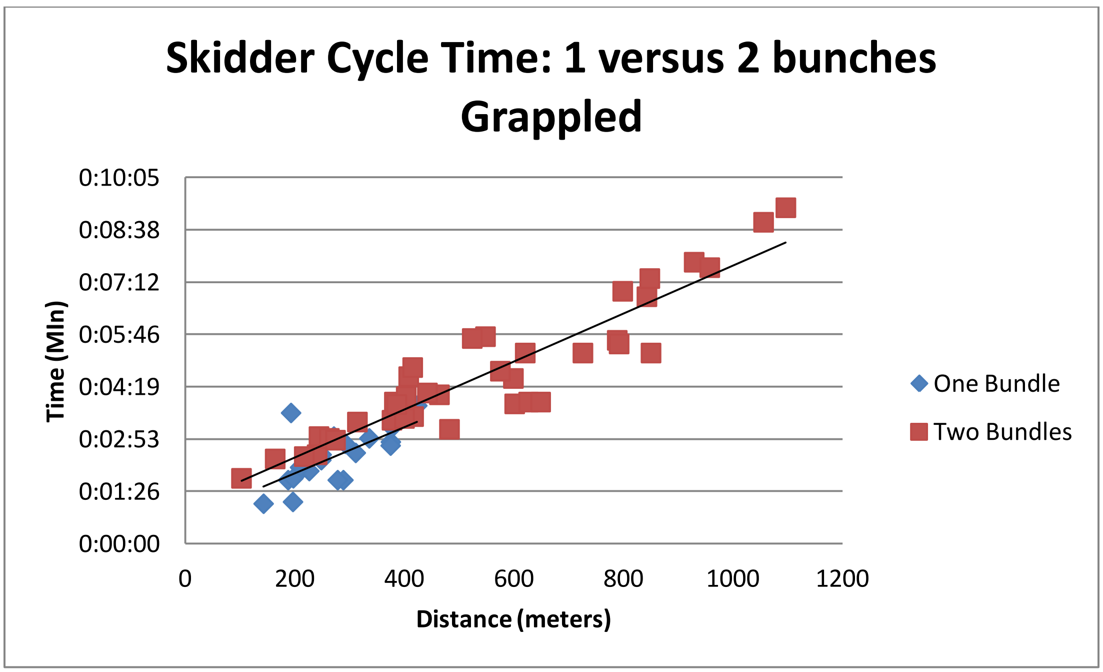

Figure 18: Scatterplot containing trend lines for skidder bunch grappled count.

From the graph, the trend lines appear to be parallel to one another suggesting that there is a relatively constant increase in time as an additional bunch is grappled. This would increase overall cycle time for the skidder while the skidder moves the same amount of tonnage. Thus, the skidder's productivity would be closer to that of the feller-buncher. It would not be a substantial decrease in productivity but would increase the utilization rate of the skidder which will better balance the system.

Increasing the productivity of the feller-buncher will show improved economics of the entire system. The feller-buncher was estimated to produce 52 tons/PMH. Increasing the number of trees per accumulation has the potential to add an additional 3 tons/PMH. A study of harvesting operators in Germany found that operators did improve from a performance level of 60% to 110% during the one year study (Purfurst 2010). So while the operator for this study had some machine experience, he only had several months operating this machine. This was also the first time he had operated in a stand that was representative of a pine energy plantation.

For these reasons (learning curve, straighter trees, logistical improvements, etc.), production improvements of 35% could be achieved. Therefore, feller-buncher production could increase from 52 tons/PMH to approximately 70 tons/PMH. While some of the new practices by the feller-buncher operator might decrease skidder productivity, the skidder should still be able to maintain a high level of production. Based on observations, achieving 70 tons/PMH is an attainable goal; maintaining that rate and processing that amount of material through the system will be challenging.

