A Comparison of Chipper Productivity, Chip Characteristics, and Nutrient Removals from Two Woody Biomass Harvesting Treatments

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Abstract

Increased costs of fossil fuels, regulatory policies, and investments by federal and state governments have caused increased interest and incentive for the use of wood as a renewable form of energy. As a result, landowners and forest managers are considering chipping whole trees and harvesting residues as a means to meet increased demand of wood chips as a renewable source of energy. However, the profitability, productivity gains, and sustainability of these alternative harvesting methods continue to be an area of research. The objective of this study was to compare two biomass harvesting treatments with regard to the characteristics of the chips they produced, chipper productivity, nutrient removals, and site disturbance. The first biomass harvesting treatment was an integrated harvest where roundwood was merchandized and hauled to the appropriate mill and limbs, tops, and small stems (residues) were chipped for hog fuel. The second biomass harvesting treatment simulated a scenario where biomass markets were competing with pulpwood markets and landowners could choose to sell wood for energy or pulp wood. In this treatment whole trees and small stems were chipped for hog fuel. A third harvesting treatment was a conventional roundwood harvest where no wood was chipped, and this treatment was used as a control for comparison of nutrient removals and site disturbance. The chips produced from both harvesting treatments were very similar, but those produced from whole trees tended to be slightly smaller than those produced from residues. Chipper productivity was significantly higher when chipping whole trees and it was also much more efficient in terms of fuel use. Estimations of nutrient removals showed that there was very little difference in the amount of nutrient removed from the biomass harvesting treatments, but both treatments removed significantly more N and Ca than the conventional roundwood harvesting treatment. There was significantly more downed and standing material left on the site after harvesting in the conventional treatment, but this did not translate into a large amount of additional nutrients left on the site. There was little difference in soil disturbance between all three treatments, and due to the dry soil conditions during harvesting, there was very little visual soil disturbance at all during harvesting.

Keywords: biomass harvesting, harvesting sustainability, nutrient removals, chip quality

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Chapter 1: Introduction

Currently the Southern United States relies on coal and natural gas to produce approximately 75 percent of its electricity (EIA 2011). This number is predicted to change because of regulatory policies as well as investments by federal and state governments in biomass energy (Conrad et al. 2010). Thirty-three states and the District of Colombia have adopted renewable portfolio standards, which are goals that mandate utilities to produce a certain percentage of electricity from renewable sources by a target date (Database of State Incentives for Renewable and Efficiency 2010). These goals range from 15 percent by 2015 to as much as 25 percent by 2025. Only three southern states, North Carolina, Texas, and Virginia, have renewable portfolio standards. However, all southern states have financial incentives promoting bioenergy (Alavalapati et al. 2009).

While the majority of renewable portfolio standards and federal and state incentives are associated with wind and solar energy, wood energy is another source of renewable energy. Wood is commonly used as a source of energy as wood pellets in home or business stoves and as feedstocks in wood-fired or co-fired electrical plants. It has been theorized that wood-energy companies will utilize mill residues, harvesting residues, urban residues, and other low valued wood (Perlack et al. 2005). However, requirements for materials used by pellet facilities, small stoves in homes or businesses, and large wood-fired or co-fired electrical power plants are different for every facility. Typically biomass electricity generation is similar to fossil fuel electricity generation in that biomass is burned for heat to produce steam that powers turbines which produce electricity. While it is generally accepted that higher quality fuels help heating systems perform better, burning the highest quality fuels may not be the intent of the facility. Some systems are installed with the intent of using locally available materials to offset the cost of using other, more expensive fuels (Biomass Energy Research Center 2007). However, smaller combustion systems (those that generate less than 250 kW) are often more sensitive to the quality of the fuel because of their combustion process and fuel handling equipment.

One source of material to feed combustion facilities is harvesting residues. Milbrant (2005) estimated that forest residues could provide 5.7×10^7 dry t $year^{-1}$ of material nationally which represents 13% of biomass nationally and 22% in the southeastern United States. At the stand level, Eisenbies et al. (2009) estimates that there are 50 to 85 dry t ha^{-1} of material available after a typical stem-only harvest on pine plantations on the southern United States. This, of course, depends on the age of the stand and the harvesting practice employed. The materials that make up harvesting residues often include limbs, tops, cull tress, and other odd sized woody debris that are considered nonmerchantable. Because of extreme variability of these materials, they have the potential to create fuels that vary in quality (Leinonen 2004). There are also environmental concerns regarding the removal of extra materials from harvested sites. These are chiefly focused on the removal of nutrients and the long term site productivity. It has long been recognized that residual materials are an important part of nutrient cycling in forest stands.

As interest in renewable energy increases, there will likely be an increased interest in harvesting residues as a source of fuel. Combustion facilities, with varying fuel quality standards, will be part of this increased interest. Therefore the research community must address the varying quality of fuels produced from different harvested materials. In addition, the site impacts and sustainability of removing additional material should be analyzed and better understood.

Chip Characteristics

Wood is most often used in direct combustion systems to generate electricity, but it can also used to generate electricity through gasification or pyrolysis. Additionally, wood can be used for space heat in homes, institutions, or manufacturing facilities. The quality of the materials used in each of these consumption processes can influence how well the system functions. Important material properties regarding conversion of woody material into energy are moisture content, calorific value, proportions of fixed carbons and volatiles, ash/residue content (which can include foreign contaminants), alkali metal content, and cellulose/lignin content (McKendry 2002). The quality factors deemed most important depend specifically on the process being used to convert the wood to energy. In most direct combustion systems, the main concerns with wood quality are moisture content, size distribution, energy content, the ash content.

The moisture content of wood typically ranges between 35 and 60 percent on a green or wet basis (Ragland et al. 1991). Softwoods typically have a moisture content around 55 percent and hardwoods typically have a moisture content of 50 percent although this can vary between species (Kofman 2006). This can affect the quality of wood chips being used in several different ways. The moisture content can affect the amount of recoverable energy, the ability to store wood chips for extended periods, and the cost of using wood chips as a fuel. During combustion, the moisture within a chip must be evaporated before the chip can burn. This causes the net energy within a chip to be lower when moisture contents are higher (Biomass Energy Resource Center 2007). Moisture content can also decrease the amount of time that chips can be stored. This is because increased moisture contents can promote fungal growth, and is especially true when there are fine particles. Higher moisture contents also limit storage during the winter because problems with chips freezing. Increased operating costs are also associated with using chips that have higher moisture contents. Because high moisture content chips contain less energy, more chips must be burned to produce the same amount of energy (Biomass Energy Resource Center 2007). Depending on the boiler being used, chips will often have to be dried to reach a specific moisture content, and this can add significant costs to using wood chips for energy production (Kofman 2006).

The desired moisture content for wood chips depends largely on the boiler that they will be burned in. For larger combustion systems the target moisture content is between 30 and 35 percent, but because of variety in boilers, some can handle moisture contents as low as 15 percent and some as high as 50 percent (Biomass Energy Resource Center 2007).

Biomass piece size distribution is an important factor mainly because of difficulties with handling material at processing facilities. If there are long, thin particles bridging occurs, which can be disruptive to conveying systems (Hartmann et al. 2006). Bridging refers to the formation of hollow cavities in hoppers or bins as material below long pieces is removed. Additionally, size distribution can affect the ability to store wood chips for extended periods of time. This is especially true when there are fine particles present that can reduce air circulation, support bacterial and fungal growth, and increase the risk of combustion (Nati et al. 2010). Varying size distributions can also influence the combustion process and emissions. While many boilers and processing facilities have the ability to handle a variety of material sizes, small combustion facilities, such as those used in homes, schools, hospitals, small businesses, etc, often have limitations on the size and type of fuel they may consume.

Wallace (1993), Leary (1995), and Auel (1996) investigated factors that affect the quality of chips to be used in different pulping processes. Size distribution, which is an important factor in the pulping process, was the main focus of these studies. In the pulp and paper industry, chips are classified according to their thickness (Borlew and Miller 1970), whereas chips being used for biomass are classified according to their largest dimension (Alakangas et al. 2006). Leary (1995) pointed out that larger pieces tended to make better chips (chips with a more uniform size distribution) and chip quality was also affected by disc speed, knife angle, anvil wear, and knife wear. Two types of chippers that are commonly used to produce fuel chips are disc and drum chippers. While the type of chipper used has some effect on the size of the chips produced, using worn blades and anvils can create an increase in the amount of fine particles, the amount of overlong particles, and chip shape becomes less defined (Kofman 2006). With regard to the material being chipped, whole tree chips including bark and foliage commonly have a more varied size distribution than chips produced from stem wood (Asikainen and Pulkkinen 1998). Nati et al. (2010) found that chipping stems produced a significantly higher percentage of acceptable chips than chipping limbs. They also found that chips produced from limb material produced a significantly higher percentage of oversized particles.

Auel (1996) classified chips in three ways: overlength/thick, acceptable, and pins/fines. These classes corresponded to what size screen chips would be caught in and described how acceptable they would be when used in a pulping process. While no official standards for fuel chips exist in the United States, the European Committee for Standardization (CEN) has prepared specifications for solid biofuels. Part of these specifications address wood chip size distribution and rate the quality of chips based on the size distribution of 80 percent of the weight (Alakangas et al. 2006). For instance, wood chips with 80 percent of their weight falling in a size class of $3.15\text{mm} < P < 16$ mm would be classified as P16 wood chips.

The energy content of a material is an expression of the amount of energy released when the material is burned and is reported in energy per unit mass such as BTU/lb. This value can either be expressed as a higher heating value (HHV) or a lower heating value (LHV). The HHV is the energy value of wood at zero percent moisture content, and the LHV is the energy value after all of the moisture has been vaporized during combustion (McKendry 2002). As this suggests, moisture content plays a large role in the amount of energy that can be recovered. When the energy content of different tree species are compared on a dry weight basis, softwoods have a higher BTU value than hardwoods, but this is not always the case because energy content can vary by moisture content of the species, density of the wood, and certain species have oils that can increase their BTU/lb value.

When biomass is combusted, it produces a solid residue called ash. Ash can create significant operational problems especially in combustion processes. Large amounts of ash can reduce the amount of recoverable energy, reduce the amount of through put at processing facilities, and increase the overall processing costs (McKendry 2002). Ash comes either from the wood itself or from dirt or grit picked up during harvesting or another part of processing. The ash content of pure wood is quite low at around 0.5 percent, but if wood and bark are burned together, this increases to about 1 percent (Kofman 2006).

Ash can cause more problems when there is a high alkali metal content. Silica found in the ash can bind with alkali metals (Na, K, Mg, P, and Ca) to form “Clinkers” that can block air ways in the furnace or boiler plant (McKendry 2002). While the silica content of the material being used may not be cause for concern, excess silica from soil can contaminate wood chips during the harvesting process.

Harvesting Logistics

Another important aspect of harvesting woody biomass is the method used and the costs associated with doing so. Watson and Stokes (1989) recognized four methods of harvesting woody biomass: 1) using specialized machines to harvest logging slash and non-commercial stems, 2) post-harvest collection following conventional logging, 3) pre-harvest collection prior to conventional logging, and 4) an integrated operation harvesting traditional roundwood products and energy wood simultaneously. Researchers have indicated that 1-pass systems are less expensive than 2-pass systems (Stuart et al. 1981, Stokes et al. 1984, Miller et al. 1987). When compared to a pre-harvest system, an integrated approach to harvesting woody biomass can be 30-40% less expensive, but the costs of harvesting pulpwood and sawlogs can be reduced following pre-harvest (Miller et al. 1987, Watson and Stokes 1989). Stokes et al. (1984) found that while an integrated approach to harvesting biomass resulted in the least cost and the highest biomass utilization, chipping costs were higher in the integrated system because chipper utilization was lower.

