# The Prevalence and Operational Feasibility of Utilizing Pre-Commercially Thinned Pine as a Woody Biomass Energy Source

Nathan Hanzelka

Thesis submitted to the faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science

In

Forestry

Jay Sullivan, co-chair

M. Chad Bolding, co-chair

Scott M. Barrett

April 22, 2015

Blacksburg, VA

**Keywords**: pre-commercially thinned, woody biomass, utilization, feasibility

# The Prevalence and Operational Feasibility of Utilizing Pre-Commercially Thinned Pine as a Woody Biomass Energy Source

Nathan Hanzelka

## Abstract

The southern pine beetle (SPB) poses a significant threat to pine forests of the southeastern US. Pre-commercial thinning (PCT) is a commonly used silvicultural practice to mitigate and prevent SPB spread in young southern pine stands. Typically, PCT represents an added management cost to landowners and thinned material is not utilized for forest products. Increased demand for woody biomass energy may provide landowners and harvesting contractors an opportunity to utilize PCT residues as a woody biomass energy feedstock, which may wholly or partially offset PCT costs. However, little information is available regarding harvestable biomass quantities in PCT stands and few studies have assessed harvesting productivity and costs in very young pine stands. To develop estimates of biomass abundance in PCT candidate stands, loblolly pine (*Pinus taeda*) stands aging 5 to 12-years old, and enrolled in the Virginia Department of Forestry Pine Bark Beetle Prevention Program (VDOF PBBPP), were inventoried across the Piedmont and Coastal Plain regions of Virginia. To attain productivity and cost estimates of utilizing small-diameter stems for woody biomass energy, a biomass harvesting case study was then conducted on a 15-year old loblolly pine stand. Results of the inventory and case study indicate that stands at the upper age limit for the PCT program may contain harvestable quantities of biomass (39.63 green tons/acre), although high harvesting costs ($23.46/green ton) relative to regional delivered biomass prices may limit the economic feasibility of utilizing PCT biomass for energy.

## Acknowledgements

I would like to thank the Virginia Department of Forestry for providing funding and resources needed to complete this project. Thanks also to the Virginia Tech Department of Forest Resources and Environmental Conservation and the USDA McIntire-Stennis program for providing additional funding and resources. Many thanks to C.K. Greene and all others at Virginia Custom Thinnings LLC for allowing me the opportunity to work with them.

Much gratitude to Tal Roberts, Will Saulnier, John Peterson, and Ilya Donner for their assistance in the field and aiding me in the relentless battle against blackberry.

My sincere thanks to Scott Barrett for his valuable advice regarding biomass operations, Ralph Amateis for his assistance with biomass equations, and Tracey Sherman, Kathie Hollandsworth, and Sue Snow for their administrative assistance over the course of this thesis project.

A very special thank you to my advisors, Dr. Jay Sullivan and Dr. Chad Bolding, for their wisdom and encouragement throughout the completion of this project.

Lastly, I would like to thank my family and friends for their love, patience, and undying support over the course of this project.

# Table of Contents

## Table of Contents (continued)

## Table of Contents (continued)

# List of Figures

# List of Tables

page

# Chapter 1. Introduction and Literature Review

## 1.1 Introduction

The southern pine beetle (SPB) is commonly regarded as a significant threat to pine forests of the southeastern US. The most recent SPB outbreak between the years of 2000 and 2002 was estimated to cause over 1 billion $ft^3$ of timber mortality losses (Coulson and Klepzig 2011). As a means of reducing the potential threat of southern pine beetle outbreak, thinning is a commonly used practice for reducing stand density. The majority of thinnings used in conjunction with SPB risk mitigation are pre-commercial thinnings (PCT), due to the relatively low commercial value small-diameter pine stands. As a result, PCT treatments represent an added management cost and will typically leave thinned stems on-site to decompose rather than be utilized. The development of woody biomass markets across the southeastern US may provide an opportunity to utilize currently non-merchantable PCT stems for woody biomass energy which may wholly or partially offset the cost of the PCT to the landowner.

Several studies surveying landowner attitudes towards biomass harvesting have shown that the majority of non-industrial private forest (NIPF) landowners are in favor of biomass harvests (e.g. Joshi and Mehmood 2010, Paula et al. 2011, Leitch et al. 2013). Considering 58% of forestland in the US south is family-owned NIPF (Butler 2008), a potential source of woody biomass energy feedstock may exist in private land holdings with PCT stand conditions. Several small-diameter biomass-only harvesting case studies have been completed to determine the productivity and harvesting costs of utilizing small-diameter stems for biomass. However, little effort has been made to quantify harvestable biomass in PCT stands and little is known about the harvesting productivity and costs associated with utilizing biomass from young pine stands with PCT conditions. In this project, we seek to develop better estimates of potential biomass availability in PCT stands and perform a biomass-only harvesting case study to assess the operational feasibility of utilizing PCT southern pine for woody biomass energy.

The thesis is organized in the following manner. Chapter 1 provides the specific study objectives and a literature review of relevant topics. Chapter 2, entitled "An Economic Feasibility Analysis of Utilizing Pre-commercially Thinned Southern Pine for Woody Biomass", provides estimations of biomass quantities in PCT stands throughout Virginia and attempts to estimate the harvesting costs associated with PCT biomass. Chapter 3, entitled "Productivity and Costs of Utilizing Small-diameter Stems in a Biomass-only Harvest", analyzes a harvesting operation and estimates the productivity and costs of utilizing young, small-diameter southern for biomass. Lastly, Chapter 4 provides insight on the implications of the findings from the previous chapters and explores opportunities for further research.

## 1.2 Study Objectives

The purpose of this project is to assess the economic and operational feasibility of utilizing pre-commercially thinned southern pine as a woody biomass energy source. Specific objectives include the following:

1) Determine the quantity and product specifications of woody biomass available on PCT candidate stands of varying site quality and stand density throughout Virginia,

2) Identify a range of suitable stand conditions needed to feasibly harvest and utilize small diameter stems for biomass using mechanical harvesting systems in conventionally classified pre-commercial stands, and

3) Develop guidelines to estimate market values of pre-commercially thinned woody biomass material under a range of stand conditions.

## 1.3 Literature Review

In order to adequately assess existing literature and determine knowledge gaps regarding the use of PCT residues for woody biomass energy, the following areas were examined and developed into independent literature review sections:

- Southern Pine Beetle Risk explores the destructive impact of SPB in the southeast and the effectiveness of utilizing PCT as a means of SPB outbreak mitigation.
- Pre-commercial Thinning examines the silvicultural benefits of PCT and the techniques used to perform PCT treatments.
- PCT Residues as a Woody Biomass Energy Feedstock examines previous attempts at utilizing PCT biomass for energy and explores the potential contribution of PCT biomass to meet current energy demands in the southeastern US.
- NIPF Attitudes towards Biomass Harvesting summarizes previous landowner surveys regarding biomass harvesting on NIPF land.
- Lastly, Small-diameter Woody Biomass Harvesting Systems examines the stand conditions, productivities, and costs of previous small-diameter woody biomass harvesting case studies.

### *1.3.1 Southern Pine Beetle Risk*

A primary reason for conducting PCT treatments in pine stands of the southeastern US is to mitigate the risk of southern pine beetle outbreak from occurring. The southern pine beetle

(*Dendroctonus frontalis)* has had a devastating effect on pine stands in the southeastern US. SPB outbreaks were estimated to cause $1.2 billion in economic losses for timber producers from 1977 to 2004 (Coulson and Klepzig 2011). An estimated 8.4 million acres of pine forest in the southern US are susceptible to losing 25% or more of their standing live basal area from SPB spread (Nowak et al. 2008). A major catalyst for SPB infestation within pine stands is the presence of very closely spaced trees; highly stocked stands are considered to be more susceptible to SPB outbreaks (Hedden and Billings 1979, Nowak et al. 2008) and past studies have often shown that SPB infested stands are commonly overstocked (Lorio 1980, Coster and Searcy 1981).

Prolific natural regeneration of southern pine can produce densely stocked stands (Grano 1969, Mann and Lohrey 1974). Thinning has proven to be an effective means of reducing SPB infestation risk in natural and planted southern pine stands (Burkhart et al. 1986, Belanger et al. 1993). Previous studies have shown that lower-density stands are unlikely to further promote local infestation because of increased individual tree vigor and SPB resistance (Coster and Gara 1968, Brown et al. 1987) and reduced SPB pheromone communication caused by increased stand air flow (Thistle et al. 2004). In regards to stand age, trees in young pine stands are less susceptible to SPB infestation because of limited inner bark for larval food supply, surface area for egg galleries (Belanger et al. 1993), and their increased ability to synthesize defense compounds (Hodges et al. 1977). Older pine trees with larger boles and increased bark surface area serve as more ideal hosts for SPB infestation (Belanger et al. 1993). Therefore, thinning stems before they reach commercial size (e.g. $\geq$ 4 inches DBH) is a preferred method for reducing southern pine infestation risk.

*1.3.2 Pre-Commercial Thinning*

In addition to reducing SPB risk, PCT typically has a positive effect on residual tree growth. Thinning stands at an early age can yield a higher annual rate of diameter growth, reducing the time before the first commercial thinning and producing sawlog-sized trees at an earlier age (Lohrey 1977, Cain 1993). Mann and Lohrey (1974) recommend that southern pine stands in the southern coastal plain with greater than 5,000 stems/acre receive PCT treatment, and thinning stands at an early age (3 – 4-years old) is most conducive to increased diameter growth and greater financial return. Waiting to thin stands after age 5 appears to produce little added growth, particularly in the case of Virginia pine (*Pinus virginiana)* stands (Miller 1951, Carvell 1966). A study conducted in a 7-year old stand of Virginia pine in southern Maryland concluded that thinning costs were not offset by increased diameter growth when the stand was thinned from 9,500 to 900 stems/acre (Fenton and Bond 1965).

The most common method for PCT in southern pine stands is selective hand thinning with the use of brush saws and chain saws, and although this method is not widely discussed in literature pertinent to PCT, similar strategies have been commonplace in Sweden to conduct PCT for over 50 years (Ligné et al. 2005). However, several studies have analyzed strip thinning as a method of accomplishing PCT in pine stands of the southern US. Grano (1969) utilized a strip thinning method in an overstocked 7-year old southern pine stand containing 25,300 stems/acre, about one-quarter of which were hardwoods. Thinning was accomplished with the use of a D-2 tractor equipped with horizontal slicing blades cutting 8 foot wide swaths with 3 foot wide uncut strips. In one of the treatment types, selective hand-thinning was used in addition to machine thinning. The use of machine and hand thinning proved to be silviculturally practical, with a growth increase of 11.7 cords/acre compared to the control, but the treatment was not found to be cost effective. However, thinning with machine-only did prove to be cost effective.

In another strip thinning study, a 6-year old stand of southern pine in Arkansas was thinned with the use of a rotary mower, cutting 12 foot wide swaths with 1 foot wide uncut strips (Cain 1993). Harvested plots measured either 132 feet by 132 feet or 122 feet by 143 feet within a 10-acre test area and a thinning cost of $25/acre was determined using a time study. The use of strip thinning in this study reduced pine density from 16,600 to 1,900 stems/acre. DBH, height, and volume/tree were significantly greater in the thinned plots versus the unthinned plots in the years following the strip thinning, and dominant and co-dominant trees were established as a result of the thinning.

A study by Lohrey (1977) examined four different strip thinning treatment types with varying swath widths. Two different swath widths were used on a 3-year old stand of loblolly pine (*Pinus taeda*): one width of 6.6 foot swaths with 6.6 foot uncut strips and another width of 7.5 foot swaths with 3.5 foot uncut strips. One of the treatments included hand-thinning combined with machine thinning where trees were machine thinned at 3-years old and hand-thinned at 5-years old. Height differences between the four treatments after 13 years of growth were not found to be significant. The study concluded that a residual stocking of no more than 750 stems/acre will produce the highest rate of pulpwood volume growth and that strip thinning is a faster and cheaper method of PCT than selective thinning by hand.

Many PCT studies have emphasized lower thinning costs during a young stand age (i.e., less than 5-years old) versus older stand ages. Strip thinning, although a less commonly used practiced than selective thinning for PCT stands, has shown to be a cost-effective method in thinning densely stocked southern pine stands (Lohrey 1977, Cain 1993). Some of these studies have also indicated that strip thinning can produce a similar silvicultural result to selective hand thinning at a lower cost (Mann and Lohrey 1974, Lohrey 1977). If PCT biomass harvests were to occur, the harvest design and methodology would most likely be similar to strip thinning. However, of the aforementioned PCT studies that were reviewed, none explored the potential use of thinned residues for woody biomass energy.

### *1.3.3 PCT Residues as a Woody Biomass Energy Feedstock*

PCT residues can potentially contribute as a feedstock to an expanding biomass energy industry in the southern US. Total woody bioenergy capacity in North Carolina, South Carolina, and Virginia is expected to increase by 29% over 2006 levels by the year 2020 (Galik et al. 2009). Use of biomass for wood-consuming bioenergy projects in the entire southern US is expected to increase to 45 million green tons (gt) per year by the year 2023 (Forisk 2015). Covering approximately 15.7 million acres, the state of Virginia is estimated to contain approximately 859 million dry tons of biomass (Dwivedi and Alavalapati 2009) of which a significant portion may be usable for biomass energy. Virginia has an opportunity to utilize a currently unutilized resource in PCT residues, considering the state ranks 5$^{th}$ compared to other states in total biomass energy plant nameplate capacity with a combined capacity of 400 MW (Biomass Magazine 2015). Those within the forest products industry have sought to capitalize on the resurging biomass energy market. Loggers in Virginia have adapted their operations to create additional woody biomass chips by adding wood chippers, chip vans, and other associated equipment (Barrett et al. 2014).

Utilizing PCT residues as a biomass energy feedstock has been suggested in past studies. High fossil fuel prices spawned interest in utilizing pre-commercial stems for woody biomass energy during the 1970’s and 1980’s (e.g., Koch and McKenzie 1976, Watson and Stokes 1989), although subsequent reductions in fossil fuel prices soon dissipated this interest. More recently, the US Department of Energy's Billion Ton Update highlights PCT residues as a potential feedstock as markets continue to develop (Perlack et al. 2011) and PCT residues from the Wildland Urban Interface are identified as a potential energy source by the US Forest Service (Staudhammer et al. 2011). In a survey of forest industry personnel, many respondents identified young pine plantations as a potential biomass energy feedstock (Kline and Coleman 2010).

Previous studies have suggested that PCT residues may be usable for woody biomass energy production. However, these studies do not consider the ownership of the land (e.g., industrial, public, private) on which the harvests would occur. With family-owned NIPF comprising 58% of total forestland ownership in the US south (Butler 2008), a significant portion of PCT biomass would most likely come from private landholdings. Therefore, a better understanding of private landowner's opinions regarding woody biomass harvesting is needed before further assessing the potential utilization of PCT residues.

#### *1.3.4 NIPF Landowner Attitudes towards Woody Biomass Harvesting*

Numerous studies have surveyed non-industrial private forest (NIPF) landowners regarding their behavior towards woody biomass harvesting. Joshi and Mehmood (2010) revealed that 57% of Virginia NIPF landowners were unaware of cellulosic energy production, and many landowners were willing to supply woody biomass for harvest at pulpwood prices, though skepticism existed regarding the degree to which biomass markets would compete with pulpwood markets. The survey also showed that younger landowners (e.g., less than 60-years old) with large pine plantations may be the preferred demographic for woody biomass harvest, similar to another survey showing that Mississippi landowners who were male and owned large acreages of pine were more likely to be knowledgeable of residue utilization for woody biomass (Joshi et al. 2012).

In a survey of NIPF landowners in Minnesota and Wisconsin, biomass prices were separated from pulpwood prices to determine differences in willingness to harvest at varying prices for biomass (Becker et al. 2013). Eighty five percent of landowners in the study were willing to supply biomass for harvest at a revenue of $5/acre, 70% were willing to supply at $0/acre, and 30% were willing to pay an unspecified amount to supply biomass in exchange for wildlife habitat or timber stand improvements. However, these levels of willingness to harvest were all within the context of an integrated harvest utilizing both commercial timber products and woody biomass products without any biomass-only harvest scenarios being considered. A survey of Kentucky landowners presented respondents with a similar integrated harvest scenario revealing 67% of NIPF landowners surveyed had an intention of including biomass in future harvests (Leitch et al. 2013). A survey of NIPF landowners in Alabama showed similar results with 73% of landowners indicating willingness to supply woody biomass (Paula et al. 2011). Major limitations to biomass harvesting listed by the survey of Kentucky landowners included lack of markets, woodland access, equipment, and price/cost-effectiveness (Leitch et al. 2013). Another survey of Minnesota, Michigan, and Wisconsin NIPF landowners varied price levels at $0, $20, $40, and $60/acre based on an assumed landowner revenue of $1 – 2/gt (Aguilar et al. 2014). Retention levels of 33% were assumed with biomass removal rates of 20 gt/acre for representative sites. Only 2% of landowners in the study indicated they would harvest woody biomass without a traditional commercial harvest. Results suggested the choice of conducting a timber harvest was more sensitive to changes in timber revenue than biomass revenue and the supply of biomass will increase as timber prices increase.

