A New Era for Forest Operations in the Southeastern Region of the United States

by

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Abstract

Forest operations in the southeastern region of the United States has remained relatively unchanged since the inception of conventional mechanized equipment. As new technologies are developed, new operational techniques emerge that have the potential to replace today's standard practices. While many of these practices have been studied elsewhere around the world, few have been researched for their applicability in the southeast.

Three separate studies were conducted. The first, used both a modeling tool as well as a field study to analyze altering establishment spacing, harvesting frequency, and harvesting machines to determine if an increase in sawtimber volumes were seen from these changes. Results depicted a minimum increase of 15 green tons per acre for sawtimber using one or more of the above mentioned techniques for the modeling tool. The field study demonstrated an additional 10 green tons per acre of biomass material could be harvested by altering establishment spacing.

The second assessed the prospective production and cost impacts of using tracked processors either in the woods in conjunction with conventional harvesting equipment or on a centralized logging depot where one processor would merchandize trees from a variety of tracts and logging contractors. The study also compared the potential production rate differences between experienced operators versus inexperienced operators. Results showed that at the end of the machines depreciated life, year 5, a logger could expect to pay $1.93 per green ton to own and operate the processor. At the end of year 10, the typical life of the machine, they would expect to pay $1.75 per green ton. Overall, the experienced operator produced 14 additional green tons per productive machine hour compared to the inexperienced operator.

The final study evaluated the differences in total stem value when merchandizing with a tracked processor versus a knuckle-boom loader. Results determined when diameter and total lengths were visually estimated, a significant difference in total value occurred, however once these two variables were adjusted to match the tracked processors more accurate measurements, no difference in value was seen even though there was still a difference in how the wood was merchandized.

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List of Abbreviations

AEC	Annual Equivalent Cost
BCAP	Biomass Crop Assistance Program
CNS	Chip-N-Saw
CTL	Cut-To-Length
DBH	Diameter at Breast Height
DOE	Department of Energy
EISA	Energy Independence and Security Act
EPA	Environmental Protection Agency
ExOp	Experienced Operator
InExOp	Inexperienced Operator
IRR	Internal Rate of Return
GT	Green Ton
MCP	Mass-Control Pollinated
MSRP	Manufacturer’s Suggested Retail Price
NIPF	Non-Industrial Private Forest-Landowner
NPV	Net Present Value
OP	Open-Pollinated
PMH	Productive Machine Hour
RMS	Resource Management Service

SMH	Scheduled Machine Hour
SRWC	Short Rotation Woody Crop
TPA	Trees Per Acre
USDA	United States Department of Agriculture
WT	Whole Tree

Chapter 1. Introduction

The southeastern part of the United States is often referred to as the wood basket of the world because of its ability to produce 19% of the world's pulp and paper products on a mere 2% of the total global forest land (BBI International 2017). This percentage doesn't include the 29 million green tons of timber that were harvested to produce wood pellets and were shipped to Europe in 2017 to promote the use of woody biomass for renewable energy (BBI International 2017; Basu 2017). As the emphasis on the use of woody biomass continues to increase around the globe, it is hard to understand why the southeastern region of the United States appears to be dragging their feet with its adoption. Looking at historical costs of production for biomass, however, one sees that woody biomass has never been profitable as a standalone product in the United States.

Although it is estimated that the southeastern regions currently produces over 33 million green tons of woody biomass per year, transportation efficiency and product quality issues for energy inhibit profitability (Ranta & Rinne 2006; Galik et al. 2009; Lancaster 2017). Past studies have shown that harvesting costs, site conditions, crew ambition/moral, transportation costs, and market prices all play a significant role in determining cost-effectiveness (Bolding et al. 2009; Botard et al. 2015). Since site conditions and crew ambition/moral are hard to control, the industry decided to focus on minimizing harvesting and transportation costs while increasing market prices.

Currently, the most efficient method of harvesting woody biomass in the United States is to integrate it with a conventional timber harvest so that incurred costs are distributed throughout the plantation's lifecycle. The woody biomass trees, tops, and limbs are then chipped in woods and transported to the closest biomass facility for further processing. This technique allows the higher price of sawtimber to compensate for the lower price of biomass, so although a loss may be incurred because of the cost to harvest and transport the biomass, the entire system as a whole remains profitable.

Reduction of transportation costs is currently being researched by analyzing how turnaround times at both the landing and the mill affect a loggers' transportation costs (Baker 2017; Daniel & Gallagher 2017). Additionally, the best way to increase market price is to increase demand, so politicians are promoting the use of renewable energy while researchers are experimenting with the benefits of incorporating tax incentives and subsidies to companies and landowners alike (Aguilar et al. 2013; Aguilar et al. 2014).

Project Objectives

This dissertation intended to ascertain alternative solutions towards making woody biomass a cost-effective product by analyzing unconventional techniques and equipment in the southeastern region of the United States. Specific objectives included:

1. Provided an informational overview of the benefits of incorporating an additional thinning regime for biomass, using alternate spacing methods such as Flexstands^{TM} and rectangularity, and using small-scale harvesting machines for conducting initial thinning to promote increased sawtimber volumes.
2. Analyzed the productivity and cost of owning and operating a swing machine with a processor head attachment in the southeastern United States, both on-site or at a centralized timber depot.
3. Determined if there was a difference between products and value when using a tracked processor and knuckle-boom loader when merchandizing the same loblolly pine stems concerning products and value.

Chapter 2. Literature Review

Biomass History

Although it has not always had the same name, the innate interest in woody biomass as a form of renewable energy is not a new concept. It was referred to as far back as 10,000 B.C., with the introduction of settled agriculture, where the Neolithic people were known to use coppiced saplings for fuelwood and poles in winter months because they found these small trees were more versatile and easier to handle (Dickmann 2006). Woody biomass was not referred to again until approximately 600 B.C. in the book of Job 14:7 where he states, "at least there is hope for a tree: if it is cut down, it will sprout again, and its new shoots will not fail." The Roman and Chinese Empires also used woody biomass profusely. Both kingdoms maintained detailed records of how they systematically calculated re-occurring growth and harvest yields for wood to meet societal needs with influxes occurring during times of war (Dickmann 2006). These records provide excellent examples that woody biomass was as cyclical in its demand in the past as much as it is today.

As time continued to progress forward, humans became interested in understanding the differences between tree species. During one of Christopher Columbus's voyages, a botanist traveled with him to the present day United States where he collected and brought back seeds from an Eastern cottonwood, *Populus deltoids.* These seeds were planted in the Royal garden and once mature hybridized with black poplar, *P. nigra*. This cultivar became known as the Canadian poplar, *P. Canadensis*, and became an important cultivar to all of Europe as a short rotation woody crop (SRWC) because of its quick growth in both height and diameter. The hybridization of the cottonwood and poplar sparked a revolution where scientists all over the world began experimenting with multiple species in an attempt to grow the ideal tree for fuelwood consumption (Dickmann 2006).

In 1850, fuelwood still accounted for approximately 91% of the domestic energy consumption in the United States (Aguilar et al. 2011). Wood continued to be used in the United States as a primary fuel for heating, cooking, and as the main building material until the late 1800s to early 1900s (EIA 2 2018). In the 1930s, the United States established breeding projects to research different cultivars for what is now known as SRWC trees (Dickmann 2006). By the late 1950's, however, most of the United States had been cut over and the remaining uncut forests were protected. Between the lack of available fuelwood and the available new technology innovations, many families began heating their homes with coal or fuel oil (Gale 2006). By 1973, only 2 percent of the nations consumed energy came from wood (Aguilar et al. 2011).

The term "biomass" was not coined until around 1975 after the price of oil increased dramatically from $0.36 per gallon in 1972 to $0.57 per gallon in 1975 due to the Yom Kippur War and the Iranian Revolution (Biomass.net 2018; CPS 2018). This term grew in popularity as fuel prices continued to rise until 1980 when fuel prices dropped below $1.00 per gallon. This resulted in the leveling of wood energy consumption until 1989. In 1989, there was a spike in wood energy consumption followed by a sharp decline in 1990 with multiple smaller upsurges and drops throughout the 90s. Renewable energy consumption for wood leveled out again in 2002 and remained relatively consistent through 2008 where a slight decline occurred due to the recession. From 2008 until 2014 wood consumption slowly increased to rise above 2409 trillion Btu's, but has since dropped back down to 2144 trillion Btu's in 2017 (EIA 1 2018).

Total biomass energy consumption includes wood energy, waste energy, and biofuels consumption. This energy division followed the same path as wood energy consumption until 1980 when waste and biofuels consumption was included. Although the general pattern remained the same until 2001, total biomass energy consumption was slightly higher than wood energy, as would be expected with the additional products. From 2001 to 2014, total energy consumption increased from 2622 trillion Btu's to 4992 trillion Btu's with the steady increase coming from biofuels consumption (EIA 1 2018). Overall, biomass fuels accounted for approximately 5% of the total primary energy in the United States in 2017. Breaking that 5% down further we see that 46% was from biofuels that primarily contained ethanol and 44% was from wood and woody biomass material. This breakdown indicates that almost 2.5% of the nation's energy comes from wood-based materials (EIA 3 2018).

Biomass Legislation & Policies

As time progressed throughout the nation's legislative history a growing emphasis on the need for biomass as a renewable energy increased as well. Although early initiatives were not focused specifically on woody biomass, its importance was soon recognized and incorporated. In 1970, the Clean Air Act (P.L. 91-604) was enacted to improve and protect the nation's air supply. This act clearly defined the U.S. Environmental Protection Agency's (EPA) role in reducing pollutants and emissions throughout the country and mandated that both the federal and state governments establish regulations for these reductions (DOE 2 2018). This act was considered the stimulant for all renewable energy policies, laws, incentives, and subsidies that have since been established.

The Energy Policy and Conservation Act (P.L. 94-163) was enacted in 1975 to begin mitigation towards poor fuel efficiency in American motor vehicles after fuel prices increased dramatically in 1973 from crude oil shortages (DOE 2 2018). In 1978, the Public Utility Regulatory Policies Act (P.L. 95-617) was enacted to promote the use of renewable resources through the electric utility industry as a clean alternative to natural gas and coal (Ashton et al. 2008). Then in 1988, the Alternative Motor Fuels Act (P.L. 100-494) was enacted to establish incentive credits for companies who promoted the use of alternative fuels in their vehicles. This act paved the way for all of the Surface Transportation Acts (P.L. 102-240) and Clean Fuels Grant Programs, which provided incentives towards the use of alternative fuels, as well as an excise tax credit program (DOE 2 2018).

The Energy Policy Act of 1992 (P.L. 102-486), was enacted to mandate alternative fuel vehicles for federal, state, an alternative fuel provider fleets. This law also aimed to decrease the nation's dependence on petroleum-based products and improve air quality by making recommendations towards all renewable energy aspects. These included but were not limited to alternative fuels, renewable energy, energy efficiency, and energy supply and demand. Some of these regulations were amended in the 2005 Energy Policy Act (P.L. 109-58), in conjunction with establishing tax incentives, grant programs, demonstrations, and testing initiatives towards the promotion of alternative fuels (DOE 2 2018). In August of 1999, President Bill Clinton signed Executive Order 13134 in order to develop and promote biobased products and bioenergy (Clinton 1999). The Biomass Research and Development Act of 2000 was enacted to research biomass feedstock's and create cooperation between the Department of Energy and the Department of Agriculture. This bill has been extended in every Farm Bill since 2002 (DOE 3 2000; Ashton et al. 2008).

The Farm Bill of 2002, also known as the Farm Security and Rural Investment Act of 2002 (P.L. 107-171), established new programs and grants to support research and manufacturing of biobased products in the United States in addition to extended funding to programs created from the Biomass Research and Development Act of 2000. This act also secured funding to educate farmers, businesses, and the general public about the benefits of using woody biomass and other materials to fuel our energy needs (Young 2002). The Energy Independence and Security Act (EISA) of 2007 (P.L. 110.-140) had similar goals as the 2005 Energy Policy Act, however, this act went an additional step and established the Renewable Fuel Standard. This standard mandated that by 2022, transportation fuel would contain at least 36 billion gallons of renewable fuels annually. Based on scientific studies conducted, if all mandates are followed in this law, greenhouse gases will be reduced by 9% by 2030 (DOE 2 2018).

The Farm Bill of 2008 (Food, Conservation, and Energy Act of 2008; P.L. 110-234), continued funding for many of the programs from the previous Farm Bill's with regards to their involvement in biobased products. The new programs it initiated included a Rural Energy Self Sufficiency Initiative, the Biomass Crop Assistance Program (BCAP), Forest Biomass for Energy, Community Wood Energy Program, and a Biofuels Infrastructure Study. All of these programs focused their attention on promoting woody biomass as a renewable energy (Duncan 2008). The next major act was the American Taxpayer Relief Act of 2012 (P.L. 112-240), which provided an extension of funding towards the United States Department of Agriculture's Loan Guarantees, Advanced Biofuel Production Payments, Advanced Biofuel Production Grants, Biodiesel Education Grants, Biomass Research and Development Initiative, and the Ethanol Infrastructure Grants that were previously established (DOE 2 2018, p. 2).

Farm Bill of 2014 was known as the Agricultural Act of 2014 (P.L. 113-79). This Act was responsible for expanding the BioPerferred Program to include forest products.

BCAP, which was enacted in 2008, was expanded to include the National Forest System, Bureau of Land Management, non-federal land, and tribal ground. Unfortunately, the 2014 Farm Bill did repeal the Forest Biomass for Energy Program which was established in 2008 (ERS 2014). The latest act was the Consolidated Appropriate Act of 2016 (P.L. 114-113), which extends and reinstates alternative fuel tax incentives, excise tax credits, and special depreciation for second generation biofuel plant property (DOE 2 2018).

The Department of Energy (DOE), Department of Agriculture (USDA), or the Environmental Protection Agency (EPA) are the main entities who oversee the distribution of funds for the above-mentioned legislation (Taxpayers for Common Sense 2015). They are in charge of determining both who is eligible to receive one of the biomass subsidies/incentive as well as the amount that is obtained. Since not all forms of biomass are created equal in terms of energy density, cost-effectiveness, land use, etc. these three entities must choose which forms of biomass are eligible to be used based on the fourteen different definitions in legislation (Taxpayers for Common Sense 2015). For example, the 2007 EISA Act does not allow biomass that has been removed from any federal land, including tribal forestland, to be used in the Renewable Fuel Standard program while the 2008 Farm Bill does (James et al. 2016). This discrepancy makes it difficult for researchers to calculate the actual availability of woody biomass in the United States. Without an accurate calculation of available woody biomass in the United States, it becomes impossible to determine market prices, legislation mandates, tax reductions, and provide potential manufacturers with a realistic idea of traveling radiuses required to create bio-products.

Products Derived from Biomass

As trees are harvested in the southeastern region of the United States, they are processed and sorted on the landing into categories depending on their diameter at breast height (dbh), merchantable height, species, and quality of the tree (SCFC 2018). Typical products include but are not limited to poles, veneer, sawtimber, canterwood, chip-n-saw, pallet wood, pulpwood, and biomass. Trees that are designated as poles are debarked and peeled to be used as utility poles around the nation. Veneer quality logs are converted into continuous sheets of thin wood that are used to cover furniture and plywood. Sawtimber is used to make lumber. Canterwood and Chip-n-saw trees are used to make small dimension lumber in addition to chips for pulpwood or biomass. Pallet wood is typically made from hardwood trees and is used to make the pallets for the manufacturing and shipping industries. Pulpwood is used to make pulp, wood composites, oriented strand board, paper, fiberboard, chips, plywood, particleboard, and mulch (Smith & Rauscher 2008). Biomass can be used to make most of the above-mentioned products, including lumber, due to the innovative technology of cross-laminated timber.

Woody biomass can be made into a variety of different products with an even wider range of uses depending on whether it is burned, converted, or processed. If biomass is burned by thermal conversion and torrefaction occurs, the material can be compressed into briquettes similar to that of charcoal. These briquettes can be burned alone or in conjunction with a fossil fuel such as coal (NGS 2012). If it is burned inside a boiler the burning wood creates enough steam to power turbines that then generate electricity to be used in industrial applications or municipal power plants. The forest products industry uses bioenergy to supply more than 70% of their energy needs, making them the most self-sufficient industry throughout the nation (Smith & Rauscher 2008).

Woody biomass is also still burned to generate heat in homes, for cooking both inside and outside, as well as simply for aesthetic purposes. While it can burn in its original state, researchers found that by compressing the residual sawdust and wood chips together they could form a pellet which increased heating efficiency levels to the 85% range (Ashton et al. 2008). These pellets are easier to store and handle and are becoming increasingly popular in cities throughout Europe where renewable energy mandates are stricter than in the United States. These pellets are also being used as bedding in stalls, during livestock shows, and even as a substitute for wood shavings in playgrounds. Using pellets as a replacement for wood shavings has been proven to be better for the environment due to the increased rate of decomposition of nutrients back into the soil (Ashton et al. 2008).

Pyrolysis occurs if there is an absence of oxygen during the heating process. Pyrolysis produces three main products; pyrolysis oil, syngas, and biochar. Pyrolysis oil, or bio-oil, resembles a tar type material and can either be used to create plastics and other fuels or to generate electricity. Syngas, short for synthetic natural gas, is oftentimes converted into methane in order to replace natural gas (NGS 2012). Biomass can also be gasified to produce a syngas, made from hydrogen and carbon monoxide, and slag which resembles a glassy liquid. This gasified syngas can be processed into chemicals, fertilizers, biofuels, or combusted for heat and electricity. The slag is oftentimes used to make shingles, cement, or asphalt (Smith & Rauscher 2008). Methane gas is also produced when microorganisms break down the biomass in anaerobic situations. This gas can be used for cooking or heating households or other facilities as needed. In general, this process rarely occurs with woody biomass in a timeframe that is sustainable for mankind (NGS 2012).

Biochar is considered to be a type of charcoal. Unlike the thermal conversion briquettes, which are used as a fuelwood replacement, biochar is known to be an excellent fertilizer additive in agricultural settings because of its carbon-rich characteristics (NGS 2012). Black liquor is produced as a by-product from wood after it has been processed into paper. This by-product is typically recycled back into a recovery boiler where it is used to power the mill so future wood can be manufactured into a paper product (NGS 2012). Hydrogen fuel cells can be used to generate electricity in remote locations, power forklifts, buses, and even airplanes. These cells receive their hydrogen after it has been chemically extracted from the biomass (Smith & Rauscher 2008).