When woody biomass is harvested and brought to a landing it can be processed by chipping, chunking, crushing, bundling, or grinding/shredding/hogging. Chipping is the most common method of processing woody biomass for energy in the southeast. Westbrook et al. (2007) found that adding a small chipper to a tree-length operation could deliver dirty chips for \$12 t^{-1} when only limbs and tops were used and \$13 t^{-1} when limbs, tops, and non-merchantable stems were used. Mitchell and Gallagher (2007) found that during a fuel treatment operation dirty chips could be produced for \$10 t^{-1}.

Westbrook et al. (2007) found that roundwood production averaged 65.8 tons per acre and 28.5 tons per acre were harvested per hour, and that producing chips did not significantly reduce the amount of roundwood produced. Similarly, Baker et al. (2010) found that adding a chipper to a traditional tree-length system did not reduce roundwood production when only limbs and tops were utilized. When non-commercial stems were utilized, roundwood production was not reduced in clearcuts, but during thinning, roundwood production had the potential to be reduced by as much as 50%.

Nati et al. (2010) performed a study that investigated how blade wear affected chipper productivity and fuel consumption. This study found that productivity decreased significantly as chipper blades became dull and fuel consumption increased as blades became dull. There was, however, no difference in productivity or fuel consumption when chipping pine versus poplar. This study did not investigate the differences in chipper productivity and fuel consumption between chipping stem wood and limbs.

Harvesting Sustainability

Harvesting operations in the Southeastern United States performed on intensively managed pine plantations often leave considerable amounts of traditionally nonmerchantable residues. After a typical stem only harvest in the southeastern USA, there can be 50 to 80 Mg ha^{-1} of dry weight biomass depending on the stand and harvesting practice employed (Eisenbies et al. 2009). These residues, which consist of limbs, tops, foliage, and noncrop species, are a viable source of materials for use as biofuels. There are, however, concerns about the effects of increased utilization of harvest residues and other forest biomass on sustainability and forest productivity (Mayfield et al. 2007). In some states, forestry Best Management Practices (BMPs), which were designed to address non-point source pollution, have been expanded to prevent degradation of site quality following timber harvesting. Past studies have shown that BMPs which minimize soil and litter layer disturbance, encourage rapid revegetation, and minimize overland flow are effective in minimizing the negative impacts of timber harvesting on water and site quality (Aust and Blinn 2004). Shepard (2006) concluded that forestry BMPs should be appropriate for harvesting woody biomass from traditional forestry systems (excluding short rotation energy plantations). However, Shepard (2006) also suggested that if greater utilization leads to increased nutrient removals and increased fertilization, special attention may be needed to prevent fertilizer from reaching streams. Several states including Missouri, Minnesota, and Pennsylvania have already issued special guidelines for biomass harvesting that seek to minimize the negative impacts of removals. Additional research is still needed to determine the sustainability and site impacts of harvesting woody biomass.

Since the early 1970's researchers have studied the effects of timber harvesting on nutrient availability and site productivity. Boyle et al. (1973) performed a study in Wisconsin that focused on nutrient removals from whole tree harvesting. In this study, all stems with a diameter larger than one inch were removed, and they suggested that this type of harvest, without shortening the rotation, could continue indefinitely without negatively impacting the amount of nitrogen (N), phosphorus (P), and potassium (K) in the soil. However, they believed that calcium (Ca) could become a limiting element over a long period of time. Federer et al. (1989) estimated changes in total soil and biomass N, Ca, K, Mg, and P over a 120 year period from published data on sites in New England and Tennessee. They found that there would be significant depletion of N, K, Mg, or P over the time period, but they found that leaching and whole tree harvesting could reduce the soil Ca 20 to 60 percent in 120 years. They suggested acid precipitation could be causing increased amounts of leaching but said that Ca loss could be mitigated by reducing acid deposition, reducing whole tree harvesting, and liming large areas of forest.

Other studies have found that whole tree harvesting has little impact on soil nutrient and organic matter and site productivity. Hornbeck and Kropelin (1982) found that nutrient removals from whole tree harvesting in northern hardwoods represented a small proportion of the total nutrient capital on the site. Additionally, they believed that removals and leaching losses would not deplete the nutrient capital over 30 year rotations. Mann et al. (1988) found that there were little differences in nutrient losses between whole tree harvesting and conventional stem only harvests. Additionally, they found that hydrologic nutrient losses following harvests were insignificant compared to the nutrients removed in wood during whole tree and stem only harvests.

Eisenbies et al. (2009) points out that, as with biomass, nutrient removals depend on stand age, harvesting practice, tree species, and tree components. At 16 years old, loblolly pine plantations can have quantities of nitrogen and phosphorus in the forest floor and in tree components that are approximately equal (Pritchett and Fisher 1987). Tree biomass, however, can contain up to three times as much calcium and magnesium and up to eight times as much potassium as the forest floor.

Study Objectives

This study has four specific objectives. The first is to determine the effects of chipper blade wear on chip quality, chipper productivity, and chipper fuel consumption. Based on the literature reviewed, we hypothesize that blade wear will cause a decrease in chip quality and chipper productivity and an increase in chipper fuel consumption. To evaluate the chip quality, samples were collected and evaluated for their size distribution. Detailed time studies and observations of the chipper were used to determine productivity and fuel consumption of the chipper. The second objective is to determine the differences in chip quality and productivity when chipping whole trees versus harvest residues. We expect whole trees to produce higher quality chips than those produce by harvesting residues. We test whether there is a difference in chipper productivity when chipping whole trees versus harvesting residues. Chip samples were collected and evaluated for quality based on their size distribution, energy content, and moisture content. Differences in productivity were determined by performing time studies while chipping whole trees and while chipping harvest residues.

The third objective is to determine differences in nutrient content of chips produced from whole trees and harvesting residues. We hypothesis that chips produced from harvesting residues will have a higher nutrient content than those produced from whole trees. Samples were collected from both types of chips and analyzed for their content of nitrogen, phosphorus, potassium, and calcium. The fourth objective is to evaluate different biomass harvesting treatments to determine differences in nutrient removals and changes in site disturbance through litter distribution and visual soil disturbance. The harvesting treatments that will be used are: 1) a commercial clearcut with harvest residues redistributed across skid trails, 2) a silvicultural clearcut with harvest residues chipped for boiler fuel, and 3) a silvicultural clearcut with all material chipped for boiler fuel. The hypothesis tested is that harvesting treatment one will have the least amount of removals as well as the least site disturbance. Harvesting treatments two and three are expected to have similar impacts on nutrient removals and site disturbance.

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Chapter 2: Chipper Productivity and Chip Characteristics From two Woody Biomass Harvesting Treatments

Abstract

Increased costs of fossil fuels, regulatory policies, and investments by federal and state governments have caused increased interest and incentive for the use of wood as a renewable form of energy. As a result, landowners and forest managers are increasingly considering chipping whole trees and harvesting residues to meet increased demand of wood chips as a renewable source of energy. However, the profitability and productivity gains from these alternative harvesting methods continue to be an area of research. This study analyzes how chipping whole trees, harvesting residues, and chipper blade wear affects chip characteristics, chipper productivity, and chipper fuel consumption. Chip characteristics varied little between whole tree chips and harvest residue chips. There were some slight differences between chip size distribution, but chips produced from both materials had a low level of fine particles and very few oversized pieces. There was a weak relationship between blade wear and chip size distribution where large pieces decreased in frequency as blades became dull and small pieces increased in frequency. Chipper productivity was significantly higher (31.7 t hr^{-1}) when chipping whole trees versus chipping harvesting residues (18.1 t hr^{-1}). The chipper consumed 66 liters hr^{-1} of fuel when chipping whole trees and 51.5 liter hr^{-1} when chipping harvesting residues, but fuel consumption per ton of wood chipped was lower when chipping whole trees (2.1 liters t^{-1} versus 3.0 liter t^{-1}). There was no indication that blade wear had a significant effect on chipper productivity or fuel consumption.

Keywords: Biomass harvesting, fuel chip quality, chipper productivity, chipper fuel consumption

Introduction

The Southeastern United States currently relies on coal and natural gas to produce approximately 75 percent of its electricity [1]. However, this number may change due to regulatory policies and significant investments by federal and state governments in renewable forms of energy [2]. Renewable portfolio standards, goals that mandate utilities to produce a certain percentage of electricity from renewable sources by a target date [3], have been adopted by thirty-three states and the District of Columbia. Only three southern states, North Carolina, Texas, and Virginia, have renewable portfolio standards. However, all southern states have financial incentives promoting bioenergy [4].

While the majority of renewable portfolio standards and government incentives focus on wind and solar energy, woody biomass is another source of renewable energy. Wood chips can be used as a solid biofuel for small and large scale applications. For example, wood chips can be used in small combustion units, large heating plants, and in wood-fired or co-fired electrical power plants. Perlack et al. [5] suggested that wood-energy facilities will utilize mill residues, harvesting residues, urban residues, and other low value wood. Harvesting residues (e.g., branches, foliage, noncrop species) could potentially provide 5.7×10^{7} tonnes year^{-1} in the United States which represents 13% of potentially available biomass nationally [6]. A typical stem-only harvest on pine plantations in the southeastern United States can leave 50 to 80 tonnes ha^{-1}of dry weight biomass.

Watson and Stokes [7] recognize four methods of harvesting woody biomass: using specialized machines to harvest logging slash and non-commercial stems, post-harvest operation following conventional logging, pre-harvest operations, and integrated operations. Past research indicates that harvesting roundwood and woody biomass simultaneously is more desirable because it requires no special equipment, results in less trafficking across the stand, and is less expensive [8, 9, 10]. A more recent study found that whole-tree harvesting could recover 8 to 40 tonnes ha^{-1} of residues by using a conventional harvesting system and adding a chipper at the logging deck[11].

Harvest residues can vary drastically in quality, and different facilities often require fuels that meet certain quality requirements. While it is generally accepted that higher quality fuels help systems perform more efficiently, burning the highest quality fuels may not be the intent of the facility. Many systems are installed with the intent of using locally available, underutilized materials to offset the cost of using other, more expensive fuels [12]. Typically, wood is used in direct combustion systems for electricity generation and is similar to fossil fuel electricity generation systems.

In direct combustion systems, where wood chips are burned without being further processed, the predominant quality concerns are moisture content, size distribution, energy content, and ash content[13]. Each of these factors can affect the efficiency of a combustion system, but the degree to which a system is influenced by each factor depends on the type of combustion system. For example, small combustion systems, those that produce 250 kW/or less, are more sensitive to inputs and typically require fuels that have low moisture contents and consistent fuel sizes, but large combustion facilities, those that produce 1MW/or more, have fewer requirements regarding moisture content or size distribution [14].

