Woody Biomass Production in the Southeastern United States

by

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Abstract

There is an increasing emphasis throughout the United States on renewable sources of energy. The shifting energy economy can create opportunities for loggers to play an important role in the renewable energy market. Loggers can seize this opportunity to increase their revenues while delivering a renewable energy feedstock to energy producers. To do so, loggers can harvest forest biomass in the form of small diameter trees, nonmerchantable stems, and forest residues. These woody materials can then be comminuted into wood chips which can be delivered to customers. However, there are costs associated with the harvesting and subsequent processing of biomass that loggers must consider, such as owning and operating a woodchipper.

Three production studies were conducted on three on-site biomass chipping operations in the Southeastern United States to determine their production rates and costs. Time study and machine rate methods were implemented to conduct this analysis. Average productivity rates for felling, skidding, and chipping were 19, 37, and 74 tons per productive machine hour. Observed cut-and-load costs for the three operations ranged from $1.62 to $5.30 more per ton than comparable roundwood harvesting operations. The numbers produced by this study can be used as a reference for other market participants or potential market participants throughout the region.

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List of Abbreviations

BA	Basal Area
DBH	Diameter at Breast Height
GHG	Green House Gas
KED	Kinetic Electronic Designs
SDT	Small Diameter Trees
TPA	Trees Per Acre
TPP	Trees Per Plot

1 Introduction

1.1 Project Background

Society is placing a growing emphasis on renewable and sustainable energy sources (BloombergNEF, 2020; Caputo et al., 2005; Hanzelka, Sullivan, et al., 2016; Zerbe, 2006). Sustainably sourced woody biomass can be a renewable natural resource and a carbon neutral fuel. Woody biomass is sustainable as the woody material is replaced after a harvest by subsequent forest growth. Biomass can be a carbon neutral fuel if the carbon that is released when it is burned is offset by the carbon that is sequestered during forest growth (Cowie et al., 2021). Where markets exist, loggers can harvest biomass from the forest and sell it to energy producers. In selling biomass to energy producers, loggers can drive revenue and become an important component of the renewable energy sector supply chain.

Woody biomass comes from two main sources: forest biomass and mill residues. This project focuses solely on the forest biomass side of woody biomass production. Forest biomass consists of both forest residues and nonmerchantable stems. Forest residues are those parts of a merchantable tree that are traditionally nonmerchantable, such as tops and branches. Residues are ordinarily left behind by logging operations as this material is low in value and most operations are not configured to process it. Nonmerchantable stems consist of materials such as small diameter trees and whole trees that, due to some defect or operational configuration, cannot be economically used to produce conventional products. Operations with the proper configuration can comminute these materials and transport them to a buyer. On these operations, forest biomass is fed through an onsite woodchipper to produce biomass wood chips. An example of the resulting wood chips can be seen in Figure 1. These biomass wood chips can be transported more economically than the uncomminuted material. This is because comminution increases a material's bulk density which allows for larger payloads. Once comminuted, wood chips are transported along roadways to the buyer.

Figure 1: A handful of biomass wood chips. Comminuted bark can be seen along with the wood chips. Biomass wood chips are also commonly referred to as dirty chips.

Buyers of biomass wood chips can use the material to produce heat or energy instead of using fossil fuels. However, wood chips have a low calorific value when compared to other energy sources such as coal or natural gas (McKendry, 2002). This low calorific value means that forest biomass produces less energy than an equivalent volume of other energy sources such as coal or natural gas. While forest biomass has the disadvantage of a lack of energy density, it has certain advantages over coal or natural gas which could incentivize its consumption. One of forest biomass' advantages is that it does not have the externalities that burning fossil fuels do. Fossil fuels take millions of years to replenish; biomass can be carbon neutral on a timescale meaningful to humanity (Cowie et al., 2021; Höök et al., 2010).

Forest biomass not only has advantages over traditional energy sources, but it also has certain advantages over other renewable energy sources, such as solar and wind. These advantages come in the form of non-intermittence, non-reliance on battery technology, and dispatchability. Energy from biomass is non-intermittent as it can be harvested at any time of day or night in all seasons if crews are set up for it. During periods of rain that limit harvest activities, operations can often minimize their downtime by moving to tracts that are on higher ground or have better drainage. Biomass does not rely on battery technology to store energy, which is still expensive and inefficient, as the energy is stored within the wood itself. Biomass does, however, need to be stored in a geographical location. Storage for woody biomass is often in the form of a chip pile in a wood yard. Energy from biomass is dispatchable as it can be burned at any time of day or night in response to changing energy demands.

While consuming woody biomass can offer benefits to the energy sector, harvesting it poses challenges for those who produce it. The major challenge of harvesting biomass is performing the harvest in an economically feasible manner. Because of the above-mentioned low energy density, woody biomass is a low value product. In addition to being a low value product, extra equipment is required to produce it. Operations that process biomass have a chipper on site whereas typical southeastern logging operations do not. Broadly, the purchase price of a whole-tree woodchipper can range from $200,000-$500,000. Even with the low economic value of the product and expensive equipment required to process it, it has been shown in the southern pine region that it is possible for loggers to generate revenue through forest biomass harvesting. However, their economic margins can be slim (Conrad et al., 2013; Hanzelka, Bolding, et al., 2016). The costs of biomass harvesting must be economically sustainable in the long run for biomass producers to stay in business.