Advantages of Incorporating a Processor into the Harvesting System

Only 20% of the world's forests are currently being harvested using cut-to-length (CTL) mechanized systems (Adebayo et al. 2007; Ponsse 2017). The other 80% are broken down between whole-tree (WT) mechanized harvesting (30%) and motor-manual methods such as the chainsaw (50%). Historically, high initial costs associated with CTL systems kept this harvesting method from competing with whole-tree (WT) systems, however as CTL became more precise and productive and labor shortages occurred more frequently, the market is starting to justify its use (Bettinger & Kellogg 1993; Schäffer et al. 2001; Jiroušek et al. 2007).

CTL systems typically only involve the use of two machines. A tracked/wheeled harvester which cuts and processes the tree in the woods directly off the stump, and a forwarder whose responsibility is to collect the processed logs and transport them to the landing where they can be loaded onto a truck and delivered to a mill. Recent studies have analyzed, compared, and determined the productivity of CTL systems in today's markets throughout Europe, Africa, and New Zealand. One study conducted in South Africa compared the CTL system with motor-manual methods of harvesting in Eucalyptus compartments. This study indicated that if the Eucalyptus was planted, the CTL system proved more productive and was determined to be the overall preferred choice of harvest system due to the increase of motor-manual costs (Ramantswana et al. 2012). Another CTL study performed in New Zealand analyzed the productivity of two harvesters with Waratah processor heads in larger diameter Radiata Pine. This study looked at the processor functionality on the landing as a processor, in the woods harvesting, and as a de-limbing tool. Results indicated that this system is very versatile and capable of performing well regardless of the required use (Evanson & McConchie 1996).

A few studies have been conducted to compare CTL systems with WT systems. One study compared both CTL and WT harvest systems to motor-manual methods and found that both mechanized systems far out-performed the chainsaw, providing loggers with options for harvesting methods. This paper also inferred that CTL optimization may become the preferred method of harvesting in South Africa due to the machine's ability to provide accurate log measurements (Eggers et al. 2010). Another study comparing the two mechanized systems took place in the Italian Alps. Results from this study found that the price that the mill paid for the final product determined which system was preferable. If sawlog prices were not significantly high, CTL systems could not be justified (Spinelli & Magagnotti 2010).

Advancements in both hardware and software technology have allowed all forestry machines to be equipped with a computerized control system called StanForD (Arlinger et al. 2003; Arlinger 2018). This software was established as the global standard for collecting data from forest machines in 1987 and is used by all major manufactures (Arlinger 2018). The standard was updated in 2010. Because of StanForD, forest processors can be configured to incorporate operator specific settings, electronic calipers, laser find-end log alignment, application-specific measuring wheels, GPS Navigation systems, cellular and satellite capabilities, support for calibration of diameter and length, base machine leveling control, heel-rack control, and onboard diagnostics (Waratah 2018). These options allow the processor to be more precise when measuring both dbh as well and length. When properly calibrated, a processing head is estimated to be within three inches of product length and an inch of dbh given the stem has no obtrusions.

These specific measurements can be seen as favorable by mills who are requesting prime lengths or plywood logs from the loggers for specific products (Donnell 2017). Prime lengths are specific log lengths and are based on both dbh as well as the log's length. Prime lengths are designated by the mills and can vary from mill to mill depending on what the end product is for the log. Plywood or "peeler" logs are also designated lengths; these logs are turned against a lathe and peeled into a sheet of wood, referred to as veneer, and are used to make plywood boards. Both prime lengths and peeler logs are typically required to be in multiples of 8 feet 9 inches in length (Timber Update 2018). The above mentioned technology advancements have also recently allowed processor manufacturers to develop preselection priority optimization and value optimization settings. These features incorporate current mill prices, with product need, dbh, and length to optimally merchandize each stem based on market demand and stem quality (Smith & Peach 2018; Waratah 2018). Market prices within the processor's software program can be modified each day with the use of a USB dongle, cellular data, satellite or Wi-Fi connection to ensure accuracy within the machine's merchandizing specifications.

Potential benefits of incorporating a processor into a conventional WT harvesting system include the ability of having a floating rather than fixed landing if the loader is also on tracks. A floating landing can minimize the skid distance between the feller-buncher and the processor. This will not only decrease travel time between machines but will also decrease the total time from when a tree is felled to when it is processed on the mill. A processor also allows the loader to solely focus on loading trailers to be hauled to the mill rather than splitting their time between the two activities. This should decrease the delay time for drivers at the landing and could even increase the number of loads hauled in a day.

Concerns of Incorporating a Processor into the Harvest System

The initial and primary concern for the logger about incorporating a processor into their current harvest system regime revolves around the initial cost to purchase the machine. The technology advancements that have been integrated into the machine to increase productivity and precision come at an expensive price. Purchase price for these machines are estimated to be around $500,000 for the carrier and attachment head combination. This is almost double the price for a knuckle-boom loader which is commonly used in the southeastern region of the United States (Sales Representative

2018). For other regions of the world, unless the trucks are self-loading, an additional loader must be purchased to load the logs onto the trailer. Oftentimes these loaders are also tracked and have a similar price tag. Currently, no official cost analysis has been conducted to determine the effects of incorporating a processor into the overall system costs.

Although there is a possibility that the increased productivity realized from incorporating the processor into the harvest system will decrease harvesting costs, the logger will likely see an increase in labor and insurance costs. Additionally, the increase in productivity could create wood availability issues for the logger if their area was not densely populated with forestland or landowners willing to harvest their wood. The increased productivity would also decrease the number of days it took to harvest a tract of land. Small tracts of land would mandate the logger move locations more frequently inadvertently increasing his overall harvesting costs.

A shortage of both over-the-road and log-truck drivers in the United States raises red flags for individuals interested in investing in a processor. Loggers are already feeling the effects from this trucking shortage, in combination with long haul distances, with standard production (ATA 2018). Increasing harvest productivity without increasing trucking capacity would not provide any monetary benefit and could in fact decrease log value if blue-stain occurred due to the delayed transport. Loggers also face the risk of increasing productivity capabilities only to be shut down by mill quotas. If the local mill is not willing to receive the logs, the logger must send the driver to a mill further away or stop harvesting wood. Neither provide loggers incentive to purchase a processor.

Measurement accuracy and precision of the processor with regards to dbh and length are also a major concern, especially with loblolly pine where minimal research has been conducted. Visual observations have been made noting that multiple passes along the stem by the processing head has a tendency to almost completely remove all bark from the stem. A better understanding of whether the processor measures the diameter inside bark or diameter outside bark is therefore required before dbh measurement accuracy, plus or minus one inch, can be determined. Abnormalities along the stem, such as protrusions from stems or disease, also have a tendency to create inaccurate readings by the measuring wheel. Processing multiple stems with a single grab is an additional opportunity to misrepresent dbh, length, and even stem count because the machine's software is not designed to recognize more than one stem in the rollers at a time.

Although StanForD files are the established method for collecting data within the forest industry, the logger may choose not to purchase certain capabilities that will allow them to optimize and merchandize their wood. Additionally, each machine can be set up to collect productivity data differently depending on the operator's preference. If the logger does not establish a habit of processing stems exactly how the software has been set, no data will available. This could be problematic when conducting productivity studies.

It is estimated that on average it takes initial operators six months to a year before becoming proficient in the machine and almost three years before becoming fully competent. This time duration is too long for a logger to wait for increased productivity and oftentimes serves as a deterrent for purchase. New machines provide the option of reverse handles for operators which drastically decreases training time, however, a difference in productivity is still observed initially. With all these concerns, loggers are hesitant to invest in a processor. Without an increase in market interest or incentives provided by the mill to purchase this machine, the likelihood of a logger incorporating a tracked processor into their harvest system is minimal.

Chapter 3. Changing Times: Altering Establishment Spacing, Harvesting Frequency, and Harvesting Machines to Promote Increased Sawtimber Volumes

Abstract

Today's landowners are faced with important decisions when establishing loblolly pine plantations in the southeastern part of the United States with regards to planting dimensions and forest management techniques. Although recent studies are beginning to demonstrate the need for change from the old practices, suppressed biomass markets and prices are hindering the transition. This paper provided readers with an informational overview of the benefits of incorporating an additional thinning regime for biomass, using alternate spacing methods such as Flexstands^{TM} and rectangularity and using small-scale harvesting machines for conducting initial thinning's. The overview was supported with both a field study as well as a modeling tool which verified using one or all of the above-mentioned techniques to increase total harvest volumes while minimizing residual stand damage. The modeling tool determined that final sawtimber volumes were increased by a minimum of 15 green tons per acre using one or more of the above techniques. When expanding this volume out to 20 acres, the minimum tract size harvested in the southeast using convention equipment, landowners could easily recover any losses incurred from the suppressed biomass markets minimizing overall risk and promoting the use of these alternative techniques.

Keywords:
Flex Plantations, Rectangularity, Small-scale Harvesting, Woody Biomass, Ptaeda Modeling

Introduction

Forest landowners in the southeastern part of the United States are faced with multiple challenges when it comes to harvesting loblolly pine (*Pinus taeda L)* from their land. First, tract sizes are shrinking as lands become more fragmentized making it hard for landowners to find loggers willing to harvest their land (Daniel & others 2012; Aguilar et al. 2014; Butler & Butler 2016a). Next, plantations that promote woody biomass harvesting are being encouraged but there are minimal markets available to sell the product to, stumpage prices are minimal if existent for the product, and today's standard sized machines aren't able to cost-effectively harvest the product so loggers aren't willing to cut the biomass for the landowner (Botard et al. 2015; BBI International 2017; Gallagher et al. 2017; Yu et al. 2017). Finally, in order for these plantations to pay for themselves, landowners need to produce the highest sawtimber volumes possible to mitigate the risk of such a long-term investment and incentivize them to re-establish the land back into timber rather than convert it to another use that provides greater financial or intrinsic value for them (Butler & Leatherberry 2004; Butler 2008; Aguilar et al. 2013).

With all the above-mentioned challenges, it becomes confusing for a landowner when trying to decide how to establish and manage their loblolly pine plantation. This paper's objectives were to provide an informational overview of the benefits of incorporating an additional thinning regime for biomass, using alternate spacing methods such as Flexstands^{TM} and rectangularity, and using small-scale harvesting machines for conducting initial thinning's to promote increased sawtimber volumes. The overview was supported with both a field study as well as a modeling tool which verified using one or all of the above-mentioned techniques to increase total harvest volumes while minimizing residual stand damage.

Biomass Harvests

Biomass harvests differ from first thinning's in a variety of ways. A pine biomass harvest is typically conducted between years 5 to 9 whereas a first thinning is between years 10-16. This difference in age generally results in a difference in size, product class, and inadvertently delivered price (Gallagher et al. 2017). This smaller diameter creates more surface bark, limbs, and needles which are undesirable when making pulp because it requires additional chemicals to be used during the breakdown of cellulosic fibers. Biomass is therefore not often used during a pulpwood shortage (Bajpai 2011). Pulpwood, however, can be a suitable alternative when biomass shortages arise so consequently market demand doesn't increase and neither does woody biomass's price.

There are over 90 pulp and paper mills in the southeastern part of the United States compared to the 41 biomass facilities that can be found in the same region. Of these 41, 12 are biomass power facilities which together produce only 563.3 megawatts of power every year from a combination of pulpwood, woody biomass, and logging residues. Sixteen of the 41 are pellet mills which are able to use both hardwood and softwood feedstock (pulpwood or woody biomass) to produce approximately 7 million green tons of pellets per year. Eleven of the 41 are pellet mills which use only softwood feedstock (pulpwood or woody biomass) to produce 4.5 million green tons of pellets per year, and 2 are pellet mills designated as woody biomass feedstock. These two mills produce over 2 million green tons of pellets annually by themselves (BBI International 2017). In general, it can be seen that even the biomass designated facilities are being supplied still with pulpwood rather than wood biomass only, indicating that there is a plethora of market potential if biomass was readily available as a product.

According to Timber Mart-South, the 2016/2017 average delivered price for woody biomass was $21.18 per green ton (Timber Mart South 2018). This price appears high and comparable to the 2016/2017 average delivered market price for pulpwood of $29.49 per green ton, however, it is deceiving. Delivered prices for woody biomass are designated for “clean” chips that come from the mill and are being delivered to another facility. These chips do not have any bark, needles, small limbs, or dirt in them. Woody biomass that comes straight from the woods can either be transported “whole tree” with tops and limbs still attached to the main stem or as “dirty chips”. Dirty chips indicate that the tree has been chipped in the woods and will have limbs, needles, bark, dirt, and the potential for other small objects mixed into the chips. The market for “dirty chips” is basically non-existent at this time, therefore, revenue from woody biomass is also not available (Mitchell & Gallagher 2007).

Although incorporation of a biomass harvests is not currently a viable solution for increasing a landowner's revenue at the time of that harvest, an additional thinning can increase total stand yield by removing trees that would either die or plateau the stands growth (Dean & Baldwin 1993; Sharma et al. 2002). The removal of biomass to decrease the stands overall density stocking allows trees to continue to grow at a competitive rate thereby inadvertently increasing the number of sawtimber trees available throughout the stand (Amateis et al. 2004). Planting with higher density stocking initially has also been shown to instigate greater competition between saplings encouraging straighter trees with fewer branches which eventually has the potential to lead to a higher quality final product (Amateis et al. 2009; Amateis & Burkhart 2012; Gallagher et al. 2017).

FlexStands™

The concept of a FlexStand™ was coined by *ArborGen: Global Reforestation Partner*, a worldwide provider of both genetically enhanced and conventional tree seedlings. This silvicultural technique involves planting conventional biomass, open-pollinated (OP), trees in-between rows of genetically improved, mass-control pollinated (MCP), trees to provide landowners with an economical solution for growing and thinning Loblolly pine stands (ArborGen Inc. 2018). This unique plantation establishment method was designed to assist in risk mitigation for future timber markets by producing multiple products from the same stand. This technique also allows landowners the flexibility of altering their management decisions based on current and expected market dynamics.

FlexStands^{TM} is considered to be high-density plantings. Although planting strategies differ depending on landowner objectives, the overall concept is to plant a high number of trees per acre by alternating/interchanging row plantings between MCP trees and OP trees. The enhanced seedlings will be spaced anywhere from 6 to 10 feet apart down the rows however the non-modified seedlings will be spaced as close as 2 feet and as far apart as 6 feet in order to increase the density stocking of the stand. Rows are typically 10-12 feet apart but have been seen as close as 5 feet apart (ArborGen Inc. 2018). Research has shown that seedling growth is not detrimentally affected by the distance between trees for the first few years of growth. Rather, the closer the seedling spacing, the more the saplings tend to focus on bole growth rather than branches or needles thereby decreasing defects that can be found in the tree (Ma 2014).

Altering seedling types throughout the stand by rows has also been proven to minimize the costs of planting to the landowner because they are no longer purchasing all genetically enhanced seedlings, of which half are eventually removed before growing to sawtimber size (Ma 2014; ArborGen Inc. 2018). FlexStands^{TM} is also proven to reduce the loss of revenue for landowners compared to if they were to plant only one seedling type. Planting only OP trees reduces the final sawtimber size inadvertently decreasing overall revenue, whereas planting only MCP seedlings results in a significantly higher increase in initial costs which must be carried through to the final harvest that is not guaranteed to be more profitable (ArborGen Inc. 2018).

With the FlexStand^{TM} system, a biomass harvest is conducted between years 6 - 9 removing all OP sapling rows in order to promote the continued growth of the stand. A pulpwood thinning is conducted around years 12-16 to once again keep the stand from stagnating in size with a final harvest being conducted between years 24 - 30 depending on tree diameters and market prices.

Revenue associated with conducting a first thinning with both the biomass and the pulpwood out of the FlexStand^{TM} does not currently mitigate the associated harvesting costs. Incorporating a biomass thinning into the management regime beforehand, however, does increase the size and overall value of the final sawtimber trees by forcing them to grow straighter and with fewer branches for the first few years of their life which results in a higher value final product (ArborGen Inc. 2018). When considering overall profitability, FlexStand^{TM} could be considered a potential solution if a biomass harvest is conducted within the conventional timber harvest as long as there were viable markets to send the products. Further promotion for the FlexStand^{TM} could occur if harvesting and relocation costs could be reduced by using small-scale equipment.

Rectangularity

Similar to the idea that a FlexStand^{TM} could be a viable option to modify planting establishment methods, rectangularity is also being studied for its feasibility to promote woody biomass in the South. Typically, conventional stand seedling establishments occur with a specific number of trees being planted per acre in a shape that resembles a square. With rectangularity, the same number of trees are planted per acre but the shape resembles a rectangle rather than a square. This configuration allows for wider spacing in-between the rows of trees making site preparation costs cheaper as well as increasing maneuverability of forestry equipment throughout the stand, inadvertently decreasing damage caused to residual trees (Amateis et al. 2004).

The concept of rectangularity has been intermittingly studied since the 1940's as researchers continue to contemplate the ideal plantation spacing for specific tree species (Sharma et al. 2002; Amateis & Burkhart 2012). Almost all studies have shown that rectangularity has no effect on tree height, diameter, volume per acre, basal area per acre or even tree survival (Gerrand & Neilsen 2000; Amateis et al. 2004; Amateis et al. 2009; Brand 2012). In fact, most studies have shown that age plays a more significant effect than rectangularity. Crown size and shape appear to be the only factors that should be taken into account when contemplating a rectangularity spacing.

Although there are a variety of spacing options with regards to rectangularity, the three most recognized coincide with 436 trees per acre (tpa), 605 tpa, and 908 tpa. A normal plantation spacing at 436 tpa would be 10 feet in-between-rows by 10 feet within-rows, compared to the rectangular option of 20 feet in-between-rows by 5 feet within the rows. At 605 tpa, a normal spacing would be 9 feet by 8 feet whereas a rectangular spacing would be 12 feet by 6 feet. Finally, at 908 tpa, a normal spacing regime would be 8 feet by 6 feet compared the rectangular spacing of 12 feet by 4 feet (Sharma et al. 2002; Amateis et al. 2004; Amateis et al. 2009).