Surveys of NIPF landowners have shown that landowners are usually willing to allow woody biomass harvests in the context of an integrated harvest. However, the utilization of PCT residues for woody biomass energy presents a unique harvesting scenario. Typically, woody biomass is harvested as a component of an integrated harvest in which both biomass and roundwood are harvested to generate revenue. Residues from PCT, traditionally a net-cost treatment since residues are unutilized, would more likely be used only for biomass and no roundwood. Therefore, biomass quantities available for harvest in small-diameter biomass-only harvest scenarios must be better understood. Furthermore, the harvesting costs associated with harvesting small-diameter stems for biomass must be examined to understand the economic feasibility of such harvests for both landowners and harvesting contractors.

*1.3.5 Small-diameter Woody Biomass Harvesting Systems*

Harvesting costs associated with utilizing small-diameter stems for biomass have been assessed in many previous studies. In Scandinavia, the "systems of innovation" approach employed by the forestry sector in several countries (Hansen 2010) has allowed for the development of many more specialized harvesting machines in comparison to North America. In one study, a variety of multi-tree processors well-suited for small-diameter woody biomass harvesting were examined for "energywood" harvesting in Scots pine (*Pinus sylvestris* L.) stands with densities ranging from 740 – 2,384 stems/acre and average diameters of ≤ 4 inches DBH (Kärhä et al. 2005). The study concluded that such machines are well-suited for energywood harvests based on residual site conditions and accessibility throughout the stand. However, no information regarding chipping costs and the total cut-and-haul cost was provided by the study.

A variety of experimental systems have been tested for use in small-diameter woody biomass harvests in the southeastern US. In an increased effort to utilize woody biomass for energy in the 1970's, Koch and McKenzie (1976) designed prototypical harvesting machines for utilizing pre-merchantable stems; however, fossil fuel price reductions soon decreased the interest in woody biomass energy, and machine designs failed to materialize. Bio-baling equipment, commonly used for small-diameter hybrid poplar harvests, was examined for use in a southern pine stand (Klepac and Rummer 2010). Understory hardwood and pine woody biomass was baled with an Anderson Group WB-55 bio-baler, producing a total in-woods harvesting cost of $17.00/gt. This cost, however, does not include chipping or transportation costs, which would reasonably incur substantial additional costs that would make the operation economically infeasible given a current delivered in-woods chip biomass price of $18.62/gt (Timber Mart South 2014). Another experimental system used a FECON FTX440 bio-harvester to harvest downed and standing small-diameter woody biomass (Roise et al. 2009). The bio-harvester was designed to chip woody biomass in swaths, collect the biomass chips with an auger, and blow the chips into a collection bin pulled behind the bio-harvester. The system showed a low utilization rate at 23% producing an in-woods harvesting cost of $172.33/gt, far from being economically feasible given current biomass prices. With design refinements, increased operator knowledge, and increased material size, the authors projected that the in-woods cost could be decreased to $17.13/gt, which they believed to be a more realistic operating cost.

The use of conventional harvesting machines to harvest small-diameter woody biomass has been explored in many previous case studies. Watson and Stokes (1989) examined the operating costs of "pre-harvesting energywood" in which stems < 1 inch DBH were harvested with conventional feller-bunchers, grapple skidders, and chippers. While the study determined that the operation could be economically feasible, limited information was provided regarding the initial stand conditions and machine productivity of the operation.

More recently, Bolding and Lanford (2005) analyzed the economic feasibility of employing a cut-to-length harvesting system to utilize non-merchantable understory hardwood stems (e.g. 0.5 – 4.0 inches DBH) for biomass in a mature pine stand located in Alabama with a total stem density of 1,232 stems/acre. The system was effective in reducing forest fuel loads, however, the total cut-and-haul cost of harvesting non-merchantable stems was much higher than the cost of harvesting merchantable stems on the same site. Decreased machine productivity and the difficulty of handling non-merchantable stems led to a high cut-and-haul cost of the non-merchantable portion ($37.06/gt) which did not compare favorably with prices paid for woody biomass at the time of the study. Biomass harvesting in conjunction with fuel reduction was also studied in southwest Oregon (Bolding et al. 2009). High cut-and-haul costs ($43.68/gt) relative to biomass prices were observed when non-merchantable stems were harvested, although stems < 3 inches DBH were not utilized.

A study in Arizona examined the use of a Valmet 603 three-wheeled feller buncher, a Caterpillar 525B skidder, a Prentice RT-100 loader, and a Bandit Beast 3680 grinder to thin ponderosa pine stands with densities exceeding 5,000 stems/acre and average diameters < 2 inches DBH (Pan et al. 2008). Harvesting component costs, in units of bone dry tons (BDT), for the feller buncher, skidder, loader, and grinder were $6.37, $6.08, $4.08, and $12.63, respectively. The on-board truck cost of $55.27/BDT was not economically feasible, assuming a market rate of $40/BDT for biomass at the time of the study, and system delays were regarded as a major limitation to machine productivity in the system.

Conrad et al. (2013) performed a biomass-only harvest on 22 and 26-year old loblolly pine stands located in North Carolina. In a stand with a total density slightly greater than 500 stems/acre, all merchantable and non-merchantable stems were harvested with conventional harvesting machines and chipped for biomass. With the biomass chip prices considered in the study, the total cut-and-haul cost of the chip treatment resulted in a negative margin for the harvesting contractor.

In Alabama, overstocked mature southern pine stands containing large proportions of stems < 5 inches DBH were harvested with conventional machines in a biomass-only operation (Mitchell and Gallagher 2007). Limited productivity information on the feller-buncher and skidder was provided by the study. However, the total cut-and-haul cost of the system ($15.18/gt) did compare favorably to the price for biomass at the time ($19.00/gt), showing that biomass-only harvests can be achieved with conventional machines.

Harvesting small-diameter woody biomass for energy has previously been studied with both experimental harvesting configurations and conventional harvesting machines. While the majority of the operations in these studies have proven not to be economically feasible, some operations have demonstrated total cut-and-haul costs that compared favorably with delivered prices for biomass. However, most of these studies have focused on biomass-only harvests in southern pine stands older than 20 years rather than younger southern pine stands that sometimes undergo PCT. Little information is provided regarding the productivity and costs of conventional harvesting machines in small-diameter biomass-only harvests of young southern pine.

### 1.4 Conclusions

A literature review was conducted on topics thought to be pertinent to utilizing PCT residues for woody biomass energy. Findings have shown that PCT is a generally accepted technique used to mitigate/prevent southern pine beetle outbreaks from occurring and PCT can provide several silvicultural benefits, including increased individual tree diameter. In regards to woody biomass energy, the capacity has grown across the southeast US and NIPF landowner studies have demonstrated that the majority of private landowners are willing to allow biomass harvesting. Finally, past small-diameter woody biomass harvesting case studies have shown that biomass-only harvests in mature southern pine stands are not usually economically feasible.

After completing this literature review, several knowledge gaps were identified. Little effort has been made towards developing estimates of biomass abundance in PCT stands. Previous studies have identified the potential use of PCT biomass for energy production, but little is known about harvestable volumes of biomass in such stands. Additionally, past harvesting case studies have provided little insight on the productivity and costs associated with utilizing small-diameter biomass in young southern pine stands with stand conditions similar to those of PCT stands.

Understanding potential harvestable quantities of biomass in PCT stands as well as the associated operating costs are critical to assessing the feasibility of utilizing PCT biomass for energy. This thesis project intends to fill some of these knowledge gaps by estimating harvestable biomass quantities in PCT stands and estimating the harvesting productivity and costs associated with utilizing PCT biomass. As biomass energy remains viable in the southeast US, the information produced by this thesis project will be valuable to a variety of stakeholders, including foresters, harvesting contractors, biomass energy facility planners, and landowners.

## Literature Cited


Aguilar, F.X., Zhen, C., and A. W. D'Amato. 2014. Non-industrial forest owner's willingness-to-harvest: How higher timber prices influence woody biomass supply. Biomass and Bioenergy, 71:202-215.

Barrett, S.M., Bolding, M.C., Aust, W.M., amd J.F. Munsell. 2014. Characteristics of logging businesses that harvest biomass for energy production. Forest Products Journal, 64(7/8):265-272.

Becker, D. R., Eryilmaz, D., Klapperich, J. J., and M.A. Kilgore. 2013. Social availability of residual woody biomass from nonindustrial private woodland owners in Minnesota and Wisconsin. Biomass and Bioenergy, 56:82-91.

Belanger, R. P., Hedden, R. L., and P. L. Lorio. 1993. Management strategies to reduce losses from the southern pine beetle. Southern Journal of Applied Forestry, 17(3):150-154.

Biomass Magazine, 2015. 2015 U.S. biomass power map. Biomass Magazine.

Bolding, M. C. and B.L. Lanford. 2005. Wildfire fuel harvesting and resultant biomass utilization using a cut-to-length/small chipper system. Forest Products Journal, 55(12):181-189.

Bolding, M. C., Kellogg, L. D., and C.T. Davis. 2009. Productivity and costs of an integrated mechanical forest fuel reduction operation in southwest Oregon. Forest Products Journal, 59(3):35-46.

Brown, M. W., Nebeker, T. E., and C.R. Honea. 1987. Thinning increases loblolly pine vigor and resistance to bark beetles. Southern Journal of Applied Forestry, 11(1):28-31.

Burkhart, H. E., Haney, H. L., Newberry, J. D., Leuschner, W. A., Morris, C. L., and D.D. Reed. 1986. Evaluation of thinning for reduction of losses from southern pine beetle attack in loblolly pine stands. Southern Journal of Applied Forestry, 10(2):105-108.

Butler, B. J. 2008 Family forest owners of the United States, 2006. General Technical Report NRS-27. USDA Forest Service North Research Station, Newton Square, Pennsylvania. 72 pp.

Cain, M. D. 1993. Ten-year results from precommercial strip-thinning: paradigm lost or reinforced?. Southern Journal of Applied Forestry, 17(1):16-21.

Carvell, K. L. 1966. The effect of stand density on the development of Virginia pine in the Ohio River area of West Virginia. Current Report 46. West Virginia University Agricultural Experiment Station. 13 pp.

Conrad, J. L., Bolding, M.C., Aust, W.M., Smith, R.L., and A. Horcher. 2013. Harvesting productivity and costs when utilizing energywood from pine plantations of the southern coastal plain USA. Biomass and Bioenergy, 52(2013):85-95.

Coster, J. E., and R. I Gara. 1968. Studies on the attack behavior of the southern pine beetle. II. Response to attractive host material. Contrib. Boyce Thompson Institute. 24:69-76.

Coster, J. E., and J.L. Searcy. 1981. Site, stand, and host characteristics of southern pine beetle infestation. Technical Bulletin 1616. USDA Combined Forest Pest Research and Development Program. 115 pp.

Coulson, R.N., and K.D. Klepzig. 2011. Southern Pine Beetle II. General Technical Report SRS-140. USDA Forest Service Southern Research Station, Asheville, NC. 512 pp.

Dwivedi, P., and J.R. Alavalapati. 2009. Stakeholders' perceptions on forest biomass-based bioenergy development in the southern US. Energy Policy, 37(5):1999-2007.

Fenton, R. H., and A. R. Bond. 1965. Pre-commercial thinning not recommended for Virginia pine stands in south Maryland. Research Note NE-40. USDA Forest Service, Upper Darby, Pennsylvania. 7 pp.

Forisk. 2015. Available at: http://forisk.com/resources/resources-from-forisk-wood-bioenergy-us-free-summary/ (last accessed February 2, 2015).

Galik, C. S., Abt, R., and Y. Wu. 2009. Forest biomass supply in the southeastern United States - implications for industrial roundwood and bioenergy production. Journal of Forestry, 107(2):69-77.

Grano, C. X. 1969. Precommercial thinning of loblolly pine. Journal of Forestry, 67(11):825-827.

Hansen, E. N. 2010. The role of innovation in the forest products industry. Journal of Forestry, 108(7):348-353.

Hedden, R. L., and R. F. Billings. 1979. Southern pine beetle: factors influencing the growth and decline of summer infestations in east Texas. Forest Science, 25:547-566.

Hodges, J.D., Elam, W.W., and W.F. Watson. 1977. Physical properties of the oleoresin system of the four major southern pines. Canadian Journal of Forest Research. 7:520-525.

Joshi, O., and S.R. Mehmood. 2011. Factors affecting nonindustrial private forest landowners' willingness to supply woody biomass for bioenergy. Biomass and Bioenergy, 35(1):186-192.

Joshi, O., Grebner, D. L., Hussain, A., and S.C. Grado. 2012. Landowner knowledge and willingness to supply woody biomass for wood-based bioenergy: Sample selection approach. Journal of Forest Economics, 19(2):97-109.

Kärhä, K., Jouhiaho, A., Mutikainen, A., and S. Mattila. 2005. Mechanized energy wood harvesting from early thinnings. International Journal of Forest Engineering, 16(1):15-25.

Klepac, J., and B. Rummer. 2010. Harvesting understory biomass with a baler. In Proc. 33rd annual Council on Forest Engineering, June 9th, 2011 Auburn, Alabama. 11 pp.

Kline, K. L. and M.D. Coleman. 2010. Woody energy crops in the southeastern United States: two centuries of practitioner experience. Biomass and Bioenergy, 34(12):1655-1666.

Koch, P., and D. W. McKenzie. 1976. Machine to harvest slash, brush, and thinnings for fuel and fiber--a concept. Journal of Forestry, 74(12):809-812.

Leitch, Z. J., Lhotka, J. M., Stainback, G. A., and J.W. Stringer. 2013. Private landowner intent to supply woody feedstock for bioenergy production. Biomass and Bioenergy, 56:127-136.

Ligné, D., Nordfjell, T., and A. Karlsson. 2005. New techniques for pre-commercial thinning–time consumption and tree damage parameters. International Journal of Forest Engineering, 16(2):89-99.

Lohrey, R. E. 1977. Growth responses of loblolly pine to precommercial thinning. Southern Journal of Applied Forestry, 1(3):19-22.

Lorio, P. L. 1980. Loblolly pine stocking levels affect potential for southern pine beetle infestation. Southern Journal of Applied Forestry, 4(4):162-165.

Mann, W. F., and R.E. Lohrey. 1974. Precommercial thinning of southern pines. Journal of Forestry, 72(9):557-560.

Miller, W. D. 1951. Thinning in old-field Virginia pine. Journal of Forestry, 49:884-887.

Mitchell, D., and T. Gallagher. 2007. Chipping whole trees for fuel chips: A production study. Southern Journal of Applied Forestry, 31(4):176-180.

Nowak, J., Asaro, C., Klepzig, K., and R. Billings. 2008. The southern pine beetle prevention initiative: working for healthier forests. Journal of Forestry, 106(5):261-267.

Pan, F., Han, H. S., Johnson, L. R., and W. J. Elliot. 2008. Production and cost of harvesting, processing, and transporting small-diameter (≤ 5 inches) trees for energy. Forest Products Journal, 58(5):47-53.

Paula, A. L., Bailey, C., Barlow, R. J., and W. Morse. 2011. Landowner willingness to supply timber for biofuel: results of an Alabama survey of family forest landowners. Southern Journal of Applied Forestry, 35(2):93-97.

Perlack, R. D., Stokes, B.J., Lead Authors. 2011. US billion-ton update: biomass supply for a bioenergy and bioproducts industry. United States Department of Energy, Oak Ridge National Laboratory, Oak Ridge, Tennessee. 235 pp.

Roise, J.P., Hannum, L.C., and G.P. Catts. Machine system for harvesting small diameter woody biomass and reducing hazardous fuels: a developmental report. In Proc. 2009 American Society of Agricultural and Biological Engineers Bioenergy Engineering Conference, October 11-14th, 2009 Seattle, Washington. 15 pp.