If a logging crew is harvesting both biomass and roundwood in what is called an integrated harvest, they may be willing to accept low margins for their biomass harvesting operation. This is because harvesting biomass can make them more competitive when bidding on a tract. Landowners tend to prefer the clean site that biomass harvesting operations leave behind over the heavily littered site that conventional logging operations typically produce. A clean site is a benefit to landowners because it makes site preparation potentially less costly overall (Miller et al., 1987; Watson et al., 1984). In the case of potential losses due to biomass production costs, integrated harvests can cover their biomass production costs with roundwood production revenue. However, this is not ideal and could lead to operators ceasing their biomass operations. For biomass harvesting operations that do not produce roundwood, the revenue they generate from biomass production must be sufficient to cover their costs. If they cannot cover their costs from biomass production, they are not economically sustainable.

Because of the economic challenges involved in harvesting biomass, individuals may be reluctant to become productive members of the market. This project aims to provide a benchmark for loggers that can aid them in making biomass harvesting decisions. The details of the operations shown in the following sections show how some existing market participants in the Southeast configure their operations. Additionally, the production rates and costs can help others to anticipate the realities of a biomass harvesting business. This project contributes to a larger network of projects that ultimately aims to produce a framework for the development of forest biomass harvesting and logistics in the Eastern United States. By learning from the resulting framework, loggers and industry participants can begin to play a larger role in the energy economy through the harvesting, processing, and delivery of forest biomass.

1.2 Objectives

The objective of this study was to determine the production rates and associated costs of biomass harvesting operations in the Southeastern United States. This was completed in the form of two sub-objectives.

1. Evaluate production rates of three forest biomass harvesting and on-site chipping operations.
2. Estimate cost to operate machines on a per unit basis when utilized on a biomass harvesting and on-site chipping operation.

2 Literature Review

2.1 Supply Chain and Challenges

The supply chain for forest biomass closely resembles the supply chains of conventional forest products. Forest biomass is harvested from the forest by operations that use logging equipment, processed at the landing or in the woods, and transported over roads to be delivered to a buyer (Baker et al., 2010; Benjamin et al., 2009; Conrad et al., 2013, 2018b; Kizha & Han, 2016; Rentizelas et al., 2009; Spinelli et al., 2020). The differences between the woody biomass supply chain and the supply chains of typical forest products are found in the processing and transport of the woody material and in certain types of buyers of the forest biomass.

The central activity of woody biomass processing is its comminution. Comminution is the breaking down of material into smaller pieces. Commonly in the Southeast biomass is comminuted on the landing, although in some cases it can also be comminuted in the woods by a mobile chipper (Spinelli et al., 2020). The comminution process itself is accomplished either with knives, in the case of chippers, or hammers, in the case of grinders. Grinders produce what is often called "hog fuel", which is comminuted woody material of highly variable proportions and is most often only utilized for heat or energy through burning (Aman et al., 2011). Chippers can be used to produce chips that are suited for either pulp and paper or energy production, depending on how they are used (Aman et al., 2011). Chippers producing pulp chips use a screen which aids in keeping wood chip proportions consistent. This consistency is often required by pulp mills. Chippers producing biomass wood chips generally do not use a screen as the chip proportion requirements are not as strict as pulp chip requirements.

Whether using a grinder or chipper, comminution makes biomass more economically feasible to transport. Comminution increases a material's bulk density which allows for larger payloads. Biomass takes up less space in its comminuted form than it does when it is in its raw form. However, comminuted woody material cannot be transported in the same manner as roundwood. It requires a different method of storage during transportation from roundwood. Instead of being loaded onto log trailers, biomass wood chips are blown into chip vans. Thus, an operation that is chipping biomass requires not only a chipper, but also a fleet of chip vans as well. If the operation does not want to sacrifice roundwood loads for biomass loads by reassigning trucks, they will also need to acquire trucks and hire truck drivers to pull chip vans. Trucking can also be outsourced to private contractors to alleviate the need to make trucking related purchases. However, whether contract trucking or using their own trucks, loggers may find it difficult to find drivers due to the truck driver shortage.

Once loaded into vans, biomass wood chips are transported to the buyer. Some of the buyers of forest biomass are typical roundwood market participants as well. An example of this type of buyer would be a paper mill that uses biomass wood chips as fuel for its boilers. Often though, the buyers of biomass wood chips are not the typical customers of loggers. While roundwood buyers transform wood into a variety of tangible products such as lumber or paper, the consumers of forest biomass burn the wood to harness its stored energy (Benjamin et al., 2009; McKendry, 2002). Alternatively, a biomass consumer could also further process the biomass wood chips to produce other products, such as wood pellets or liquid fuels (Kenney & Ovard, 2013; McKendry, 2002).

Every supply chain has certain unique challenges. The bioenergy supply chain is no exception. The spatial distribution of forest biomass is one challenge to the forest biomass supply chain. Whereas some energy feedstocks such as natural gas and coal can be found in large quantities in centralized locations, forest biomass is scattered over large geographical areas. The scattered nature of forest biomass makes it uneconomical to construct infrastructure that could be used to transport the material, such as train tracks. This spatial distribution results in high transportation costs as it is necessary to haul the material over the road using trucks and chip vans (Caputo et al., 2005; Gonzalez et al., 2011; Rentizelas et al., 2009). An example of these trucks and vans can be seen in Figure 2. Another result of the spatial distribution is that harvest operations must move frequently. Once a site has been harvested, the operation must move on to a new site. This constant movement of the harvest operation entails costs and lost production. A forest harvesting machine incurs hourly costs whether it is being used or not. These costs are referred to as fixed costs and include depreciation, interest, insurance, and taxes (Miyata, 1980). To offset these costs, the machine must be involved in productive activity. The amount of time that a machine is productive is referred to as productive machine hours (PMH). However, when operations move from site to site, they accumulate non-productive hours. These non-productive hours negatively affect an operation’s revenue.