Chip size distribution is an important quality factor not only because it affects the way a combustion system functions, but it is also one of the few factors that can be easily manipulated by producers [15]. Often chip size distribution depends on chipper type, tree part, tree species, and knife setting [16]. Early studies focused on size distribution as it relates to a chip’s ability to be used in different pulping processes. Borlew and Miller [17] identified chip thickness as one the most important factors in the Kraft pulping process, however fuel chips are classified according to their largest dimension [18]. More recent studies have focused on the relationship between size distribution and the ability to use wood chips as a source of energy [16, 18]. While there is no standard for acceptable wood chip size distribution in the United States, the European Committee for Standardization has worked to develop quality standards for different fuels [19]. Regarding size distribution the highest quality chips have the main fraction (80% by weight) falling between 3.15 mm and 16 mm and the lowest quality wood chips have the main fraction between 3.15 mm and 300 mm. In all instances, fines (< 3 mm) should not make up more than five percent of the chips by weight [19].

For energy production systems, producing suitable chips is important for several reasons. Oversized particles can jam feeding systems and have a tendency to “bridge” [20, 12]. “Bridging” is the formation of hollow cavities in feeding hoppers as material below is removed, which can cause some systems to shut down because the hopper seems to be out of chips when it is not. A large amount of fines (<3mm) can also produce problems when moisture contents are either too high or too low by reducing system efficiency and increasing emissions [21].

This study fills a gap in the literature by investigating differences in chip characteristics and chipper productivity as a result of alternative woody biomass harvesting treatments. The two harvesting treatments analyzed in this study are chipping whole trees and chipping harvesting residues. Additionally, the study was designed to determine the effect of chipper blade wear on chip size distribution, chipper productivity, and chipper fuel consumption.

Materials and Methods

A study site was selected in Bertie County, North Carolina on a 52 ha (128 ac) loblolly pine (*Pinus taeda L.*) plantation. The site is located in the lower Coastal Plain and is part of the Roanoke River Basin. It is a wet pine flat with slopes of less than 2 percent, and it is underlain by Ultisols, primarily Leaf loam soils, with a small portion of Lenoir fine sandy loam[22]. While these soils are classified as poorly to somewhat poorly drained, their drainage has been improved by the installation of an extensive ditch network. The plantation was established in the late 1980s by Champion International Corporation, and it is currently managed by Forest Investment Associates.

Three replications of two harvesting treatments (six experimental units) were conducted according to a randomized complete block design. Each set of treatments shared a landing and treatments were set up so that there was similar skid distance within each block. The treatments were: 1) An integrated roundwood and fuel chip clearcut with merchantable and non-merchantable being felled. Stems were cut by the feller buncher, and merchantable stems were skidded to a loader to be processed as roundwood and non-merchantable ones were skidded to a chipper. Merchantable stems were those greater than 10 cm diameter at breast height (dbh) and non-merchantable were those less than 10 cm dbh. Merchantable materials were processed as a tree length southern commercial clearcut, and saw timber, chip-n-saw, and roundwood pulpwood were processed and transported to the appropriate mill. Limbs, tops, and non-merchantable sized trees were chipped and delivered for use as boiler fuel. 2) A fuel chip harvest in which merchantable and non-merchantable stems were felled and skidded together. In this treatment, all stems were chipped as whole trees and delivered as boiler fuel. The purpose of this treatment is to simulate a circumstance in which the price of energy chips and roundwood pulpwood are equal, and landowners and harvesting contractors can choose between delivering roundwood pulpwood to a pulpmill or delivering chips to an energy facility. A third treatment in which no material was chipped was used as part of a separate study, but no data from that harvesting treatment was collected for this study (Figure 1).

The study utilized a Conehead 585 in-woods drum chipper. It was powered by a 500 hp diesel engine and had a 568 liter fuel capacity. The chipper was not new and had over 3,000 machine hours at the beginning of the study. The drum had four blades, an outside diameter of 86.36 cm, and tapered down to a 60.96 cm diameter at the center of the drum.

To determine characteristics of chips produced during harvesting, chip samples were collected from the chip stream at the chipper output spout while each chip van was being loaded (Figure 2). To detect changes in chip characteristics due to wearing chipper blades, three samples per van were collected from a minimum of ten vans for each treatment unit for a total of 180 samples. Samples were collected at equal time intervals so that the last sample from a van and the first sample from the next van would not be taken when the chipper blades had the same amount of wear. Meaning, a chip van was partially filled before the next sample was taken. The time that each sample was collected was recorded. Notes were made of when blade changes took place, and when combined with the recorded times, was used to estimate chipping time on the blades for each sample. Samples were collected during active operation of the chipper so that productivity would not be affected. Chip samples were averaged approximately 4.5 kg green.

Chip sample size distribution was analyzed using a Williams Classifier with seven trays (10 mm bar screen, 50 mm circular screen, 22 mm circular screen, 16 mm circular screen, 10 mm circular screen, 3 mm circular screen, and a pan to catch fines). Each sample, which was labeled by block, treatment, and van, was put in the machine for two minutes, and the amount of the sample that was retained in each tray was weighed to determine weight distribution in each size class. Samples were also weighed prior to sorting to make sure that none of the sample was lost during sorting.

Additional samples, one per chip van, were collected for determining the moisture content and energy content of chips from each treatment, and this meant a minimum of 60 samples (10 from each treatment unit). Samples were approximately one kilogram and were stored in sealed plastic bags to prevent moisture loss, and placed in a freezer prior to analysis. Samples were then transferred into paper bags and oven dried for two weeks, then reweighed to determine moisture content on a wet basis. A well mixed portion from each of the smaller samples was ground in a Wiley mill through a 1 mm screen. After grinding, higher heating values (HHV) were determined using a Parr Bomb Calorimeter. The HHV (expressed in MJ/kg) was used as an indication to the amount of energy that could be obtained from burning the wood chips for fuel.

During harvesting an elemental time study was performed to estimate chipper productivity. The time spent (excluding delays) filling each van was recorded, and the tonnes loaded onto each van (a minimum of ten vans from each treatment unit) were obtained from mill scale tickets. These values were used to estimate chipping productivity in tonnes per hour. Chipper fuel consumption was also recorded for each van load of chips. The chipper started filling each load when the fuel tank was full, and once chipping was complete the chipper was refueled. A fuel gauge attached to the nozzle measured consumption to the nearest tenth of a liter. From this data, we calculated liters of fuel consumed per hour and per ton of wood chipped. We were also able to investigate changes in chipper productivity and fuel consumption as chipper blades became dull.

The impact of blade wear on size distribution was analyzed using multiple linear regression and STATA software [23]. In the regression equation, time on blades and harvesting treatment were regressed on the percent of a chip sample that fell into each size class, where time is a proxy variable for blade wear (delay free chipping time in minutes) and treatment is a binary variable where residue chipping is equal to one (Equation 1). Separate regressions were run for each size class for a total of seven regressions.

Equation 1: $\%\ in\ size\ class = \beta_0 + \beta_1\ time + \beta_2\ treatment$

Fuel consumption and productivity data were analyzed using SAS v9.2 statistical software [24]. The harvesting treatment was used as an indicator variable to test for significant differences between treatments. Analysis of moisture content and energy content was done using analysis of variance. The size distribution of chips were analyzed using Chi-squared.

Results and Discussion

Chip Characteristics

The higher heating values (HHV) were very similar for chips produced from whole trees and residues (19.9 MJ/kg and 19.3 MJ/kg respectively), with no significant difference between the two (Table 1). Westbrook et al. [11] found the higher heating values of residue chips ranged from 18.6 to 19.6 MJ/kg, and Baker et al. [25] found that the higher heating values of residue chips ranged from 17.1 to 20.5 MJ/kg. The values estimated in these two studies were similar except for the lower values found in Baker et al [25].

The moisture content of residue chips (39.5 % wet basis) was similar to those values found by Westbrook et al. [11] and Baker et al. [25], but was significantly lower ($p<0.05$) than chips produced from whole trees (Table 1). This difference is likely a result of how harvesting was performed. During the harvest of whole tree chips, stems were skidded to the chipper within days of being felled, but residues from the integrated harvest were often piled for several weeks before they were skidded to the chipper for processing. As the residues were piled for an extended period, they dried out more than the recently harvested stems creating a difference in moisture content.

Chip size distribution varied little between treatments. There is a significant difference between treatments for the 22 mm size class and the 3 mm size class (Figure 3), but both classes are considered acceptable for hog fuel wood chips according to the European Committee for Standardization’s specifications for solid biofuels [19]. On average, both treatments produced a high percentage of chips that were an acceptable size and varied from as low as 78 % acceptable to as much as 97 % acceptable. Nati et al. [16] found that the size distribution of pine logs and limbs can vary by a similar amount. However, the chips produced in this study were generally smaller than what has been found in other studies. Where Nati et al. [16] found that pine logs and branches produced chip samples that had 45 % of the sample weight between 16mm and 3mm, this study found that samples of whole trees averaged 85 % in this size class and samples of residues averaged 81 % in this size class.

Results of the size distribution regression analysis are reported in Table 3. All equations are significant at $\alpha = 0.05$ except for the percent of particles < 3 mm. This indicates that there was no statistically significant relationship between blade wear and the percent of particles < 3 mm, and the data showed that there was essentially no change in the percentage of these particles present as blades became dull. For particles that were 16 mm and larger, there was a negative relationship with blade wear. This result suggests that as blades become dull, the amount of particles 16 mm and larger will decrease. Conversely, blade wear will increase the amount of particles 10 mm and smaller. The relationship found in these results is opposite from what would typically be expected from blade wear. Nati et al. [16] found that blade wear caused a significant increase in the amount of larger particles. Differences in the chipper or blade settings of the chipper used in this study could potentially account for differences between the results of these studies. These differences could have also resulted from the differences in the duration a set of blades was used. In this study, a set of blades lasted long enough to fill five chip vans, but Nati et al. [16] could fill almost twice as many vans on a set of blades. It is possible that if blades had been used longer that there may have been a different or more pronounced change in particle size distribution.

This analysis also shows that residue chips are generally smaller than whole tree chips. Spinelli and Hartsough [26] and Nati et al. [16] found that chips produced from whole trees will generally be smaller than those produced from branch material. The production of smaller chips from harvesting residues could be the result of differences in strength properties of the smaller residue material and the whole tree material. The whole trees could have also slowed the speed of the chipper drum enough to cause differences in the size of chips produced.

Chipper Productivity and Fuel Consumption

During the harvest, 1,743 tonnes of whole tree chips and 637 tonnes of residue chips were produced from 12.8 hectares and 18.8 hectares respectively. The chipper was able to fill vans with whole tree chips significantly faster (44 minutes) than residue chips (59 minutes) ($p < 0.0001$), and payloads averaged 22.76 tonnes when chipping whole trees and 16.54 tonnes when chipping residues. A new set of blades were installed after an average of 4.1 hours of chipping (4.9 truck loads) when treatments were combined. However, when chipping limbs and tops blades only lasted 3.5 hours (3.6 truck loads), and when chipping whole trees blades would last an average of 4.7 hours (6.3 truck loads) before replacement.

Estimations of chipper productivity and fuel consumption are displayed in Table 2. The results of the time study indicate that there are statistically significant differences in productivity when chipping harvesting resides and chipping whole trees ($p<0.0001$). The average productivity for chipping harvest residues was 18.1 tonnes per hour and the average productivity when chipping whole trees was 31.7 tonnes per hour. There were several factors that influenced productivity. One of the more obvious factors is the inability of the vans to achieve a full payload when being filled with residue chips. On average, the moisture content (wet basis) of residue chips was 6% less than whole tree chips, however, this alone could not account for the 27% difference in payloads. The most influential factor was the chipper being unable to shoot residue material all the way to the front of the chip van, and chip vans often had very little in the front of the van. Due to design limitations of the chipper, the outfeed spout could only make minor adjustments to the direction it was shooting.