As forestry equipment continues to grow in dimension, landowner holdings are decreasing in size. Rectangularity could provide a viable solution to the increasing amounts of damage unintentionally administered to residual trees when thinning's occur. With rectangularity, the need for small-scale harvesting equipment becomes less of an issue, allowing the equipment industry to continue to focus on producing larger more powerful machines. Non-industrial private forest landowners (NIPFs) would also benefit from this technique by being able to strategically plant rows in a manner which allowed for optimal growth and harvest of the tract in future years while allowing for machine maneuverability.

Small Scale Harvesting

NIPFs account for 36% of all of the forest land, 1+ acres, in the United States. Of this percentage, 13% comes from landowners who reside in the southeastern part of the United States (Butler & Butler 2016b; Butler & Butler 2016a). According to the national survey conducted in 2006, the majority of acres owned by NIPF landowners is between 1-49 acres (Butler & Leatherberry 2004; Butler 2008). As woody biomass becomes a more desired commodity, the forest industry will begin to look for further resources to supply to their mills. In addition to experimenting with genetic improvements for tree growth and establishment/planting modifications, mills will likely turn to the NIPF landowners for greater contribution.

Research has shown that it is unprofitable for a logger to harvest trees on less than twenty acres because today's equipment is too expensive for the harvest to result in economically feasibility after relocation costs, capital investments, labor, and fuel expenses are withheld from revenue (Athanassiadis & others 1997; Burdg & Gallagher 2011). Additionally, upholding today's high standards for best management practices can become an issue due to the large size of standard machines which measure approximately 10-11 feet wide, can range from 20-30 feet in length, weigh between 30,000-50,000 lbs, and have 174-300 HP for engine power (Caterpillar 2018; Deere & Company 2018). Even though a majority of the feller-bunchers and skidders in the south have articulated steering, these equipment specifications can inflict significant damage on residual trees when working in minimal acreage, conducting pulpwood thinning’s, or even biomass thinning’s.

Ideally, the top leaders in the forest equipment industry would design feller-bunchers and skidders that met the economic and environmental requirements of harvesting an area that was less than 20 acres in size. These machines would need to be small enough to maneuver through narrow spaces and rows without causing significant residual damage. The machines would need to be capable of handling trees approximately 55 feet in height and 9 inches in diameter. Ultimately, producers must be able to provide these machines at a cost which makes harvesting small tracts profitable. Realistically, however, equipment continues to grow in size to meet the market demand for larger and more powerful machines. Until market demand increases for smaller machines, minimal advancements will be made by the industries leaders.

Although purchasing small-scale feller-bunchers and skidders in the United States is currently a daunting task, finding forestry attachments that connect to skid-steers, compact tracked loaders, and mini-excavators is not. The ability to connect to a variety of attachments, both forestry-related and otherwise, to complete the immediate task at hand has made these machines the most versatile options available on today’s market. Because of the advancements that have been made on these machines in both horsepower and hydraulic pressure flow technology, manufacturers have been able to create a system called “high flow”. This system allows operation of attachments requiring significant speed and/or torque such as the harvester saw-heads which were previously impossible on such small machines.

These small-scale machines are dimensionally smaller, ranging from 3 - 7 feet in width and 8 - 15 feet in length depending on make and model which suggests increased mobility in small tight areas. Machine weights and range from approximately 2,500 to 9,500 pounds for the skid-steers/compact tracked loaders and 8,500 to 18,500 pounds for the mini excavators. Machine engine power ranges from 65-106 hp for skid-steers/compact tracked loaders and 40-65 hp for the mini excavators (Caterpillar 2018; Deere & Company 2018). These specifications indicate that these machines can be transported with a pickup truck and trailer rather than with a semi and lowboy trailer as is required for standard forestry equipment, inadvertently decreasing transportation costs. These machines are also known for having a low ground pressure which minimizes ground disturbance making them environmentally friendly. Finally, initial purchase price differences between small-scale and standard forestry equipment can be as low as one quarter to as high as one half of the cost depending on make, model, and attachment configuration.

Methods

Case Study Site Description:

The field study was conducted on the Solon Dixon Forestry Education Center in Covington County, Alabama. The site consisted of a total of approximately 2.66 acres on Dothan and Malbis sandy loams. Stand 1 was 1.02 acres in size and contained a loblolly pine plantation with 8ft x 6ft spacing. Stand 2 was 1.64 acres in size and was considered a flex plantation stand. The spacing configuration consisted of every third row being 10ft by 4ft spacing planted with OP seedlings while all other rows were MCP seedlings planted with a 10ft by 8ft spacing. Both stands were established with their rows facing in an east-west direction with a twenty-foot corridor separating the two stands. The stands were approximately eight years old at the time of harvest, in May 2017, with minimal mortality found in either stand.

A Caterpillar 279D compact track loader machine with a Fecon FBS1400 Single Knife Tree Shear attachment head was used to remove every third row from both stands for a harvested basal area of 70. The track loader weighed approximately 10,000 lbs, had 73 HP engine power, was 6 feet wide and 7 feet long. The sheared trees were collected in the shear heads' accumulating arm until full where the bundle would then be laid down within the row. A turbo forest mini skidder was used to collect the bundles and remove them from the site. This machine weighed 7,500 lbs, had 50 HP engine power, was 6 feet wide, and 12 feet in length. No time study was conducted in this analysis so operational costs could not be calculated.

Approximately two bundles per row in stand 1 and three bundles per row in stand 2 were randomly selected to be measured for a total of 16 bundles in stand 1 and 12 bundles in stand 2. Individuals trees were measured out of each selected bundle. Overall, 88 trees were measured in stand 1 and 79 trees were measured in stand 2.

Data were recorded and analyzed in Microsoft Excel. Results for the field data were analyzed by grouping trees by dbh class using 1-inch intervals from 3-9 inches. Basal area was calculated per size class as was the overall basal area that was removed from each stand. The average weight per tree was calculated for each size class and protracted out to determine the overall tonnage harvested per size class for one acre. Total green tons removed per stand were calculated to use as a reference for comparison. A stump count was conducted in each row per stand to use a reference for actual tree removal data. Two-sample t-tests were conducted in Minitab to determine if there were statistical differences between the field data for total height, weight, basal area, or dbh between Stand 1 and Stand 2.

Ptaeda Study Model Description

A comparison model study was conducted using a loblolly pine plantation modeling tool named Ptaeda 4.0. Six separate models were run with this tool; one each for stands 1 (M1) and 2 (M3) with a biomass harvest at year 8, thinning's at year 16 and final harvests at year 28. A third model (M5) was run to simulate a rectangularity setting with 12ft x 4ft spacing (908 tpa) that could be compared against Stand 1. This model followed the same parameters as the previous two with regards to thinning and harvest schedules. The other three model simulations (M2, M4, & M6) only conducted pulpwood thinning's at year 16 with final harvests at year 28.

Each model incorporated specific parameters relating the models as close to field conditions as possible. Stand information included site productivity of 85, total rotation lengths of 28 years, planting distances between trees and between rows of 8x6, 10x6, and 12x4. Site information included physiographic regions based in the Coastal Plain, well-drained drainage class, and no fertilization at planting. Merchandizing options and limits resulted in pulpwood tops at 2 inches with minimum dbh at 5 inches, chip and saw tops at 4 inches with dbh at 8 inches, and sawtimber tops at 6 inches with dbh at 11 inches. All topwood from chip and saw and sawtimber product classes were added into the pulpwood product class. All trees were calculated using green weight (green tons/acre with bark) measurements. No economic parameters were designated. Mid-rotation treatments varied by harvest plan. Biomass harvests were conducted using a 3rd-row and low (70 basal area) thin method at year 8 with 16 year thinning's conducted with a targeted residual basal area of 70 square feet. One thinning harvests included a third row and low (70 basal area) thinning conducted at year 16 only.

Ptaeda data that was recorded into excel included: the site index, the treatment conducted, dominant height, average dbh, average height, average crown ratio, dbh class, tree number, basal area, total weight (green ton), pulpwood weight harvested (green ton), chip n saw weight harvested (green ton), and sawtimber weight harvested (green ton). Clark & Saucier were referenced to calculate the predicted green weight in pounds of total tree (wood, bark, and foliage) in the Coastal Plain, based on dbh size class for total tree height using the following equation:

$$Y=0.23369*(dbh^{2}*total\ height)^{0.96673}$$

This number was converted to green tons and then multiplied by the total number of trees in each size class to find total tons per size class. Weights were calculated for each treatment year both before and after each harvest treatment by dbh size class but only the harvested treatment weights were used to calculate price per green ton. Harvest weights were then calculated per product class following the previously mentioned mechanizing limits.

Biomass weight was calculated using the difference between Clark and Saucier total tree green weight from the Ptaeda model merchandized green weight in each dbh size class. These weights were summed to determine a biomass weight in green tons for tops, limbs, and needles. One inch through four-inch dbh size class weights for total tree height from Clark and Saucier were also included when available to determine total biomass available in the woods for that harvest treatment year. Regardless of intentions to collect all biomass available, recent studies have estimated that approximately 30% of the biomass harvested remains in the woods (Lancaster 2017). For this reason, 30% of the biomass harvest weight was removed from the final biomass tonnage values. New total weights for each harvest were calculated to incorporate this 30% loss in biomass harvest.

Price per green ton was calculated for each product class as was total revenue for each treatment. Revenue, net present value at 3% (NPV), internal rate of return (IRR) were calculated both with biomass as well as without biomass. Cost for stand establishments for the landowner was calculated using reference numbers from the "Costs & Trends of Southern Forestry Practices 2012" by the Alabama Cooperative Extension System (Dooley & Barlow 2013). Item description prices were based on numbers for the southern coastal plain on a per acre basis and included chemical site preparation at $89.41, burning after chemical site prep $53.44, hand planting costs for bare root seedlings $62.78, fertilizer at establishment $104.95, and seedling costs per thousand $48.69 per thousand. Logging costs were not calculated since the biomass harvest costs would need to be calculated using small-scale equipment and that information is not currently available. Additionally, logging costs are not typically incurred by the landowner directly, rather they are removed from the landowner's final revenue received from harvest.

Results

Field Study

88 trees were measured in Stand 1 out of the 232 that were harvested. Of the trees that were measured, 6 were within the 3-inch dbh class, 9 were in the 4-inch dbh class, 26 were within the 5-inch class, 34 within the 6-inch class, 12 were in the 7-inch class, 1 in the 8-inch class and none were found to be within the 9-inch dbh class. The average dbh for the stand was 6 inches with an average height of 39 feet. The residual basal area was approximately 70 down from the original 120 before harvesting. Tree weights for each dbh class were averaged to calculate the average weight per tree in each dbh class as well as the average dbh weight per acre. A final weight for Stand 1 was calculated at 84,690 pounds or 42.35 green tons that were removed from a one-acre tract.

Table 1. Summary data for the 8x6 stand of harvested trees 1.

DBH Class	Harvested Tree Count	Basal Area	Green Tons Harvested
3	6	0.99	0.78
4	9	2.65	1.97
5	26	11.95	10.69
6	34	22.51	18.92
7	12	10.81	8.99
8	1	1.18	1.00
9	0	0.00	0.00

79 of the 568 harvested trees were measured in Stand 2. Of those trees 3 were within the 3-inch dbh class, 16 were in the 4-inch dbh class, 32 were within the 5-inch class, 16 within the 6-inch class, 10 were in the 7-inch class, 1 in the 8-inch class and 1 was found to be within the 9-inch dbh class. The average dbh for the stand was also 6 inches with an average height of 40 feet. The residual basal area was approximately 70 down from the original 120 before harvesting. Tree weights for each dbh class were averaged to calculate the average weight per tree in each dbh class as well as the average dbh weight per acre. A final weight for Stand 2 was calculated at 105,158 pounds or 52.58 green tons that were removed from a one-acre tract.

Table 2. Summary data for the 10x6 harvested stand 2.

DBH Class	Harvested Tree Count	Basal Area	Green Tons Harvested
3	3	0.05	0.52
4	16	0.09	6.33
5	32	0.14	19.81
6	16	0.20	12.59
7	10	0.27	11.80
8	1	0.35	1.50
9	1	0.44	0.03

Visual observations were made following the harvests to collect information concerning damage made to residual trees. For the purpose of the study, damage was classified as any scrape or mark that was longer than 6 inches and cut through the bark into the trees cambium layer. Less than 5% damage was found in Stand 1 and none of the damage appeared to be significant enough to cause mortality. Less than 1% damage was observed in Stand 2, also none of which appeared harmful enough to cause mortality.

Two-sample t-tests were conducted to determine if there were any significant differences between the two stands with regards to the tree weights, dbh, height, or basal area. All variables except tree weight were found to be statistically insignificant. Tree weights, however, had a P-value of 0.045 at the 95% significance level. An additional comparison was conducted to determine if Stand 1 trees weighed more than Stand 2 trees. This t-test was also found to be significant at the 95% level with a P-value of 0.023.

Ptaeda Model Green tonnage

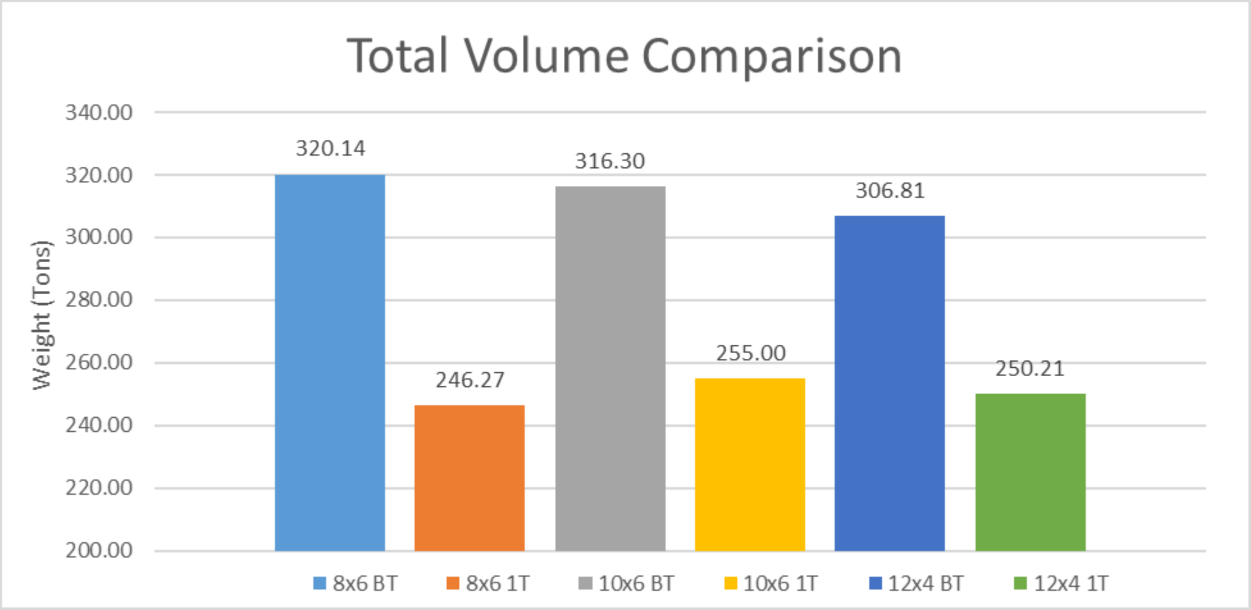

Figure 1. Comparison of total volume for the entire rotation for all Ptaeda models.

The Ptaeda model that included biomass in the harvest for Stand 1 (M1) had an average dbh of 5 inches with an average tree height of 31.5 feet after year 8. There were approximately 39 total green tons harvested at that time, all of which were designated as biomass. At year 16 a 2nd thinning resulted in an average dbh of 9.27 inches and an average height of 62.7 feet. Approximately 88 total green tons were removed with 11 green tons coming from biomass, 5 green tons from pulpwood, 70 green tons from chip and saw, and 2 green tons coming from sawtimber. Final harvest at year 28 resulted in an average dbh of 11.58 inches and 83.7 feet for an average height. Approximately 165 total green tons were removed with 19 green tons coming from biomass, 0 green tons from pulpwood, 67 green tons from chip and saw, and 79 green tons coming from sawtimber. In total 291 green tons were removed from the stand during the three harvests, with 69 green tons coming from biomass, 5 green tons from pulpwood, 137 green tons from chip and saw, and 80 green tons from sawtimber.

Conventional Ptaeda model for Stand 1 that did not include a biomass harvest, also known as one thinning (M2), had an average dbh of 8.31 inches and an average height of 60.1 feet after the 1st thinning at year 16. There were approximately 83 total green tons harvested, 11 green tons came from biomass, 40 green tons from pulpwood, 32 green tons from chip and saw, and 1 green ton from sawtimber. Final harvest at year 28 resulted in an average dbh of 10.45 inches and an average height of 81 feet. 151 total green tons were removed from the final harvest with 18 green tons coming from biomass, 3 green tons from pulpwood, 93 green tons from chip and saw, and 25 green tons from sawtimber. In total 234 green tons were harvested from the tract with 28 green tons coming from biomass, 42 green tons from pulpwood, 125 green tons from chip and saw, and 39 green tons from sawtimber.

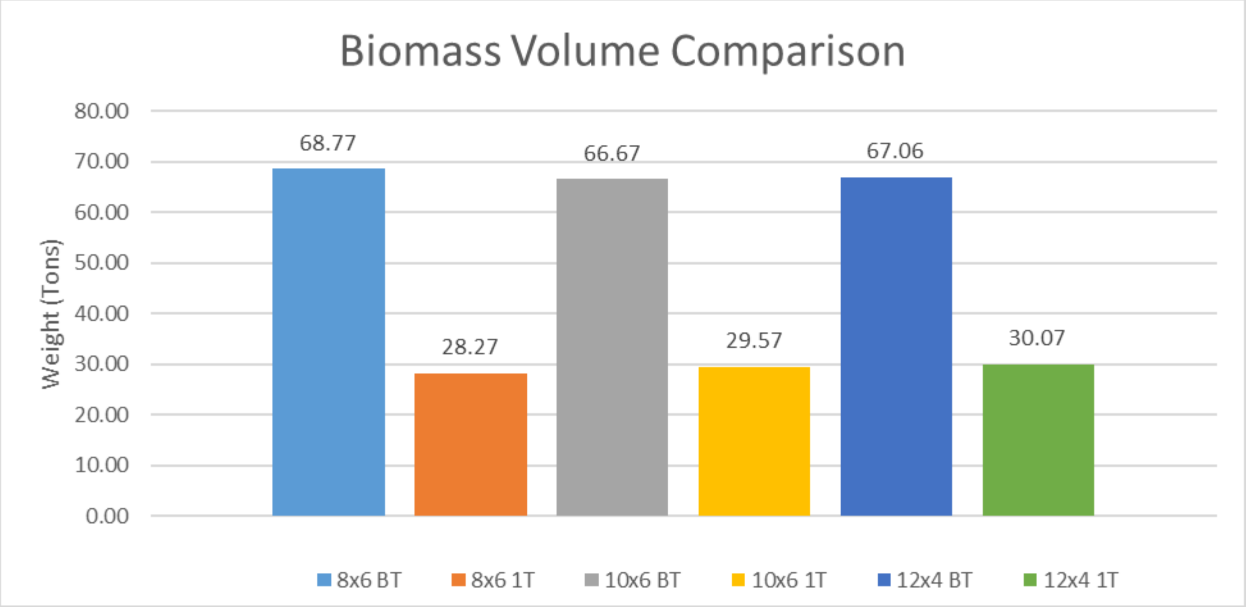

Figure 2. Comparison of biomass volume for the entire rotation for all Ptaeda models.