Figure 2: Truck hauling a chip van. The whole-tree woodchipper is pictured blowing wood chips into the back of the van.

The low energy density of woody biomass is another challenge for the supply chain. The energy density of forest material is lower than the energy density of traditional energy feedstocks such as coal or petroleum by approximately 40-55% (Caputo et al., 2005; McKendry, 2002). This means that woody biomass will produce less energy than an equivalent volume of fossil fuels. Forest biomass, in addition to having a lower energy density than other energy feedstocks, also has a lower bulk density (Allen et al., 1998). This lower bulk density means that given equal weights of biomass and fossil fuel, the biomass will take up more space. The result of these two factors is a further increase in the cost of transporting the biomass material (Allen et al., 1998; Caputo et al., 2005).

Trucking is a major economic challenge for southern loggers, a fact which has been documented by several surveys. A 2017 survey of South Carolina loggers revealed that 96% of logging businesses saw substantial increases to their trucking insurance costs and that many businesses had trouble filling their trucking positions (Hiesl, 2020). Another 2017 survey in Georgia revealed that trucking was the second biggest challenge to logging business owners, second only to mill quotas (Conrad et al., 2018b). Insurance costs and truck driver shortages were again cited as major contributors to the trucking challenge (Conrad, 2018). Trucking is also the most expensive portion of a forest harvesting operation, accounting for between 30% and 50% of an operation's costs (Allen et al., 1998; Caputo et al., 2005; Hanzelka, Bolding, et al., 2016; Koirala et al., 2017). The burden of trucking can be a larger challenge to biomass operations than to logging operations as biomass operations require their trucks to haul less valuable material.

Because of the combination of the in-woods costs associated with producing a low value product and the costs of transportation, forest biomass producers often produce biomass with slim economic margins (Conrad et al., 2011; Hanzelka, Bolding, et al., 2016). Biomass competes in the open market with other sources of energy such as natural gas and coal. Unfortunately for biomass producers, in the current macroeconomic climate, gas and coal are cheaper for energy producers to buy (EIA, 2021a, 2021b). If price of natural gas or coal rises, biomass would be more competitive. Even then, margins could continue to be slim as the cost of fuel for the harvest equipment and trucks would likely also be higher in that economic climate. Like much of the macroeconomy, the price of other energy sources is outside the control of biomass producers. What is more within the power of the biomass producers is the cost to harvest biomass. If the cost to produce and deliver biomass comes down, producers could see healthier margins.

2.2 Harvesting Methods

The harvesting portion of the supply chain is the focus of this study. Forest harvesting methods vary throughout the United States. For example, chainsaw felling is commonplace in mountainous regions of the United States and cut-to-length operations are common in the Lake States while mechanized whole-tree harvesting systems are predominant in the Southeast (Conrad et al., 2018a, 2018b). Southeastern biomass harvesting operations inherit much of their operational configurations from the logging operations typical to the area. That is, they employ rubber-tired feller-bunchers to fell the material, grapple skidders to skid the felled material, and knuckleboom loaders to feed the material into their chipper.

While logging equipment is used in harvesting biomass, the equipment is used to harvest smaller material than a typical logging operation would handle. Harvesting this small diameter material, such as the material pictured in Figure 3, poses challenges and increases costs for an operation every single time the material is handled due to the material’s low bulk density (Benjamin et al., 2009; Grushecky et al., 2007; Magagnotti et al., 2021). Logging equipment is generally built to handle material larger than 6 inches DBH (Benjamin et al., 2009; Bolding et al., 2009). Logging equipment is designed with large material in mind as that material is more valuable than small diameter material and is readily available. The large design serves southern loggers well on a typical roundwood harvest, as they are the among the most productive loggers in the United States (Conrad et al., 2018a). However, this same design leads to inefficiencies when handling materials that the equipment was not designed to handle, such as small diameter biomass material. Due to this incongruity between the heavy logging equipment and the type of material they handle when on biomass harvesting operations, operators can expect to see productivity losses.

Figure 3: SDT and low-quality woody material that is unfit for making traditional forest products. Most of the stems pictured here have a diameter less than 4 inches.

In the Southeast, the use of a feller-buncher is the most common felling method. When felling small diameter trees (SDT), a feller-buncher will often hold many stems in its felling head concurrently (Laitila et al., 2007). Previous studies have determined that feller-buncher productivity suffers when felling SDT (Akay et al., 2004; Jernigan et al., 2016; Magagnotti et al., 2021). To minimize production losses, a feller-buncher harvesting SDT can fell several stems in a single forward motion before dumping its load. This multi-stem handling cuts down both on the time spent on the back-and-forth movement typical to a feller-buncher's felling cycle. Employing this strategy on a biomass harvesting operation allows the feller-buncher to spend less time per tree and less time traveling than if it would if it were to fell and dump a single small stem at a time (Laitila et al., 2007). This minimization of productivity loss by handling many small stems at the same time is a necessity due to the low market value of this type of material.

Grapple skidders are the primary method of wood transport on a harvest site due to their ability to grab many stems at a time. Cable skidding can be productive enough for sites with large trees, but using a cable skidder on biomass material is impractical due to the small diameters and number of stems in a pile (Grushecky et al., 2007). Even operations that produce 100% of their biomass from forest residues would benefit from using a grapple skidder as opposed to a cable skidder because of the need to manipulate residues on the landing. While distance is the primary factor that affects skidder productivity, payload weight also has a large effect on productivity. Because of the low bulk density of woody biomass, a grapple full of small diameter material does not have as much mass as a grapple full of large diameter material

(Benjamin et al., 2009). Thus, skidder productivity suffers as well when handling small diameter material.