Staudhammer, C., Hermansen, L. A., Carter, D., and E. A. Macie. 2011. Wood to energy: using southern interface fuels for bioenergy. USDA Forest Service Southern Research Station, Asheville, North Carolina. 100 pp.

Thistle, H.W., Peterson, H., Allwine, G., Lamb, B.K., Strand, T., Holsten, E.H., and P.J. Shea. 2004. Surrogate pheromone plumes in three forest trunk spaces: composite statistics and case studies. Forest Science, 50:610-625

Timber Mart South. 2014. Norris Foundation, University of Georgia, Athens, Georgia. 4th quarter.

Watson, W. F., and B.J. Stokes. 1989. Harvesting small stems–A southern USA Perspective. In Proc. of the International Energy Agency, Task VI, Activity 3 Symposium, Harvesting small trees and forest residues. USDA Forest Service Southern Forest Experiment Station, Auburn, Alabama. pp. 131-139.

# Chapter 2. An Economic Feasibility Analysis of Utilizing Pre-commercially Thinned Southern Pine as a Woody Biomass Energy Source

## 2.1 Abstract

The use of woody biomass as a feedstock for wood-burning energy facilities and wood pellet-producing mills has increased across the US south in recent years. Feedstock for these energy facilities and pellet mills comes in a variety of forms, including roundwood, logging residues, and secondary wood-manufacturing by-products. Residues from pre-commercial thinning (PCT) of southern pine stands, a practice sometimes used in the southeast to mitigate southern pine beetle outbreak risk that traditionally incurs an added cost to landowners, may be an unutilized resource suitable for biomass energy production. Utilization of thinning residues from PCT may provide an opportunity to reduce or offset the costs of southern pine beetle risk mitigation. Potential use of PCT biomass has been suggested by previous studies, but little effort has been made to quantify amounts available for utilization. Using a list of NIPF properties enrolled in the Virginia Department of Forestry Pine Bark Beetle Prevention Program, we conducted inventories of southern pine stands scheduled to undergo PCT in Virginia to determine estimates of potentially harvestable biomass. Inventory results suggest stands in the 5 – 7 and 8 – 12-year old age groups contain total standing volumes of 14.47 and 39.63 green tons per acre of biomass, respectively. The study determined that PCT stands in the 8 – 12-year old age group may contain sufficient volumes for economically feasible harvests based on removal estimations, thinning costs, and regional average biomass prices.

## 2.2 Introduction

The use of woody biomass energy as an alternative to fossil fuels has gained significant interest within the United States over the last several decades. Announced and operating wood-consuming bioenergy projects in the US are expected to increase to a total use of 84 million green tons (gt) per year by 2023, of which 45 million gt/year of wood use is attributed to the US South (Forisk 2015). Several wood-fired energy plants have been created or retrofitted from existing energy plants to utilize biomass as an alternative energy source with US biomass energy nameplate capacity totaling 6,850 MW (Biomass Magazine 2015). Compared to other states, Virginia ranks 5$^{th}$ in biomass energy plant total nameplate capacity. At least seven biomass energy facilities have been constructed in Virginia for a combined nameplate capacity of over 400 MW utilizing a variety of feedstock sources including municipal solid waste, forest residues, and wood waste. Using a “rule of thumb” of 10,000 gt/year of biomass needed to create 1 MW of energy, roughly 4,000,000 gt/year is required to fuel these energy plants in Virginia.

Construction of wood pellet-producing mills has also increased throughout the US in response to greater demands for alternative energy sources. The existing maximum production capacity of pellet mills in the United States totaled 9,422,500 tons in 2014 with at least eight pellet mills in Virginia producing pellets for both domestic use and exports (Biomass Magazine 2014). A large proportion of pellet production can be attributed to the European Union’s “20-20-20” campaign to reduce energy dependence on fossils fuels and increase utilization of renewable energy sources by the year 2020 (Guo et al. 2013, European Commission 2014). Fiber needed for pellet production previously consisted of predominately sawmill residues and other secondary wood manufacturing by-products with a small proportion sourced from pulpwood and logging residues (Spelter and Toth 2009). However, recent increased global demand for wood pellets has increased the amount of primary forest products, like pulpwood, used for producing pellets for exports from the southeast US (Hoefnagels et al. 2014).

A potential feedstock for domestic biomass energy facilities which has not been explored extensively are the biomass residues left behind in young pine stands as a result of pre-commercial thinning (PCT). PCT is an intermediate stand treatment used to increase individual tree diameter and reduce stand susceptibility to southern pine bark beetle outbreak (Burkhart et al. 1986, Nowak et al. 2008). Dense southern pine stands often pose a greater risk for southern pine beetle infestation, and diameter growth is often limited in such stands. PCT treatments are typically net cost treatments that do not produce revenue and therefore equate to management investments or added expenses to landowners, although some states offer cost-share programs to encourage PCT. In Virginia, the Virginia Department of Forestry Pine Bark Beetle Prevention Program (VDOF PBBPP) offers a 60% cost-share to NIPF landowners who wish to conduct PCT and meet program criteria (Watson et al. 2013). Pine stands enrolled in the VDOF PBBPP must be at least 5 acres in size with stems no older than 15-years old and an average stem size not exceeding 4 inches DBH (VDOF 2014). Additionally, pre-treatment density of stands must be at least 800 stems/acre and post-treatment residual density must be from 300 - 500 stems/acre.

Traditionally, PCT treatments leave thinned stems on site, remaining unused for any type of wood or energy production (Perlack et al. 2011). Previous interest in fossil fuel energy alternatives during the 1970’s and 1980’s led to attempts at harvesting pre-commercial stems (e.g. Koch and McKenzie 1976, Watson and Stokes 1989), but reductions in fossil fuel prices soon dissipated interest in harvesting small-diameter biomass. As woody biomass energy markets have since become more viable, utilizing PCT biomass may become economically feasible. The potential use of PCT biomass for energy has more recently been suggested by the

USDA Forest Service (Staudhammer et al. 2011) and the US Department of Energy (Perlack et al. 2011). Furthermore, surveys of non-industrial private forest (NIPF) landowners throughout the US have shown that landowners are usually willing to allow woody biomass harvesting (Joshi and Mehmood 2010, Paula et al. 2011, Becker et al. 2013). However, little effort has been made to quantify realistic thinned biomass quantities available for harvest in young, small-diameter southern pine stands considering the relatively low commercial value of stems < 4 inches DBH.

Since PCT treatments normally incur an added cost to the landowner, utilizing PCT biomass for energy may reduce the cost, cover harvesting expenses, or even produce a profit if removed biomass quantities are substantial enough and harvesting costs are low enough. The purpose of this study is to estimate potentially harvestable biomass in PCT stands and examine the costs associated with harvesting PCT biomass versus the costs of conducting a conventional PCT treatment. Specific goals were to: 1) inventory biomass abundance in PCT stands prior to thinning and examine stand characteristics, and 2) estimate PCT biomass removals and harvesting costs to explore the economic feasibility of PCT biomass harvests.

The layout of the paper is the following. First, we outline the methods used to inventory PCT stands. Second, we present biomass quantities by stand age class, density, and stem diameter. Third, we estimate potential biomass removals across age classes and explore the potential revenues and harvesting costs (e.g. $/acre and $/gt) from utilizing removed biomass. Finally, we summarize our findings, discuss limitations to utilizing PCT stands as a biomass energy source, and highlight future opportunities for research in this area.

## 2.3 Methods

*2.3.1 Inventory*

Considering the lack of information regarding biomass quantities available for harvest in small-diameter pine stands, measurements are needed to assess the economic feasibility of harvesting PCT biomass for energy. Stands were selected for measurement from among stands enrolled in the VDOF PBBPP. Plots within 18 stands located across Virginia were measured to estimate woody biomass volume[1]. Stands selected for measurement were chosen using a variety of criteria including age, location, availability for measurement prior to thinning, and landowner permission. Plots were distributed among stands to measure no more than 1 plot per acre. Selected stands had been either planted or naturally regenerated with loblolly pine (*Pinus taeda*), as determined by the VDOF forester responsible for the stand, and they usually contained a large number of loblolly pine "volunteer" regenerated trees, with a small number of stands containing large numbers of Virginia pine (*Pinus virginiana*) volunteers.

Stands were measured using a total of 241 – 1/250$^{th}$ acre fixed-radius circular plots. Though plot size is relatively small, with the high density of pine stands that traditionally undergo PCT, a small plot size was practical for this application. Past PCT studies have examined treatments on stands with average densities exceeding 5,000 stems/acre (Mann and Lohrey 1974, Lohrey 1977) and another study observed a 7-year old pine stand with an average density of 25,300 pine stems/acre in southern Arkansas (Grano 1969). Even with the relatively small plot size used for this study, substantial time was needed by researchers to collect measurements on each plot given the high stand density.

[1] For all intents and purposes, the use of the word "volume" throughout the paper is in reference to mass (e.g. green tons/acre)

The minimum size of measured stem diameters was 1.0 inch DBH, and tallys were recorded in 1 inch diameter classes. Pine stem heights were similar within each plot. Therefore, stem heights in each plot were obtained by measuring three randomly selected stems, to the nearest 1 foot, in each 1 inch diameter class and averaging the values to determine the representative height for the corresponding diameter class. Emphasis was placed on measuring stands greater than 5 years old, as older stands are expected to have a higher potential for containing volumes of woody biomass sufficient for mechanical recovery. Stands were located within the following nine counties in Virginia: Accomack, Albermarle, Brunswick, Chesterfield, Dinwiddie, Essex, Lunenburg, Middlesex, and Southampton (Figure 2.1). Additional information regarding the use of herbicides and the type of regeneration of the stand, i.e. natural or planted, was obtained from the VDOF forester responsible for each stand’s cost-share program application. Age groups were developed based on the number of plots measured to form two age groups, 5-7 and 8-12-years old, which were then compared for differences in density, diameter, and volume.

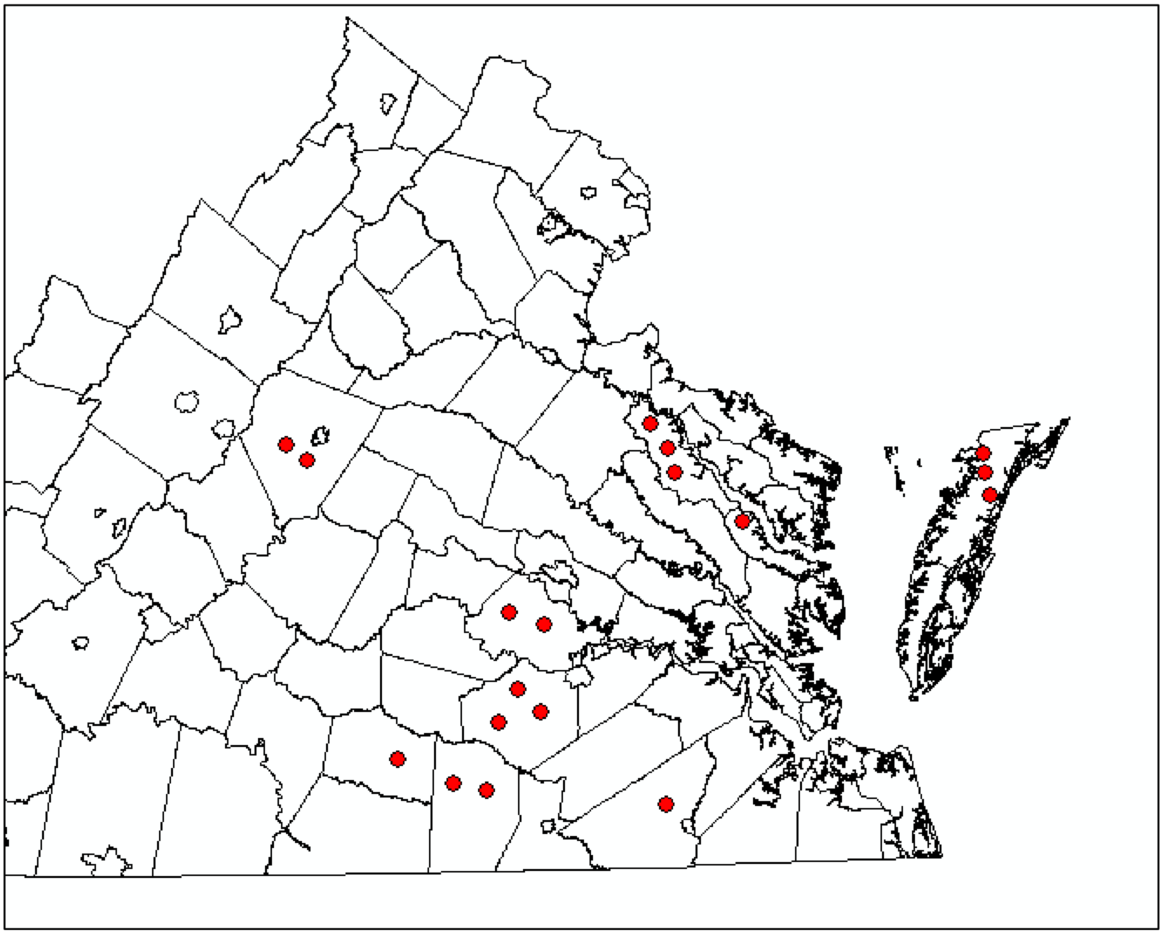


Figure 2.1. PCT stand inventory locations in Virginia, measured August 2013 – July 2014

Biomass quantities were calculated from plot-level data using a combination of biomass equations (Clark and Saucier 1990, Bullock and Burkhart 2003). Clark and Saucier's biomass equation was developed from southern pine trees spread across 135 study plantations in Alabama, Georgia, South Carolina, and Florida with ages 15 – 35-years old. Of the Natural Coastal Plain southern pine trees measured in their study, 100 of the 1,285 total trees were < 5 inches DBH with an overall range of 1.1 – 24.0 inches. Bullock and Burkhart's equation was developed from 970 loblolly pine trees sampled from the Georgia Piedmont, East Texas, and the Coastal Plain and Piedmont regions of Virginia. The DBH range of all trees measured in their study was 0.8 inches – 12.3 inches, while the DBH range of the 261 trees they measured in

Virginia was 2.5 inches – 11.4 inches. Although the density of the sampled trees used for both equations is not identified, it is likely that the density of trees in our study is much higher than trees sampled for these equations. When the Bullock and Burkhart equation is applied to 1 inch DBH stems, a negative value for volume results. Hence, we used Bullock and Burkhart's equation for all trees > 1 inch DBH, given that their equation is based on trees sampled from sites similar to our study. For all 1 inch DBH trees in our analysis, Clark and Saucier's equation for Natural Coastal Plain southern pine, as we believe it produces a more realistic volume estimate for stems in this diameter class. Although the size range and density of the trees in our dataset may be outside the intended use of these equations, we believed the use of this combination of equations would provide the best estimate of PCT stand volume possible.

### *2.3.2 Statistical Analysis*

SAS JMP statistical software was used to conduct statistical analysis of the inventory data. The Tukey-Kramer Honestly Significant Difference test, completed at the $\alpha = 0.05$ level, was used to gain a better understanding of how the variable means differed among our sampled plots.

## 2.4 Results and Discussion

### *2.4.1 Inventory*

Among all sampled plots ($n = 241$), planting is the more common source of regeneration, with only 31% of sampled plots being regenerated naturally. The use of herbicides also is common, with 80% of sampled plots having received herbicide treatment at an early stand age (Table 2.1). Stand density of pine for natural stands is higher than planted stands (*p-value* = 0.049) with 4,273 stems/acre compared to 3,544 stems/acre and the 8-12 age group exhibits a higher density than the 5-7 age group ($p < 0.001$) with 4,420 stems/acre compared to 3,120 stems/acre. Pine density of sampled plots ranges from 250 – 11,000 stems/acre with the majority containing 600 – 1,000 stems/acre (Figure 2.2). The mean DBH class of inventoried plots increases as stand density decreases (Figure 2.3).