Stand 2's biomass inclusion harvest (M3) resulted in an average dbh of 5.52 inches with an average tree height of 32 feet after year 8. There were approximately 37 total green tons harvested at that time, all of which were designated as biomass. At year 16 a 2nd thinning resulted in an average dbh of 9.66 inches and an average height of 63.4 feet. Approximately 87 total green tons were removed with 11 green tons coming from biomass, 0.5 green tons from pulpwood, 74 green tons from chip and saw, and 2 green tons coming from sawtimber. Final harvest at year 28 resulted in an average dbh of 12.06 inches and 84.7 feet for an average height. Approximately 164 total green tons were removed with 19 green tons coming from biomass, 0 green tons from pulpwood, 35 green tons from chip and saw, and 110 green tons coming from sawtimber. In total 288 green tons were removed from the stand during the three harvests, with 67 green tons coming from biomass, 0.5 green tons from pulpwood, 108 green tons from chip and saw, and 112 green tons from sawtimber.

Stand 2's one thinning harvest (M4) had an average dbh of 8.81 inches and an average height of 60.8 feet after the 1st thinning at year 16. There were approximately 85 total green tons harvested, 11 green tons came from biomass, 23 green tons from pulpwood, 51 green tons from chip and saw, and 0 green ton from sawtimber. Final harvest at year 28 resulted in an average dbh of 11.05 inches and an average height of 81.0 feet. Final harvest tonnage resulted in 158 total green tons being removed with 19 green tons being from biomass, 0 green tons from pulpwood, 79 green tons from chip and saw, and 60 green tons from sawtimber. In total 242 green tons were harvested from the tract with 30 green tons coming from biomass, 23 green tons from pulpwood, 130 green tons from chip and saw, and 60 green tons from sawtimber.

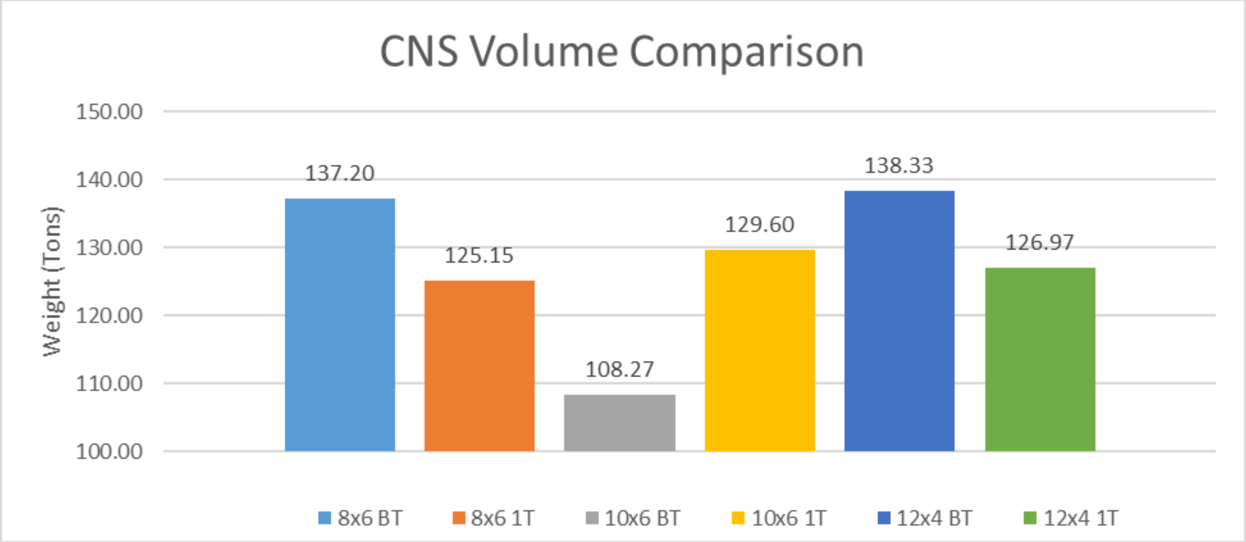

Figure 3. Comparison of CNS volume for the entire rotation for all Ptaeda models.

Stand 3's biomass inclusion harvest (M5) resulted in an average dbh of 4.87 inches with an average tree height of 31.2 feet after year 8. There were approximately 38 total green tons harvested at that time, all of which were designated as biomass. At year 16 a 2nd thinning resulted in an average dbh of 8.68 inches and an average height of 61.2 feet. Approximately 88 total green tons were removed with 12 green tons coming from biomass, 25 green tons from pulpwood, 50 green tons from chip and saw, and 1 green ton coming from sawtimber. Final harvest at year 28 resulted in an average dbh of 10.82 inches and 81.9 feet for an average height. Approximately 153 total green tons were removed with 18 green tons coming from biomass, 0 green tons from pulpwood, 89 green tons from chip and saw, and 46 green tons coming from sawtimber. In total 278 green tons were removed from the stand during the three harvests, with 67 green tons coming from biomass, 25 green tons from pulpwood, 138 green tons from chip and saw, and 48 green tons from sawtimber.

Conventional Ptaeda model for Stand 3 that did not include a biomass harvest, also known as one thinning (M6), had an average dbh of 6.57 inches and an average height of 41.7 feet after the 1st thinning at year 16. There were approximately 84 total green tons harvested, 11 green tons came from biomass, 43 green tons from pulpwood, 30 green tons from chip and saw, and 0 green ton from sawtimber. Final harvest at year 28 resulted in an average dbh of 8.96 inches and an average height of 62.9 feet. 154 total green tons were removed from the final harvest with 19 green tons coming from biomass, 5 green tons from pulpwood, 97 green tons from chip and saw, and 33 green tons from sawtimber. In total 237 green tons were harvested from the tract with 30 green tons coming from biomass, 47 green tons from pulpwood, 127 green tons from chip and saw, and 33 green tons from sawtimber.

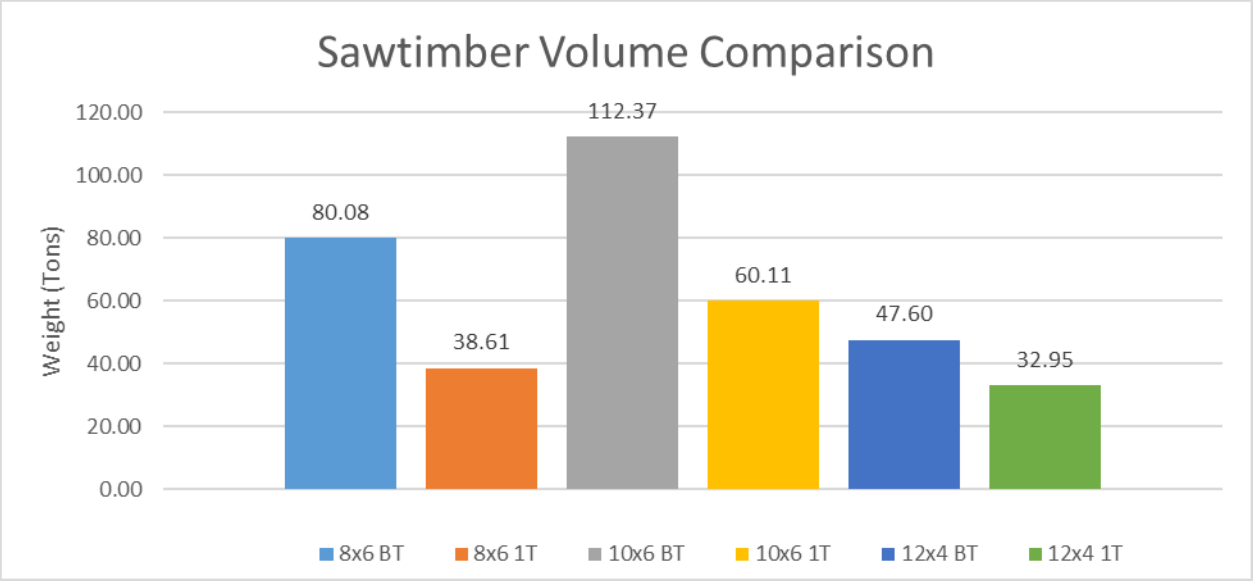

Figure 4. Comparison of sawtimber volume for the full rotation for all Ptaeda models.

Although M1 had slightly higher total and biomass tonnage overall, M3 was a close second and produced the most sawtimber in the final harvest by 32 green tons over M1. All models which included the biomass thinning produced more total weight, biomass tonnage, and sawtimber tonnage than the alternative model with the same spacing. Model 5 had the smallest net gain in the above-mentioned product classes with approximately 15 more green tons of sawtimber, 37 more green tons of biomass, and 41 more green tons in overall volume than in comparison to M6. Stand's 1 and 3 had higher chip and saw volumes in the biomass thinning models, however, Stand 2 did not. M6 and M2 had the two highest pulpwood volumes which were expected since they produced the least in all other product classes. Overall M2, the conventional stand with regards to spacing and harvest regime, performed the worst with regards to total volume produced.

Ptaeda Model Prices

All costs occurred at establishment for all models, regardless of harvest type or spacing configuration. Differences in cost pricing were due to the number of trees planted therefore resulting in Stand 1 and Stand 3's costs to be -$354.79 an acre at year 0 while Stand 2's costs were only -$345.98 an acre at year 0. Information regarding small-scale machine harvesting costs are not currently available therefore only costs incurred by the landowner could be calculated.

Overall profit was calculated for each harvest regime within each stand. Additionally, profits were calculated to both include as well as exclude profits from woody biomass to demonstrate the differences in revenue and final profits. This exclusion of biomass prices still assumed that the biomass was harvested at each cut, however, no profit was received by the landowner for this product. Profits for M1 were $4,041.33 an acre when biomass was included and $3,972.56 an acre without biomass prices included. M2 received $3,158.49 an acre for harvests with biomass and $3,130.22 an acre for harvests without biomass payment.

Profits for M3 were $4,282.56 an acre when biomass was included and $4,215.89 an acre without biomass prices included. M4 received $3,577.75 an acre for harvests with biomass and $3,548.18 an acre for harvests without biomass payment. Profits for M5 were $3,476.81 an acre when biomass was included and $3,409.75 an acre without biomass prices included. M6 received $3,105.95 an acre for harvests with biomass and $3,075.88 an acre for harvests without biomass payment.

Table 3. Pricing & Revenues for Stand 1

Stand 1: Site Index 85 (Coastal Plain)- 8x6 Spacing (908 tpa)													
Model Data with Biomass Left in the Woods													
Biomass Thinning	Pulp $/ton	CNS $/ton	Saw $/ton	Biomass $/ton	Total Harvest Revenue w/ Biomass ($)	Total Harvest Revenue no Biomass	Total Cost ($)	Profit ($) w/ Biomass (No NPV)	Profit ($) w/ Biomass (NPV 3%)	% IRR w/ Biomass	Profit ($) no Biomass (No NPV)	Profit ($) no Biomass (NPV 3%)	% IRR no Biomass
Before Biomass Thinning (Year 8)	-	-	-	-	-	-	(354.79)						
Biomass Thinning (Year 8)	-	-	-	38.89	38.89	-	-						
Before 2nd Thinning (Year 16)	731.21	847.64	38.76	-	-	-	-						
2nd Thinning (Year 16)	44.11	1,208.62	40.06	11.19	1,303.98	1,292.79	-						
Final Harvest (Year 28)	-	1,156.79	1,877.77	18.69	3,053.25	3,034.56	-						
Total					**4,396.12**	**4,327.35**	**(354.79)**	**4,041.33**	**1,842.66**	**12.02%**	**3,972.56**	**1,777.17**	**11.74%**
One Thinning													
Before 1st Thinning (Year 16)	1,034.96	701.80	-	-	-	-	(354.79)						
1st Thinning (Year 16)	379.58	548.76	32.47	10.49	971.30	960.81	-						
Final Harvest (Year 28)	23.17	1,608.81	892.22	17.78	2,541.98	2,524.20	-						
Total					**3,513.28**	**3,485.01**	**(354.79)**	**3,158.49**	**1,367.67**	**10.46%**	**3,130.22**	**1,347.22**	**10.41%**

Overall profit with a net present value at 3% was calculated to demonstrate to landowners what today's value of harvesting would be for all six model types. Three percent was used specifically for landowners to be able to compare results against today's interest rates. NPV's for M1 was $1,842.66 an acre when biomass was included and $1,777.17 an acre without biomass prices included. M2 received $1,367.67an acre for harvests with biomass and $1,347.22 an acre for harvests without biomass payment.

NPV's at 3% for M3 was $1,957.67 an acre when biomass was included and $1,894.45 an acre without biomass prices included. M4 received $1,581.25 an acre for harvests with biomass and $1,559.88 an acre for harvests without biomass payment. NPV's for M5 was $1,563.66 an acre when biomass was included and $1,499.70 an acre without biomass prices included. M6 received $1,339.14 an acre for harvests with biomass and $1,317.50 an acre for harvests without biomass payment.

Table 4. Pricing & Revenues for Stand 2

Stand 2: Site Index 85 (Coastal Plain)- 10x6 Spacing (727 tpa)

Model Data with Biomass Left in the Woods

Biomass Thinning	Pulp $/ton	CNS $/ton	Saw $/ton	Biomass $/ton	Total Harvest Revenue w/ Biomass ($)	Total Harvest Revenue no Biomass ($)	Total Cost ($)	Profit ($) w/ Biomass (No NPV)	Profit ($) w/ Biomass (NPV 3%)	% IRR w/ Biomass	Profit ($) no Biomass (No NPV)	Profit ($) no Biomass (NPV 3%)	% IRR no Biomass
Before Biomass Thinning (Year 8)	-	-	-	-			(345.98)						
Biomass Thinning (Year 8)	-	-	-	37.10	37.10	-	-						
Before 2nd Thinning (Year 16)	553.84	1,114.16	-	-			-						
2nd Thinning (Year 16)	3.88	1,268.93	52.02	10.98	1,335.81	1,324.83	-						
Final Harvest (Year 28)	-	597.70	2,639.33	18.60	3,255.64	3,237.04	-						
Total					**4,628.54**	**4,561.87**	**(345.98)**	**4,282.56**	**1,957.67**	**12.36%**	**4,215.89**	**1,894.45**	**12.09%**
One Thinning													
Before 1st Thinning (Year 16)	889.60	1,022.38	-	-			(345.98)						
1st Thinning (Year 16)	220.27	874.99	-	10.92	1,106.18	1,095.27	-						
Final Harvest (Year 28)	-	1,359.31	1,439.58	18.66	2,817.55	2,798.89	-						
Total					**3,923.73**	**3,894.15**	**(345.98)**	**3,577.75**	**1,581.25**	**11.21%**	**3,548.18**	**1,559.88**	**11.16%**

Internal rates of return were calculated for each stand's model to demonstrate the exact discount rate that would be received by a landowner when net present value for the investment was zero. This method of evaluating capital expenditure proposals was chosen to more accurately depict potential benefits for landowners with regards to their investments choices with the 6 model options. IRR for M1 was 12.02% when biomass was included and 11.74% without biomass prices included. M2 received 10.46% for harvests with biomass and 10.41% for harvests without biomass payment.

IRR for M3 was 12.36% when biomass was included and 12.09% without biomass prices included. M4 received 11.21% for harvests with biomass and 11.16% for harvests without biomass payment. IRR for M5 was 11.28% when biomass was included and 10.98% without biomass prices included. M6 received 10.34% for harvests with biomass and 10.29% for harvests without biomass payment.

Table 5. Pricing & Revenues for Stand 3

Stand 3: Site Index 85 (Coastal Plain)- 12x4 Spacing (908 tpa)

Model Data with Biomass Left in the Woods

Biomass Thinning	Pulp $/ton	CNS $/ton	Saw $/ton	Biomass $/ton	Total Harvest Revenue w/ Biomass ($)	Total Harvest Revenue no Biomass ($)	Total Cost ($)	Profit ($) w/ Biomass (No NPV)	Profit ($) w/ Biomass (NPV 3%)	% IRR w/ Biomass	Profit ($) no Biomass (No NPV)	Profit ($) no Biomass (NPV 3%)	% IRR no Biomass
Before Biomass Thinning (Year 8)	-	-	-	-	-	-	(354.79)						
Biomass Thinning (Year 8)	-	-	-	37.59	37.59	-	-						
Before 2nd Thinning (Year 16)	722.20	526.47	30.84	-	-	-	-						
2nd Thinning (Year 16)	239.69	851.94	32.00	11.92	1,135.55	1,123.63	-						
Final Harvest (Year 28)	-	1,532.94	1,107.97	17.56	2,658.47	2,640.91	-						
Total					**3,831.61**	**3,764.54**	**(354.79)**	**3,476.81**	**1,563.66**	**11.28%**	**3,409.75**	**1,499.70**	**10.98%**
One Thinning													
Before 1st Thinning (Year 16)	1,027.91	578.72	-	-	-	-	(354.79)						
1st Thinning (Year 16)	410.44	518.25	-	10.78	939.46	928.69	-						
Final Harvest (Year 28)	42.09	1,670.72	789.17	19.29	2,521.28	2,501.99	-						
Total					**3,460.74**	**3,430.67**	**(354.79)**	**3,105.95**	**1,339.14**	**10.34%**	**3,075.88**	**1,317.50**	**10.29%**

Overall, M3 procured the highest values in all categories with M1 a close second. M3 was third with regards to highest overall values, however, it was first in the one thinning category indicating that Stand 2 produced the highest profits in total. Stand 1 had the greatest variation between biomass thinning values versus one thinning values while Stand 3 had the least variation. Comparing IRR values for biomass thinning with biomass versus one thinning without biomass resulted in Stand 1 having the greatest variation at 1.61%, Stand 2 with a variation of 1.2%, and Stand 3 with a variation of 0.99%. Similar trends can be seen when comparing profits without NPV and profits with a 3% NPV for biomass thinning's with biomass versus one thinning's without biomass in all stands.