On the landing, knuckleboom loaders are commonly used to feed wood into chippers. As with the feller-bunchers and skidders, loaders can mitigate the lost productivity from handling small diameter material by handling multiple small diameter stems at the same time. Trailer-mounted loaders are common on biomass harvesting operations. Track loaders can also be utilized. Track loaders allow for more flexibility on the deck than trailer-mounted loaders. This flexibility could be required for operations that produce a mix of biomass chips and roundwood or operations that produce wood chips after all other machines have left the site.

The culmination of the harvest is the processing of the woody material in the chipper. Some biomass harvesting operations may choose to chip material with a small and mobile in-woods chipper (Manzone & Spinelli, 2013; Mihelič et al., 2018; Spinelli et al., 2020). However, in the Southeast, powerful chippers that operate on the landing are more common (Jernigan et al., 2013; Spinelli et al., 2020). This is due to the fact that chippers that are made to remain on landings are built larger and stronger, leading to increased productivity (Hanzelka, Bolding, et al., 2016; Harrill & Han, 2012).

The equipment selections used by an operation is only one aspect to a harvest. How operations utilize their equipment also influences their productivity and costs. Two common operational patterns are the one-pass system and the two-pass system. A one-pass harvesting system is one in which the feller-buncher fells roundwood and SDT and places them in separate piles. The piles of SDT are then skidded to the chipper while the piles of roundwood are brought to the roundwood processing area on the deck (Miller et al., 1987; Stokes et al., 1985; Watson et al., 1986). The name of the system stems from the fact that it only takes one pass of the equipment to complete the harvest. A two-pass harvesting system is one in which SDT is harvested and comminuted before any roundwood harvesting activity takes place. After the SDT in the understory is harvested, the roundwood harvest begins. The name of this system stems from the fact that harvesting take place in two distinct phases (Miller et al., 1987; Stokes et al., 1985; Watson et al., 1986).

Studies have compared the costs associated with one-pass and two-pass biomass harvesting systems. Previous research shows that one-pass systems are more cost-efficient than two-pass systems. The cost efficiency realized from a one-pass harvesting systems is a result of two factors: higher biomass utilization and less feller-buncher maneuvering (Miller et al., 1987; Stokes et al., 1985; Stokes & Watson, 1986; Watson et al., 1986).

Utilizing a two-pass system allows the operators to clear out the understory before harvesting larger trees. One reason for doing this is so that SDT do not get destroyed by large falling trees during roundwood operations (Stokes et al., 1985). However, previous studies were able to determine that biomass utilization is higher during a one-pass operation. This higher biomass utilization is due to the fact that a one-pass system is able to utilize not only SDT in the understory but also forest residues produced in the processing of roundwood (Stokes et al., 1985; Stokes & Watson, 1986; Watson et al., 1986).

A consequence of the two-pass system is that the feller-buncher must maneuver around the merchantable timber to get to the SDT on the first pass. This added maneuvering results in lost productivity for the feller-buncher, increasing the cost of the system (Stokes et al., 1985; Watson et al., 1986). The feller-buncher is also required to traverse the entire stand twice, once to harvest SDT, once to harvest merchantable timber. This essentially doubles the distance that the feller-buncher would travel on a one-pass harvest.

One-pass systems are also referred to as integrated harvesting systems (Hudson, 1995). Studies have been done on the relationships that occur between products and machine productivity on integrated forest harvest sites. Baker et al. (2010) studied roundwood harvesting operations that also produced biomass chips through the integration of a small chipper. He found that producing biomass from residues did not affect roundwood production. Additionally, producing biomass chips from understory material did not affect roundwood production on clearcut harvests. However, producing biomass chips from understory material on thinnings reduced roundwood production. A subsequent study by Conrad et al. (2013) found that harvesting understory biomass decreased the productivity of the feller-buncher and skidder. Conrad et al. (2013) found that producing biomass wood chips during an integrated harvest has the potential to reduce hourly roundwood production and increase the cost of the operation. Both studies recommended that until markets for forest biomass improve roundwood production should not be sacrificed to increase biomass production.

2.3 Woody Biomass for Energy

The United States is moving toward green energy (BloombergNEF, 2020; Caputo et al., 2005; Hanzelka, Sullivan, et al., 2016; IEA, 2020; Richard, 2010; Zerbe, 2006). Electricity generation from renewables in the United States rose 77% over the last decade (BloombergNEF, 2020). Additionally, renewables had the highest rate of growth of all energy sources globally in 2019 (IEA, 2020). Of renewables, solar, wind, and hydroelectric energy together produce the most power (BloombergNEF, 2020). However, as some believe that 10% of energy in the United States could eventually come from woody biomass (Zerbe, 2006), woody biomass should not be overlooked as an ingredient in America's renewable energy mix.

Some question whether woody biomass should be considered carbon neutral, as burning it releases carbon into the atmosphere (Agostini et al., 2014). However, woody biomass can be considered a carbon neutral energy source if the material is sustainably sourced and appropriate spatial and temporal horizons are considered (Cowie et al., 2021; Jenkins & Kroeger, 2020). Sustainably sourced woody biomass is a carbon neutral fuel as the carbon it gives off when it is burned is offset by the carbon that it sequestered during forest growth. However, if the forest is not allowed to regrow after a harvest than there is a net positive carbon emission associated with burning woody biomass. Additionally, if only a single stand is considered in GHG calculations, then it would take the entire growth rotation of that stand for carbon emissions to level back to zero. This can take many years depending on the stand. But when considered on a multiple-stand scale, carbon sequestration and emission can be in balance on a shorter time scale. A multiple-stand scale consideration makes a difference because as one stand's carbon is released, the surrounding stands are constantly sequestering carbon. Thus, the forest growth in the larger area can offset the carbon losses of a single stand.