Table 2.1. Pine density (stems/acre) characteristics on inventoried PCT stands in Virginia

| | | n | Mean density (stems/acre) | Std. Error |
|---|---|---|---|---|
| | Overall | 241 | 3,771 | 171.87 |
| Age (years) | 5-7 | 120 | $3{,}117^{A}$ | 209.83 |
| | 8-12 | 121 | $4{,}419^{B}$ | 259.48 |
| Regeneration Type | Natural | 75 | $4{,}273^{C}$ | 296.08 |
| | Planted | 166 | $3{,}544^{D}$ | 208.84 |
| Herbicide Use | Non-sprayed | 48 | $3{,}676^{E}$ | 354.20 |
| | Sprayed | 193 | $3{,}794^{E}$ | 195.90 |

A, B means not connected by the same letter are significantly different (α = 0.05) between age groups
C, D means not connected by the same letter are significantly different (α = 0.05) between regeneration type
E, F means not connected by the same letter are significantly different (α = 0.05) between herbicide use

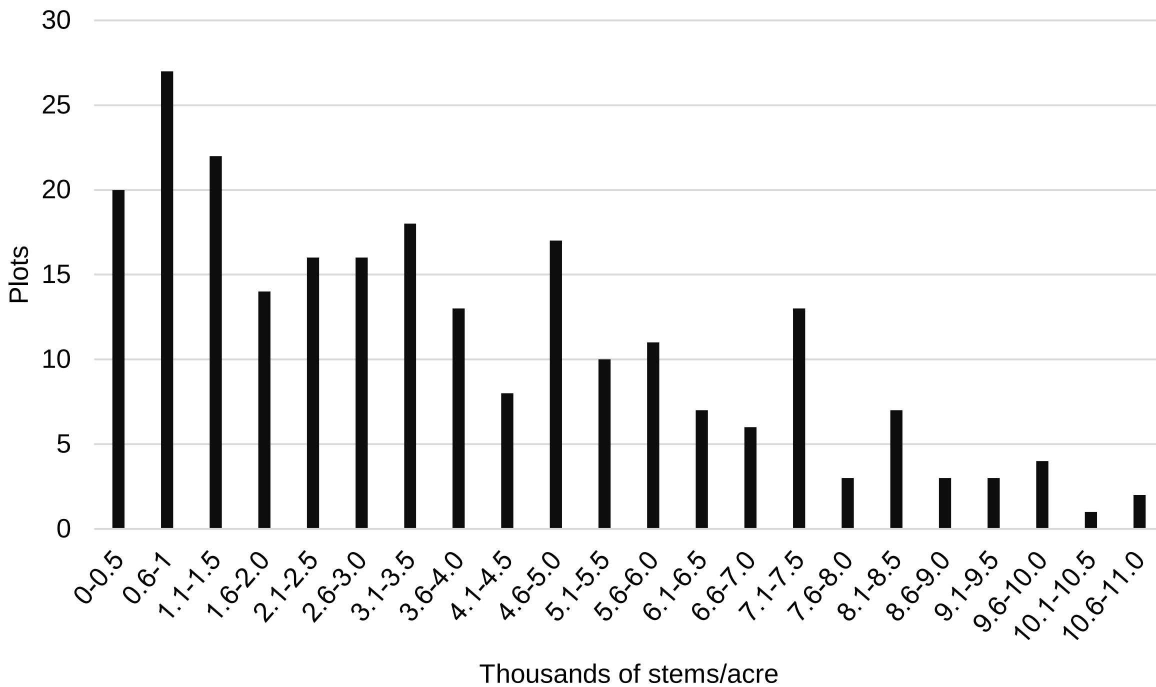



Figure 2.2. Plot distribution by stand density of pine on inventoried PCT stands in Virginia

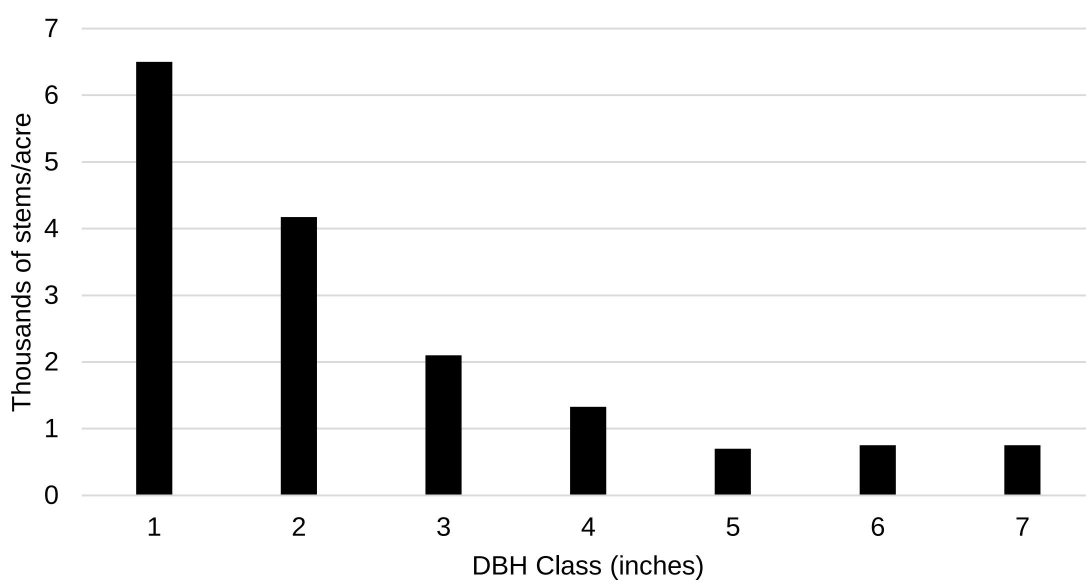


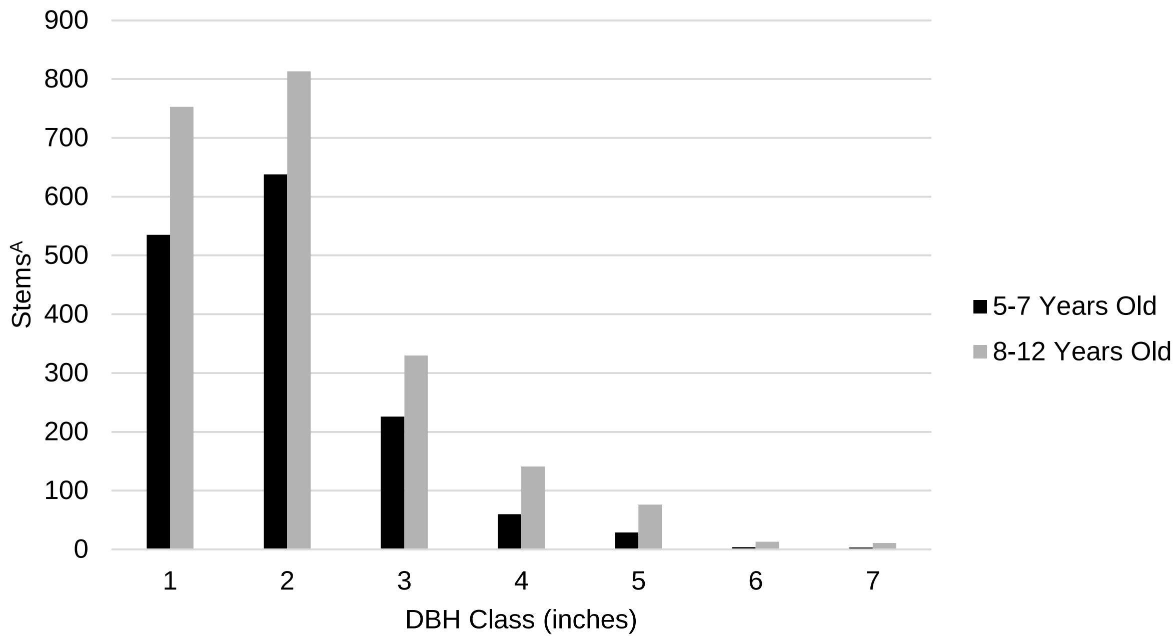

Figure 2.3. Mean stand density of pine by DBH class on inventoried PCT stands in Virginia

The average DBH for all measured plots was 2.47 inches (Table 2.2). Plots in stands that were sprayed with herbicides showed a significantly higher DBH than non-sprayed plots ($p$ = 0.006), likely a result of lower stand density. The diameter distribution for all measured stems nearly resembles a reverse-J curve (Figure 2.4); had the inventory included stems less than 1.0 inch DBH for measurement, a stronger inverse relationship between total stems measured and DBH would have appeared. The greater majority of all plots measured had an average DBH < 5 inches with most plots falling into the 2 inch DBH class (Figure 2.5).

Table 2.2. Stem DBH (inches) characteristics on inventoried PCT stands in Virginia

| | | n | Mean DBH (inches) | Std. Error |
|---|---|---|---|---|
| | Overall | 241 | 2.47 | 0.07 |
| Age (years) | 5-7 | 120 | $2.39^{A}$ | 0.09 |
| | 8-12 | 121 | $2.56^{A}$ | 0.10 |
| Regeneration Type | Natural | 75 | $2.44^{C}$ | 0.14 |
| | Planted | 166 | $2.49^{C}$ | 0.08 |
| Herbicide Use | Non-sprayed | 48 | $2.10^{E}$ | 0.15 |
| | Sprayed | 193 | $2.56^{F}$ | 0.07 |

A, B means not connected by the same letter are significantly different (α = 0.05) between age groups
C, D means not connected by the same letter are significantly different (α = 0.05) between regeneration type
E, F means not connected by the same letter are significantly different (α = 0.05) between herbicide use




[A] Stems less than 1.0 inch not measured during inventory

Figure 2.4. Diameter distribution of measured stems on inventoried PCT stands in Virginia

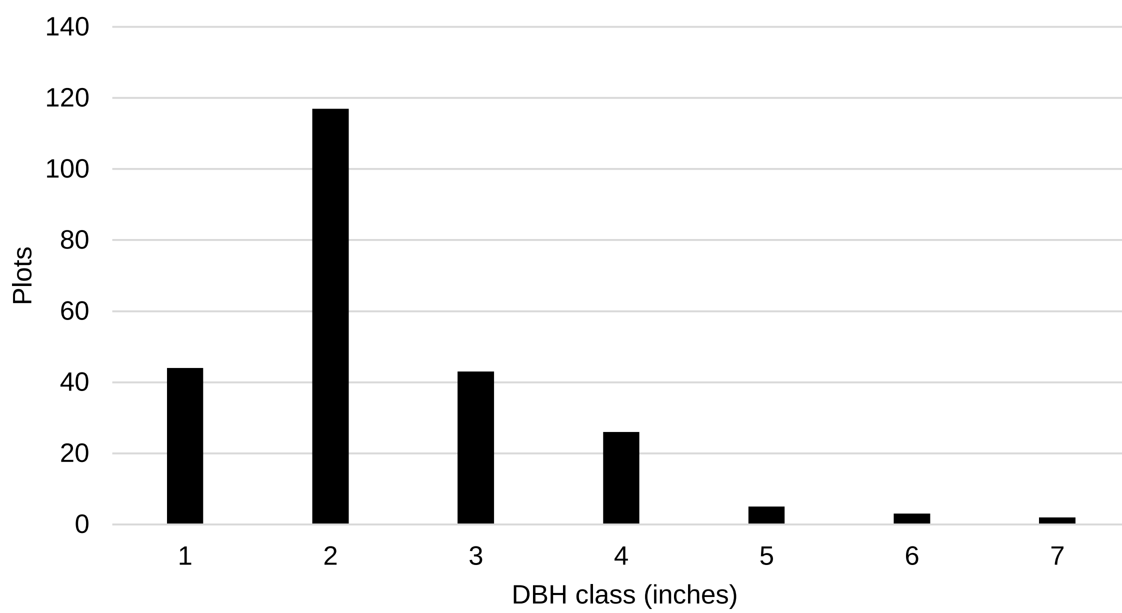



Figure 2.5. Plot distribution by DBH class on inventoried PCT stands in Virginia

An overall average pine volume of 27.1 gt/acre was observed from the sampled plots (Table 2.3). Plots in natural stands showed a significantly higher volume than planted stands ($p < 0.001$) with 34.66 gt/acre compared to 23.68 gt/acre, which could be attributed to the higher density of natural stands. Plots in stands that were sprayed with herbicides showed a significantly higher volume than non-sprayed stands ($p < 0.001$) with 30.08 gt/acre compared to 14.82 gt/acre, which was expected since most herbicide applications are meant to deter the growth of hardwoods and encourage pine growth. Volumes for plots in the 8 – 12 age group were significantly higher than plots in the 5 – 7 age group ($p < 0.001$) with 39.63 gt/acre compared to 14.47 gt/acre. Across all plots measured, volume appears to show a positive relationship with plot DBH (Figure 2.6).

Table 2.3. Pine volume (gt/acre) characteristics on inventoried PCT stands in Virginia

| | | n | Mean volume (gt/acre) | Std. Error |
|---|---|---|---|---|
| | Overall | 241 | 27.10 | 1.45 |
| Age (years) | 5-7 | 120 | 14.47[A] | 0.77 |
| | 8-12 | 121 | 39.63[B] | 2.28 |
| Regeneration Type | Natural | 75 | 34.66[C] | 3.47 |
| | Planted | 166 | 23.68[D] | 1.34 |
| Herbicide Use | Non-sprayed | 48 | 14.82[E] | 1.47 |
| | Sprayed | 193 | 30.08[F] | 1.71 |

A, B means not connected by the same letter are significantly different (α = 0.05) between age groups
C, D means not connected by the same letter are significantly different (α = 0.05) between regeneration type
E, F means not connected by the same letter are significantly different (α = 0.05) between herbicide use

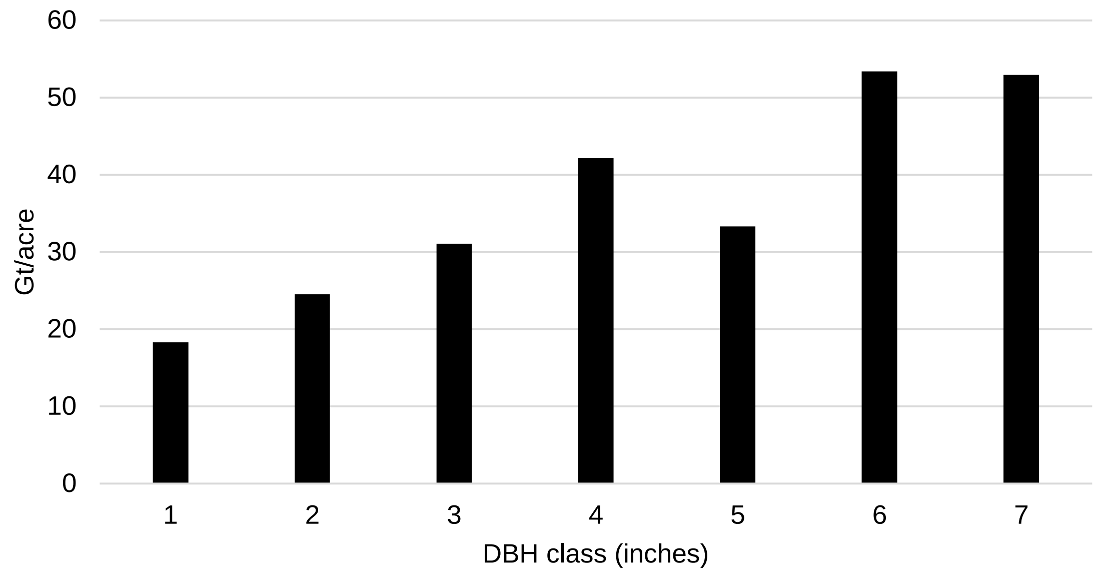



Figure 2.6. Mean volume by DBH class on inventoried PCT stands in Virginia

*2.4.2 Estimated Removed Volumes*

Results from the inventory were used to estimate the removed volume of PCT stands. Target stand densities, obtained from the VDOF forester responsible for each PCT stand, ranged from 350 – 484 stems/acre for the 241 plots measured and a target density of 400 stems/acre was assumed for 43 plots whose actual target densities were not identified. For the purpose of estimating removed volume, the average tons per stem volume was calculated for each of the two age groups based on the average volume and density in each age group. Subtracting the target density from the average initial density for each plot produced an estimated removed density which could then be combined with the calculated tons per stem to determine an estimate of removed PCT biomass volume.

Using this calculation, removed volumes for the 5 – 7 and 8 – 12 age groups average 11.41 and 33.31 gt/acre, respectively (Table 2.4). The estimated removed volume per acre of the 8 – 12 age group compares favorably to the minimum commercial harvest volume guideline of

30 gt/acre used in the southern US (Baker et. 2010), although this minimum volume is based on roundwood (stems ≥ 4 inches DBH) and not pre-commercial stems (< 4 inches DBH). It should be noted that the actual removed volumes from a biomass harvest may be less than indicated, depending on the selection method, as this estimation assumes a random selection of small- and large-diameter stems, while the actual proportion of small-diameter stems harvested would likely be much greater than large-diameter stems. Also, these values only reflect the removal of pine stems, therefore, a small additional component of hardwood volume could potentially be expected.