Discussion

ArborGen's high-density planting technique of using OP trees in-between rows of MCP improved trees provides landowners with an excellent solution for today's plantation establishment concerns. By inter-planting non-genetically enhanced trees to be harvested for biomass or pulpwood, landowners are able to save money while still promoting larger volumes in sawtimber harvests in the final year as was seen in both the field study and Ptaeda model. Stand 2 was able to produce 10 green tons more biomass per acre than Stand 1 in the field study and was only 2 green tons less in the biomass thinning Ptaeda model. When market prices increase for woody biomass in the southeastern part of the United States, FlexStands^{TM} will be a viable option for landowners to increase their revenue.

Until that time, adding a biomass thinning to a FlexStand^{TM} has already shown to increase final sawtimber volumes, as was seen when comparing the additional 32 green tons gained per acre from M3 versus M1 in the sawtimber product class. This is a significant amount of volume added on a per acre basis. When assuming landowner's minimum acreage is 20 acres and multiplying that by the additional 32 green tons, that's an additional 640 green tons of wood to be sold at sawtimber prices which can make a significant impact on a landowner's final revenue value. IRR was also seen to be 0.36% higher in comparison to a conventionally spaced tract of land, all of which can add up in the long run.

FlexStands^{TM} also positively promote the use of small-scale harvesting during the stands initial thinning's as was observed during the field study where less than 1% damage was incurred in Stand 2. This is believed to be due to the wider spacing configuration which allowed the smaller machines to maneuver in-between rows easier than in conventional spacing with standard sized machines. Although Stand 1 had less than 5% damage throughout the stand, all of the damage incurred was due to the narrow row widths. Having standard sized machines would have likely resulted in significantly higher damage percentages resulting in fewer trees reaching sawtimber status. Even though no field studies were conducted using rectangularity, it can be inferred from the field studies above that less damage would have incurred in-between rows since spacing widths are even wider.

The Ptaeda model study resulted in rectangularity being the least favored in comparison to all other stands, however, it should be noted that when a biomass thinning was included, M5 still produced the third largest tonnage for biomass and total volumes. M5 also came in fourth in sawtimber volumes behind M4 and was fourth largest in profit and IRR values indicating this method is still a plausible option for landowners to increase their overall volumes and revenues. This option is best suited for landowners who do not wish to use small-scale harvesting machines but instead would rather harvest with standard sized machines throughout the life-cycle of the plantation.

T-tests within the field study depicted no statistical difference between any of the variables except between the weight of Stand 1 and Stand 2 with Stand 1 weight being greater. An explanation for this difference is not currently available. All trees were planted at the same time of year in similar site and soil conditions. They came from the same nursery, were both OP designated trees, and received the same moisture amounts once planted. DBH was also slightly greater for Stand 1, however, this number was not found to be statistically significant. Interestingly, tree height averages were slightly higher for Stand 2, however, this number was also not found to be significant. Further research needs to be conducted to understand the differences in weight between the two stands.

Overall, both the field and modeling study verified that harvesting with one thinning only and using a conventional planting establishment regime will result in lower total harvested volumes. Incorporating a biomass thinning into a stands management plan will produce the highest volumes in regards to overall biomass, sawtimber, and total harvest volumes. This management style will also provide landowners an additional year of revenue to assist with establishment costs and further minimize the risk of waiting for final harvest. Once the biomass market becomes viable, landowners and loggers alike will reap the benefits of the increased revenue.

Conclusion

As times continue to constantly change, so do our techniques and technology we use for loblolly pine plantation establishment and thinning's. Incorporation of biomass thinning harvests, alternative plantation spacing dimensions, and small-scale harvesting machines during initial thinning's all have the potential to provide the landowner with increased total volumes and more specifically increased sawtimber volumes. This increase in volume not only benefits the landowner but also the logger harvesting the unit. The additional volume provides an alternative incentive for incorporating biomass harvests or high-density plantings into plantation establishment until market prices rise for woody biomass.

Chapter 4. Productivity & Costs of Tracked Processors in the United States Southeastern Logging

Abstract

While a majority of the mills in the south still prefer full-length trees, a select few have come full circle and are starting to provide loggers with incentives and subsidies if they haul processed, prime length wood to their mills. Researchers believe there is an opportunity for loading unprocessed full-length trees onto a truck to be hauled to a centralized timber depot where it will then be processed/merchandized by a tracked harvester. This system would allow loggers to maintain their conventional logging system but would remove the necessity of de-limbing, processing, or merchandizing the wood at the landing. In order to determine the costs and benefits of using a processor attachment on a tracked loader at a depot, a time study was conducted. Results showed that at the end of the machine's depreciated life, year 5, it will cost the logger $1.93 per ton to own and operate the processor. It will cost $1.75 at the end of year 10, which is considered to be the actual life of the machine. The study also compared the difference in productivity between an operator with less than one month's experience on the processor to an operator with over 11 years' experience to determine the potential loss of productivity when switching initially. The study depicted a gain in productivity in both operators, with the experienced operator producing 14 additional green tons per productive machine hour in comparison to the inexperienced operator.

Keywords:
forestry swing machine, timber yard, productivity, cost analysis, forestry excavator, sensitivity analysis, processing head

Introduction

Harvesting systems have changed throughout the years in conjunction with the length of the wood being harvested. Historically, trees were felled with axes, then bucked up with saws into manageable lengths for horses, mules, and oxen to drag out (Knight 2012). Only desirable logs were removed from the forest while the remainder of the tree was left in the woods. Machines soon replaced animals, allowing loggers to haul longer pieces of wood, although the timber was still cut to specific lengths. Machines continued to increase in horsepower, size, and capacity in the woods while mills were also improving their technological skills. These advances in technology enabled the mills to optimize the logs that were delivered by cutting marketable dimensions regardless of log length.

This technology also promoted the utilization of the small diameter wood, tops, and limbs we now refer to as biomass (Burdette 1995). Higher utilization percentages obtained from processing longer-length logs provided incentives for mills to pay higher stumpage rates for full-length trees over cut-to-length logs. This instigated whole-tree harvesting and today's conventional logging method in the southeastern United States where harvesting is typically based around three pieces of equipment; a feller-buncher, skidder, and knuckle-boom loader with a pull through de-limber (Wilkerson et al. 2008). These machines work together to fell, skid (in-woods transport), de-limb, sort, and load tree-length material onto trailers where they are transported directly to the mill to be manufactured into specific products.

While a majority of the mills in the south still prefer full-length trees, a select few have come full circle and are starting to provide loggers with incentives and subsidies if they haul processed, prime length wood to their mills. These mills are encouraging loggers to invest in dangle-head processors attached to a purpose-built forestry excavator, insisting that the increase in overall production for the logger will be significant enough to justify the purchase of this additional piece of equipment (Donnell 2017). If all aspects of the harvesting system were balanced, the operation would be able to transport more tonnage each day because the loader would no longer be processing wood while loading the trailer. Instead, the wood would be processed ahead of the truck arriving or a separate machine would be used to load trucks so processor production is not delayed.

In addition to the increased production, processors have the capability of producing prime length timber to the nearest inch based off mill specifications for that day. This allows mills to pay a higher premium for prime length logs rather than whole-tree wood. Although it would appear mills are backtracking in production efficiency, they actually decrease their cost and increase their timesaving’s by minimizing the amount of biomass they are paying top dollar for in tonnage simply to have hauled away or burnt once at the mill. Between the increase in final product price and the increase in the number of delivered trucks per day, it is believed that the costs incurred when purchasing this additional piece of machinery are outweighed by its benefits without assistance, incentives, or price premiums from the mills. Realistically, issues of machine utilization, tract size, truck availability, and the necessity of having an affordable transportation cost for future biomass markets have the ability to hinder this system in the southeastern United States.

Maintaining a completely balanced harvesting system is difficult in the South because of the small tract sizes, long-haul distances on single/two-lane roads, and variability in tree size and species. Instead, researchers believe there is an opportunity for loading unprocessed full-length trees onto a truck to be hauled to a centralized timber depot where it will then be processed/merchandized by a tracked processor. This system would allow loggers to maintain their conventional logging system but would remove the necessity of de-limbing, processing, or merchandizing the wood at the landing. Once at the depot, a tracked loader would unload the trees and a swing machine would process, sort, and merchandize the wood to be re-loaded and delivered to their respective mills.

This timber depot would allow drivers from multiple logging crews within the nearby area to deliver to one location, reducing their destination travel time and effectively increasing the number of loads hauled in day. In addition to benefiting the drivers, the delivery of trees from multiple loggers increases the utilization of the processor making it more efficient and would provide a cost-effective method of transporting biomass material from the landing.

Although harvesters and processors are being researched more significantly in many parts of the world, in the southeastern United States little is known about them (Evanson & McConchie 1996; Eggers et al. 2010; Spinelli & Magagnotti 2010; Ramantswana et al. 2013). The goal of this study was to analyze the productivity and cost of owning and operating a swing machine with a processor head attachment in the southeastern United States. This information was then to be used to make inferences concerning the applicability of utilizing a tracked processor both on-site or at a centralized timber depot. Additionally, a comparison was made to determine the difference in productivity between an inexperienced operator against an experienced operator.

Methods

A time study was conducted in order to determine the productivity, costs, and benefits of using a processor attachment on a tracked loader. A 2154G John Deere Swing Machine with a 622B Waratah processor head was chosen for the experiment due to its applicability and availability for this experiment. In order to demonstrate productivity for a logger's initial purchase as well as actual machine productivity, the production from two different operators was collected and analyzed. The first operator (ExOp) was provided by Waratah and had more than eleven years' experience operating harvesters and processors. This individual simulated the potential productivity of the machine when using an experienced operator. The second operator (InExOp) had less than one months' experience working with this type of machine, however, did have extensive experience operating a knuckle-boom loader. This individual simulated the productivity time of switching an operator from a knuckle-boom loader to a processor for potential loggers interested in operating a tracked processor on their sites.

Figure 5 Visual image of the tracked processor used during the study.

The experiment was conducted approximately four miles northwest of Rockford, Alabama off highway 22. The property was located in the central part of the state and was managed by Resource Management Service (RMS). The tract was contract harvested by Indus-Tree who provided the feller-buncher, skidder, and loader which supplied the harvester with wood for the study. The entire tract of land being harvested was approximately 645 acres in size and was comprised of approximately 30-year-old loblolly pine (*Pinus taeda)* plywood and pulpwood. Although hardwood stems were occasionally intermixed into the loads skidded to the landing, they were not included in the study. Both operators time studies were conducted using wood from the same geographic location for continuity purposes.

Data for the time study was recorded for both operators with three methods. The first method involved using visual observation of the machine and the logs that were processed. Diameter, length, product class, and general notes were kept regarding each tree that was processed. Starting and ending times were recorded as well as additional times of significance to be used as a reference later. The second method was to video record the harvester from three different locations to ensure the tree was being viewed at all times regardless of how the harvester was rotated. One video recorder was located outside the machine, one directly inside facing the front windshield to view out, and the final was situated so that it could observe information concerning each tree as it was processed from the in-cab monitor. The final method was to record the data on the machine itself using Waratah's TimberRite 30 Lite Software program (Waratah 2018).

The time study was conducted using the video recordings and a harvester/processor time study program created by John Deere in excel. An observation was defined as the time it took to process each tree, with cycle times beginning once the observer could see that the processor had picked up and found the the log. Due to the lack of visibility on some logs, a point was designated on the video where the processor’s boom intersected with the carrier as the start cycle time. This point was designated to ensure consistency throughout the time study. The start cycle ended when the processing head found the end of the log, which also initiated the next cycle names process log 1. Process log 1 cycle ended when the saw came out to process the first log, initiating process log 2. This cycle also ended when the saw came out to process log 2 which initiated process log 3. Process log three ended when the saw came out which initiated the last cycle known as the discard top and swing to deck cycle. The discard top and swing to deck cycle ended once the processor’s boom once again intersected with the designated point on the carrier iniating the start cycle time.

Table 6 Cycle times designation for the processor's time study.

Processor’s Cycles	Cycle Time Initiated	Cycle Time Ended
Start Cycle	When the processor’s boom intersected with the carrier	When the processing head found the end of the log
Process Log 1	When the processing head found the end of the log	When the saw came out to process the first log
Process Log 2	When the saw came out to process the first log	When the saw came out to process the second log
Process Log 3	When the saw came out to process the second log	When the saw came out to process the third log
Discard Top/Swing to Deck	When the saw came out to process the third log	When the processor’s boom intersected with the carrier

Fuel usage was collected using John Deere's JD Link System, which provided detailed information regarding the total amount of fuel used per day. The amount of fuel burned when at idle, working, average fuel rate, work time, and engine hours could be tracked on a daily, monthly, and even yearly basis (John Deere 2018).

Data Analysis

Data were input into an Excel spreadsheet. Diameter breast height (dbh) distribution of the data was calculated in total as well as for each operator. The total number of trees were calculated for each time trial by both diameter class as well as product class. Total tons and volume produced per hour were calculated using Clark and Saucier's tables to verify data collected by Waratah's TimberRite 30 Lite program and the data collected from video observations (Clark III & Saucier 1990).

Results were then input into Minitab 18 where descriptive statistics were calculated on all variables. Two-sample t-tests with confidence intervals were conducted comparing all variables against both operators to determine if there were significant differences between operators. One-tailed t-tests were then conducted on all statistically significant variables to determine the strength of the difference. Linear regression models were developed for the total productivity of both operators in conjunction, for each operator separately, and for each operator by product class. All models were calculated with delays. An economic analysis was conducted using Dr. Robert Tufts before-tax cash-flow spreadsheet (Tufts & Mills Jr 1982).

Results

Overall, 1079 observations were made with both operators after removing outliers and incomplete data, with 611 observations being made throughout 6-time trials with ExOp and 468 observations from InExOp during 5-time trials. Descriptive statistics for all variables can be viewed in tables 1 and 2. Dbh distribution ranged from 6 inches to 18 inches for both operators with over 70% of the trees classified between 8 to 12 inches dbh (see figure 5).

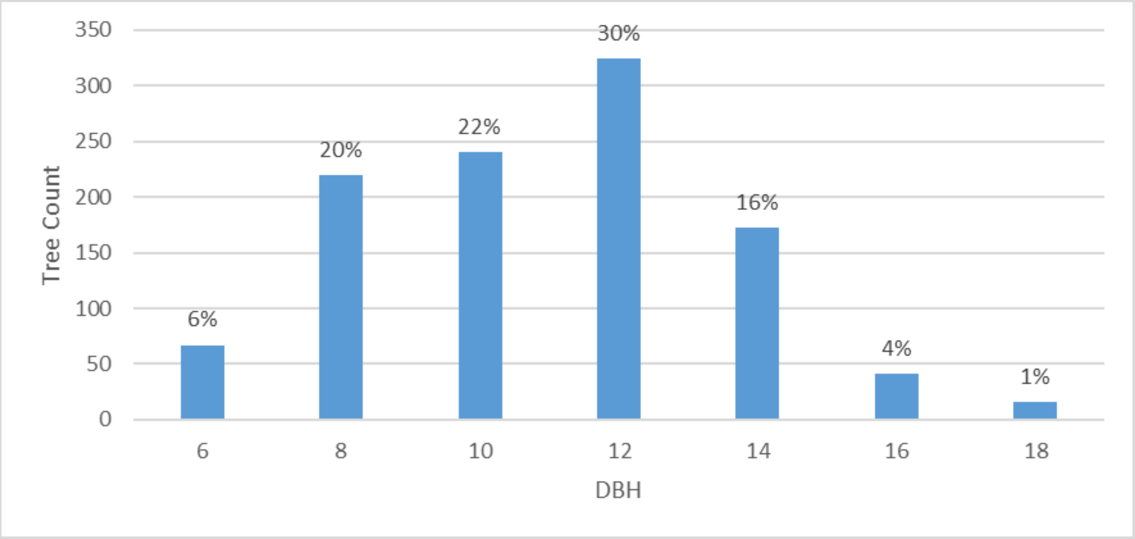

Figure 6. Total DBH distribution (inches) of each size class for both operators.

ExOp processed a range of six to fifty-two additional trees from each dbh class in comparison to InExOp, however, when basing the comparison against the proportion of trees processed by each operator the range was only a 0% to 5% difference (see figure 6).

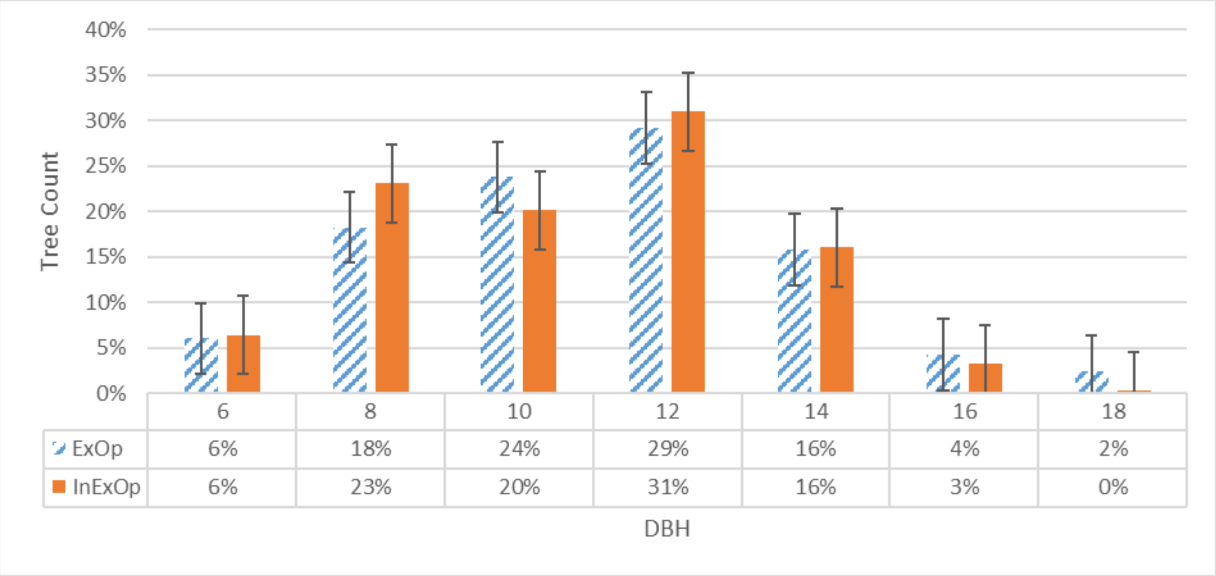

Figure 7. A comparison of DBH distribution (inches) of each size class between operators with standard errors included.