Woody biomass is at a disadvantage to fossil fuels in terms of energy production, as it is not as energy dense or efficient as fossil fuels (Benjamin et al., 2009; Caputo et al., 2005;

McKendry, 2002). However, the net carbon neutrality of forest biomass is its main advantage over fossil fuels. Biomass does not have the negative externalities that burning fossil fuels such as coal and gas do. Replacing fossil fuels with biomass can decrease net GHG emissions (Caputo et al., 2005; Cowie et al., 2021; Kizha & Han, 2016; Reid et al., 2020). Biomass is also a renewable natural resource on time-scales meaningful to man-kind, unlike fossil fuels which take millions of years to replenish (McKendry, 2002).

Forest biomass has advantages over some other renewable energy sources as well. Energy sources such as wind and solar are intermittent, which can negatively impact reliability and cost (Gowrisankaran et al., 2016; Reid et al., 2020; Ren et al., 2017). Because of this, energy from solar and wind need to have a battery storage solution to meet the energy needs of the country. However, energy storage in batteries can be expensive and inefficient. Forest biomass harvesting activities are not as seasonally dependent as wind or solar energy. Even when harvesting operations are shut down due to weather, forest biomass can be a year-round source of energy if energy producers maintain an adequate inventory. During periods of rain that limit harvest activities, operations can often minimize their downtime by moving to tracts that are on higher ground or have better drainage. Energy from forest biomass is not time of day dependent, as it can be burned at any time of day in response to changing energy demands. Additionally, if there are enough laborers and markets permit, harvesting activities can continue throughout the night-time hours. Energy from forest biomass also does not need to be stored in batteries, as energy is stored within the wood itself. Biomass does need to be stored in a geographical location if energy producers want to keep an inventory. Storage for woody biomass often is in the form of a chip pile in a wood yard. Biomass energy is easily dispatchable to demand as energy producers can burn the woody material directly in response to a need (Jenkins & Kroeger, 2020).

3 Materials and Methods

3.1 Study Sites

Three forest biomass harvesting operations were observed during this study. Study sites for the production studies were chosen based on the location of forest biomass chipping operations. Communication was established with the harvesting crews or their supervisors prior to each study to ensure that harvest sites were representative of their crews' typical operating conditions. Studies were done in the region of biomass markets by necessity, as biomass harvesting cannot take place economically without a buyer. All three operations harvested in the Coastal Plain region of the Southeastern United States. The locations of the three operations which were visited are shown in Figure 4. The boundaries of each site are shown in Figures 5 through 7. Operation A was harvesting from May 18th through 29th, 2020, on an 80.9-acre tract near Bonifay, FL. Operation B was observed harvesting from July 15th through 23rd, 2020, on a 92.7-acre tract south of Gainesville, FL. Operation C was observed harvesting from December 15th through 17th, 2020, on a 10.2-acre tract near Dublin, GA. This last operation would not have been harvesting on such a small tract had it not just finished harvesting an approximately 32-acre tract less than 0.5 mile down the road.