The lower chipper productivity when chipping residues and lower truck payloads when filled with residue chips could have major implications about the costs of harvesting biomass. Conrad et al. [27] performed a cost analysis as part of a separate study on this site. Their results suggested that chipping residues could have a cut and load rate that was \$2 t^{-1} more than chipping whole trees. Their results also showed that chipping costs were nearly \$5 t^{-1}more when chipping harvesting residues. Additionally, decreased payloads could significantly increase the cost of hauling chips. Assuming a haul rate of \$0.10 t^{-1} $km^{-1}$and a haul distance of 80 km, the trucking costs of whole tree chips would be \$113.80, and the trucking costs of residue chips would be \$144.53.

Spinelli et al. [28] investigated factors that influence chipper productivity and found that tree part (i.e. stems or branches) had a significant effect on chipper productivity. In their study, stem pieces were much larger than branch pieces which resulted in proportionally larger grapple loads being fed into the chipper. In this study, whole trees being fed into the chipper were, in some cases, large enough to be merchandized as sawtimber. Delays caused by the operator could have influenced the estimates of productivity. Productivity was calculated excluding major delays, but these did not include delays that lasted for less than one minute. Nati et al. [16] and Spinelli et al. [28] point out that delays cannot only reduce machine productivity but also blur the differences caused by wood characteristics.

In this study, there was no indication that blade wear (as indicated by the amount of chipping time on the blades) was a significant predictor of chipper productivity. Regression analysis showed that blade wear (as represented by the amount delay free chipping time) had no significant effect on chipper productivity. While chipping time did have a negative relationship with productivity, it was not significant in the regression model ($p = 0.147$). Nati et al. [16] found blade wear to significantly affect chipper productivity. They found that after a set of blades had chipped 215 t, chipper productivity decreased by 15% or 5 t per hour. The amount of chips produced during their observations could have filled nine chip vans (assuming each van had a 22 t payload), and a set of blades in our study lasted, on average, long enough to fill five chip vans. If blades had been left on the chipper longer, it is possible that our study would have observed more significant changes in chipper productivity. However, the decision to change blades was made by the harvesting contractor who did so when they felt it would be beneficial.

There was a significant difference in chipper fuel consumption between treatments ($p<0.0001$). When chipping harvest residues, the chipper consumed an average of 51.5 liters per hour of chipping, and when chipping whole trees the chipper consumed an average of 66.0 liters per hour. However, the fuel consumed per van load of chips was almost identical for both treatments, and the tonnes chipped per liter of fuel consumed were higher when chipping whole trees. When chipping whole trees, the chipper consumed 2.1 liters of fuel per tonne chipped, and when chipping residues, the chipper consumed 3.0 liters of fuel per tonne chipped. Spinelli et al. [28] found similar variations in fuel consumed per tonne chipped and attributed this to differences in productivity. They pointed out that productivity when chipping stem wood was much higher, and when chipping branches the productivity was so low that unit consumption grew drastically.

There was no detectable relationship between the amount of fuel consumed by the chipper and blade wear (as represented by the amount of delay free chipping time). Nati et al. [16] found that fuel consumption increased by 49% after chipping 215 t of wood. It should be noted that despite fuel consumption being higher when chipping whole trees, productivity was also much higher. This points to the volume chipped as a greater influence on fuel consumption rather than blade wear. This is also evident when productivity (tonnes per hour) is compared to fuel consumption (in liters per hour). As the productivity of the chipper increased from 10 tonnes per hour to 50 tonnes per hour fuel consumption increased from about 50 liters per hour to approximately 90 liter per hour (Figure 4).

Conclusions

In this study, chip characteristics varied little between whole tree chips and harvest residue chips. While the moisture content of residue chips was lower, it was a factor that only influenced the productivity of the operation and had little effect on the quality of the chips produced. Moisture content of the material can be an important factor if materials are to be used in boilers that are sensitive to higher moisture, but when used as hog fuel, moisture content is generally not a major concern unless it exceeds 50 %. There were slight difference in chip size distribution between treatments, but there were only significant differences in two size classes. There were also no differences in the amount of fines and oversized particles present in either whole tree or residue chips. The presence of oversized or undersized particles is generally undesirable, but in this study, there were not excessive amounts of either particularly oversized particles. For use as hog fuel, chips produced from whole trees or harvesting residue would be good sources of feedstock.

While there was a relationship between blade wear and chip size distribution, the results were opposite of what is typically expected. The results from this study showed that chips become smaller as blades become dull. One explanation of this could be the setup of the chipper which could include blade settings, anvil settings, or the cutting speed. These settings could have influenced the size distribution of the chips, but they would still not explain blade wear. It is possible that blade wear could have been more controlled if each set of blades were used for the same amount of time or had chipped the same volume of material.

Chipper productivity was significantly higher when chipping whole trees versus harvesting residues. This is not surprising since whole trees would easily provide more weight per bundle when fed into the chipper and truck payloads were significantly higher when filled with whole tree chips. The differences in payloads were likely the result of design limitations of the chipper that did not allow it to adjust the direction it was shooting chips into the van. When feeding a bundle of harvesting residues into the chipper, it was often the case that only one or two pieces out of the entire bundle would successfully go through the chipper before the operator would have to readjust the bundle. However, a more detailed time study would have to be conducted in order to single out minor delays such as this. Bolding and Lanford [29] found that the amount of time spent clearing jams in a chipper were directly related to the design limits of the chipper, and this could point to the chipper in this study not being designed handle residues and smaller stems. It may also be useful to estimate the weight of each bundle being chipped as a more accurate estimation of chipper productivity. It should also be noted that much of the material chipped in the whole tree treatment was much larger than what would be expected in current biomass harvesting operations. The purpose of this treatment was to simulate a scenario where there was a large biomass market and landowners had a choice between selling material as pulpwood or fuel chips, but in this study, material that would normally be merchandised as chip-n-saw or sawtimber was chipped for hog fuel. It is possible that chipper productivity was skewed as a result of chipping such large material. If markets were adequate to support a chip only treatment, it is likely that a more suitable chipper would have been used. The results of this study are chipper specific, and if a newer or different type of chipper had been used, the results of this study could have been significantly different.

It is also important to note the potential differences in costs associated with chipping and trucking. The results of Conrad [27] suggest that chipping residues could be significantly more expensive than chipping whole trees. Additionally, when full payloads are not achieved, the cost of trucking greatly increases. The decreased payloads could easily be attributed to operator inexperience, limitations of the chipper, or differences in the materials filling the van. Future research should investigate how each of these effect chip vans achieving full payloads.

There was no detectable relationship between blade wear and chipper productivity; however, this could be because blades were not left on the chipper long enough. Nati et al. [16] performed a similar analysis of the effects of blade wear on chipper productivity, but blades were left on the chipper for almost twice as long as in this study. In this study, the decision to change a set of blades was made by the operator when he perceived a change in productivity, but our results show that there was no actual change in productivity. This indicates that chipper blades could have been changed too often causing underutilization of a set of blades and an increased amount of time spent performing maintenance on the machine. While there are many factors that can influence how quickly a set of blades becomes dull, future research could focus on the useful life of chipper knives to help harvesting contractors perform in-woods chipping more efficiently.

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Tables and Figures

Table 1. Descriptive statistics of the higher heating value (HHV) expressed in MJ/kg and the percent moisture content expressed on a wet basis for chips produced from whole trees and from residues. Statistical differences (p=0.05) are indicated by different letters within columns.

	Mean	**SD**	**Min.**	**Max.**
HHV (MJ/kg)				
Whole Tree	19.91a	0.71	18.78	21.18
Residues	19.28a	0.44	18.21	20.36
Moisture Content				
Whole Tree	45.80b	6.74	29.78	58.34
Residues	39.55c	6.88	25.39	56.34

Table 2. Chipper productivity measured in tonnes per productive machine hour and chipper fuel consumption measured in liters consumed per productive machine hour and liters consumed per tonne of material chipped for chipping residues and whole trees.

	$t\ hr^{-1}$	$lit\ hr^{-1}$	$lit\ t^{-1}$
residues	18.1a	51.5a	3.0a
whole trees	31.7b	66.0b	2.1b

Table 3. Regression analysis of the effect of blade wear, as represented by delay free chipping time, on chip particle size distribution. The percent of chips in each size class would be estimated using the equation: $y = \beta_0 + time * \beta_1 + treatment * \beta_2$. Time represents the delay free chipping time (in minutes) on a set of blades, and treatment was used as a dummy variable where 0 = whole tree chips and 1 = residue chips.

Size Class	Intercept	Time	Treatment	Adjusted R^2	F-Value	Model P-Value
Bar Screen	4.186	-0.00463	-1.327	0.116	12.77	< 0.0001
29 mm	2.950	-0.00143	-0.966	0.110	12.10	< 0.0001
22 mm	7.895	-0.00472	-2.106	0.136	15.14	< 0.0001
16 mm	21.194	-0.00516	-3.352	0.080	8.76	0.0002
10 mm	34.885	0.007556	1.130	0.043	5.02	0.0076
3 mm	23.264	0.009731	6.619	0.183	20.99	< 0.0001
< 3 mm	5.540	-0.00130	0.820	-0.0072	0.36	0.6992

Figure 1. Color infrared photograph showing the harvest layout of the study site. The roundwood treatment was part of a separate study making the area used in this study 33 hectares.

Figure 2. This image displays the method used to collect wood chips from the chip stream without causing delays in the operation of the chipper.

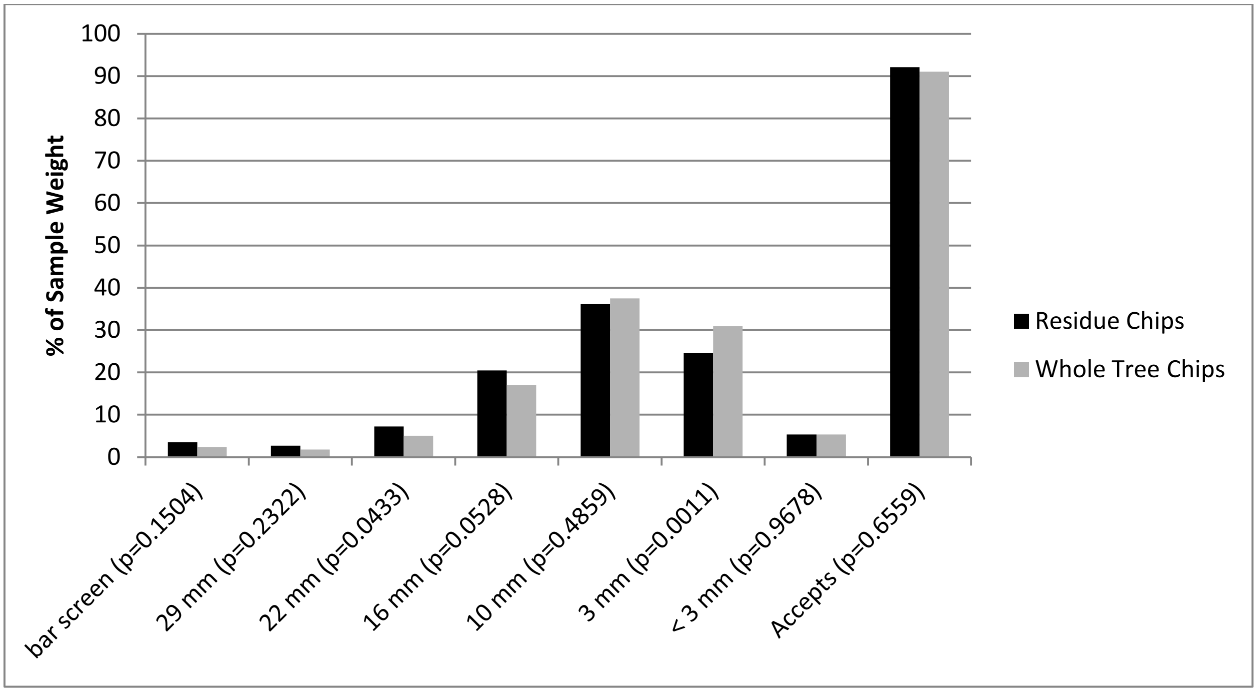

Figure 3. Size distribution of chip samples for residue chips and whole tree chips and the statistical significance of differences between chip types. Accepts are classified as those smaller than the bar screen and larger than 3mm.