Table 2.4. Estimated removed volumes by age group on inventoried PCT stands in Virginia

| Age (years) | Removed (tons/acre) |
|---|---|
| 5-7 | 11.41 |
| 8-12 | 33.31 |

*2.4.3 Conventional PCT Costs*

PCT treatment costs for inventoried stands were obtained from the VDOF. Conventional, non-removal thinning costs, after applying the 60% cost-share, for stands inventoried in the 5 – 7 and 8 – 12 age groups averaged $85.39/acre and $83.25/acre, respectively (Table 2.5). Typically, harvesting costs incurred by loggers are expressed in units of $/gt rather than $/acre (Timber Mart South 2014). Therefore, in order to compare the cost of conventional treatment to the cost of harvesting PCT biomass, we used the actual PCT treatment costs to calculate the thinning cost in units of $/gt by dividing the estimated removed PCT biomass volume for each age group by the per acre cost. These estimated costs (with 60% cost-share applied) for the 5 – 7 and 8 – 12 age groups were $7.74/gt and $2.50/gt, respectively.

Table 2.5. Thinning costs to landowner on inventoried PCT stands in Virginia

| | Actual ($/acre)[1] | | Estimated ($/green ton) | |
|---|---|---|---|---|
| Age (years) | With 60% cost-share | Without cost-share | With 60% cost-share | Without cost-share |
| 5-7 | $85.54 | $142.57 | $7.74 | $12.90 |
| 8-12 | $83.25 | $138.75 | $2.50 | $4.17 |

[1]Source: VDOF PBBPP application records

*2.4.4 Harvesting PCT Biomass*

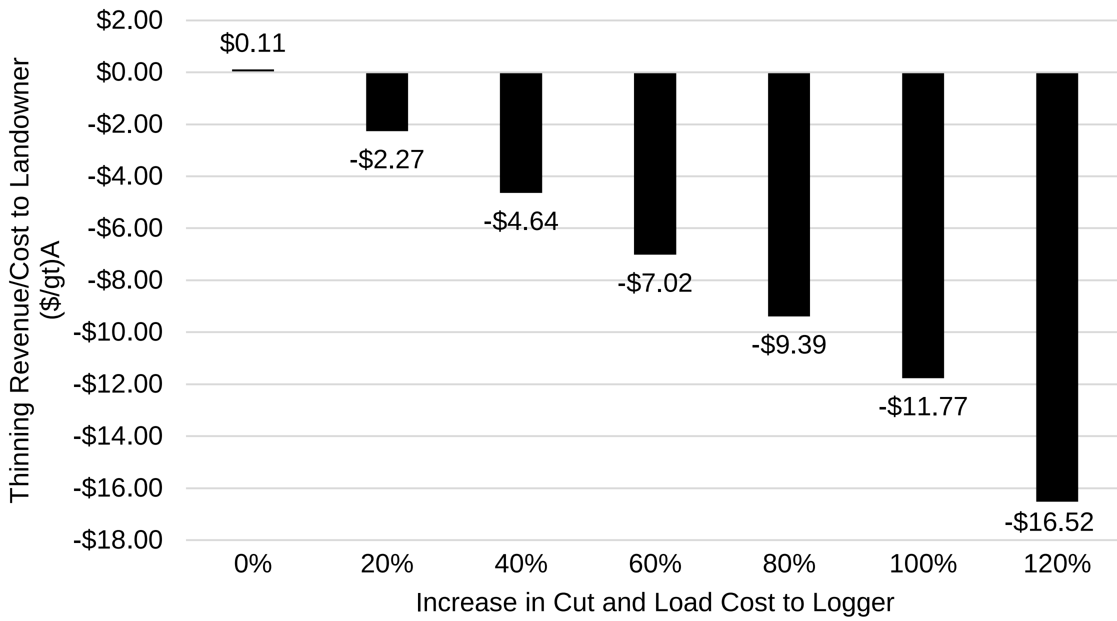
Of the potential products to be produced from harvesting PCT biomass, we believed "in-woods whole tree pine chips" would be the most likely product since in-woods chips are commonly produced from whole-tree chipping operations (Timber Mart South 2014). It should be noted that in-woods chips are normally made from biomass that has already been transported from the woods to the landing (i.e. "tops, limbs, limited bole material, and otherwise pre-commercial material"), therefore, we would expect higher harvesting costs associated with utilizing PCT biomass since stems would have to be cut and transported from the woods to the landing.

Decreased productivity rates associated with the lower per stem volumes of non-merchantable/PCT biomass could further lead to higher harvesting costs. In studies analyzing the harvesting costs of utilizing both merchantable and non-merchantable stems for biomass, total cut-and-load costs were $9.18/gt (Mitchell and Gallagher 2007), $14.58/gt[2] (Pan et al. 2008), and $39.83/gt (Bolding et al. 2009). A forest fire fuels reduction study estimated a cost of harvesting non-merchantable stems at $25.70/gt (Bolding and Lanford 2005). The harvesting machine configurations, productivities, and initial stand densities varied widely among these studies. Of

[2] Calculated from a listed cost of $29.16 per bone dry ton assuming 50% moisture content

these studies that were completed in the southeast US (Bolding and Lanford 2005, Mitchell and Gallagher 2007), stand conditions were greatly different from typical PCT stand conditions, in which average stem diameters are lower and average per acre stand densities are much greater. Therefore, further information regarding machine productivity and costs in stand conditions more representative of typical PCT stands would provide better insight on harvesting costs associated with PCT biomass.

Understanding this likelihood of higher harvesting costs associated with harvesting PCT biomass, we estimated thinning costs (assuming sub-profitable harvests) to a landowner at varying levels of harvesting costs to a logger. Using regional average prices for delivered in-woods pine biomass chips and average cut and load rates, haul rates, and haul distances for plantation thinnings in the southeast US coastal plain (Timber Mart South 2014), the landowner's thinning revenue/cost ($/gt) was estimated at percentage-based levels of increased cut and load costs (Figure 2.7).




[A]Assumes in-woods pine price of $18.62/gt, cut and load rate of $11.88/gt, haul rate of $0.13/gt/loaded mile, and minimum average haul distance of 51 miles (Timber Mart South 2014)

Figure 2.7. Thinning revenue/cost to landowner ($/gt) at varying levels of cut and load cost to logger

Considering the estimated $/gt of the conventional PCT treatment costs (with 60% cost-share applied) for the 5 – 7 and 8 – 12-year old age groups, landowners may have an opportunity to reduce the cost of treating their overstocked stands by electing to harvest PCT biomass. If harvesting PCT biomass were to increase cut and load costs for the 8 – 12-year old age group by 20% or less, landowners would be better off paying a logger to thin the stand ($2.27/gt) rather than paying for a conventional PCT treatment ($2.50/gt). For the 5 – 7-year old age group, an increase in the cut and load cost of 60% or less suggests a lower thinning cost paid to a logger ($7.02/gt) than for conventional PCT treatment ($7.74/gt).

**2.5 Conclusion**

A total of 241 plots across 18 southern pine stands enrolled in the VDOF PBBPP were measured in Virginia to estimate harvestable biomass in PCT treatment in stands of varying ages. Total stand density averaged 3,771 stems/acre, with the majority of measured stems falling into the 2 inch DBH class. Inventory measurements were separated by age group, 5 – 7 and 8 – 12-years old, to determine mean standing biomass quantities of 14.47 and 39.63 gt/acre in each respective age group. Estimated removed biomass quantities and thinning costs for the 8 – 12 age group suggest that landowners may have an opportunity to reduce the cost of conventional PCT treatment by allowing loggers to harvest PCT biomass.

In order for PCT biomass harvesting to become profitable, the value of the standing PCT biomass must outweigh the harvesting costs incurred by loggers. However, since conventional PCT treatments incur a cost to landowners, PCT biomass harvesting might be financially attractive to landowners even if thinning costs exceed revenues paid to a logger, as landowner payments may be less than the cost of a conventional PCT treatment. Although the estimated biomass removals and thinning costs in this study provide some insight on this issue, there are several areas in which more work is needed to more accurately assess whether or not harvesting PCT biomass is economically feasible. Current biomass equations need to be improved to include more stems sampled from smaller (< 4 inch) DBH classes to produce more accurate estimates for woody biomass energy production. More accurate estimates of removed volumes are also needed as the volumes in this study were based hypothetically on a target PCT density that was not actually measured following the completion of PCT in each stand. Finally, better information is needed regarding machine productivity and costs of equipment operating in small-diameter southern pine stands to develop accurate estimates of PCT biomass harvesting costs.

**Literature Cited**


Aguilar, F.X., Zhen, C., and A. W. D'Amato. 2014. Non-industrial forest owner's willingness-to-harvest: How higher timber prices influence woody biomass supply. Biomass and Bioenergy, 71:202-215.

Baker, S., Greene, D., and T. Harris. 2012. Impact of timber sale characteristics on harvesting costs. In Proc. Southern Forest Economics Workshop, Charlotte, North Carolina. pp. 94-105.

Becker, D. R., Eryilmaz, D., Klapperich, J. J., and M.A. Kilgore. 2013. Social availability of residual woody biomass from nonindustrial private woodland owners in Minnesota and Wisconsin. Biomass and Bioenergy, 56:82-91.

Biomass Magazine. 2014. 2014 U.S. and Canada pellet mill map. Biomass Magazine's Pellet Mill Magazine.

Biomass Magazine. 2015. 2015 U.S. biomass power map. Biomass Magazine.

Bolding, M. C. and B.L. Lanford. 2005. Wildfire fuel harvesting and resultant biomass utilization using a cut-to-length/small chipper system. Forest Products Journal, 55(12):181-189.

Bolding, M. C., Kellogg, L. D., and C.T. Davis. 2009. Productivity and costs of an integrated mechanical forest fuel reduction operation in southwest Oregon. Forest Products Journal, 59(3):35-46.

Bullock, B. P. and H.E. Burkhart. 2003. Equations for predicting green weight of loblolly pine trees in the South. Southern Journal of Applied Forestry, 27(3):153-159.

Burkhart, H. E., Haney, H. L., Newberry, J. D., Leuschner, W. A., Morris, C. L., and D.D. Reed. 1986. Evaluation of thinning for reduction of losses from southern pine beetle attack in loblolly pine stands. Southern Journal of Applied Forestry, 10(2):105-108.

Clark, A. and J.R. Saucier. 1990. Tables for Estimating Total-Tree Volumes, Stem Volumes, and Volumes of Planted and Natural Southern Pines in the Southeast. Georgia Forest Research Paper 79: Research Division, Georgia Forestry Commission. 27 pp.

European Commission. 2014. The 2020 climate and energy package. Available at: http://ec.europa.eu/clima/policies/package/index_en.htm (last accessed May 28, 2014).

Forisk. 2015. Available at: http://forisk.com/resources/resources-from-forisk-wood-bioenergy-us-free-summary/ (last accessed February 2, 2015).

Grano, C. X. 1969. Precommercial thinning of loblolly pine. Journal of Forestry, 67(11):825-827.

Guo, Z., Hodges, D. G., and T.M. Young. 2013. Woody biomass policies and location decisions of the woody bioenergy industry in the southern United States. Biomass and Bioenergy, 56:268-273.

Hoefnagels, R., Junginger, M., and A. Faaij. 2014. The economic potential of wood pellet production from alternative, low-value wood sources in the southeast of the US. Biomass and Bioenergy, 71:443-454.

Joshi, O., and S.R. Mehmood. 2011. Factors affecting nonindustrial private forest landowners' willingness to supply woody biomass for bioenergy. Biomass and Bioenergy, 35(1):186-192.

Joshi, O., Grebner, D. L., Hussain, A., and S.C. Grado. 2013. Landowner knowledge and willingness to supply woody biomass for wood-based bioenergy: Sample selection approach. Journal of Forest Economics, 19(2):97-109.

Koch, P., and D.W. McKenzie. 1976. Machine to harvest slash, brush, and thinnings for fuel and fiber--a concept. Journal of forestry, 74(12):809-812.

Lohrey, R. E. 1977. Growth responses of loblolly pine to precomerrcial thinning. Southern Journal of Applied Forestry, 1(3):19-22.

Mann, W. F. and R.E. Lohrey. 1974. Precommercial thinning of southern pines. Journal of Forestry, 72(9):557-560.

Mitchell, D. and T. Gallagher. 2007. Chipping whole trees for fuel chips: A production study. Southern journal of applied forestry, 31(4):176-180.

Nowak, J., Asaro, C., Klepzig, K., and R. Billings. 2008. The southern pine beetle prevention initiative: working for healthier forests. Journal of forestry, 106(5):261-267.

Pan, F., Han, H. S., Johnson, L. R., and W. J. Elliot. 2008. Production and cost of harvesting, processing, and transporting small-diameter (≤ 5 inches) trees for energy. Forest products journal, 58(5):47-53.

Paula, A. L., Bailey, C., Barlow, R. J., and W. Morse. 2011. Landowner willingness to supply timber for biofuel: results of an Alabama survey of family forest landowners. Southern Journal of Applied Forestry, 35(2):93-97.

Perlack, R. D., Stokes, B.J., Lead Authors. 2011. US billion-ton update: biomass supply for a bioenergy and bioproducts industry. United States Department of Energy, Oak Ridge National Laboratory, Oak Ridge, Tennessee. 235 pp.

Spelter, H. and D. Toth. 2009. North America's wood pellet sector. USDA Forest Service Forest Products Laboratory, Madison, Wisconsin. 23 pp.

Staudhammer, C., Hermansen, L. A., Carter, D., and E. A. Macie. 2011. Wood to energy: using southern interface fuels for bioenergy. USDA Forest Service Southern Research Station, Asheville, North Carolina. 100 pp.

Timber Mart South. 2014. Norris Foundation, University of Georgia, Athens, Georgia. 4th quarter.

Virginia Department of Forestry. 2014. Available at: http://www.dof.virginia.gov/costshare/health/pbbp.htm (last accessed February 2, 2015).

Watson, W. F., and B.J. Stokes. 1989. Harvesting small stems–A southern USA Perspective. In Proc. of the International Energy Agency, Task VI, Activity 3 Symposium, Harvesting small trees and forest residues. USDA Forest Service Southern Forest Experiment Station, Auburn, Alabama. pp. 131-139.

Watson, A. C., Sullivan, J., Amacher, G. S. and C. Asaro. 2013. Cost sharing for pre-commercial thinning in southern pine plantations: Willingness to participate in Virginia's pine bark beetle prevention program. Forest Policy and Economics, 34:65-72.

# Chapter 3. Productivity and Costs of Utilizing Small-diameter Stems in a Biomass-only Harvest


## 3.1 Abstract

Increased use of woody biomass for energy has increased the number of in-woods chipping operations across the southeastern US. Young loblolly pine (*pinus taeda*) stands that undergo a first commercial thinning, or sometimes a pre-commercial thinning, may serve as a potential raw material source for these chipping operations. A harvesting case study was completed using activity and elemental time studies to analyze conventional logging equipment thinning and chipping a 15-year old planted loblolly pine stand located in the coastal plain of Virginia. All stems in the harvest were chipped for biomass and no pulpwood or sawtimber was produced. Overall individual machine productivity rates for the feller-bunchers, skidders, and chipper were 30.77, 23.42, and 83.67 green tons (gt) per productive machine hour, respectively. A total cut-and-haul cost of $23.46/gt was calculated using the Auburn Harvesting Analyzer (AHA). Hauling was found to comprise the largest component of total costs at 33% or $6.94/gt. Conducting sensitivity analyses by balancing the operation in the AHA reduced the cut-and-haul cost by 5% to $22.28/gt. Considering a regional average delivered price of $17.35/gt for in-woods whole-tree pine biomass chips, the operation in the case study failed to break even. Results of this study suggest that current delivered in-woods pine chip prices are outweighed by harvesting costs in biomass-only harvests of young pine stands; however, optimally balancing operations will improve feasibility.