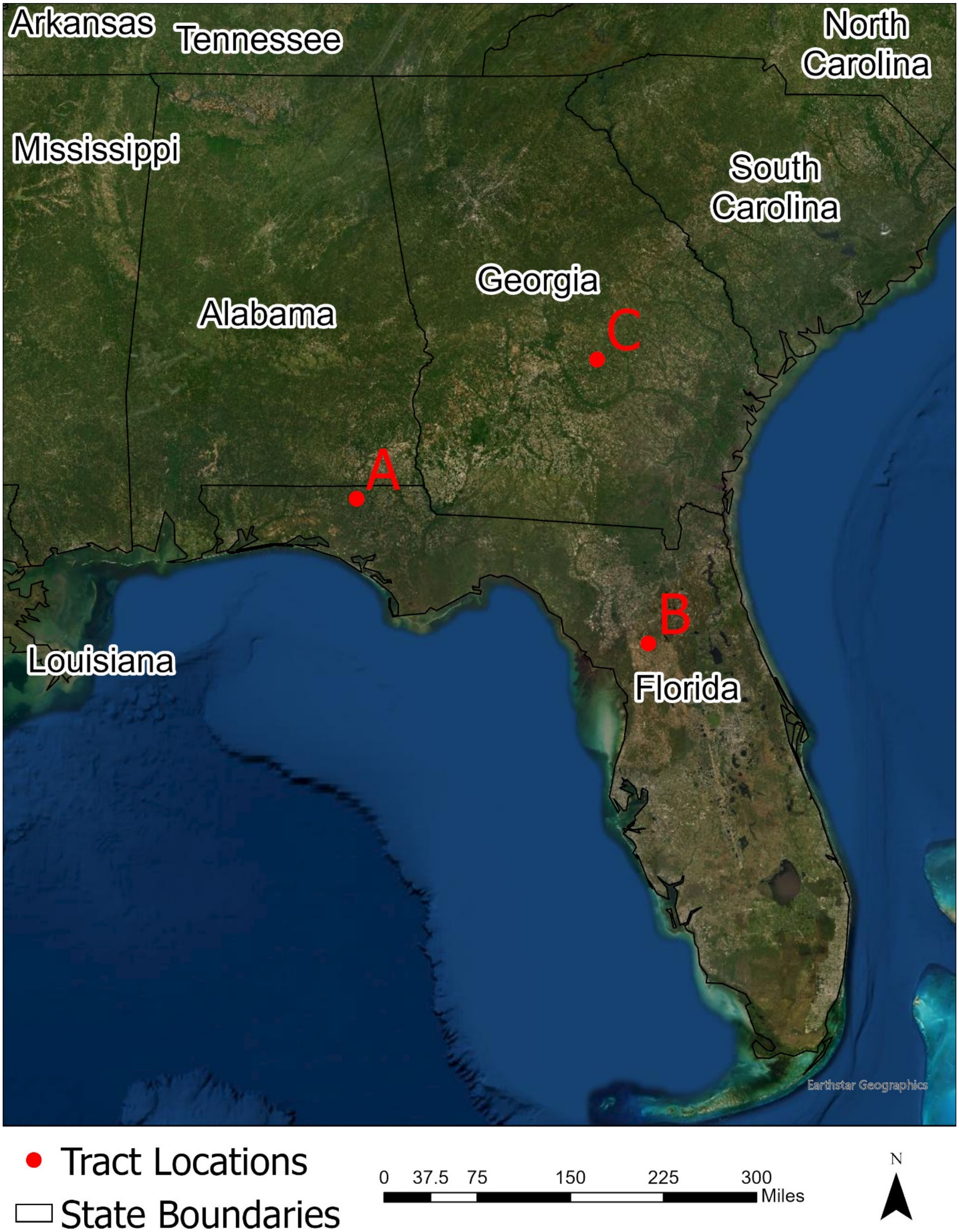

Figure 4: Geographical location of the three study sites. (A) Bonifay, FL, (B) Gainesville, FL, (C) Dublin, GA. All sites were located in the Coastal Plain of the Southeastern United States.

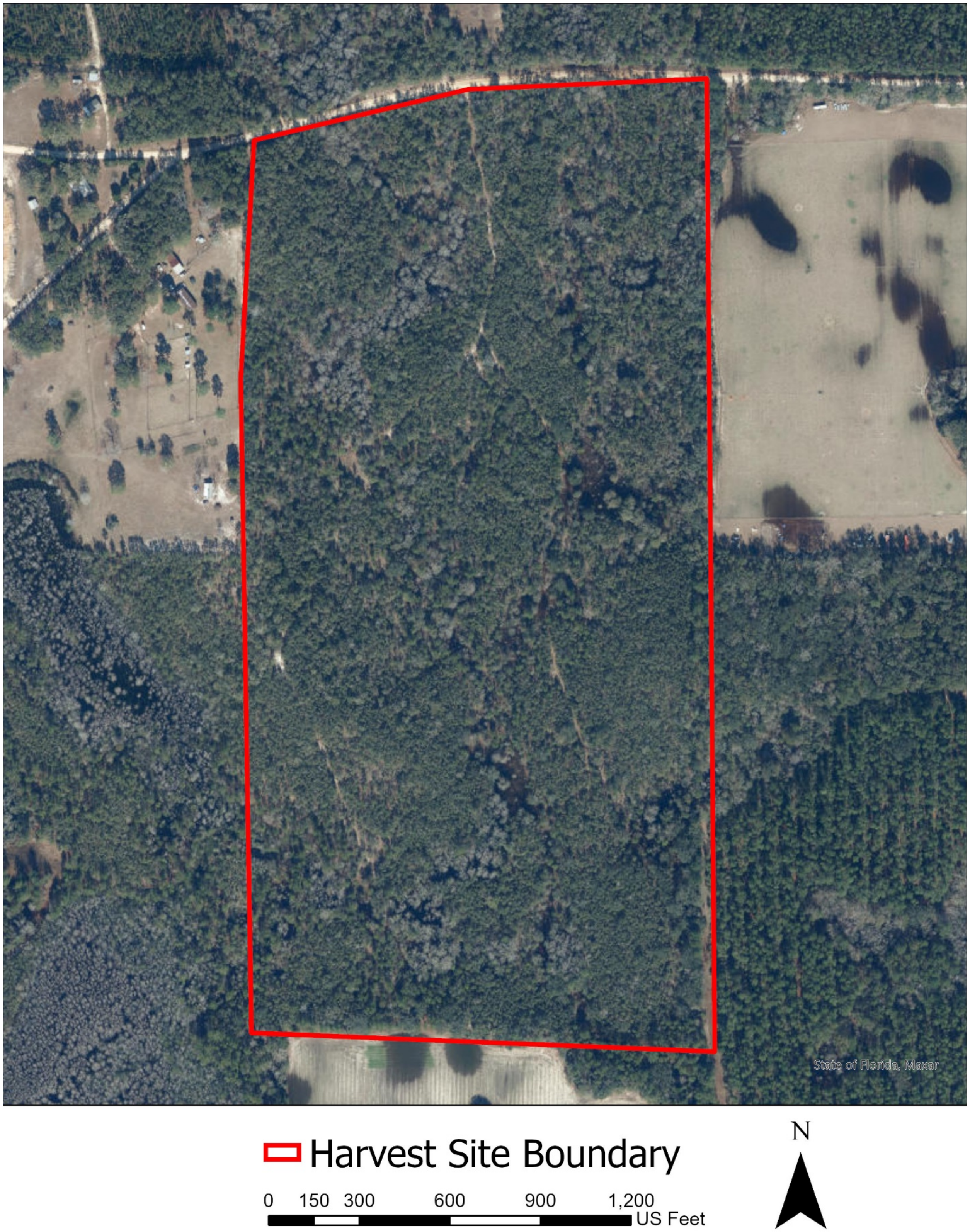

Figure 5: The 80.9-acre tract near Bonifay, Florida, where operation A was harvesting in May of 2020. Satellite imagery accessed on