In the current analysis, the feller-buncher accrues a cost of $3.48/ton and the skidder costs $1.78/ton while producing 78,975 tons/year. Under the improved production estimates and assuming the system can handle the additional volume, annual production will increase to 106,313 tons/year. Using the same before-tax cash flow model utilized for current costs per ton, the 845D will reduce unit costs to $2.65/green ton, which is a decrease of $0.83/ton. The skidder will also decrease costs per ton because of additional volume moving through the system. When the new production levels are input into the skidder before-tax cash flow model, the cost of skidding decreases to $1.53/green ton, a savings of $0.25/ton. The resulting combined total cost for harvesting and skidding is $4.18, a decrease of $1.08 per ton from the original estimate.

Assuming 28 tons per truck load, production levels of 106,313 tons/year over 225 days per year will average approximately 17 trucks per day. While this production level is higher than that observed in the study period, improved chipper productivity, reduced turn-around time, and additional trucks will facilitate the system to reach these production levels. The savings stated above relates to the felling and skidding functions only; system limits outside of felling and skidding may make the cost savings from 52 to 70 tons/PMH difficult to realize. Dropping the costs by this amount will have huge implications on the success of the biomass harvesting system.

VII. Conclusions

In this study, a Tigercat 845D feller-buncher equipped with a shear head was used to harvest and a modified 630D skidder was used to skid the whole trees to the deck. The analysis of the machines took place on an 11 year old pine plantation near Monroeville, AL. The 10.8 acre tract took a total of 22.5 hours to harvest. Production and cost numbers were calculated for each machine working separately. These numbers were further analyzed for prospective system improvements. The feller-buncher averaged 52 green tons/PMH during the study. Crooked trees, operator inconsistency and lack of experience hindered production. The before tax annual equivalent cost for the feller-buncher was determined to be $275,067 per year. By applying the productivity observed in this study, the cost per ton over a 10 year lifespan would be $3.48.

Skidder production was tested for two operators. The inexperienced operator had difficulty with machine controls which led to a productivity of 53 green tons/PMH. However, the experienced operator achieved a productivity of 123 green tons/PMH. The main difference between the two operators was the experienced operator's ability to efficiently grapple larger bunches and increased travel speeds. The annual equivalent cost for the skidder was determined to be $141,323. By applying the productivity, the cost per ton over a 10 year lifespan would be $1.78.

The estimated felling and skidding cost for the two machines in an energy plantation setting is $5.26/ton with a production level of 78,975 tons/year. With improved feller-buncher productivity due to operator experience, production levels could be increased to 106,313 tons/year. This would decrease costs for felling and skidding by $1.08, which would have huge implications on the viability of the system.

VIII. Recommendations for Further Research

The high tonnage system needs additional testing to examine different operational methods and productivity change in different stand types. As previously stated, this case study evaluates the machines in a clean chip operation on one stand type. One major recommendation is to implement a commercial harvest without using the flail. Operating the current system without the flail should increase chipper productivity, in turn leaving more room on the deck for the skidder to place trees. Another component of the operation that should be investigated is deck configuration. The location of the wood in relation to the loader should be investigated through further research. Finding the optimal position for the skidder to drop the stems could increase both loader and skidder productivity by reducing machine interactions.

The feller-buncher operator did not operate in small stem clearcuts very often. If he had more experience, feller-buncher productivity could be increased. A study should be done after he has more experience and training based on the findings of this study. Training the operator to harvest in a consistent pattern could increase productivity.

Currently, the USDA Forest Service is evaluating the system in a cold logging situation. This situation is when the feller-buncher is the only machine on site. The trees are harvested and allowed to transpirationally dry. Transpirational drying is defined as felling the tree and leaving the foliage intact to release moisture that is locked within the stem. The skidder and chipper come at a later date to finish the harvesting process.

Drying time is being evaluated as well as the productivity of each machine and the entire system. If successful, the moisture content of the wood could be significantly reduced at a no additional cost for the refining facility that values low moisture content. This would be a major cost savings technique in the conversion process. Another component of this field drying treatment would be to find a compensation package for delivering dry material. Currently, loggers in the south get paid on a green weight basis. If less water is being transferred, total delivered weight for a standard load is reduced which lessens profitability for the logger, so there isn't any incentive for loggers to field dry material.

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