### 3.2 Introduction

Interest in woody biomass energy has increased rapidly throughout the southeastern US. For biomass energy-producing facilities in this region, loblolly pine (*Pinus taeda*) has the potential to serve as a major feedstock (Munsell and Fox 2010). Biomass utilized by conventional integrated harvesting operations is typically regarded as a by-product from the production of primary forest products, i.e., pulpwood and sawtimber (Baker et al. 2010, Barrett et al. 2014). A first commercial thinning of loblolly pine stands to harvest pulpwood is often conducted between stand ages of 10 and 20 years (Demers et al. 2013). At earlier stand ages, a pre-commercial thinning (PCT) is sometimes conducted to improve individual tree growth and reduce susceptibility to southern pine beetle outbreak (Burkhart et al. 1986, Nowak et al. 2008). PCT can often be completed with the use of hand crew-operated brush saws to thin and leave stems on-site (VDOF 2015), contrary to first commercial thinning operations in which conventional harvesting equipment is used to harvest merchantable stems (Demers et al. 2013). Since traditional PCT treatments do not utilize any thinned stems for pulpwood or biomass to produce any type of revenue, an added management cost is typically incurred to the landowner.

The merchantable volume available for harvest in a stand will greatly dictate the decision of whether or not to harvest. Much of the volume harvested in first commercial thinning operations comes from merchantable-sized stems (≥ 4 inches DBH) which are processed for pulpwood (Demers et al. 2013). A regional assessment of harvested volumes across the southeast showed that minimum commercial partial harvest removed volumes did not deviate much from 30 green tons (gt) per acre (Baker et al. 2012). However, these volumes are largely based on commercial products > 4 inches DBH (i.e., pulpwood and sawtimber); little is known regarding biomass quantities available for potential harvest in pre-commercial stands, in which the majority of stems are of non-merchantable size (< 4 inches DBH) (Grano 1969, Lohrey 1977). Density in PCT stands commonly exceed 5,000 stems/acre (Grano 1969, Lohrey 1977, Cain 1993) which is typically much greater than stands that undergo a first commercial thinning, which more commonly contain less than 1,000 stems/acre (Demers et al. 2013). It is unlikely that PCT stands contain enough merchantable-sized stems to warrant pulpwood harvesting like that of most first commercial thinnings, but given the current demand for biomass energy, sufficient volumes of biomass from non-merchantable stems may be present to warrant a biomass-only harvest.

In the 1970’s and 1980’s, attempts were made to harvest pre-commercial stems for use as woody biomass energy in response to emerging biomass markets at the time (Koch and Mackenzie 1976, Watson and Stokes 1989). Koch and McKenzie (1976) designed prototypical harvesting machines capable of utilizing pre-commercial stems. Their study suggested that highly dense stands (e.g. 4,858 – 16,194 stems/acre) of 6 year old southern pine may yield between 10 – 20 gt/acre of biomass usable for energy production. However, machine design issues, including limited compatibility with hardwoods and maneuverability complications, greatly limited the operational feasibility of the prototypical machines. Additionally, high oil prices resulting from the energy crisis of the early 1970’s soon subsided following the study, decreasing interest in woody biomass as an alternative energy source. In response to another energy crisis in the 1980’s, Watson and Stokes (1989) examined the harvesting costs of “pre-harvesting energywood” in which stems < 1 inch DBH were harvested to fuel a wood-fired boiler. Conventional equipment, including feller-bunchers with shear heads, grapple skidders, and in-woods chippers, were used. The study concluded that utilizing stems < 1 inch for energy production could be economically feasible “especially when the costs of fossil fuels are high” but the relatively low price of fossil fuels at the time of the study gave energy producers little incentive to utilize small diameter stems for biomass energy. With the improved productivity of modern-day harvesting equipment and the current prices paid for woody biomass, interest in utilizing small-diameter stems for biomass has resurfaced.

More recent case studies conducted in North America have investigated productivity and harvesting costs of using conventional equipment to utilize non-merchantable and/or pre-commercial stems in biomass harvesting operations (e.g. Bolding and Lanford 2005, Mitchell and Gallagher 2007, Pan et al. 2008, Conrad et al. 2013). Bolding and Lanford (2005) analyzed the feasibility of employing a cut-to-length harvesting system to utilize non-merchantable understory hardwood stems (e.g. 0.5 – 4.0 inches DBH) for biomass in a 40 – 60-year old pine stand located in Alabama with a total stem density of 1,232 stems/acre. The study determined that the system was effective in reducing forest fuel loads; however, the total cut-and-haul cost of harvesting non-merchantable stems was much higher than the cost of harvesting merchantable stems on the same site. The high cut-and-haul cost of the non-merchantable portion was due to decreased machine productivity and difficulty of handling small stems and did not compare favorably with prices paid for woody biomass at the time of the study.

Research in Arizona examined the use of conventional harvesting equipment to thin ponderosa pine stands with densities exceeding 5,000 stems/acre and average diameters < 2 inches DBH (Pan et al. 2008). System delays were regarded as a major limiting factor to machine productivity in the system and total cut-and-haul costs in this study also exceeded prices paid for woody biomass.

Conrad et al. (2013) performed biomass-only harvests on 22 and 26-year old loblolly pine stands located in North Carolina with stand densities slightly greater than 500 stems/acre. All harvested stems, whether merchantable or non-merchantable size, were chipped for biomass. The total cut-and-haul cost of the biomass harvest did not compare favorably to delivered chip prices.

A separate case study in Alabama examined biomass-only operations utilizing large proportions of stems < 5 inches DBH in overstocked southern pine stands aging 30 and 37-years old with stem densities less than 500 stems/acre (Mitchell and Gallagher 2007). Productivity analysis was only completed on the loader and chipper in the operation, providing little insight on feller-buncher and skidder productivity. However, the cut-and-haul cost of the operation in this study did compare favorably with current prices for woody biomass, indicating that merchantable biomass-only harvests can be achieved with conventional harvesting equipment.

Of the aforementioned studies, those conducted in the southeastern US were completed in pine stands older than 20 years that possess a larger quantity of merchantable stems and lower densities than the younger pine stands that undergo PCT. Insight on machine productivity and costs of utilizing small-diameter stems with conventional harvesting equipment during biomass-only harvests has been provided by these studies, but no consideration has been given to the potential use of stands with PCT conditions.

There is clear potential for utilizing PCT stands for biomass-only harvests. However, limited information is available regarding merchantable biomass volumes and machine productivity in PCT stands. Furthermore, past case studies have produced varied results regarding economically feasible cut-and-haul costs during biomass-only harvests of pine stands. The purpose of this study was to assess the productivity and harvesting costs of a biomass-only harvest operation using conventional harvesting equipment to utilize small-diameter stems in a stand near the margin of profitability between PCT and first commercial thinning conditions. Specific objectives were to: 1) characterize stand density and volume attributes, 2) attain machine productivity information, 3) estimate harvesting component costs), and 4) assess the economic feasibility of the operation by comparing total cut-and-haul costs to regional prices for biomass.

**3.3 Methods**

The 15 year old planted loblolly pine study site comprised a single stand of 87 acres and was located in Greensville County, Virginia, within the Coastal Plain physiographic region. A combination row and select thinning prescription was used to thin all stems 50 feet between corridors and selectively thin non-merchantable-sized stems between the rows to retain higher quality merchantable-sized pine stems. Stems were selected for harvest by the feller-buncher operators to reduce the initial stand density of 723 pine stems/acre to a residual 330 pine stems/acre. Loblolly pine was the dominant overstory species while understory species included red maple (*Acer rubrum*), sweetgum (*Liquidambar styraciflua*), blackgum (*Nyssa sylvatica*), sourwood (*Oxydendrum arboretum*), white oak (*Quercus alba*), blackjack oak (*Quercus marilandica*), willow oak (*Quercus phellos*), and American holly (*Ilex opaca*). The major soil type for the tract was Roanoke loam, classified as poorly drained (Web Soil Survey 2013). Pre- and post-harvest stand inventories were conducted to record species and measure the height and DBH of stems. Individual tree volumes were calculated using Bullock and Burkhart's (2003) equation for loblolly pine and Clark et al.'s (1986) equations for hardwoods. A Trimble Ranger GPS unit equipped with SOLO Forest GPS software (Trimble 2015) was used for inventory navigation and grid design. Measured plots consisted of 45, 1/100$^{th}$ acre fixed-radius plots for all stems < 2 inches DBH and 45, 1/10$^{th}$ acre fixed-radius plots for all stems > 2 inches DBH.

The harvest was designed to first bisect the tract with one main skid trail, row thin approximately every 4$^{th}$ row perpendicularly to the main skid trail, and then selectively thin between rows. Harvesting equipment used for the case study included: three Tigercat 718 feller-bunchers, two Caterpillar 535C grapple skidders, one Tigercat 234 loader, one Peterson 4300 in-woods chipper, five semi-trucks, and six chip vans. Each of the three feller-bunchers were operated by different individuals with Operator 3 having more experience than Operators 1 and 2. Each of the two skidders were also operated by different individuals with Operators 1 and 2 having roughly the same level of experience while the loader was operated by one single individual who also operated the chipper via remote control. All equipment operators were regarded as well-experienced. All stems harvested in the operation were whole-tree chipped for biomass and no roundwood was produced. Chips produced during the study were taken to one of two 50 MW wood-fired energy plants: Plant 1 located in Franklin, VA, 30 miles from the site, or Plant 2 located in Hopewell, VA, 69 miles from the site.

Activity sampling (Olsen and Kellogg 1983) was used to assess the range of non-productive and productive activities performed by the loader, chipper, and both skidders. Past harvesting case studies have used activity sampling to determine machine utilization rates as well as potential bottlenecks in the overall operation (Bolding et al. 2009, Conrad et al. 2013). Each machine used in the skidding and chipping components of the operation were observed by collecting activity information at fixed intervals of 1-minute. Observed activities for the skidders included: off landing, cleaning landing debris, arriving from inhaul, departing for outhaul, decking turn, waiting on chipper, refuel and maintenance, mechanical repairs, non-mechanical delay, idle, and other. Loader activities included: feeding chipper, cleaning landing debris, waiting on skidder, waiting on chip van, refuel and maintenance, mechanical repairs, non-mechanical delay, idle, and other. Chipper activities included: chipping, waiting on loader, refuel and maintenance, mechanical repairs, non-mechanical delay, idle, and other.

Elemental time studies for the felling and bunching, skidding, and chipping functions were completed by collecting observations on five of the fifteen total workdays required for the harvest. Productivity for each component, in units of gt per productive machine hour (PMH), was derived from first multiplying the mean number of stems by the average volume per removed stem and then dividing that value by the mean cycle time.  Each feller-buncher time cycle began after the previous bunch was dropped and ended when the observed bunch was dropped. Ocular and audial estimates were used to count the number of stems in each bunching cycle after physically counting stems in initial bunches to calibrate estimates. Spatial data were also collected on a handheld GPS in an attempt to relate the properties of harvested trees in each feller-buncher cycle to the pre-harvest inventory. From the location of where the researcher was standing, a waypoint was logged on the GPS whenever a feller-buncher cycle began (Figure 3.1). Operator and thinning type (row or select) were also recorded for each observation. Time elements for the skidding component included total turn time and delay time. Each skidding cycle began when the observed turn was picked up and ended when the following turn was picked up. The main skid trail length was measured and distances were flagged in 100 ft. increments for estimating each skid distance. Time elements for the chipping cycle included chipping time and delay time with chipping cycle time defined by the time required to fill each chip van.

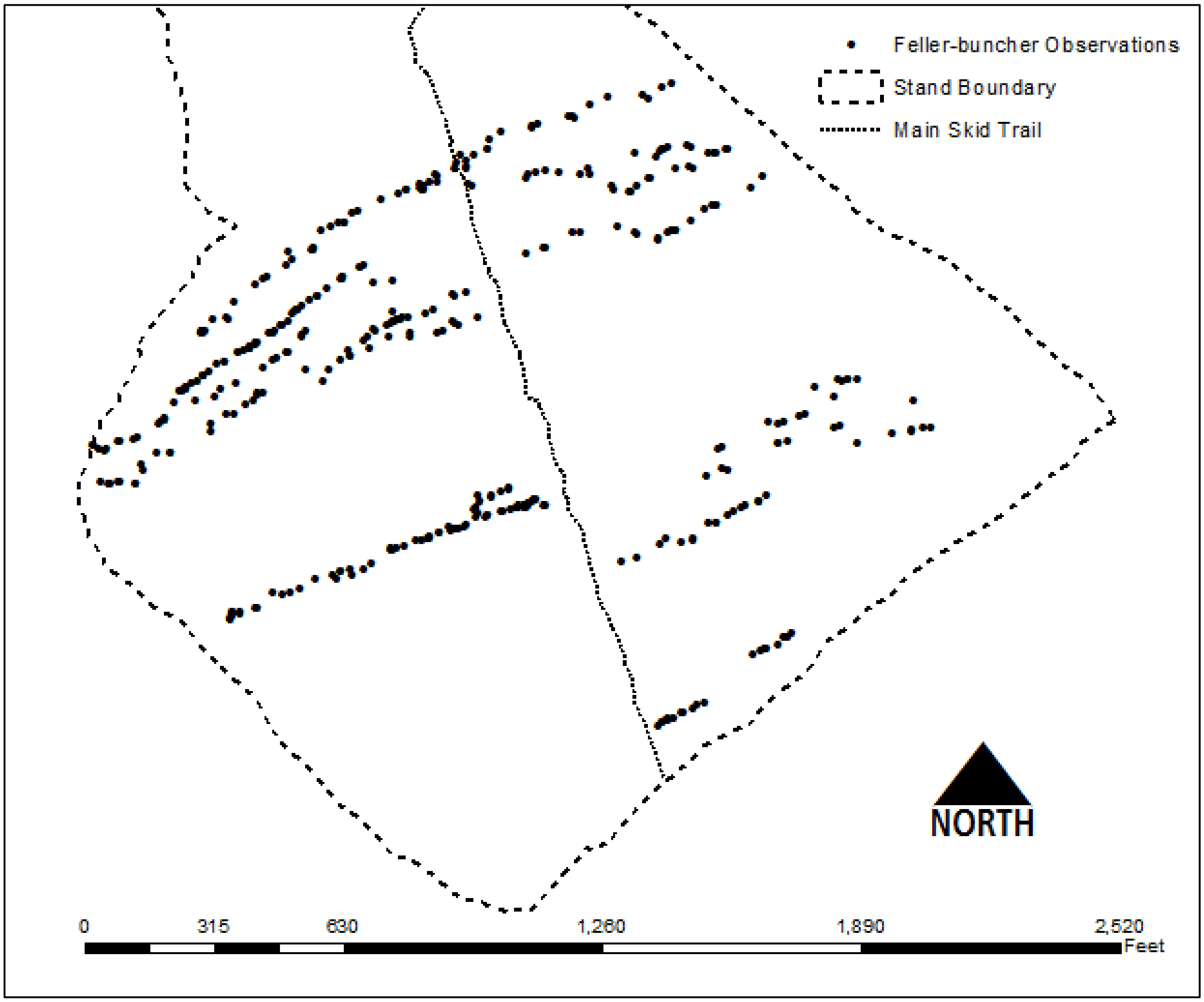


Figure 3.1. Logged GPS waypoints of feller-buncher cycle locations on case study site located in the Virginia Coastal Plain region

A two-sample, two-tailed t-test assuming non-equal variance (α = 0.05) was used to determine possible differences within the feller-buncher and skidder cycle data. For feller-buncher cycles, operator and thinning type were compared by the time per bunch and the number of stems per bunch. For skidders, operator and thinning type were compared by the time per skid turn, the number of stems per skid turn, and the skidding distance.

Machine rates (Miyata 1980) for the feller bunchers, skidders, chipper, and trucks were calculated and entered into the Auburn Harvesting Analyzer (AHA) (Tufts et al. 1985) to calculate harvesting costs in $/gt. Initial machine purchase prices for the feller-bunchers, skidders, and chipper were obtained directly from the logging contractor. Truck and chip van prices were estimated from on-line classifieds (Forestry Equipment Sales 2014) of similar equipment. Salvage value, machine life, interest, insurance and taxes, lubrication rate, maintenance and repair, and overhead assumptions were determined from Brinker et al. (2002). Utilization rates were calculated by dividing the observed number of productive machine hours (PMH) by the number of scheduled machine hours (SMH) for each machine. Fuel consumptions rates were obtained from Greene et al. (2014) and the Peterson website (Peterson Corporation 2014). Fuel costs were obtained from Timber Mart South (Timber Mart South 2014) and labor costs were based on figures from the US Bureau of Labor Statistics (US Department of Labor 2014).