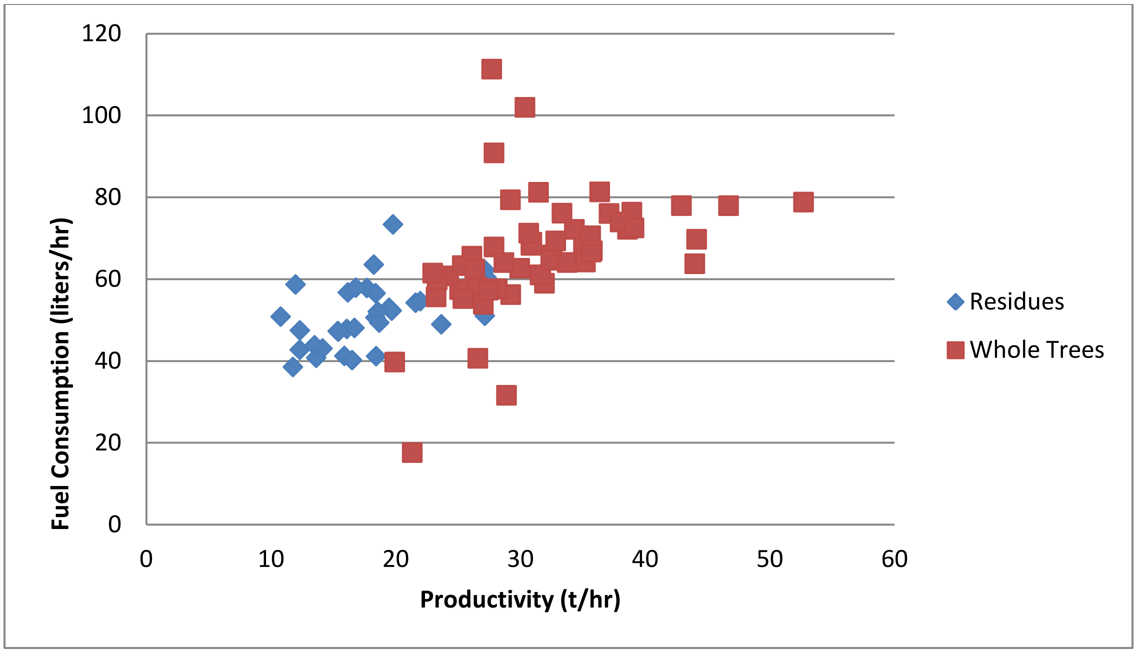

Figure 4. Relationship between productivity (tonne per productive machine hour) and fuel consumption (liter per productive machine hour) for the chipper when chipping residues and whole trees.

Chapter 3: Biomass Harvesting Sustainability of Multiple Treatment Scenarios in the Coastal Plain of North Carolina

Abstract

Timber harvests performed in the southeastern United States often leave a considerable amount of harvesting slash on the site after operations are complete. This slash, which contains a large proportion of limbs, tops, foliage, and other traditionally non-merchantable materials, is a potential source of biomass for renewable energy production. There are, however, concerns about the sustainability of removing this additional material. This study compared nutrient removals and sustainability of two biomass woody harvesting treatments (an integrated harvest and a biomass only harvest), and used a conventional stem only harvest as a baseline for comparison. We found that nutrient concentrations were significantly higher in residue chips than in whole tree chips. The amount of N and Ca removed during harvesting was significantly higher when harvesting biomass than with a conventional stem only roundwood harvest. There were no differences in removals between the integrated harvest and the biomass only harvest. The conventional harvesting treatment had significantly more residues left on the site after harvesting, but there was no statistical difference between residual nutrients. There were few differences in visual soil disturbance between harvesting treatments; however, the integrated treatment had significantly less area that was undisturbed. There is little indication from these results that the removal of residues and whole trees has a negative effect on site quality. The biomass harvests observed in this study would be unlikely to cause long term damage to the site.

Keywords: Harvesting sustainability, nutrient removals, site quality, harvesting soil disturbance

Introduction

Harvesting operations in the southeastern United States performed on intensively managed pine plantations often leave considerable amounts of traditionally nonmerchantable residues following harvesting. After a typical stem only harvest in the southeastern USA, there can be 50 to 80 Mg ha^{-1} of dry weight biomass remaining depending on the stand and harvesting practice employed (Milbrant 2005). These residues, which consist of limbs, tops, foliage, and noncrop species, are a viable source of materials for use as biofuels. There are concerns about the effects of increased utilization of harvest residues and other forest biomass on sustainability and forest productivity (Mayfield et al. 2007). Forestry Best Management Practices (BMPs) were designed to address non-point source pollution and water quality, and in some states have been expanded to address site quality impacts following biomass harvesting. Past studies have shown that BMPs which minimize soil and litter layer disturbance, encourage rapid revegetation, and minimize overland flow are effective in minimizing the negative impacts of timber harvesting on water and site quality (Aust and Blinn 2004). In addition, Shepard (2006) concluded that forestry BMPs should be adequate for harvesting woody biomass using traditional forestry systems (excluding short rotation energy plantations). However, Shepard (2006) also suggested that if greater utilization leads to increased nutrient removals and increased fertilization, special attention may be needed to prevent fertilizer from reaching streams. Several states including Missouri, Minnesota, and Pennsylvania have already issued special guidelines for biomass harvesting that seek to minimize the negative impacts of removals. Benjamin et al. (2010) describes the biomass retention guidelines of Maine that also seek to minimize the effects of biomass harvesting.

Researchers have focused on site productivity and the effects of timber harvesting for many years. Specifically, they have looked at how the removal and redistribution of forest biomass affects nutrient cycling within timber stands. Boyle et al. (1973) performed a study in Wisconsin that focused on nutrient removals from whole tree harvesting. In this study, all stems with a diameter larger than one inch were removed, and they concluded that this type of harvest, without shortening the rotation, could continue indefinitely without negatively impacting the amount of nitrogen (N), phosphorus (P), and potassium (K) in the soil. However, they believed that calcium (Ca) could become a limiting element over a long period of time. Federer et al. (1989) estimated changes in total soil and biomass N, Ca, K, Mg, and P over a 120 year period from published data on sites in New England and Tennessee and found that there would be significant depletion of N, K, Mg, or P over the time period. They found that leaching and whole tree harvesting could reduce the soil Ca 20% to 60 % in 120 years. They suggested acid precipitation could be causing increased amounts of leaching but said Ca losses could be mitigated by reducing whole tree harvesting and liming large areas of forest.

Other studies have, however found that whole tree harvesting has little impact on soil nutrients, organic matter, and site productivity. Hornbeck and Kropelin (1982) found that nutrient removals from whole tree harvesting in northern hardwoods represented a small proportion of the total nutrient capital on site. Additionally, they believed that removals and leaching losses would not deplete the nutrient capital over 30 year rotations. Mann et al. (1988) found that there were little differences in nutrient losses with whole tree harvesting and conventional stem only harvests. Additionally, they found that hydrologic nutrient losses following harvests were insignificant compared to the nutrients removed in wood during whole tree and stem only harvests.

More recently, Eisenbies et al. (2009) points out that, as with available biomass for removal, nutrient removals during a harvest depend on stand age, harvesting practice employed, tree species, and tree components utilized. At 16 years old, loblolly pine plantations can have quantities of N and P in the forest floor and in tree components that are approximately equal (Pritchett and Fisher 1987). Tree biomass, however, can contain up to three times as much Ca and Mg and up to eight times as much K as the forest floor. Other studies have found that rates of nutrient loss depend on the harvesting practice employed, the time of year harvesting took place, and the site preparation technique used (Hornbeck and Kropelin 1982; Tew et al. 1986; Robertson et al. 1987; Mann et al. 1988). Hornbeck and Kropelin (1982) performed a study in which removals from a northern hardwood site were observed, and results from this study indicated that the removal of foliage during harvesting significantly increased the amount of nutrients removed from the site. They also suggested that all attempts be made to leave foliage on the site because of their potential to rapidly incorporate nutrients into the soil capital. Phillips and Van Lear (1984) suggested that harvesting during dormant seasons would have little meaningful affect on nutrient drain since nutrients are translocated from foliage to perrinal tissue prior to leaf fall. Additionally, Eisenbies et al. (2005) did not observe any meaningful patterns of changes in soil-site productivity with changes in residues on the forest floor. They did point out that the potential benefits of increased organic matter on overall productivity are great, but they are not entirely predictable.

The objective of this study is to compare different intensity biomass harvesting treatments and estimate the amount of nutrients removed from chipping and utilizing woody biomass. This information will determine differences in nutrient removals when harvesting residues for biomass or when harvesting whole trees for biomass. Additionally this study aims to estimate how litter on the forest floor is disturbed during woody biomass harvesting. By building on existing literature, this study will produce more information on the feasibility and sustainability of harvesting woody biomass for energy.

Materials and Methods

This study was conducted in the summer of 2010 in Bertie County, North Carolina on a 52 hectare (128 acre) loblolly pine (*Pinus taeda L*) plantation. The site is located in the lower Coastal Plain and is part of the Roanoke River Basin. The site is considered to be a wet pine flat with slopes of less than 2%, and is underlain by Ultisols, primarily a Leaf loam, with a small percentage of Lenoir fine sandy loam (USDA Natural Resource Conservation Service 2011). These soils are classified as poorly to somewhat poorly drained with the depth to the water table at 0 to 30 cm. However, drainage was improved by an extensive network of ditches. The plantation was established by Champion International Corporation in the mid 1980s and is currently managed by Forest Investment Associates.