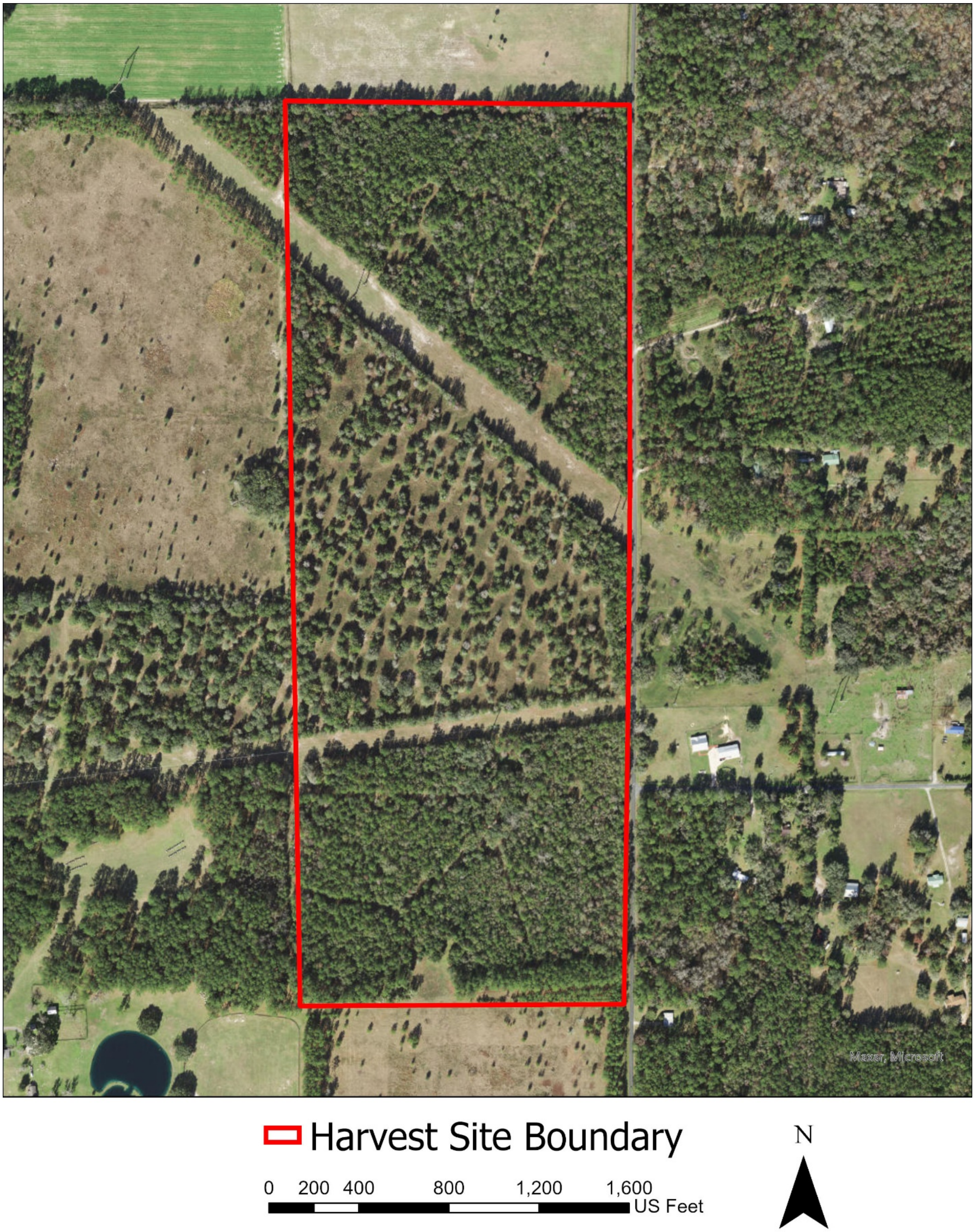

Figure 6: The 92.7-acre tract near Gainesville, Florida, where operation B was harvesting in July of 2020. Acreage does not include the two rights-of-way that pass through the tract.

Figure 7: The 10.2-acre tract near Dublin, Georgia, where operation C was harvesting in December of 2020.

3.2 Stand Inventory

Stand characteristics on sites A and B were measured on unharvested areas of the stands using a timber cruise while the harvesting operations were in progress to ascertain initial stand conditions of the study sites. On operations A and B, ten 10^{th} acre fixed radius plots were established on each site. All stems within a plot that had a DBH of at least two inches were measured and classified into one-inch diameter classes. Stem heights were established with the use of a clinometer. A timber cruise was not completed on operation C, as the understory was almost completely felled upon arrival of observers. For operation C, biomass tree dimensions were visually estimated as the feller-buncher was cutting and forming piles of SDT. During the analysis of each sites' characteristics, trees were classified into hardwood and softwood classifications to account for differences in densities. Stand volume was calculated using the tree volume tables published by Clark, Saucier, and McNab (Clark et al., 1986; Clark & Saucier, 1990). An example of the cruised material can be seen in figure 8.

Figure 8: Small diameter woody material on operation A. Hat included for scale.