T-tests were conducted to compare differences in dbh, log length, volume, pounds, number of logs per tree, and tree density between the two operators. None of the variables were found to be statistically different, indicating that differences in productivity could not be associated with the differences in processed trees.

Actual Productivity

Measured productivity for InExOp's five-time trials resulted in an average of 74 tons of wood, or approximately 217 logs, processed per hour (see table 6). This operator demonstrated that he was capable of processing approximately two trees per minute with a majority of the trees possessing two logs within each tree.

Table 7. Actual productivity for InExOp by individual time trial and overall average.

Productivity	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Avg.
Total # Trees	118	93	86	74	89	**92**
Tons/Hr	69	83	74	78	66	**74**
Logs/Hr	210	241	231	227	174	**217**
Trees/Min (CR)	2	3	2	2	2	**2**

ExOp was able to process on average 88 tons of wood, or approximately 250 logs per hour, based on the results of six-time trials (see table 7). This operator demonstrated that they were capable of processing approximately three trees per minute with a majority of the trees possessing two logs within each tree. Overall, ExOp was able to produce 14 additional tons of wood an hour.

Table 8. Actual productivity for ExOp by individual time trial and overall average.

Productivity	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Avg.
Total # Trees	82	128	101	108	88	105	**102**
Tons/Hr	85	77	86	85	82	116	**88**
Logs/Hr	271	258	251	250	225	245	**250**
Trees/Min (CR)	3	3	3	3	2	3	**3**

Figures 7 and 8 provide visuals for both general productivity as well as a comparison of the operator's actual productivity. These graphs demonstrate that the larger diameter classes take longer to process as well as that InExOp's productivity is lower than ExOp.

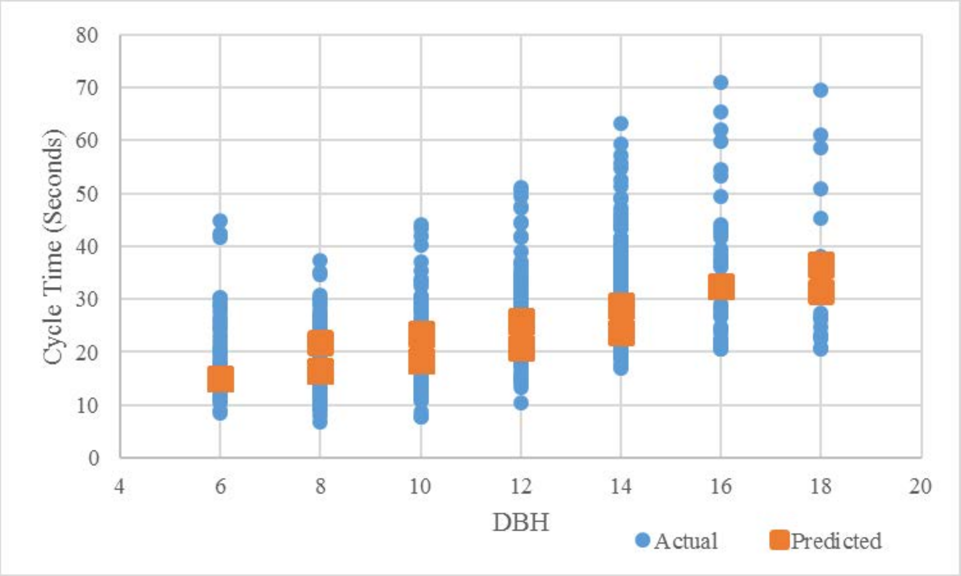

Figure 8. Actual productivity of processor when both operator's data are combined demonstrating the average amount of time, in seconds, it takes to process a tree within a specific dbh class (inches).

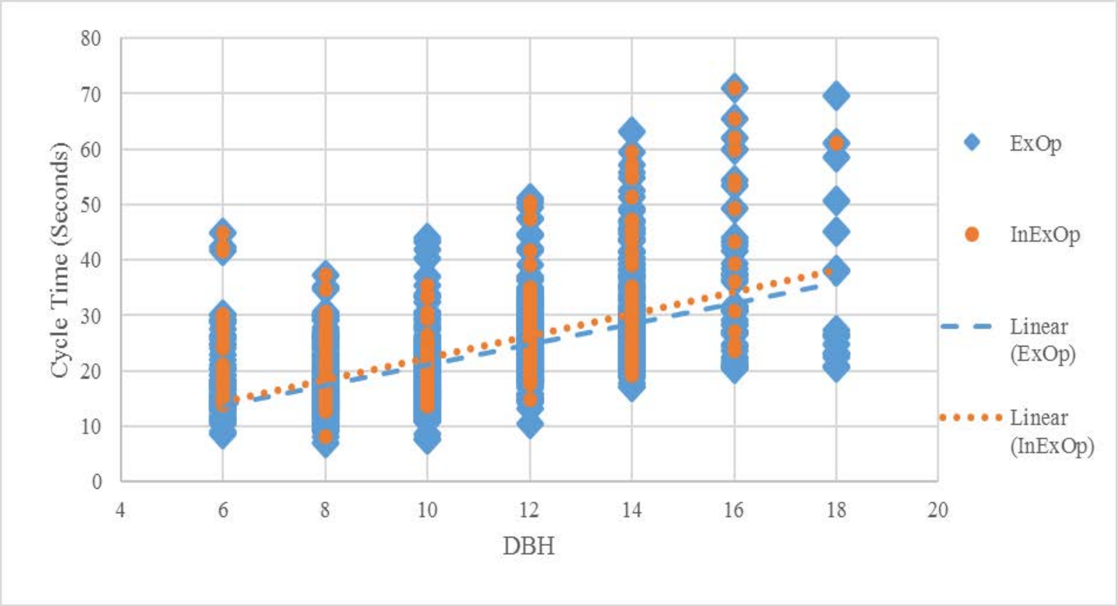

Figure 9. A comparison of both operator's observed production rate. InExOp had an R^2 of 28 % while ExOp had an R^2 of 30%

Two-sample, two-tailed t-tests were conducted on the productivity variables to determine if there was a statistical difference between operator productivity (see table 8). Where:

$$H_0 = ExOp - InExOp = 0$$

$$H_1 = ExOp - InExOp \neq 0$$

Fuel consumption (gal/hr), productivity (ft^3/hr), productivity (tons/hr), and productivity (logs/hr) were found to be statistically significant at the 95% level or higher and were repeated as a one-tailed t-test where:

$$H_0 = ExOp - InExOp = 0$$

$$H_1 = ExOp - InExOp > 0$$

All variables were found to be statistically significant at the 95% level indicating that ExOp's productivity was significantly greater than InExOp in all productivity measurements (see table 9).

Table 9.Two-tailed t-test results comparing productivity variables against operators.

Column1	ExOp Mean	ExOp SD	InExOp Mean	InExOp SD	p-value
Fuel Consumption, gal/hr	7.36	0.10	7.11	0.10	0.003
Productivity, ft3/hr	2850	444	2381	218	0.056
Productivity, tons/hr	88	14	74	7	0.056
Productivity, logs/hr	250	15	217	26	0.046
Cycle Rate, trees/min	3	0	2	0	0.144
Volume Processed, ft3	156	21	137	15	0.108
# of Logs Processed	1791	415	1509	175	0.183
Mass Processed, tons	56	13	47	5	0.183

Table 10. A one-tailed t-test comparing productivity variables against operators.

	ExOp Mean	ExOp SD	InExOp Mean	InExOp SD	p-value
Fuel Consumption, gal/hr	7	0	7	0	0.002
Productivity, ft3/hr	2850	444	2381	218	0.028
Productivity, tons/hr	88	14	74	7	0.028
Productivity, logs/hr	250	15	217	26	0.023

Predicted Productivity

In addition to determining the actual productivity of the processor, linear regression models were developed using cycle time in total seconds as the dependent variable and both tons/tree and logs/tree as the independent variables to estimate predicted productivity of the processor. Three models were developed in total (see table 10 for details).

Table 11. Linear regression values for all three processor models.

Model	SS	MS	F-Value	P-Value	R2	Adj R2
M1	33823	16911	232.96	<0.0001	30.22%	30.09%
M2	38698	12899	189.35	<0.0001	34.57%	33.42%
M3	40807	10202	154.05	<0.0001	36.46%	36.22%

The initial model (M1) combined all product classes and operator's performance together to provide a general productivity estimation for the processor.

$$M1 = \text{Cycle Time (in secs)} = 8.252 + 10.91 \times W\ (\text{tons/tree}) + 5.275 \times N\ (\text{logs/tree})$$

M1 had an R-squared of 30.22% and a p-value of <0.0001 at the 95% significance level. This model produced a constant of 8.252 seconds indicating that this was the minimum amount of time it took to process a tree regardless of the weight or number of logs harvested per tree.

The second model (M2) separated observed productivity for each operator. This model also had a p-value of <0.001 at the 95% significance level and had an R-squared of 34.57%.

$$M2 = \text{Cycle Time (in secs)} = ExOp = -10.6 + 16.20 \times W\ (\text{tons/tree}) + 12.40 \times N\ (\text{logs/tree})$$

$$\text{Cycle Time (in secs)} = InExOp = 0.33 + 16.20 \times W\ (\text{tons/tree}) + 12.40 \times N\ (\text{logs/tree})$$

The coefficient for ExOp was -10.60 seconds while InExOp had a coefficient of 0.33 seconds indicating that ExOp could process a tree 10.93 seconds faster than InExOp given the same tonnage and number of logs per tree. The final model (M3) estimated each operator's productivity based on which product class they were processing.

$$M3 = \text{Plywood Cycle Time (in secs)} = \text{ExOp} = -11.51 + 16.36 \times W \text{ (tons/tree)} + 12.22 \times N \text{ (logs/tree)}$$

$$\text{Pulpwood Cycle Time (in secs)} = \text{ExOp} = -0.87 + 16.36 \times W \text{ (tons/tree)} + 12.22 \times N \text{ (logs/tree)}$$

$$\text{Plywood Cycle Time (in secs)} = \text{InExOp} = -8.68 + 16.36 \times W \text{ (tons/tree)} + 12.22 \times N \text{ (logs/tree)}$$

$$\text{Pulpwood Cycle Time (in secs)} = \text{InExOp} = 1.96 + 16.36 \times W \text{ (tons/tree)} + 12.22 \times N \text{ (logs/tree)}$$

This model had an R-squared of 36.46% with a p-value of <0.001 at the 95% significance level. Coefficient results indicated that both operators could process plywood logs 10.64 seconds faster than they could a pulpwood log if the tree weighed the same number of pounds and had the same number of logs in it. These regressions also indicated that ExOp could process plywood and pulpwood 2.83 seconds faster than InExOp.

Economic Analysis

A before-tax cash flow cost analysis was estimated for the processor using a spreadsheet developed by Dr. Robert Tufts of Auburn University (Tufts & Mills Jr 1982). Initial investment price for the 2154 G tracked swing machine with a 622B Waratah head was approximately $575,000 (Sales Representative 2018). Trade in value was estimated to be 20% of the manufacturer's suggested retail price (MSRP) or $115,000 but with a book value of $0 at trade-in. For the purpose of the study, a $50,000 down payment was established with an annual percentage rate of 6% for 60 months (Great Western Bank PC 2018). Insurance and property taxes were combined to equal 6% with a discount rate of 5% for the analysis. Fringe benefits were set at 40% (see table 11).

Table 12. Discounted before-tax cash flow cost analysis for the processor and attachment head.

DISCOUNTED BEFORE-TAX CASH FLOW COST ANALYSIS 2154 G Tracked Swing Machine w/ 622B Waratah Head				
Purchase price	$575,000		Discount rate	5.00%
Trade-in	$115,000		Finance APR	6.00%
BV of trade-in	$0		Marginal tax rate	0.00%
Down payment	$50,000		Amount financed	$410,000
Number of payments	60		Monthly payment	$7,926
Expense Option	$0		Adjusted basis	$460,000
Hours per day	9.00		Expected life, years	10
Days per year	225		Residual value end of life	20.00%
Fuel & Lube (/hr)	$22.78		Inflate F&L	2.00%
Maint & Repair (/hr)	$11.36		Inflate M&R	2.00%
Labor rate (/hr)	$18.00		Inflate labor	2.00%
Fringe benefit %	40.00%		Utilization	70.00%
Insurance & taxes	6.00%		Production (tons/PMH)	81.00

AEC Cost per ton	($251,273) ($2.19)	($243,290) ($2.12)	($235,728) ($2.05)	($228,576) ($1.99)	(221,822) ($1.93)
	Year 1	Year 2	Year 3	Year 4	Year 5
Salvage value	$491,363.64	$416,090.91	$349,181.82	$290,636.36	$240,454.55
ACRS Dep	$83,636.36	$75,272.73	$66,909.09	$58,545.45	$50,181.82
Book value	$376,363.64	$301,090.91	$234,181.82	$175,636.36	$125,454.55
Fuel & Lub	$32,290.65	$32,936.46	$33,595.19	$34,267.10	$34,952.44
Repair & Maint.	$16,102.80	$16,424.86	$16,753.35	$17,088.42	$17,430.19
Addl. Maintenance					
Labor	$53,865.00	$54,942.30	$56,041.15	$57,161.97	$58,305.21
Insurance	$34,500.00	$29,481.82	$24,965.45	$20,950.91	$17,438.18
Total Expenses	$136,758.45	$133,785.44	$131,355.15	$129,468.39	$128,126.02

AEC Cost per ton	($214,385.25) ($1.87)	($209,791.99) ($1.83)	($206,305.27) ($1.80)	($203,573.32) ($1.77)	($201,388.54) ($1.75)
	Year 6	Year 7	Year 8	Year 9	Year 10
Salvage value	$198,636.36	$165,181.82	$140,090.91	$123,363.64	$115,000.00
ACRS Dep	$41,818.18	$33,454.55	$25,090.91	$16,727.27	$8,363.64
Book value	$83,636.36	$50,181.82	$25,090.91	$8,363.64	$0.00
Fuel & Lub	$35,651.49	$36,364.52	$37,091.81	$37,833.64	$38,590.32
Repair & Maint.	$17,778.79	$18,134.37	$18,497.06	$18,867.00	$19,244.34
Addl. Maintenance					
Labor	$59,471.31	$60,660.74	$61,873.95	$63,111.43	$64,373.66
Insurance	$14,427.27	$11,918.18	$9,910.91	$8,405.45	$7,401.82
Total Expenses	$127,328.86	$127,077.81	$127,373.73	$128,217.53	$129,610.13

Maintenance and repair costs were estimated using Edwin S. Miyata's publication for *"Determining Fixed and Operating Costs of Logging Equipment"* (Miyata 1980; Miyata & Steinhilb 1981). Fuel price for number two off-road diesel was $2.785 during the time of the study (U.S. EIA 2018). Fuel usage rates were collected from the JD Link system within the processor for each productive machine hour (John Deere 2018). An average of 7.25 gallons per hour was established and used for the study. Lubrication prices were established as per the time of the study and Miyata was used to determine the final fuel and lube rate of $22.78 per hour. Productivity was determined by combining the observed productivity of both operators for an average of 81 tons. The expected life of the machine was set at 10 years, 20,000 scheduled machine hours, with inflated fuel and lubrication, maintenance and repair, and labor rates all set at 2% per year. Utilization rate was established at 70% for the analysis.

The processor's annual equivalent cost (AEC), the cost of owning and operating the processor throughout the duration of its life when considering the time value of money, was found to be $221,822 or $1.93 per green ton (gt) at the end of year 5 and $201,389 or $1.74/gt at year 10 (Tufts & Mills Jr 1982; Jernigan et al. 2016). Both of these numbers were included for comparison purposes since the end of year 5 is when most machines are considered to be fully depreciated for tax purposes. An after-tax cash flow cost analysis was conducted using a marginal tax rate of 28% but leaving all other parameters the same which resulted in an AEC of $167,889 or $1.46/gt at the end of year 5 and an AEC of $149,641 or $1.30/gt at the end of year 10 (see table 12). This analysis was performed to demonstrate the potential costs of the processor under the government tax rate system.

Table 13. Discounted after-tax cash flow cost analysis for the processor and attachment head.