Three replications of three harvesting treatments (9 experimental units) were conducted on the site according to a randomized complete block design (Figure 1). The harvest treatments were: 1) A roundwood only tree length southern pine commercial clearcut. In this treatment, sawtimber, chip-n-saw, and roundwood pulpwood were harvested and transported to appropriate mills. This treatment is typical of harvests in the area and served as a control. 2) An integrated roundwood and fuel chip clearcut with both merchantable and non-merchantable being felled. Stems were separated by the feller buncher, and merchantable ones were skidded to a loader to be processed as roundwood and non-merchantable ones were skidded to a chipper. Merchantable stems were those greater than 10 cm diameter at breast height (dbh) and non-merchantable ones were those less than 10 cm dbh. Merchantable materials were processed as a tree length commercial clearcut, and saw timber, chip-n-saw, and roundwood pulpwood were transported to appropriate mills. Limbs, tops, and non-merchantable materials were chipped and delivered for use as boiler fuel. 3) A fuel chip harvest in which all merchantable and non-merchantable stems were felled and skidded together. All materials in this treatment were chipped as whole trees and delivered as boiler fuel. The purpose of this treatment was to simulate a circumstance in which the price of energy chips and roundwood pulpwood are equal, and landowners and harvesting contractors can choose between delivering roundwood pulpwood to a pulpmill and delivering chips to an energy facility.

Prior to harvest, each block was sampled to determine stand composition of both merchantable (diameter greater than 10 cm and greater than 6 m tall) and non-merchantable (diameter less than 10 cm) materials. Fixed radius plots, approximately one per 0.4 hectares, of one twenty-fifth hectare in size were established and all merchantable stems within the plot were measured. Non-merchantable stems within a 125th hectare plot were measured, and all material less than 2.5 cm in diameter was tallied. To further classify biomass in the stand prior to harvest, samples of litter from the forest floor were collected at every third plot (approximately one every one and one-half hectares). At these plots, all of the litter (above mineral soil) was collected within a 30 cm by 30 cm square area. These samples were stored in sealed plastic bags, dried, and weighed to determine the amount of litter on the forest floor. Visual estimates of physical soil disturbance and forest floor litter composition were done at every other plot (approximately one every one-half hectare). At each plot where visual estimates were made, a circular area of 125th hectare was established and divided into four quadrants. The litter composition was classified by the percent of litter covering a one fiftieth acre area that was 1) bare soil, 2) litter only, 3) light slash, 4) heavy slash, and 5) piles, and the soil disturbance was classified by the percent of the area that was 1) churned, 2) deep rut (>20 cm), 3) shallow rut (<20 cm), 4) compression track, and 5) no disturbance (Eisenbies et al. 2002).

Once harvesting was completed, visual estimates of physical soil disturbance and litter classification was again conducted to estimate site disturbance during harvest. A one twenty-fifth hectare plot was established every ¼ hectare, and estimations of soil disturbance and litter classification were performed at each plot. An additional soil disturbance category was also added, which described the condition where the soil had been traveled over but there was no clear evidence of physical disturbance.

A post harvest cruise was also performed to estimate the amount of downed and standing woody material left after harvesting. Every half a hectare, a one-tenth acre fixed radius plot was established and all downed woody material with a minimum length of 35 cm and a minimum small end diameter of 2.5 cm within the plot were measured. All materials left standing with a diameter of 2.5 cm or greater were also measured. Nutrients contained within residual woody materials were estimated using the nutrient content of residue chips collected during harvesting. This estimation assumed that downed woody materials left on the site after harvesting would be residues with a very similar nutrient content as the residue chips sampled during the harvest.

To determine the amount of nutrients removed from the site by chips, samples of chips were collected during the chipping process. One sample was collected from a minimum of ten chip vans for each treatment unit, and resulted in a minimum of thirty samples for each treatment. Samples were stored in sealed plastic bags and were kept refrigerated to prevent decomposition. Once all samples were collected they were transferred to paper bags and dried at 65°C until they were no longer losing moisture. A well mixed portion of the dried samples were then ground through a 1 mm screen and stored in a dryer. All samples were analyzed for their content of nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca). The results of this analysis yielded the percent the sample that was made up of each nutrient. The concentration of nutrients in the samples was then extrapolated to estimate the amount of nutrients removed from the site.

There were no samples taken of wood removed from the conventional harvesting treatment since no chipping was conducted, so removals from this treatment were estimated using the nutrient concentrations calculated for whole tree and residue chips. Nutrient removals by chips (kg ha^{-1}) were made for the biomass only and the integrated harvesting treatments, and removals from the conventional treatment were then calculated by subtracting the removals from the integrated harvest from those of the biomass only harvest. This calculation assumed that the materials chipped in the integrated harvest were only residues and that the materials chipped in the biomass only harvest were boles and residues.

Statistical analysis was performed using SAS v9.2 statistical software. Changes in litter composition, visual soil disturbance, and nutrient content were analyzed using PROC GLM procedure, and differences between harvesting treatments were determined using the Tukey means separation test. All statistical tests were performed with an alpha of 0.05.

Results and Discussion

Pre-Harvest Site Characteristics

Results from the pre-harvest litter samples estimated an average of 12.10 tonnes per hectare of litter on the forest floor across all blocks. Block one had 9.00 tonnes per hectare, block two had 10.98 tonnes per hectare and block three had 16.58 tonnes per hectare. These estimates are consistent with estimates from other studies on similar aged stands (Eisenbies et al. 2009). The increase in the amount of litter on the forest floor for block one to block three is likely caused by the increase in the amount of switch cane (*Arudinaria gigantia*) present. The pre-harvest cruise showed that there was a substantial increase across blocks (Table 1) that corresponded to the number of mature trees per acre. The lack of mature trees in block three is likely the cause of increased switch cane that crowded out other understory species.

Removals from Site

During the harvest, 6,673 tonnes of material were removed from the site (128 t ha^{-1}). Of this, 637 tonnes were residue chips, 1,743 tonnes were whole tree chips, and 4,293 tonnes were removed as roundwood. Table 2 shows the total tonnes removed from each treatment. Chip samples from whole trees and harvest residues were analyzed for their content of N, P, K, and Ca (Table 3). Residue chips had a slightly higher concentration of N, P, and K, and almost double the amount of Ca. Figure 2 shows the nutrient concentration of Ca, N, P, and K from chips produced from whole trees and harvest residues. The significantly higher nutrient concentration ($p < 0.0001$) in residue chips is not surprising since harvesting residues are comprised of mainly limbs and tops, and are known to have a disproportionally large concentration of nutrients.

Nutrient concentrations were extrapolated to estimate the amount of nutrients removed during harvesting in kg ha^{-1}. To estimate the nutrients removed via bole wood, the nutrients per hectare removed from the residues was subtracted from the nutrients per hectare removed from whole trees. Estimates of nutrient removals from just bole wood based on the difference in whole tree and residue chips were within the range of published data (Table 5). However, the results found in this study did not closely resemble those of any one study.

Table 6 shows the differences in nutrient removals between harvesting treatments. In terms of kg ha^{-1} of nutrients removed, conventional harvesting treatments had significantly lower removals ($p<0.05$) of N and Ca. The amount of N removed from the conventional harvesting treatment spread out over 25 years (which would be the same rotation length as the one harvested) would be 2.1 kg ha^{-1} yr^{-1} and the integrated and biomass only removals would be equal to 3.5 kg ha^{-1} yr^{-1}. Atmospheric deposition of N near the project area is around 14.64 kg ha^{-1} yr^{-1}, which would replenish the nutrients removed from the conventional treatment in a little over three years and the biomass only and the integrated treatments in six years based on this assumption (Phillips et al. 2005).

The survey of residual material on the site found that the conventional harvesting treatment had the highest volume of residual material left on the site, and with the exception of block three, it was the only harvesting treatment to have any residual standing material. Estimates of residual nutrients in the form of logging slash were generated using the average nutrient concentration of residue chips. Table 4 shows the amount of residual material as well as the nutrients within the residual material that were left on the site. The conventional harvesting treatment had significantly more residual material and subsequently more residual nutrients than the other harvesting treatments. This, however, does not mean that there was a large amount of nutrients left on the site in the form of harvesting residues, and these residuals had little effect on the removals of all harvesting treatments.

Forest Floor Characteristics

Pre-harvest visual estimates of the composition of the forest floor showed that 95 percent of block one was litter only, 94 % of block two was litter only, and 95 % of block three was litter only. The remaining composition was light slash which was likely left from a past thinning. Visual estimates for soil disturbance showed that there was no disturbance in all of the blocks. These estimates of disturbance did, however, exclude evidence of previous silvicultural activities such as beds and windrows since they were not caused as a result of the current harvesting activities which was the scope of this study.

The post-harvest visual classification of litter showed that the ground cover was still dominated by litter only, however, there were large increases in light slash and bare soil in all treatments. The biomass only harvesting treatment had a statistically significant larger percentage of cover in bare soil and litter only and it also had the lowest percentage covered by light slash, heavy slash, and piles. The integrated harvesting treatment had a statistically significant higher percentage of cover in litter only and light slash than the biomass only treatment. This is would not be expected since both of these treatments should have been removing the same material, and there was no difference between these treatments in the survey of residual material. The only difference during the harvesting process was the technique in which material was brought to the landing. In the integrated treatment, whole trees were brought to the landing and limbs and tops were chipped once roundwood stems were processed, and small stems were skidded to the landing separately. In the process it is possible that the skidders were not able to collect and transport all of the smaller material that might be considered light slash. In the biomass only treatment, whole trees were bunched and skidded with small material, and this could have made it easier for skidders to collect the smaller material. Although the survey of residual material did not find a difference in the volume of material left on the site after harvesting, material that was considered light slash was not typically large enough to be measured. Not surprisingly, the conventionally harvesting treatment had a statistically significant higher percentage of cover in light slash, heavy slash, and piles. These results are further explained by the post harvest survey that found significantly higher volumes of residual material following the conventional harvesting treatment. Results for all treatments from the post-harvest litter classification are displayed in Table 7. Loading decks were not included in the results because they were shared for all harvesting treatments. Eisenbies et al. (2005) found that during harvesting the amount of harvest residues left on the site can vary greatly. Their study found that on the least disturbed sites, only 4 % of the soil was bare, and on the most disturbed sites nearly 50 % of the soil was bare. In all instances, there were much higher amounts of light and heavy slash left. However, the amount of light slash in the conventional harvesting treatment of this study was comparable to the amount of light slash in the most disturbed category, and it had more area covered in piles than any category reported by Eisenbies et al. (2005).

During the harvest there was little visual soil disturbance overall, and there was very little difference between harvesting treatments. About 50 % of the area in all harvesting treatments had no disturbance, but there was a statistically significant higher percentage of area with no disturbance in the conventional (55.71 %) and biomass only (55.87 %) harvesting treatments (Table 8). This is likely the result of skidders making extra passes in the integrated harvesting treatment to collect bundles of small stems. There was a small percentage of the area (< 10 %) that had been traveled over but there was no visual disturbance to the soil. This disturbance category was added because the dense thickets of switch cane created mats when machinery traveled over them. In many cases it was obvious that these matted areas were main skid trails and had been repeatedly traveled over, but there were no visual signs of soil disturbance.

The lack of soil disturbance is largely a function of dry soil conditions during harvesting.. The shallow water table and the drainage ditches that criss-crossed the site were clear signs that this could have been a wet harvesting site, and if this had been a wet weather harvest, there would have likely been differences in soil disturbance between harvesting treatments. Eisenbies et al. (2004) found that wet weather harvesting significantly increased the amount of soil disturbance. However, the same study found that dry harvesting resulted in increased amounts of bare soil and less harvesting residues. Eisenbies et al. (2005) points out that the benefits of increased organic matter on productivity are great, but they are not predictable. Increasing residues can increase the moisture availability, but this also depends on the organic matter left which influences nutrient and moisture relationships (Childs et al. 1986).