## 3.4 Results and Discussion

### *3.4.1 Stand Characteristics*

Stand inventories showed a pre-harvest total density of 4,930 stems/acre, of which 723 stems/acre were loblolly pine, and a post-harvest density of 674 stems/acre including 267 stems/acre of loblolly pine (Table 3.1). The majority of stems measuring ≥ 2 inches DBH were loblolly pine with a smaller component of hardwoods, and all stems < 2 inches DBH were hardwood. Although the greater majority of the stand was dominated by a loblolly pine overstory, some smaller portions of the stand were dominated by red maple and oak species. Loblolly pine comprised 75% of the initial 77 gt/acre pre-harvest volume and 76% of the 34 gt/acre post-harvest volume, equating to a total removed volume of 43 gt/acre. Although the majority of all harvested stems were ≤ 4 inches DBH (Table 3.2), the majority of the total harvested volume was derived from stems > 4 inches DBH (25.89 gt).

Table 3.1. Initial, residual, and harvested stand volume and density characteristics of case study site

| | Initial (pre-harvest)[A] | Residual (post-harvest)[A] | Harvested (Initial – Residual) |
|---|---|---|---|
| Volume (gt/acre) | | | |
| All stems | 76.99 | 34.27 | 42.72 |
| Pine[B] | 57.91 | 26.19 | 31.72 |
| Hardwood[BC] | 19.08 | 8.08 | 11.00 |
| | | | |
| Density (stems/acre) | | | |
| All stems | 4,930 | 674 | 4,256 |
| Pine[B] | 723 | 267 | 456 |
| Hardwood[BC] | 4,207 | 407 | 3,800 |

[A] Number of observations = 45
[B] Plot size = 0.1 acres (stems ≥ 2 inches DBH)
[C] Plot size = 0.01 acres (stems < 2 inches DBH)

Table 3.2. Initial, residual, and harvested stand density and volume harvested by DBH class of case study site

| DBH Class | Initial Density (stems/acre) | Residual Density (stems/acre) | Harvested Density (stems/acre) | Volume Harvested (gt/acre) |
|---|---|---|---|---|
| 1 | 1,456 | 144 | 1,312 | 2.76 |
| 2 | 520 | 465 | 55 | 4.64 |
| 3 | 222 | 168 | 54 | 3.36 |
| 4 | 197 | 136 | 61 | 5.44 |
| 5 | 171 | 98 | 73 | 6.86 |
| 6 | 108 | 42 | 66 | 4.20 |
| 7 | 88 | 46 | 42 | 6.44 |
| 8 | 37 | 17 | 20 | 3.40 |
| 9 | 20 | 13 | 7 | 3.51 |
| 10 | 10 | 3 | 7 | 1.05 |
| 11 | 3 | 1 | 2 | 0.43 |

*3.4.2 Activity Sample*

Non-productive activities (i.e. waiting on chipper, refuel and maintenance, mechanical repairs, non-mechanical delay, and idle) comprised low percentages of the 939 sampled time observations equating to utilization rates of 84.3% and 91.5% for skidder Operators 1 and 2, respectively (Table 3.3). These rates are higher than equivalent measures in published guidelines (Miyata 1980, Brinker et al. 2002) and in similar studies (e.g. Bolding et al. 2009, Pan et al. 2008), implying that both skidder operators were highly productive. Both skidders were off the landing for the majority of the sampled time, 70.2% and 79.2% for skidder Operators 1 and 2, respectively, likely a result of the long skidding distances endured on the operation.

Table 3.3. Proportions of observed machine activities on case study site

| Loader | | Chipper | | Skidders | | |
|---|---|---|---|---|---|---|
| | | | | | *Operator 1* | *Operator 2* |
| % | | | | | | |
| Feeding chipper | 57.9 | Chipping | 57.9 | Off landing | 70.2 | 79.2 |
| Cleaning landing debris | 0.7 | Waiting on loader | 5.0 | Cleaning landing debris | 2.7 | 1.7 |
| Waiting on skidder | 6.0 | Waiting on chip van | 22.6 | Arriving from inhaul | 3.9 | 3.3 |
| Waiting on chip van | 22.5 | Refuel and maintenance | 2.3 | Departing for outhaul | 4.3 | 3.3 |
| Refuel and maintenance | 0 | Mechanical repairs | 0 | Decking turn | 3.3 | 3.9 |
| Mechanical repairs | 0 | Non-mechanical delay | 9.7 | Waiting on Chipper | 0.5 | 0.1 |
| Non-mechanical delay | 9.7 | Idle | 0.5 | Refuel and maintenance | 0 | 0 |
| Idle | 0.9 | Other | 1.9 | Mechanical repairs | 0 | 0 |
| Other | 2.3 | | | Non-mechanical delay | 1.7 | 3.3 |
| | | | | Idle | 11.1 | 2.8 |
| | | | | Other | 2.3 | 2.3 |
| Total | 100.0 | Total | 100.0 | Total | 100.0 | 100.0 |

Loader and chipper activities were synonymous with one another since all stems were whole-tree chipped and no product merchandising took place. Feeding the chipper/chipping accounted for 57.9% of the scheduled time, generating a chipper utilization rate lower than those in published guidelines (Miyata 1980, Brinker et al. 2002) and a collection of chipper productivity studies (Spinelli and Visser 2009). The low utilization rate of the chipper could possibly be attributed to the relatively large proportion of sample time spent waiting on chip vans (22.6%), suggesting that additional chip vans would have improved chipper utilization. Despite the low utilization rate, mechanical delays (i.e. one single chipper knife change) only accounted for 2.3% of sampled time, lower than that of the 8.0% average in the Spinelli and Risser (2009) study. Although this knife change incurred a relatively short delay in this study, more frequent knife changes could reasonably be expected in biomass-only harvests in comparison to integrated harvests due to more regular chipper use.

### *3.4.3 Feller-buncher Time Study*

A total of 398 feller-buncher cycles were observed ($n$ = 398) with a total bunching time of 632.93 minutes and total delay time of 37.65 minutes. Overall, feller-buncher cycles exhibited an average delay-free time of 1.50 minutes/cycle with 19 stems in each bunch (Table 3.4). However, since the feller-bunchers were cutting stems with diameters < 1 inch DBH, exact stem counts proved difficult to obtain, and the actual number of stems per bunch was likely greater than observed in most bunches. These overall average cycle times and stem counts translated to a mean productivity rate of 30.77 gt/PMH.

Table 3.4. Feller-buncher time study statistics

| | | Time per bunch (minutes) | | Stems per bunch | | Productivity (gt/PMH) |
|---|---|---|---|---|---|---|
| | n | Mean | SE | Mean | SE | |
| Overall | 398 | 1.50 | 0.031 | 19 | 0.38 | 30.77 |
| Row Thinning | 226 | 1.75[a] | 0.041 | 22[a] | 0.47 | 30.51 |
| Select Thinning | 172 | 1.17[b] | 0.035 | 17[b] | 0.56 | 35.32 |
| Operator 1 | 170 | 1.78[A] | 0.044 | 22[A] | 0.56 | 29.89 |
| Operator 2 | 129 | 1.43[B] | 0.055 | 19[B] | 0.62 | 32.17 |
| Operator 3 | 99 | 1.09[C] | 0.043 | 16[C] | 0.76 | 35.67 |

a, b means not connected by the same letter are significantly different (α = 0.05) between thinning types
A, B, C means not connected by the same letter are significantly different (α = 0.05) between operators

Cycle times and the number of stems per bunch varied by operator, with Operator 3 averaging 1.09 minutes/bunch with 16 stems, both significantly lower than Operators 1 and 2 (*p-values* < 0.001). The low cycle times of Operator 3 translated into a greater productivity rate than Operators 1 and 2 at 35.67 gt/PMH which was expected considering Operator 3 had several more years of experience than the other operators. Select thinning resulted in significantly shorter cycle times and fewer stems per bunch than row thinning ($p < 0.001$), with a time per bunch of 1.75 minutes in row thinning as compared to 1.17 minutes in select thinning and stems/bunch counts of 22 and 17, respectively. As a result, productivity during row thinning was less than select thinning with 30.51 gt/PMH compared to 35.32 gt/PMH, respectively. This difference in thinning productivity rates could be attributed to the larger number of select thinning cycles performed by Operator 3 (99 of 172 observations), the most experienced operator, and the large number of row thinning cycles performed by Operator 1 (170 of 226 observations), the least experienced operator.

### 3.4.4 Skidder Time Study

A total of 145 skidder cycles were observed ($n$ = 145) with a total skid time of 1,503 minutes and delay time of 48 minutes. Delay-free skid time averaged 10 minutes per skidding cycle with 97 stems per turn and an average distance of 1,427 feet from the turn pick-up location to the landing (Table 3.5). On average, overall skidder productivity was 23.42 gt/PMH.

Table 3.5. Skidder time study statistics

| | | Time per skid turn (minutes) | | Stems per skid turn | | Skid distance (feet) | | Productivity (gt/PMH) |
|---|---|---|---|---|---|---|---|---|
| | n | Mean | SE | Mean | SE | Mean | SE | |
| Overall | 145 | 10.04 | 0.48 | 97 | 2.76 | 1427 | 41.68 | 23.42 |
| Row Thinning | 101 | $11.33^{a}$ | 0.63 | $88^{a}$ | 2.90 | $1568^{a}$ | 50.08 | 18.82 |
| Select Thinning | 44 | $7.06^{b}$ | 0.43 | $118^{b}$ | 4.90 | $1103^{b}$ | 48.08 | 40.47 |
| Operator 1 | 83 | $9.00^{A}$ | 0.49 | $95^{A}$ | 4.20 | $1186^{A}$ | 33.41 | 25.56 |
| Operator 2 | 62 | $11.41^{B}$ | 0.90 | $99^{A}$ | 3.17 | $1751^{B}$ | 67.72 | 21.01 |

a, b means not connected by the same letter are significantly different (α = 0.05) between thinning types
A, B means not connected by the same letter are significantly different (α = 0.05) between operators

Similar to the feller-bunchers, significant differences were found between skidder operators. Skid turn times were significantly less for Operator 1 as compared to Operator 2 ($p$ = 0.021) with 9.00 minutes/turn compared to 11.41 minutes/turn, respectively. However, Operator 2 had significantly greater skid distances ($p < 0.001$), nearly 600 feet further than Operator 1, which contributed to longer skid turn times. The number of stems per turn was not significantly different between the operators ($p = 0.452$). Operator 1 often demonstrated a more predictable technique than Operator 2, usually combining three to four bunches created by the feller-buncher from one area into one skid turn, whereas Operator 2 often combined three to four bunches from different rows to comprise a turn.

Stems per skid turn were significantly fewer in row thinning (88 stems/turn) than select thinning (118 stems/turn) ($p < 0.001$). This difference was likely caused by the lower number of stems needed to comprise a turn during row thinning since this thinning type removed more large diameter stems than select thinning. Skid turn times were significantly shorter when skidding stems from a select thinning as compared to skidding from a row thinning ($p < 0.001$) with 7.06 minutes/turn and 11.33 minutes/turn, respectively. However, significantly longer skid distances for the row thinning ($p < 0.001$) caused by the selection of observation locations may have influenced these times, considering the turns observed from row thinnings were skidded over 400 feet further than turns observed from selecting thinning. Additionally, machine maneuverability in the stand was improved following select thinning which may have further contributed to reduced skid turn times for select thinning. The productivity rate for the select thinning was greater than the row thinning with 40.47 gt/PMH compared to 18.82 gt/PMH, respectively. This large difference in productivity between thinning types was believed to be influenced by a combination of factors including the longer skid distances for row thinning and a possible disproportionate sampling of select thinning observations (only 44 of 145 total observations).

*3.4.5 Chipper Time Study*

Chipper observations took place over five workdays with 41 loads taken to Plant 1 and 7 loads to Plant 2 ($n$ = 48). Total observed van loading time was 1,112 minutes and total delay time was 118 minutes equating to an average delay-free time of 19.13 minutes/load and an average delay time of 3.79 minutes/load. Complications caused by weather led to longer observed load times during the fourth work day and operations were completely halted the following day, which was not observed. With an average chip van payload of 26.67 gt/load, the overall average chipper productivity was 83.67 gt/PMH. The observed removed volume totaled 1,280 gt, and haul distances averaged 71.2 miles round-trip.

Mill tickets and other associated information were obtained from the logging contractor. A total of 167 loads were transported from the tract: 120 to Plant 1, 44 to Plant 2, and 3 to a third plant which was not observed during the case study. Multiple plant breakdowns during the operation led to a greater number of deliveries to Plant 2 than was expected initially. Fifteen workdays were spent on the site removing a total volume of 4,405 gt.

*3.4.6 Harvesting Costs*

To develop an estimate of harvesting costs, the Auburn Harvesting Analyzer (AHA) was used with the collected data and other information regarding machine and labor costs (Table 3.6). Costs of $16.52/gt on-board truck and $23.46/gt total cut-and-haul were estimated using the AHA (Table 3.7). All trucks and chip vans were owned by the logging contractor and no contract trucking was used to transport biomass to the energy facilities. Hauling was the largest portion of the cut-and-haul cost at 33% ($6.94/gt) followed by felling at 24% ($5.12/gt), chipping at 22% ($4.67/gt), and skidding at 21% ($4.34/gt) (Figure 3.2).

Table 3.6. Machine rate (Miyata 1980) assumptions used to calculate harvesting costs

| | Tigercat 718 feller-buncher | Caterpillar 535C skidder | Tigercat 234 loader | Peterson 4300B chipper | Kenworth truck and chip van |
|---|---|---|---|---|---|
| Initial cost ($) | $200,000 | $250,000 | $225,000 | $400,000 | $170,000 |
| Salvage value (% of initial) | 20 | 20 | 20 | 20 | 20 |
| Machine life (years) | 5 | 5 | 5 | 5 | 5 |
| Interest rate (%) | 10 | 10 | 10 | 10 | 10 |
| Insurance and taxes (% of initial) | 4.5 | 5 | 1.5 | 2.5 | 5 |
| Fuel consumption (gallons/PMH) | 6.56 | 5.09 | 3.71 | 16.73 | 5 |
| Fuel cost ($/gallon) | 3.53 | 3.53 | 3.53 | 3.53 | 3.70 |
| Fuel and lubrication ($/PMH) | 32.42 | 25.15 | 18.33 | 103.35 | 22.20 |
| Maintenance and repairs ($/PMH) | 17.02 | 18.56 | 27.93 | 38.10 | 18.83 |
| Labor ($/SMH) | 18 | 18 | 24 | 0 | 16 |
| Utilization (%) | 60 | 84.3[α]/91.5[β] | 58.6 | 57.9 | 65 |
| Number of machines | 3 | 2 | 1 | 1 | 5 |

[α] Skidder Operator 1
[β] Skidder Operator 2

Table 3.7. Auburn Harvest Analyzer (Tufts et al. 1985) productivity inputs and cost outputs of harvesting equipment

| *Machine Productivity* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| FELLING | | SKIDDING | | LOADING | | CHIPPING | | HAULING | |
| Avg Stems per Bunch = | 19 | Avg Stems per Turn = | 97 | Avg Payload (tons) = | 26.67 | Avg Payload (tons) = | 26.67 | Avg Payload (tons) = | 26.67 |
| Avg Bunch Volume (tons) = | 0.79 | Avg Turn Volume (tons) = | 3.92 | Time per Load (minutes) = | 19.13 | Time per Load (minutes) = | 19.13 | Round Trip Time (hours) = | 2 |
| Time per Bunch (minutes) = | 1.50 | Time per Turn (minutes) = | 10.04 | | | | | | |
| Tons/PMH = | **30.77** | Tons/PMH = | **23.42** | Tons/PMH = | **83.76** | Tons/PMH = | **83.76** | Tons/PMH = | **13.34** |
| Oper Effy = | **1.0** | Oper Effy = | **1.0** | Oper Effy = | **1.0** | Oper Effy= | **1.0** | Oper Effy= | **1.0** |
| *Machine Cost* | | | | | | | | | |
| D ($/SMH)= | **16.00** | | **20.00** | | **18.00** | | **32.00** | | **13.6** |
| II&T ($/SMH)= | **5.80** | | **7.50** | | **5.18** | | **10.00** | | **5.10** |
| F&L ($/PMH)= | **32.42** | | **25.15** | | **18.33** | | **103.35** | | **22.20** |
| M&R ($/PMH)= | **26.67** | | **20.69** | | **27.65** | | **55.27** | | **18.83** |
| Labor($/SMH)= | **18.00** | | **18.00** | | **24.00** | | **0.00** | | **16.00** |
| Fringe (%)= | **45** | | **45** | | **45** | | **45** | | **45** |
| Avail.(%) = | **90** | | **96** | | **100** | | **98** | | **90** |
| Number = | **3** | | **2** | | **1** | | **1** | | **5** |

| Function | Tons /PMH | Avail% | Tons/SMH One | All | Utiliz% | Cost per SMH Fixed | Oper | Labor | Total | Cost $/Ton |
|---|---|---|---|---|---|---|---|---|---|---|
| Felling | 30.77 | 90.00 | 27.69 | 83.08 | 48.71 | 65.40 | 86.35 | 78.30 | 230.05 | 5.12 |
| Skidding | 23.42 | 96.00 | 22.48 | 44.97 | 96.00 | 55.00 | 88.02 | 52.20 | 195.22 | 4.34 |
| Loading | 83.76 | 100.00 | 83.76 | 83.76 | 53.68 | 23.18 | 24.68 | 34.80 | 82.66 | 1.84 |
| Chipping | 83.76 | 98.00 | 82.08 | 82.08 | 53.68 | 42.00 | 85.15 | 0.00 | 127.15 | 2.83 |
| Hauling | 13.34 | 90.00 | 12.00 | 60.01 | 67.44 | 93.50 | 138.36 | 80.00 | 311.86 | 6.94 |
| Support | Pickups, Chainsaws, Foreman, and Overhead | | | | | | | | | 1.29 |
| Road Work | Gravel Entrance | | | | | | | | | 0.14 |
| Moving | 4.00 hours spent moving men & equipment to tract | | | | | | | | | 0.96 |

| | | | |
|---|---|---|---|
| | | On board truck Cost/Ton | 16.52 |
| System Rate (tons/SMH) = | 44.97 | System Cost/Ton | 23.46 |
| Weekly production (tons) = | 1799 | | |
| Days required to cut tract = | 11 | | |