DISCOUNTED AFTER-TAX CASH FLOW COST ANALYSIS 2154 G Tracked Swing Machine w/ 622B Waratah Head				
Purchase price	$575,000		Discount rate	5.00%
Trade-in	$115,000		Finance APR	6.00%
BV of trade-in	$0		Marginal tax rate	28.00%
Down payment	$50,000		Amount financed	$410,000
Number of payments	60		Monthly payment	$7,926
Expense Option	$0		Adjusted basis	$460,000
Hours per day	9.00		Expected life, years	10
Days per year	225		Residual value end of life	20.00%
Fuel & Lube (/hr)	$22.78		Inflate F&L	2.00%
Maint & Repair (/hr)	$11.36		Inflate M&R	2.00%
Labor rate (/hr)	$18.00		Inflate labor	2.00%
Fringe benefit %	40.00%		Utilization	70.00%
Insurance & taxes	6.00%		Production (tons/PMH)	81.00

AEC	($215,426.49)	($193,109.98)	($182,154.47)	($174,300.74)	($167,889.28)
Cost per ton	($1.88)	($1.68)	($1.59)	($1.52)	($1.46)
	Year 1	Year 2	Year 3	Year 4	Year 5
Salvage value	$491,363.64	$416,090.91	$349,181.82	$290,636.36	$240,454.55
ACRS Dep	$83,636.36	$75,272.73	$66,909.09	$58,545.45	$50,181.82
Book value	$376,363.64	$301,090.91	$234,181.82	$175,636.36	$125,454.55
Fuel & Lub	$32,290.65	$32,936.46	$33,595.19	$34,267.10	$34,952.44
Repair & Maint.	$16,102.80	$16,424.86	$16,753.35	$17,088.42	$17,430.19
Addl. Maintenance					
Labor	$53,865.00	$54,942.30	$56,041.15	$57,161.97	$58,305.21
Insurance	$34,500.00	$29,481.82	$24,965.45	$20,950.91	$17,438.18
Total Expenses	$136,758.45	$133,785.44	$131,355.15	$129,468.39	$128,126.02

AEC	($161,418.67)	($157,244.26)	($154,085.17)	($151,615.26)	($149,641.32)
Cost per ton	($1.41)	($1.37)	($1.34)	($1.32)	($1.30)
	Year 6	Year 7	Year 8	Year 9	Year 10
Salvage value	$198,636.36	$165,181.82	$140,090.91	$123,363.64	$115,000.00
ACRS Dep	$41,818.18	$33,454.55	$25,090.91	$16,727.27	$8,363.64
Book value	$83,636.36	$50,181.82	$25,090.91	$8,363.64	$0.00
Fuel & Lub	$35,651.49	$36,364.52	$37,091.81	$37,833.64	$38,590.32
Repair & Maint.	$17,778.79	$18,134.37	$18,497.06	$18,867.00	$19,244.34
Addl. Maintenance					
Labor	$59,471.31	$60,660.74	$61,873.95	$63,111.43	$64,373.66
Insurance	$14,427.27	$11,918.18	$9,910.91	$8,405.45	$7,401.82
Total Expenses	$127,328.86	$127,077.81	$127,373.73	$128,217.53	$129,610.13

A sensitivity analysis was conducted to better understand how a change in utilization, productivity, the price of fuel per gallon, and the cost of maintenance and repair per productive machine hour affected the AEC at years 5 and 10. Overall results depicted a minimal increase in the cost/ton when both fuel prices and maintenance and repair prices increased while the cost/ton decreased when production and utilization increased. Cost per green ton increased from $1.67/gt to $1.88/gt when fuel prices increased from $2.00/gal to $4.00/gal at year 10 (see figure 9).

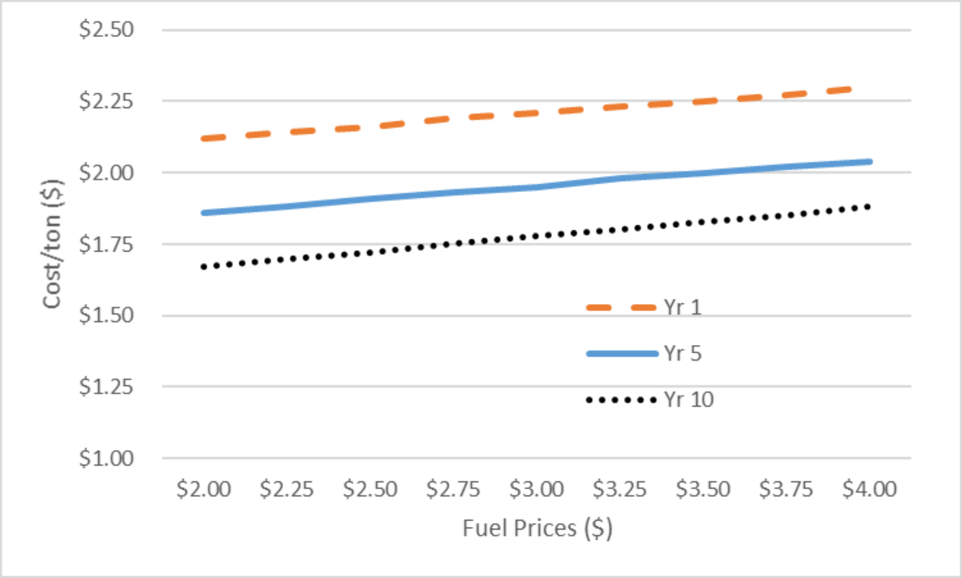

Figure 10. Sensitivity analysis depicting how a change in fuel price affects processor cost per ton in years 1, 5, and 10.

Cost per green ton increased from $1.68/gt to $1.85/gt when maintenance and repair costs increased from $6.00/PMH to $18.00/PMH at year 10 (see figure 10).

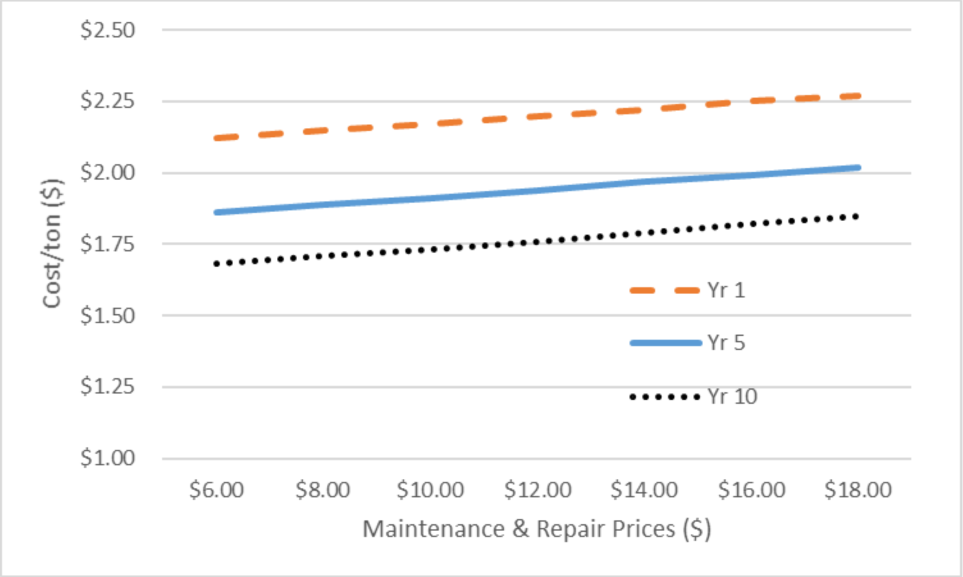

Figure 11. Sensitivity analysis depicting how a change in the price for maintenance and repairs affects processor cost per ton in years 1, 5, and 10.

Increasing productivity from 65 gt to 125 gt decreased cost/ton from $2.19/gt to $1.14/gt at year 10 while cost/ton decreased from $3.44/gt down to $1.53/gt when increasing utilization from 30% to 85% (see figures 11 & 12).

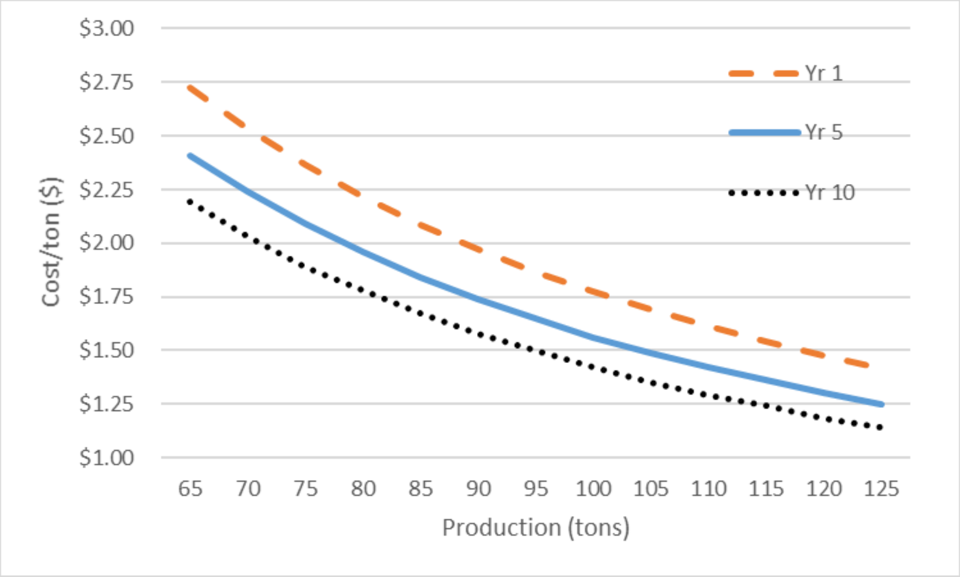

Figure 12. Sensitivity analysis depicting how a change in productivity (tons/hr) effects processor cost per ton in years 1, 5, and 10.

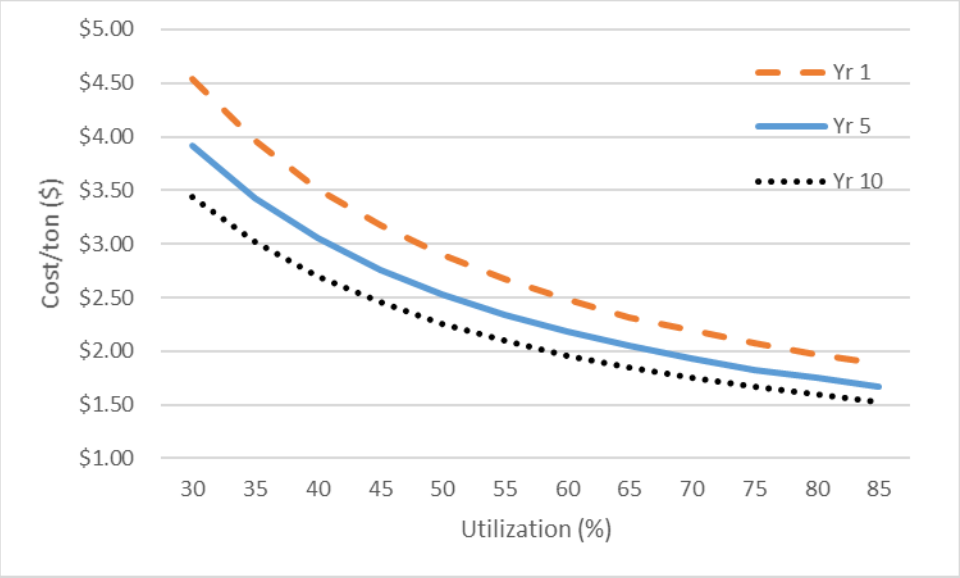

Figure 13. Sensitivity analysis depicting how a change in processor utilization affects processor cost per ton in years 1, 5, and 10.

Discussion

This study was conducted in the Piedmont of Alabama where loblolly pine trees are known to be smaller in both diameter as well as length, therefore less merchandizing was necessary after the prime lengths were cut. If additional processing had been required, results from both the actual productivity study as well as the regression analysis indicated that the amount of time taken to process each stem would have been significantly longer for InExOp than ExOp. Likely, greater extremes between operators would have been observed.

Regardless of wood type, InExOp was able to produce approximately 74 green tons/hour or almost 17 truckloads a day if one truckload weighs 28 tons and each operator has 70% utilization for a 9-hour day. ExOp, on the other hand, is capable of producing 88 tons/hour or just under 20 truckloads a day given the same conditions. When incorporating utilization rates, the differences between loads increases, but all studies have shown a statistically significant difference between the two operators indicating ExOp was able to produce more wood overall.

If all of the other harvesting machines were able to maintain or increase production, and final product transportation was not a bottleneck, incorporating a processor into a logger's system may potentially increase productivity for the logger. As mill's become more stringent on the allowable log lengths for their prime cuts, the necessity of incorporating a processor into the system will become imminent.

Unfortunately, this study did not track mill specifications per stem so it is unknown how many cuts were made that were outside of the mill's allowable target. Future research is recommended on this topic to better understand the number of mismeasurements that were made from the wheel, the lack of daily calibration, or inaccurate analysis because the diameter outside the bark was miss-measured when the processor was required to run the head up and down the stem multiple times for delimbing purposes.

A previous study at Auburn University determined the feasibility of incorporating a centralized timber depot for processing whole trees would be difficult logistically due to the current state and federal road regulations for log truck trailer weights (Lancaster 2017). Limitations to processing at a depot or a landing included the machine's utilization rate, the availability of trucks to transport the processed stems and/or the whole trees to the depot, and the availability of the biomass market if the timber depot were to become a reality.

A comparison between before-tax and after-tax AEC and cost/ton resulted in an almost $50,000 or $0.50/ton difference in both year 5 and 10. This decrease in cost is explained by the decrease in overall tax liability held by the operator due to their increase in expenses. Overall, however, the dollar plus increase per ton added to the logger for incorporating the processor may be compensated by additional tonnage if they are able to produce in a days' time regardless of whether they are processing on the landing or in a depot, as well as any incentive the mill is providing.

The sensitivity analysis demonstrated that regardless of the AEC year, extreme fluctuations in both fuel prices or maintenance and repair prices only had approximately a $0.20 increase in the final cost/ton. An increase in production rates per ton, however, decreased the cost/ton over a $1.00/ton. Increasing utilization rates from 30% to 85% decreased the cost per ton of the processor by almost $2.00/ton. These results indicated that operators should be less concerned with changes in fuel and maintenance costs and be more concerned with their production and utilization rates. Because productivity and utilization are generally assumed to be related, there is a real opportunity for an operator to more than double their daily productivity if they were able to increase their utilization rates by simply loading whole trees onto a trailer to be processed at a centralized timber depot rather than processing on the landing. This opportunity, however, does assume the logger's bottleneck is in processing and loading trucks rather than cutting, skidding, or trucking.

Conclusion

In conclusion, regardless of the operator’s level of experience, incorporating a processor into the conventional harvesting system in the southeastern United States could potentially increase a logger’s overall productivity, both at a centralized timber depot or at the landing itself. AEC at year 10 was $201,389 or $1.75 per ton before tax and $149,641 or $1.30 per ton after tax. Although minimally, these costs could increase the cost per ton for a conventional harvest system in the southeast. While the increase in productivity would likely compensate for the additional cost per ton, at best the system would be equally as expensive or still more expensive. Incorporation of the tracked processor into a centralized logging depot could increase the machines utilization rate making it as as low as $1.53 per ton to operate and own because the machine should have a continuous supply of wood to process. The depot could be ideal for loggers if trucking was not a bottleneck and could allow them to increase their overall productivity and efficiency in the woods as well.

Chapter 5. Differences in total stem value when merchandizing with a tracked processor versus a knuckle–boom loader in *Pinus taeda*

Abstract

Using tracked processors over knuckle–boom loaders to increase total value per tree when merchandizing timber on the landing has become a topic of interest in the southeastern region of the United States. This study compared merchantability values, product classes, and product weights of loblolly pine (*Pinus taeda*) for both machines to determine if there was a significant difference between machines when processing the same tree. In order to process the same tree twice, the chains from the tracked processor had to be removed from the bottom saw bar. This allowed the processor to simulate the merchandizing process without actually marking or cutting the tree for a more realistic comparison. Data were analyzed using paired t–tests and two–way ANOVA models. Results depicted that when the knuckle–boom loader visually estimates diameter and total lengths, a significant difference in value occurs. Once diameter and total length are modified to match the tracked processors for more accurate measurements, however, no difference in value was seen. These results demonstrate that until mill specifications become more stringent, there is little incentive for loggers to purchase a tracked processor if their only motivation is to increase merchantability values.

Keywords:

Forest excavator, tracked processor, knuckle-boom loader, merchandizing

Introduction

Promotion towards using tracked processors to merchandize timber on the landing in place/in conjunction with knuckle-boom loaders has become a topic of interest in the southeastern region of the United States. Although this region is known for transporting full-length trees, also known as whole tree (WT), loggers are still required by mills to de-limb and cut the tops off each tree to a specific diameter depending on the product they are transporting. This process is currently conducted using a knuckle-boom loader with a pull-through de-limber or a chain-flail de-limber for both pulpwood and chip-n-saw (CNS) logs. Loggers who are able to harvest plywood logs typically use a knuckle-boom loader with a slasher saw attachment or a full-length log that is placed next to the loader. This log has been marked to identify specific market lengths so the loader operator can simply lay the unprocessed log next to the marked log to use as a cutting reference. In all the aforementioned cases, visual estimation is used to identify product classes, product lengths, diameter at breast height (dbh), and top dbh.

In addition to mills current demands for specific top dbh, a select number of mills are starting to require lengths on tree length material be within three inches. This request is forcing loggers to find alternative methods to process and merchandize their wood. One option is to use a tracked/wheeled processor, which can merchandize either whole tree or dimension length wood. In order to encourage the adoption and purchase of these processors, a few mills are providing incentives for loggers in their region with the mindset that by investing in the logger they are actually investing in their mill. If loggers purchased a processor to merchandize their wood, this should result in fewer loads per unit that is penalized due to inaccurate measurements. Additionally, they would potentially increase productivity at the landing as well as producing less waste at the mill due to variable log lengths.

A processor is also said to be able to increase a logger's merchantable stem value because of technological advancements in computer software such as when using Waratah's TimberRite H-16, TimberRite 30H, & TimberRite 30Lite systems (Evanson & McConchie 1996; Waratah 2018). A logger can input market products into the machines computer system and prioritize them so that an operator simply pushes a button to determine product availability. The TimberRite H-16 system can learn typical stem profiles to make the most merchantable bucking choices, choosing the product with the highest value for the entire tree rather than one product. At this neither time the TimberRite 30H or 30Lite are capable of learning stem profiles, however, they are still capable of prioritizing products based on market value and market need (Waratah 2018). These value-added opportunities are in contrast to smaller dbh pulp or bioenergy feedstock where good economies of scale are necessary (Jernigan et al. 2016).

Merchandizing comparison studies are difficult because no two trees are exactly alike and a stem can only be truly merchandized once. For this reason, very few studies have been conducted to compare merchandizing abilities. Those that have occurred did not use the same tree more than once and were focused on productivity rather than merchandizing (Evanson & McConchie 1996; Becker et al. 2006; Adebayo et al. 2007, p. 200; Eggers et al. 2010; Spinelli & Magagnotti 2010; Ramantswana et al. 2013; Thompson et al. 2015). The objective of this study was to determine if there was a difference between the tracked processor and knuckle-boom loader when merchandizing the same loblolly pine stems with regards to products and value.

Methods

The study was conducted on a 645–acre tract managed by Resource Management Services (RMS) five miles west of Rockford, Alabama. The tract had been planted approximately 30 years ago and was primarily comprised of loblolly pine (*Pinus taeda*). Although hardwood stems were being harvested and merchandized on this tract, they were not included in the study.