Conclusions

The objective of this study was to determine the differences in nutrient removals of two different biomass harvesting treatments and to look at how biomass harvesting disturbs the forest floor. Overall, the removal of nutrients between the integrated harvesting treatment and the biomass only harvesting treatment were not very different. In fact, only N and Ca had significantly less amounts removed during the conventional harvesting treatment, but the conventional treatment did have less amounts of P and K removed during the harvest. This would be expected since the materials removed (limbs, tops, and small, traditionally non-merchantable material) during the biomass harvests have a disproportionally higher concentration of nutrients than bole wood. Additionally, the conventional harvesting treatments had much more material on the site once harvesting was completed. However, the additional material left on the site did not translate into significantly more nutrients left on the site in the form of harvesting residues. Although it is generally accepted that increased amounts of residual material on the sited are good for future stand health, it is difficult to predict exactly how much benefit will be gained from leaving this material. Continued research of nutrient cycling in forest stands could create a better understanding of how residues affect this cycle.

There were essentially no differences in visual soil disturbance between the harvesting treatments. The integrated harvest did have significantly less area that was undisturbed, but this difference accounted for 5 % less area that had been undisturbed.

It is clear that removing additional material from a site will result in the removal of additional nutrients, but it is unclear whether or not this practice is sustainable. Complete nutrient budgets do exist for whole tree harvesting systems, but they tend to vary based on specific site conditions.

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Tables and Figures

Table 1. Preharvest estimates of trees per hectare, tonnes per hectare, and basal area per hectare for the three blocks on the study site in Bertie County, North Carolina. Material that were larger than 10 cm dbh were considered merchantable and material smaller than 10 cm dbh were considered non-merchantable.

Species	Stems ha^{-1} (> 10cm dbh)	Green t ha^{-1} (> 10cm dbh)	Stems ha^{-1} (< 10cm dbh)	Green t ha^{-1} (< 10cm dbh)	Basal Area (m^2 ha^{-1})
Block 1					
Pinus taeda	344.2	173.2			18.0
Acer rubrum	14.3	1.4	164.7	1.6	0.6
Liquidambar styraciflua	120.1	12.7	1047.9	6.3	3.2
Other	22.5	3.1	818.3	0.4	0.8
Total	501.1	190.4	2030.9	8.3	22.6
Block 2					
Pinus taeda	157.4	104.7			10.7
Acer rubrum	26.2	9.4	70.6	0.2	0.7
Liquidambar styraciflua	177.2	57.2	1976.0	19.5	7.7
Arundinaria gigantea			5222.3		
Other	4.1	2.5	846.8	5.0	0.9
Total	364.9	173.8	2893.4[a]	24.7	20.0
Block 3					
Pinus taeda	179.6	114.3			11.2
Acer rubrum	33.6	7.4	224.5	0.2	1.2
Liquidambar styraciflua	121.3	16.1	598.8	7.1	3.8
Arundinaria gigantea			63857.0		
Other	1.5		149.7		
Total	336.0	138.2	973.0[a]	7.3	16.2

[a] Excludes *Arundinaria gigantea*

Table 2. Actual harvested hectares, tonnes harvested, and tonnes per hectare harvested for each block and treatment unit from the study site in Bertie County, North Carolina.

Treatment	Hectares Harvested	Roundwood Harvested (tonnes)	Chips Harvested (tonnes)	t ha^{-1} of Roundwood Harvested	t ha^{-1} of Chips Harvested
Conventional	19.6	2342	0	119.13	0
Integrated	18.8	1951	637	101.24	33.74
Biomass Only	12.8	0	1743	0	136.80
Total	51.2	4293	2380	110.18[a]	85.27[a]

[a] Average tonne ha^{-1} harvested excluding treatments with none harvested

Table 3. Nutrient content of wood chips produced from whole trees and harvesting residues. Numbers within each column that are followed by a different letter are statistically different (alpha = 0.05).

	% of sample by weight			
Material	**Ca**	**N**	**P**	**K**
Residues	0.44a	0.19a	0.03a	0.17a
whole trees	0.27b	0.13b	0.02b	0.11b

Table 4. Post-harvest measure of residual biomass for treatment and the residual nutrients on the site from down and standing material. Numbers with different letters in each column correspond to statistically significant differences (alpha = 0.05).

			residual nutrients kg ha^{-1}			
Treatment	Down Woody Material (t ha^{-1})	Residual Standing Material (t ha^{-1})	N	P	K	Ca
Conventional	10.88a	7.73a	12.31a	2.15a	11.01a	28.72a
Integrated	3.69b	0.81a	2.98a	0.52a	2.67a	6.95a
Biomass Only	2.53b	0.21a	1.82a	0.32a	1.36a	4.24a

Table 5. Nutrient removals from stem wood only harvests of loblolly pine (*Pinus taeda*) from our study site in Bertie County, North Carolina and other published in the southeastern United States.

Source	Biomass (t ha^{-1})	N	P	K	Ca
		---------------Kg ha^{-1}---------------			
Study Site	119	44.68	7.93	38.76	100.08
Li et al. 2005	37	46.00	3.00	15.00	68.00
Mann et al. 1988	85	63.00	6.00	35.00	71.00
Mann et al. 1988	58	59.00	5.00	20.00	80.00
Pehl et al. 1984	148	112.00	16.00	61.00	146.00
Wells et al. 1975	125	112.00	14.90	89.00	112.00
Ku and Burton 1973	-	122.00	12.00	68.00	138.00

Table 6. Biomass removals from each harvesting treatment as well as the change in nutrient removals from the conventional harvesting treatment. Statistically significant differences between treatments (alpha = 0.05) are designated by different letters next to the nutrients removed.

		---kg ha^{-1}---							
Treatment	t ha^{-1} Harvested	N	Δ from conventional	P	Δ from conventional	K	Δ from conventional	Ca	Δ from conventional
Conventional	119.1	51.57a	0	9.16a	0	44.73a	0	115.52a	0
Integrated	135.0	86.74b	35.17	15.03a	5.87	77.17a	32.44	197.43b	81.91
Biomass Only	136.5	86.74b	35.17	11.96a	2.80	61.75a	17.02	197.43b	81.91

Table 7. Post-harvest visual classification of litter as designed by Eisenbies et al. 2005 for each harvesting treatment. Statistical differences within columns are designated by different letters (alpha = 0.05)

	-------------------------------------% of area			---------------------------------------
Harvesting Treatment	Bare Soil	Litter Only	Light Slash	Heavy Slash	Piles
Conventional	4.23a	42.89a	41.19a	5.94a	5.56a
Integrated	4.74a	69.04b	23.82b	0.94b	1.27b
Biomass Only	8.33b	75.69c	15.28c	0.64b	0.00b

Table 8. Post-harvest visual classification of soil disturbance for each harvesting treatment (decks were not included in these estimations because there was too much cover to visually estimate soil disturbance).

	--- % of area---					
Harvesting Treatment	Churned	Deep Rutting	Shallow Rutting	Compression Track	Traveled but not Disturbed	No Disturbance
Conventional	0.00	0.00	0.00	40.80a	3.47a	55.71a
Integrated	0.00	0.00	0.00	40.20a	9.77a	50.00b
Biomass Only	0.00	0.00	0.00	43.09a	0.99a	55.87a

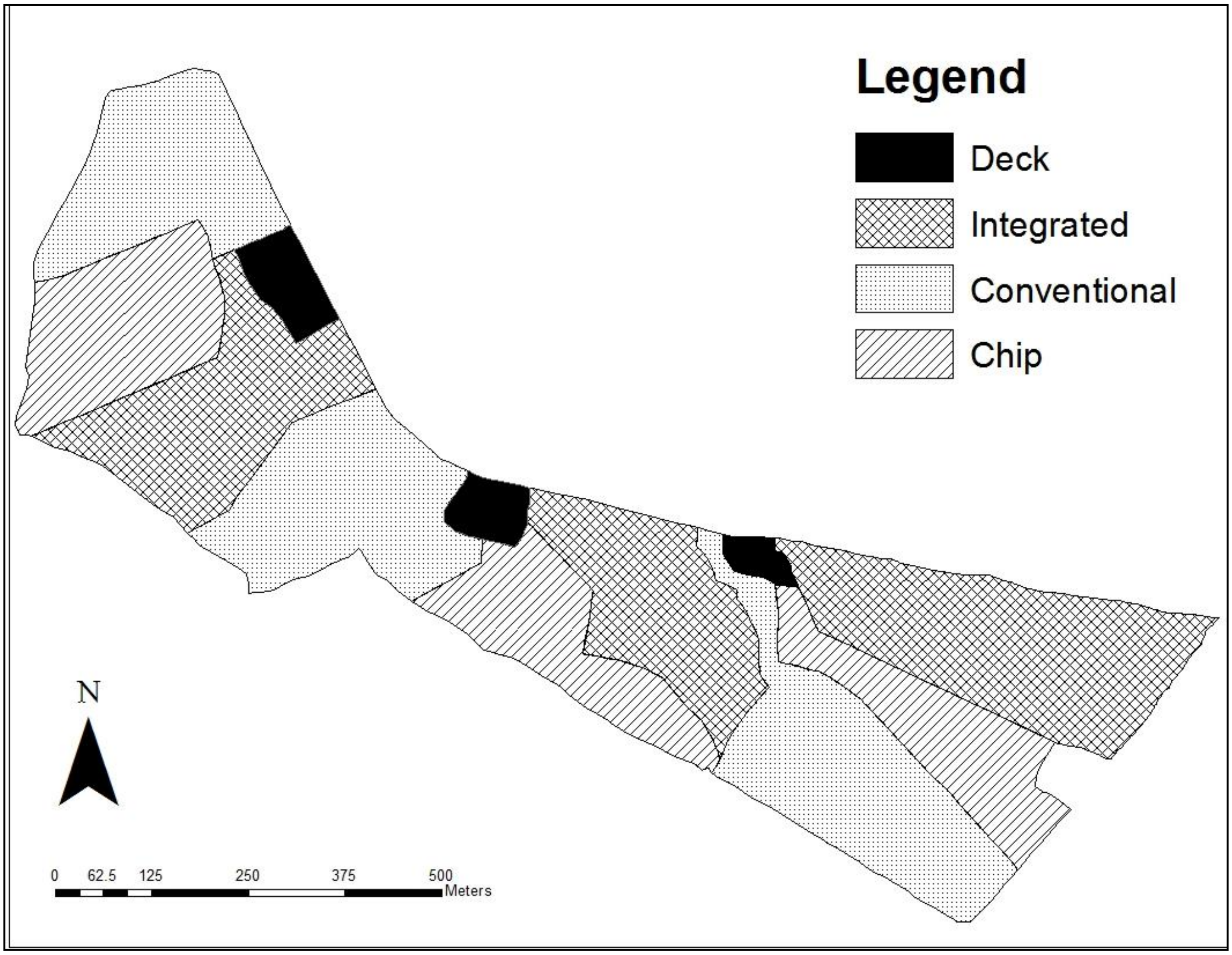

Figure 1. Harvest layout map showing treatment units and deck locations.