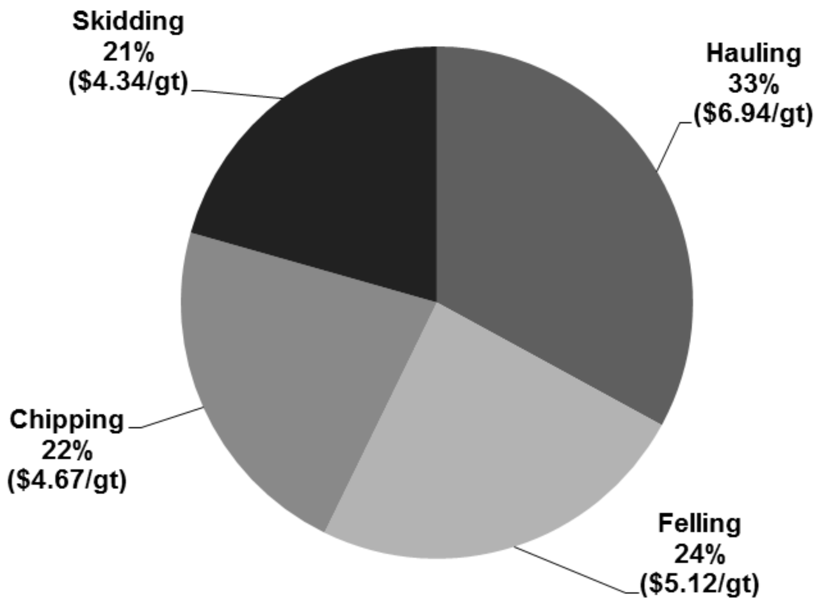



Figure 3.2. Harvesting component costs as a percentage of the total cut-and-haul cost

Past case studies have also observed hauling as the greatest proportion of the total cut-and-haul cost when utilizing small-diameter stems as caused by un-maximized payloads, long haul distances (e.g., Bolding and Lanford 2005), and extensive off-highway travel distances (e.g., Pan et al. 2008). However, high hauling costs in this study were most likely a result of the relatively large number of trucks owned by the harvesting contractor (5 trucks) and not the factors in these previous studies, considering that nearly all payloads were maximized, the average loaded distance was less than 40 miles, and nearly all travel was on paved roads. Additionally, felling costs comprised a larger component of total cut-and-haul costs in this study compared to similar studies (e.g., Pan et al. 2008, Bolding et al. 2009), most likely due to the high harvesting costs of using three feller-bunchers in this study whereas other studies only used one single feller-buncher.

The calculated system rate of the observed machine configuration, defined as the harvesting function with the lowest productivity rate, was skidding at 44.97 gt/scheduled machine hour (SMH). It was believed by the logging contractor that three feller-bunchers were needed to balance the productivity of the two skidders. However, sensitivity analysis completed in the AHA showed that by reducing the number of feller-bunchers from three to two, the system is balanced, and the total cut-and-haul cost is reduced to $22.28/gt, a reduction of 5%. With the system balanced, the discrepancy between the productivities of the feller-bunchers and skidders is reduced from 38.11 gt/SMH to 10.42 gt/SMH, and actual function utilization of the feller-bunchers is improved, increasing from 44.97% to 73.07%.

### 3.5 Conclusion

The purpose of this case study was to analyze the effects of utilizing small-diameter stems on harvesting costs. Past case studies have examined the use of small-diameter stems during integrated harvest scenarios in which conventional products were harvested as well. This case study was unique in that all harvested stems were chipped for biomass energy and no merchandising took place during the course of the operation. Using collected data and harvesting cost assumptions in the AHA, we calculated a total cut-and-haul cost of $23.46/gt. Hauling was found to be the largest component of the total cut-and-haul cost at 34%, consistent with other small-diameter stem utilization case studies. Assuming a delivered price of $17.35/gt, this operation failed to break even. However, balancing the operation in the AHA by reducing the number of feller-bunchers from three to two was found to produce a cut-and-haul cost of $22.28/gt, suggesting that this operation could be nearly economically feasible with an adjusted machine configuration.

Results of this case study provide further insight into harvesting costs associated with removing small diameter stems for woody biomass energy. However, certain limitations must be considered when interpreting the results. Several unique characteristics regarding the operation used in this case study must be considered, including the relatively close proximity (30 miles) of the biomass energy facility to which the majority of the chips were taken, the relatively large size of the operation (3 feller-bunchers, 2 skidders, 5 trucks), and the decision of the logging contractor to forgo the opportunity of merchandising any stems that could have possibly been used for pulpwood (25.89 of the 42.72 gt/acre total harvested volume was > 4 inches DBH). Furthermore, this study did not separate harvesting costs of utilizing conventionally non-merchantable stems (< 4 inches DBH) from merchantable stems (> 4 inches DBH); harvesting costs were calculated for all diameter classes in aggregate. Therefore, it remains unclear at which diameter class (i.e. 4 inches, 3 inches, etc.) woody biomass becomes merchantable. Additional research regarding biomass-only harvests of young pine stands would help to further explain the harvesting costs associated with chipping small-diameter stems for biomass.

## Literature Cited


Baker, S. A., Westbrook Jr, M. D., and W.D. Greene. 2010. Evaluation of integrated harvesting systems in pine stands of the southern United States. Biomass and Bioenergy, 34(5):720-727.

Baker, S., Greene, D., and T. Harris. 2012. Impact of timber sale characteristics on harvesting costs. In Proc. Southern Forest Economics Workshop, Charlotte, North Carolina. pp. 94-105.

Barrett, S.M., Bolding, M.C., Aust, W.M., and J.F. Munsell. 2014. Characteristics of logging businesses that harvest biomass for energy production. Forest Products Journal, 64(7/8):265-272.

Bolding, M. C. and B.L. Lanford. 2005. Wildfire fuel harvesting and resultant biomass utilization using a cut-to-length/small chipper system. Forest Products Journal, 55(12):181-189.

Bolding, M. C., Kellogg, L. D., and C.T. Davis. 2009. Productivity and costs of an integrated mechanical forest fuel reduction operation in southwest Oregon. Forest Products Journal, 59(3):35-46.

Brinker, R.W., Kinard, J., Rummer, B., and B. Lanford. 2002. Machine rates for selected forest harvesting machines. Circular 296 (revised). Alabama Agricultural Experiment Station, Auburn University, Auburn, Alabama. 29 pp.

Bullock, B. P. and H.E. Burkhart. 2003. Equations for predicting green weight of loblolly pine trees in the South. Southern Journal of Applied Forestry, 27(3):153-159.

Burkhart, H. E., Haney, H. L., Newberry, J. D., Leuschner, W. A., Morris, C. L., and D.D. Reed. 1986. Evaluation of thinning for reduction of losses from southern pine beetle attack in loblolly pine stands. Southern Journal of Applied Forestry, 10(2):105-108.

Cain, M. D. 1993. Ten-year results from precommercial strip-thinning: paradigm lost or reinforced?. Southern Journal of Applied Forestry, 17(1):16-21.

Clark, A., Saucier, J.R., and W.H. McNab. 1986. Total-tree weight, stem weight, and volume tables for hardwood species in the southeast. Georgia Forest Research Paper 60. Research Division, Georgia Forestry Commission. 45 pp.

Conrad, J. L., Bolding, M.C., Aust, W.M., Smith, R.L., and A. Horcher. 2013. Harvesting productivity and costs when utilizing energywood from pine plantations of the southern coastal plain USA. Biomass and Bioenergy, 52(2013):85-95.

Demers, C., Long, A., and J. Nowak. 2010. Thinning Southern Pines-A Key to Greater Returns. Florida Cooperative Extension Service. School of Forest Resources and Conservation, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL. 5 pp.

Forestry Equipment Sales. 2014. Available at: https://forestryequipmentsales.com/34/Log-Trucks.html (last accessed Dec. 24, 2014).

Grano, C. X. 1969. Precommercial thinning of loblolly pine. Journal of Forestry, 67(11):825-827.

Greene, W. D., Biang, E., and S. A. Baker. 2014. Fuel consumption rates of southern timber harvesting equipment. Proc. 37th Counc. For. Eng. Ann. Meeting. Moline, IL. 5 pp.

Koch, P., and D.W. McKenzie. 1976. Machine to harvest slash, brush, and thinnings for fuel and fiber--a concept. Journal of Forestry, 74(12):809-812.

Lohrey, R. E. 1977. Growth responses of loblolly pine to precommercial thinning. Southern Journal of Applied Forestry. 1(3):19-22.

Mitchell, D., and T. Gallagher. 2007. Chipping whole trees for fuel chips: A production study. Southern Journal of Applied Forestry, 31(4):176-180.

Miyata, E.S. 1980. Determining fixed and variable costs of logging equipment. General Technical Report NC-55. USDA Forest Service North Central Forest Experimental Station, St. Paul, Minnesota. 20 pp.

Munsell, J. F., and T. R. Fox. 2010. An analysis of the feasibility for increasing woody biomass production from pine plantations in the Southern United States. Biomass and Bioenergy, 34(12):1631-1642.

Nowak, J., Asaro, C., Klepzig, K., and R. Billings. 2008. The southern pine beetle prevention initiative: working for healthier forests. Journal of Forestry, 106(5):261-267.

Pan, F., Han, H. S., Johnson, L. R., and W. J. Elliot. 2008. Production and cost of harvesting, processing, and transporting small-diameter (≤ 5 inches) trees for energy. Forest Products Journal, 58(5):47-53.

Peterson Corporation. 2014. Available at: http://www.petersoncorp.com/index.php?option=com_content&view=article&id=957:biomass-fuel-processing&catid=155:applications&Itemid=834 (last accessed Dec. 24, 2014).

Spinelli, R., and R. J. Visser. 2009. Analyzing and estimating delays in wood chipping operations. Biomass and Bioenergy, 33(3):429-433.

Timber Mart South. 2014. Norris Foundation, University of Georgia, Athens, Georgia. 3rd Quarter.

Trimble Navigation Limited. 2015. Available at: http://www.trimble.com/forestry/solo-360.aspx?dtID=overview& (last accessed Apr. 24, 2015).

Tufts, R. A., Lanford, B.L., Greene, W.D., and J.A. Burrows. Auburn harvesting analyzer. Compiler 3(2):14-15

United States Department of Labor Bureau of Labor Statistics. 2014. Available at: http://www.bls.gov/oes/current/oes454022.htm (last accessed Dec. 24, 2014).

Virginia Department of Forestry. 2015. Available at: http://www.dof.virginia.gov/locations/chesterfield.htm (last accessed Apr. 24, 2015)

Watson, W. F., and B.J. Stokes. 1989. Harvesting small stems–A southern USA Perspective. In Proc. of the International Energy Agency, Task VI, Activity 3 Symposium, Harvesting small trees and forest residues. USDA Forest Service Southern Forest Experiment Station, Auburn, Alabama. pp. 131-139.

Web Soil Survey. 2013. Available at: http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx (last accessed May 27, 2014).

# Chapter 4. Implications and Further Research

The purpose of this thesis project was to determine the abundance of woody biomass available for potential harvest in PCT stands by conducting inventories of stands with PCT conditions and then assess harvesting productivity and costs of harvesting small-diameter biomass by completing a case study on a site with ‘near-PCT’ conditions. This project was unique in that harvestable biomass in PCT stands has not previously been quantified and little work has been done to analyze forest operations in biomass-only harvests of young pine stands. When combined, these two components of the thesis project provide valuable insight in assessing the potential use of PCT stands for biomass harvesting. Our PCT stand inventory results suggest that some stands at the upper age limit for PCT (e.g., 8 – 12 years old) may possess biomass volumes great enough to warrant a biomass harvest as opposed to a conventional PCT treatment. Our case study results suggest that small-diameter biomass-only harvests prove difficult to be economically feasible given their relatively high harvesting costs, although optimally balanced operations will improve feasibility. This chapter will explore the implications of this thesis project and the potential opportunities for further research.

The results from this project will be useful for a variety of stakeholders, including foresters, harvesting contractors, energy facility planners, and landowners. Foresters and harvesting contractors can use the PCT biomass estimations as a baseline in evaluating available harvest volumes in young southern pine stands. The costs from the case study provide these same stakeholders with estimations of the harvesting costs associated with utilizing young southern pine for biomass. For energy facility planners, PCT biomass estimations will aid in determining the potential contribution of PCT stands as a feedstock for domestic woody biomass energy facilities. Lastly, project results will help landowners assess the decision between conducting a conventional PCT treatment versus conducting a small-diameter biomass harvest. In the case where the cost of harvesting PCT biomass is wholly or partially outweighed by the revenue associated with utilizing biomass, it may be more cost-effective for landowners to allow a biomass harvest instead of a conventional PCT treatment.

Further research is needed to more effectively analyze biomass volumes in PCT stands. To more accurately predict the volume in these stands, growth and yield equations must be improved upon to include more sampling of small-diameter stems (e.g., < 4 inches DBH). Many growth and yield equations for southern pine are focused on stems ≥ 4 inches DBH. In Chapter II, a combination of equations was used to estimate biomass volume. The creation of equations meant specifically for southern pine stems 1 – 3 inches DBH would provide more suitable means for predicting volumes of small-diameter stems. In addition to better equations, a wider sampling distribution would further improve biomass volume estimations. The PCT stand inventory in this project was only able to collect data on sites throughout Virginia. Since PCT is a silvicultural practice used throughout the southeast, biomass volume estimates in other southeastern US states would provide more accurate measures of region-wide PCT biomass volumes. Considering the variety of site factors (i.e. soil type, precipitation, nutrient availability) that affect the growth and yield of southern pine, PCT biomass volumes may vary substantially across the region.

Additional work is also needed to further assess the productivity and harvesting costs of utilizing young southern pine stands for biomass. As discussed in Chapter III, the majority of previous biomass-only harvesting case studies have focused on southern pine stands older than 20 years containing relatively large volumes of standing biomass. Although the case study in this project took place on a 15-year old southern pine stand with near-PCT conditions, further research on multiple sites with varying stand-level characteristics (i.e. age, density, average

DBH, etc.) would provide more insight on the feasibility of harvesting PCT biomass. A range of operational-level characteristics (i.e. harvest intensity, machine configurations, proximity to energy facilities, etc.) would provide additional insight as well.

Overall, this project has demonstrated that PCT stands may be suitable for harvesting biomass in certain scenarios. If harvesting costs were to decrease relative to delivered prices for woody biomass, harvesting PCT biomass would become more financially attractive to both harvesting contractors and landowners. As long as PCT remains a common silvicultural practice to reduce stand density and woody biomass energy markets remain viable, the utilization of PCT biomass presents a potential management strategy that benefits multiple stakeholders.