A 2154G John Deere Swing Machine with a 622B Waratah processing attachment head was used to represent the tracked processor and was compared against a 234B Tigercat knuckle–boom loader with a pull-through de-limber and slasher saw for the study. Both machines were set up on the same landing, close enough to pass stems between each other while still maintaining a safe working distance from one another. Samples were collected on two separate landings with 50 trees being merchandized on each landing. One hundred trees were sampled in total. The chains were removed from the tracked processors top and bottom bars so the attachment could realistically simulate harvesting the tree without causing any damage to the tree before transfer to the knuckle-boom loader operator. TimberRite 30Lite, one of Waratah's software systems which displays stem information, was monitored for dbh, total length, product class, product length, and number of products per tree (Waratah 2018). Similar measurements were recorded visually on the knuckle-boom loader as the operator called them out.

During the study, the skidder would drag a pull of trees and deposit them in front of the tracked processor. The tracked processor operator would grab a tree and go through the motions of processing the stem without the chains using the preassigned product class buttons to determine the ideal products for the tree. He would begin by attempting to cut a plywood log out of the butt. If the trees dbh and top merchantable height were found acceptable by TimberRite 30Lite then the "cut" would be made, otherwise, the attachment would automatically slide down to the next acceptable product. This process was followed for the entire length of the tree or until reaching a two-inch top, the minimum top dbh for pulpwood stem. Overall, the tracked processor operator's intentions were to maximize the total value received out of each tree.

The tree, now removed of all its branches after being run through the processor, was transferred on the ground next to the knuckle-boom loader. This operator processed the stem to later be loaded and transported to the mill. To make the study as realistic as possible, the loader operator called out his estimated dbh, product classes, and product lengths for each stem. Total length was estimated by adding up all product lengths and then using Clark & Saucier to determine the missing top height. The knuckle-boom operator merchandized stems based on current market needs for the day and what products would bring him the highest value rather than maximize the total value of the stem.

Out of the 100 trees sampled, two were removed from the dataset because they did not match the studies predetermined criteria of being loblolly pine. Data were recorded in Microsoft Excel initially. Clark & Saucier equations were used to find the number of pounds for each total tree. These equations also determined pounds per ply log, per CNS log, and per pulpwood log for both the tracked processor and knuckle-boom loader (Clark III & Saucier 1990). These weights were then converted into tons per product class and multiplied with a stumpage rate to determine the price per ton per product class as well as the total value of each tree for both machine types. Prices were found using Timber Mart South's 2017 third quarter's rates to demonstrate the total value of each tree when the study was conducted (Timber Mart South 2018).

Data were then input into MiniTab 18.0 where paired t-tests were conducted on dbh, total length, and total value per stem. Ideally, paired t-tests would have been conducted on all variables for comparison, however, since merchandizing each stem did not always result in the same products being included by both machines this was not feasible. Two-way ANOVA's were used to compare machine type (factor) against product classes, product class weight, product class values, and total value for a total of 13 variables (responses) being analyzed in the study with dbh and total length being used as covariates. Stepwise regression with significance of 0.05 was used to filter out the insignificant variables in the model.

Results

Initial results from the paired t-tests depicted all three variables; dbh, total length, and total value to be statistically significant at the 95% level with the knuckle-boom loader having greater dbh, total lengths, and total values. As mentioned previously, all dbh and lengths were visually estimated by the knuckle-boom loader operator, which indicated potential error and bias to the data analysis when continuing forward and testing differences in total values and tonnage. To alleviate this bias, the knuckle-boom loaders estimated dbh and total lengths were modified to match the processor's precise measurements. Because the knuckle-boom loader operator estimated dbh in two-inch dbh classes, each tree's dbh recorded by the processor was modified to match the two-inch classification method. Differences in total length were added or subtracted from the pulpwood estimation on the knuckle-boom loader values so total height matched the processors. After these modifications were made the paired t-test resulted in no difference in total value between machine types.

Of the two-way ANOVA models that were run on the original 13 variables, six of these variables were found to have a statistical difference between the factor, machine type, and the response it was tested against at the 0.05 significance level. Total value was not found to be statistically significant through the ANOVA. The significant responses included: plywood logs, pulpwood logs, CNS tons, pulpwood tons, CNS value, and pulpwood value. Plywood 2 was the variable used when more than one plywood log was merchandized from a single stem. It should be noted however that CNS tons and pulpwood tons had the exact same p-values, F-value, and R^2 as CNS value and pulpwood value. Only coefficients were different.

Both covariates assisted in explaining the Plywood logs ANOVA model in addition to machine type (p-value 0.006). These variables, dbh (p-value <0.0001) and total length (p-value 0.036), were associated with the changes in the number of feet of plywood logs that were produced. This model had an adjusted R^2 of 36.70%. Regression equations for the machines were as seen above in Table 13 indicating that the tracked processor produced approximately 4-foot longer lengths of plywood logs.

Table 14. List of all variables tested in the two-way ANOVA models comparing the knuckle-boom loader against the tracked processor with equations for significant variables.

Variable	Signficiant Difference at p-value <0.05	Equations if Significant	R2	F-Value	P-Value	n
Plywood Logs (ft)	Yes	(TP) Ply Logs (ft) = -4.93+2.201*DBH+0.1750*TL	0.381	2.867.82	0.0063	133
		(KBL) Ply Logs (ft) = -8.31+2.201*DBH+0.1750*TL				
Plywood 2 Logs (ft)	No					
CNS Logs (ft)	No					
Pulpwood Logs (ft)	Yes	(TP) Pulp Logs (ft) =22.86+0.5633*TL	0.581	16.73	< 0.00001	37
		(KBL) Pulp Logs (ft) = 17.97+0.5633*TL				
Pulpwood Tops (ft)	Yes	(TP) Pulp tops (ft) = -14.48+.0566*TL	0.221	22.75	< 0.00001	174
		(KBL) Pulp tops (ft) = -7.00+0.566*TL				
Pulpwood Combined (ft)	Yes	(TP) Pulp Comb (ft) =36.49-3.084*DBH+0.367*TL	0.321	35.44	< 0.00001	196
		(KBL) Pulp Comb (ft) = 47.12-3.084*DBH+0.367*TL				
Plywood Weight (tons)	No					
Plywood 2 Weight (tons)	No					
CNS Weight (tons)	Yes	(TP) CNS (tons) = 0.0061+0.002289*TL	0.256	60.93	< 0.00001	196
		(KBL) CNS (tons) = -0.1071+0.002289*TL				
Pulpwood Weight (tons)	Yes	Pulp Comb (tons) = 0.1867 - 0.0489*TP+0.0489&KBL	0.109	23.68	< 0.00001	196
Value of Plywood ($)	No					
Value of Plywood 2 ($)	No					
Value of CNS ($)	Yes	(TP) $ CNS = 0.092+0.0348*TL	0.256	60.93	< 0.00001	196
		(KBL) $ CNS = -1.626+0.0348*TL				
Value of Pulpwood ($)	Yes	$ Pulp Comb = 1.5607 - 0.4088*TP+0.4088&KBL	0.109	23.67	< 0.00001	196
Total Value of Stem ($)	No					

Pulpwood logs ANOVA had a p-value of 0.039 for machine type. The two covariates, dbh (p-value <0.0001) and total length (p-value 0.006), were associated with changes in the number of feet of pulpwood that was produced. This model had an adjusted R^2 of 31.05%. Regression equations for the machines were as seen above in Table 13 indicates that the knuckle-boom loader produced approximately 5-foot longer lengths of pulpwood.

CNS tonnage ANOVA had a machine type p-value of 0.001 to assist in explaining the model in addition to the covariate total length (p-value 0.019). This model had an adjusted R^2 of 24.85%. Regression equations for the machines were as seen above indicating that the tracked processor produced 0.05656 tons more of CNS than the knuckle-boom loader. The pulpwood ANOVA had a p-value of <0.0001 for machine type which was its only significant variable. The model had an adjusted R^2 of 10.41% and the regression equation depicted that the knuckle-boom loader produced 0.0489 more tons of pulpwood over the tracked processor. Both the CNS value and pulpwood value ANOVA's resulted in the exact same p-values and adjusted R^2 as CNS and pulpwood tons. Regression equations, however, differed. The knuckle-boom loader was able to produce \$0.41 more per tree in pulpwood value; however, the tracked processor was able to produce \$0.86 more per tree than the knuckle–boom loader for CNS value.

Discussion

Total value per tree was found to be statistically significant when using the visually estimated dbh and total lengths recorded by the knuckle-boom loader operator. These results indicated that knuckle-boom operators could actually be losing money if they are underestimating the dbh and lengths of stems rather than overestimating or being precise with their measurements. Although visual estimation is currently the common practice for merchandizing trees in the southeastern region of the United States, some mills are beginning to demand more specific product specifications from the loggers, which could make visual estimation a technique of the past. Utilization of a processing attachment head on either a tracked or wheeled machine would guarantee product specifications if calibrated correctly, allowing loggers to inadvertently decrease the number of trucks that were turned away from the scale house due to imprecise visual estimates when merchandizing trees.

Total value per tree was not found to be statistically significant once dbh and total length were adjusted to match the tracked processors measurements indicating that using the processing head did not actually increase the logger's total merchantability value on a per stem basis as previously believed. The differences seen in the CNS and pulpwood values, however, to represent the difference between the knuckle-boom operator who merchandized stems based on current market needs for the day and what products would bring the highest value in that area rather than maximize the total value of the stem.

During the study, the knuckle-boom operator discussed how the CNS mills were on quota but plywood mills were not restricted so he tried to optimize each stem to get the highest value of plywood logs out rather than CNS. This resulted in having four stems, which had plywood 2 logs whereas the tracked processor had none. If the knuckle-boom operator wasn't able to make a plywood log out of the stem he inferred that he gained more value out of putting the log into pulpwood rather than CNS when considering trucking distances to mills. Overall, the knuckle-boom operator had less overall CNS logs which were found to be statistically significant with regards to weight but not feet.

Plywood logs and pulpwood logs were found to be statistically significant with regards to the number of feet merchandized by each machine. In both cases, although the knuckle-boom loader harvested more total products than the tracked processor, the processor was able to get additional feet out of each product, which aided to its significance. The additional feet once again tie back having the precise measurements from the processor versus having to visually estimate where the top dbh is on each product. Since plywood is purchased in prime lengths, the additional four feet was only significant in this variable rather than carrying through to tonnage and value. There was potential, however, for not only plywood value, but also total value per stem to be found statistically significant if plywood length distance were to have had a couple more feet added to the tracked processors final ANOVA coefficient.

Ideally, this study would be repeated using the TimberRite H-16 software system to determine if the ability to learn whole stems profiles increases total value for a tracked processor. The TimberRite 30H or H-16 software system was not originally installed in the 2154G John Deere Swing machine. Although both systems can be installed to override the 30Lite system it was not done for this study.

In general, it is not completely surprising that total value was not statistically different between the two machines. Prices per ton per product class are the same regardless of whether merchandizing is conducted by maximizing the total value of the stem or current market needs for the day. Due to the site characteristics, a majority of the trees were merchandized with a single plywood log with the additional tree length classified as pulpwood. This left minimal opportunity for the tracked processor to demonstrate its technological capability. The site was however typical of the region indicating that tree height and quality should be taken into consideration for any person interested in purchasing a processor.

Conclusion

Unless mills in the southeastern United States become more stringent with their product specifications, there is little motivation for loggers to invest in a processing head to increase value when merchandizing. Future studies may reveal that the tracked processor increases productivity on the landing giving the logger the opportunity to haul more loads in a day which increases his profit, however, at this time no additional value is gained by the logger when merchandizing his trees with the tracked processor over a knuckle-boom loader.

Chapter 6. Conclusions

All standard practices were deemed unconventional at some point in time before being considered progressive. Woody biomass is no exception. As we follow woody biomass through history we see this proven time and time again as the product would gain and lose public interest with the rise and fall of available standard resources. Each time woody biomass has peaked in interest; innovative technologies were sparked into fruition. Some of these technologies have even been used to create other more efficient and sustainable renewable resources. The invention of compressing sawdust into pellets to heat facilities more efficiently or powering remote locations using biomass generated hydrogen fuel cells are two such examples.

This idea is further supported when analyzing how legislation and policy changes could continue to assist with the promotion of woody biomass. Although funding and interest in woody biomass have increased over the last fifteen years through legislative acts, there is no guarantee that these programs will continue to be funded in the future. Additionally, having a strong dependence on a single form of energy positions the United States to be extremely vulnerable, much like we currently are with petroleum and other fossil fuels. Since the ultimate goal of this nation is to have multiple energy resources active and available at all times, it is likely that legislation and funding for woody biomass will continue to provide funding until they deem woody biomass has met its required maximum capacity. Until that time comes, however, programs or subsidies that assist with harvesting and transportation costs would continue to greatly increase woody biomass feasibility, especially in the southeastern region of the United States.

Incorporating a biomass thinning into a stands management plan was shown to produce the highest volumes in regards to overall biomass, sawtimber, and total harvest volumes in this study. This management style could also provide landowners with an additional opportunity for revenue to assist with establishment costs and further minimize the risk of waiting for final harvest. When market prices increase for woody biomass in the southeastern part of the United States, FlexStands^{TM} could be a viable option for landowners to increase their revenue. ArborGen's high-density planting technique of using OP trees in-between rows of MCP improved trees was shown to provide a solution for plantation establishment concerns. Inter-planting non-genetically enhanced trees to be harvested for biomass or pulpwood decreased landowner's seedling costs while still promoting an opportunity for increased volumes by up to 32 green tons in sawtimber harvests during the final year, on a per acre basis. IRR was also seen to be higher in comparison to a conventionally spaced tract of land.

FlexStands^{TM} also positively promoted the use of small-scale harvesting during the stands initial thinning's in this study. This was believed to be due to the wider spacing configuration which allowed the smaller machines to maneuver in-between rows easier than in conventional spacing with standard sized machines. Rectangularity was observed as being best suited for landowners who do not wish to use small-scale harvesting machines but instead would rather harvest with standard sized machines throughout the life cycle of the plantation.

For loggers looking at increasing harvest productivity on standard sized equipment, incorporation of a tracked processor could be the way to go at both a centralized timber depot or at a landing. Integration of a processor into a logger's system could increase their overall profit or decrease the number of days worked once the machine cost was covered. As mill's become more stringent on the allowable log lengths for their prime cuts, the necessity of incorporating a processor into the system may become imminent.

Comparing the gain in productivity for the tracked processor in comparison to a knuckle-boom loader resulted in a minimum of 10 truckloads a day for inexperienced processor operators. A production estimate of 20 truckloads a day were estimated for experienced processor operators assuming each truckload weighed 28 tons and the operator worked a 9 hour shift. These numbers also assumed that the operator never ran out of wood to process on the landing or at a timber depot where multiple loggers in the area were delivering whole trees.

A previous study determined it would be logistically difficult to incorporate a centralized timber depot into the southeastern region of the United States. This study does not argue with their findings, but suggests that if an increase in logger's overall productivity on an hourly, daily, and weekly basis were to occur, the timber depot concept may be reassessed for feasibility. Until that time occurs, however, there were several limitations to using a tracked processor at a landing. These included but were not limited to; the overall size of the forest tract to be harvested being too small, the machines utilization rate being too low, the low availability of trucks to transport the processed stems, and the lack of an available biomass market if the timber depot were to become a reality.

In addition to the limitation of using the tracked processor on the landing, the logger may incur additional harvest costs by incorporating this machine into their conventional harvesting system. If the mills are not providing sufficient compensation, the piece of equipment becomes too costly for the logger to operate. This study also depicted a minimal increase in costs with price fluctuations in both fuel and maintenance costs; however, a significant increase in costs occurred with the decrease of production and utilization rates.

Other observations made with the tracked processor included recognizing that using the processing head did not actually increase the logger's total merchantability value on a per stem basis as predicted although the processor did obtain additional lengths out of each product. While the knuckle-boom loader did actually harvest more total products than the tracked processor, both machines still averaged four products per stem. This study indicated that knuckle-boom operators could actually be missing high value products if they are underestimating the dbh and lengths of stems rather than overestimating or being precise with their measurements.

Although visual estimation is currently the common practice for merchandizing trees in the southeastern region of the United States, some mills are beginning to demand more precise product specifications from the loggers, which could make visual estimation a technique of the past. Until that time comes, however, there is little incentive for loggers to incorporate a processor into their harvesting system.

Overall, there is a plethora of theories concerning the best tactics towards making woody biomass a cost-effective product. Many are deemed impractical while others are not implemented because they are unconventional. Simply put, they do not conform to the normal standards of practice. These unconventional techniques and technology applications, however, may provide the answer to making woody biomass a cost-effective product from the beginning of the supply chain to the end in the future given the right circumstances. At this time, the above-mentioned innovations do not appear to be innovative enough to compensate for the low, to non-existent market prices for woody biomass in the southeastern region of the United States.

Chapter 7. Future Work

Continued research is recommended for all of the studies to search for additional means of promoting woody biomass in the southeastern region of the United States. A continuation of the Flexstand^{TM} versus conventional spacing stand study is possible from the same stand since only a biomass thinning occurred, so we suggest two follow up studies occur at years 16 and 30. These studies could validate the legitimacy of the modeling data for those same stands. It is also suggested that additional Flexstand^{TM} and rectangularity stands are established to continued to further validate the results found for biomass green ton weights found in year 8. Finally, we recommend that enough stands are established so future harvests can be conducted using both conventional and small-scale equipment so a proper comparison can be determined.

Future work concerning the productivity of the tracked processor should include multiple studies to be conducted throughout the southeast to ensure a variety of site characteristics as well as stand characteristics. Continued comparisons between experienced operators versus inexperienced operators would ensure a correct baseline for each operator was established. During future time studies, the number of cuts made should be recorded for analysis. The time study should be conducted during the actual processing of the trees and not via the video recordings. Further collaboration is necessary with Waratah and John Deere to establish a proper software data collection method as well.

Similar to the tracked processor productivity, additional studies need to be conducted for the knuckle-boom versus track processor merchandizing comparison. These studies need to be recorded using video recorders in addition to the software programs and verbal communication. Ideally, this study would be conducted on the weekends or not during working hours to ensure enough time was provided to both operators for merchandizing. Dbh and total length of each tree need to be measure before merchandizing as well as after the knuckle-boom loader makes their final cuts. This will ensure accuracy and allow for a baseline to be established concerning the visual estimation accuracy for merchandizing stems. Finally, market availability needs to be removed as an element of concern for the operators to ensure prioritization of stem value.

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