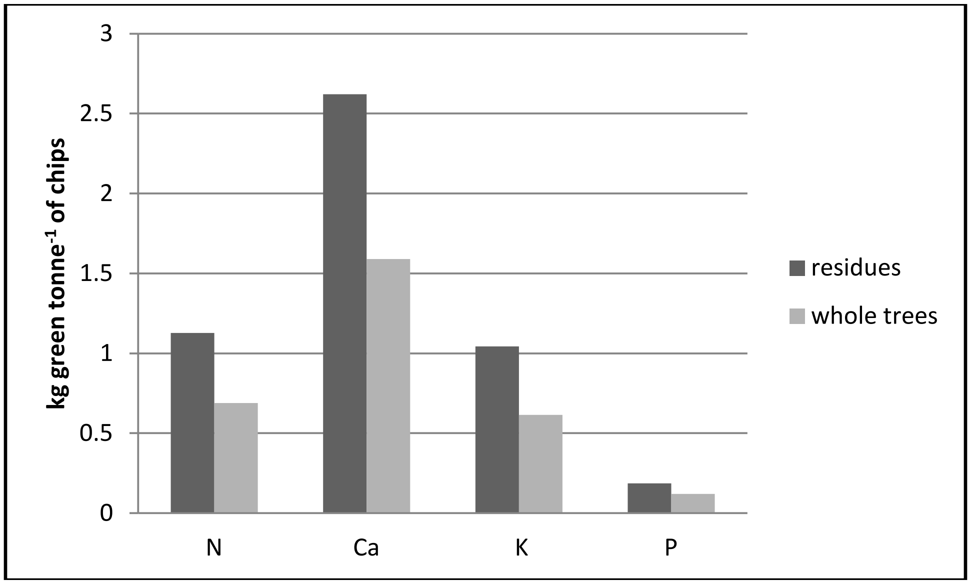

Figure 2. The nutrient content (in kg per green tonne of chips) of chips produced for residues and whole trees. The differences between residues and whole trees were statistically significant for all nutrients ($p<0.0001$).

Chapter 4: Conclusion

Study Objectives

The objectives of this study were to examine differences in characteristics of wood chips produced from whole trees and harvesting residues, evaluate the effects of chipping whole trees and harvesting residues on chipper productivity and fuel consumption, and to evaluate the effects of blade wear on chipper productivity, chipper fuel consumption, and chip characteristics. In this portion of the study, two harvesting treatments were utilized: 1) An integrated roundwood and fuel chip clearcut with merchantable and non-merchantable stems being felled. Stems were cut by the feller buncher, and merchantable stems were skidded to a loader to be processed as roundwood and non-merchantable ones were skidded to a chipper. Merchantable stems were those > 10 cm diameter at breast height (dbh) and non-merchantable ones were those < 10 cm dbh. Merchantable materials were processed as a tree length commercial clearcut, and saw timber, chip-n-saw, and roundwood pulpwood were harvested and transported to appropriate mills. Limbs, tops, and non-merchantable materials were chipped and delivered for use as boiler fuel. 2) A fuel chip harvest in which merchantable and non-merchantable stems were felled and skidded together. All materials in this treatment were chipped as whole trees and delivered as boiler fuel. The purpose of this treatment was to simulate a circumstance in which the price of energy chips and roundwood pulpwood are equal, and landowners and harvesting contractors can choose between delivering roundwood pulpwood to a pulpmill and delivering chips to an energy facility.

This study also evaluated the sustainability of harvesting woody biomass for energy by comparing nutrient removals of three different harvesting treatments. Harvesting treatments one and two were the exact treatments described above. The third harvesting treatment was a fuel chip harvest in which merchantable and non-merchantable stems were felled and skidded together. All materials in this treatment were chipped as whole trees and delivered as boiler fuel. The purpose of this treatment was to simulate a circumstance in which the price of energy chips and roundwood pulpwood are equal, and landowners and harvesting contractors can choose between delivering roundwood pulpwood to a pulpmill and delivering chips to an energy facility. Sustainability was also evaluated by comparing the visual soil disturbance and visual classification of litter on the forest floor between each harvesting treatment.

Objective 1 and 2

In this portion of the study, chip samples were collected from active harvesting operations that were chipping whole trees and harvesting residues. The data analyzed were moisture content, energy content, and size distribution of the chip samples. Moisture content and energy content data were analyzed in SAS v9.2 statistical software (SAS Institute 2008) using the PROC GLM procedure. Size distribution data were analyzed using Chi-squared. To determine the effects of blade wear on size distribution, regression analysis were performed in STATA statistical software. Chipper productivity and chipper blade wear were evaluated by performing elemental time studies and measuring fuel consumption of the chipper. Productivity was determined by measuring the delay free time to fill a van load of chips and using load weights to estimate tons produced per hour by the chipper. Fuel consumption was measured after every load of chips. Differences between materials were determined using the Proc GLM procedure. All procedures were considered significant based on an alpha of 0.05.

The energy content of chips (expressed as a higher heating value) was determined using a Parr bomb calorimeter. There was no significant difference between chips produced from whole trees or residues and they had an average energy content of 19.91 MJ/kg and 19.28 MJ/kg respectively. There was a significant difference in moisture content. Chips produced from whole trees had an average moisture content of 45.8 % (wet basis), and chips produced from residues had an average moisture content of 39.6 % (wet basis). This difference was most likely the result of delays in the chipping operation. Whole trees were usually chipped within days of felling, but residues would often be piled for weeks before chipping.

Size distribution was determined using a William's Chip Classifier with seven size categories. There was a significant difference between treatments for two size classes; however, there was no difference between the amount of acceptable chips produced. In general, whole trees produced smaller chips, but neither treatment produced an excessive amount of fines or oversized particles. Regression analysis showed that as blades became worn the amount of larger particles produced decreased and the amount of smaller sized particles began to increase. Blade wear did not have any effect on the amount of fine particles produced. The chipper used in the study was a Conehead 585 drum style chipper, and could have influenced the size of the chips produced. Conehead chippers, produced by Dynamic Manufacturing, have an hourglass shaped drum that is supposed to help the chipper slice wood chips and produce more uniform chips. However, this particular machine had well over 3,000 engine hours, and did not necessarily function as it was designed to. The blade anchors of two blades had previously been torn out of the machine as well as one anvil anchor, and this could have changed the angle of the blades and the anvil.

There was a significant difference in productivity when chipping whole trees and when chipping residues. Whole tree chipping had a much higher productivity with average production levels at 31.29 tonnes hour^{-1} and residue chipping having an average productivity of 18.58 tonnes hour^{-1}. The differences in productivity could have been the result of several things. One is that the residue material had a lower moisture content that could have resulted in lower truck payloads. Another factor that could have caused this difference is piece size. The whole trees could be fed into the chipper much more efficiently than a bundle of harvest residues. Often only a few pieces from a residue bundle would go through the chipper at one time. Regression analysis showed that blade wear had no effect on chipper productivity.

Fuel consumption was measured after each load was filled, and there was a significant difference when chipping whole trees and when chipping harvest residues. When chipping whole trees the average fuel consumption was 66.7 liters hour^{-1} and when chipping harvest residues fuel consumption was 39.22 liters hour^{-1}. However, chipping harvest residues consumed more fuel per tonne chipped than chipping whole trees. Regression analysis did not show any relationship between blade wear and fuel consumption. Fuel consumption seemed to be more closely related to the productivity of the chipper rather than blade wear. As chipper productivity increased so did chipper fuel consumed per hour, but the chipper was still able to operate more efficiently in terms of liters of fuel consumed per tonne of wood chipped.

The costs associated with chipping whole trees versus harvesting residues are another important consideration. A separate study performed on this site showed that the cut and load costs as well as the chipping costs of harvesting residues were higher than whole trees. Additionally, the inability of the harvesting contractor to completely fill a van when chipping harvesting residues substantially increased the trucking costs of residue chips.

Objective 2 and 3

In this portion of the study, chip samples were collected and analyzed for their content of nitrogen, phosphorus, potassium, and calcium. Estimations for nutrient removals via bole wood were done by estimating the nutrients removed by whole tree and residue chips in kg ha^{-1}, and the amount of removals by residue chips was then subtracted from the removals by whole tree chips as an estimation of removals by only bole wood. A visual classification of the soil disturbance and litter composition were conducted to evaluate the disturbance of the forest floor during harvesting. Each classification was done prior to harvesting and again when harvesting was completed. The study was designed as a completely randomized block design, and there were three blocks with each block containing all three harvesting treatments. Nutrient content data were analyzed using SAS v9.2 statistical software (SAS Institute 2008) using the PROC GLM procedure. Changes in litter composition were analyzed using the PROC GLM procedure, and treatment differences were determined using a Tukey means separation test. Differences were considered significant based on an alpha of 0.05.

Analysis of chip samples showed that residue chips had a higher concentration of nutrients than whole tree chips. This would be expected since residues are made up of limbs, tops, and small stems which are known to contain more nutrients proportionally than bole wood. Based on this analysis we were able to estimate the nutrients removed from each treatment during harvesting. There was no statistical difference in the nutrients removed from the biomass only and the integrated harvesting treatment. This was expected since there was no difference in the materials being removed from each treatment and the amount of material removed during harvesting was very similar. The conventional harvesting treatment removed significantly less N (51.57 kg ha^{-1}) and Ca (115.52 kg ha^{-1}) than the other harvesting treatments, but there was no statistical difference in the amount of P or K removed during harvesting. Assuming that the next rotation would last another 25 years until the final harvest, N removals for the conventional treatment could be broken into 2.1 kg ha^{-1} yr^{-1} and N removals from the integrated and the biomass only treatments would be 3.5 kg ha^{-1} yr^{-1}. While the amount of removals is significantly more in the integrated and the biomass only treatments, they are not large enough to cause damage to the site quality. Atmospheric deposition will replace the N removed from the conventional treatment within three years and six years in the integrated and biomass only treatments. Additionally, fertilizer could be applied to hasten the replacement of nutrients removed.

Prior to harvest, there was no visual soil disturbance and the forest floor was made up of 95 % litter only and 5 % was light slash that was left over from when the stand was thinned. The post harvest visual classification of soil disturbance showed that there was little disturbance during harvesting for all treatments. There was significantly less percentage of area that had no disturbance in the integrated harvesting treatment, but there were no statistical differences in any other disturbance category. The post-harvest classification of litter did show differences between harvesting treatments. There was a significantly higher percentage of bare soil in the biomass only treatment, but only 8 % of the soil was bare compared to 4 % in the conventional and integrated treatments. The biomass only treatment also had the highest percentage coverage of litter only and the least in light slash, heavy slash, and piles. The conventional harvesting treatment had the lowest percentage coverage of litter only and the highest percentage coverage in light slash, heavy slash, and piles. Post harvest estimates of residual material on the site showed that the conventional harvesting treatment had the most with 18.61 t ha^{-1} and the integrated and the biomass only harvesting treatments had 4.5 t ha^{-1} and2.74 t ha^{-1}, respectively. These numbers support the findings from the visual estmates of material on the forest floor.

When compared to the conventional harvesting treatment, the integrated and the biomass only treatments were not extremely different. While there were differences in the nutrient removals, the removals were not necessarily large enough to cause any damage to the site.

Visual soil disturbance was not very different either. However, if soil conditions had not been dry during harvesting, it is possible that there would have been treatment differences. It is important to note that other forms of site disturbance (erosion and compaction) were not investigated in this study. Changes in erosion potential were deemed inconsequential since slopes on the site never exceeded 1%. Compaction was the focus of a separate study conducted at the same time.

Literature Cited

SAS Institute Inc. 2008. SAS/STAT® 9.2 User's Guide The GLM Procedure. SAS Institute Inc. Carey, NC