3.3 Production Studies

Production studies were conducted on all three operations. Feller-buncher, skidder, loader, and chipper utilization data were recorded using Kinetic Electronic Designs Activity Recorders model VR081R (*Kinetic Electronic Designs*, 2020), which can be seen in Figures 9 and

10. The activity recorders were fixed to the inside of each machine’s cab –in the case of the chipper, inside of an attached external toolbox– by use of double-sided tape in an upright position. From this position, they recorded vibrations. The collected vibration information signals when each piece of equipment was running and gave insights into machine utilization. The activity recorders could keep their battery life for the entirety of each study so there was no need to handle them during the course of a study.

Figure 9: KED Activity Recorder attached to the interior surface of a window in the loader. Picture taken in Bonifay, Florida.

Feller-bunchers were observed periodically throughout each production study. Periods of approximately ten minutes at a time at various times throughout the study period were devoted to observing feller-buncher activity while they were harvesting SDT. The following data was gathered during each feller-buncher observational period: number of stems per bunch, bunches of stems per pile, and number of piles. The term “bunch” represents a group of stems held in the felling head at one time. The term “pile” represents a grouping of bunches placed on the ground. Since a pre-harvest cruise was unable to be done for operation C, stem diameters were estimated and recorded for each tree the feller-buncher harvested during observational periods at this harvest site. While non-ideal, this method allowed for estimations of feller-buncher productivity.

Skidder turn data was recorded using the Columbus P1 GPS Data Logger (*Columbus*, 2020), which can be seen in Figure 10. The GPS data logger was attached to the front of the KED Activity Recorder in the skidder with Velcro. The GPS was configured to create a data point every 20 feet. Each data point included information on spatial and temporal positioning. From this data, information such as number of turns and average distance of turns were derived. The product skidded on each turn was deduced by observing the location on the deck where the skidder ended its turn. Each turn was considered to begin as the skidder was moving off the landing and end when the skidder was leaving the landing again following its traverse. Measuring a cycle in this way, from leaving to leaving, ensured continuous cycles. The GPS data logger was configured in such a way as to go into sleep mode during periods of inactivity to conserve battery life. Even with this battery conservation technique, the GPS required recharging on a weekly basis. Interacting with the GPS data was done using the accompanying TimeAlbumPro software (*Columbus*, 2020).

Figure 10: Two Columbus P1 GPS Data Loggers velcroed to the front of a KED Activity Recorder placed in the cab of the skidder. Picture taken in Bonifay, Florida.

An in-person observer recorded landing activity such as repairs, delays, and truck loading time. As a redundancy measure, landing activity was also recorded with a camcorder while trucks were being loaded with chips (Figure 11). Due to battery and memory constraints, the camera was turned off between loads. Scale tickets were obtained from the loggers in the weeks following the harvest and used to determine volume related data.

Figure 11: Camcorder recording landing activities.

3.4 Machine Cost Analysis

In order to cost out each operation, the machine rate method was employed (Miyata, 1980). The method laid out by Miyata in 1980 is intended for loggers to use to appraise the production costs of their logging equipment (Miyata, 1980). The sum of a machine's fixed costs, operating costs, and labor costs yield that machine's total equipment cost. When the total equipment cost of each machine on an operation is added together, the sum is the total operating cost of an operation. The machine rate method utilizes many assumptions about an operation and its equipment to calculate machine costs on an hourly basis. Assumptions introduce possible error; to reduce the amount of error in the calculated costs, it is best to use the machine rate in a comparison. If assumptions are kept constant between comparisons, making a comparison between operations helps to negate faulty assumptions.

Each biomass harvesting operation studied during this project has been costed out using the machine rate method. The assumptions made for this analysis can be found in Appendices A and B. For each operation, a theoretical conventional roundwood operation was established and costed out on an SMH basis and a production basis. The theoretical operations ran the same equipment as the observed operations, excluding the chippers. Each theoretical operation was assigned a weekly production rate that is typical to southeastern loggers (Conrad et al., 2018a). This method allowed for direct comparisons between the costs of running biomass harvesting operations to the costs of running conventional logging operations.

3.5 Statistical Analysis

Statistical analyses were conducted using JMP with an alpha level of 0.05 (SAS Institute Inc., 2013). One-way ANOVA and Tukey's HSD multiple comparison were run on feller-buncher, skidder, loader, and chipper data.

4 Results and Discussion

4.1 Harvest Equipment and Configuration

4.1.1 Operation A

Operation A (Figure 5) was running a Tigercat 720G feller-buncher, Tigercat 620E grapple skidder, Barko 595B trailer mounted loader, and Morbark 4036 whole-tree chipper (Figures 12 through 15). This operation had between 5 and 8 company owned trucks hauling wood chips each day, with each hauling 2.4 loads per day on average. This allowed them to haul an average of 13.1 loads per day over a ten-day period. The one-way haul distance for their product was 33 miles; about a 45-minute one-way trip.

All woody material that was harvested by this operation was fed through the chipper to form biomass wood chips. The goal of the harvest was to clear the tract of all standing woody material so that a pine plantation could be established. Because of this, this harvest could be considered the first step of site preparation. The comminuted material from this site was destined to be made into wood pellets by the customer.

Operation A harvested on one site for the entirety of the study period. That site was the 80.9-acre tract which can be seen in Figure 5. The landing was moved once during the harvest, with the second landing being less than 300 yards from the original landing. The feller-buncher, skidder, and loader operators on operation had 10 years, 4 months, and 25 years of experience on their respective machines.

Figure 12: Tigercat 720G feller-buncher from operation A with a bunch of SDT in its felling head. A pile of SDT can be seen in the background.

Figure 13: Tigercat 620E grapple skidder from operation A with a grapple full of SDT.

Figure 14: Barko 595B trailer mounted loader from operation A feeding SDT into a Morbark 4036 whole-tree chipper on the landing.

Figure 15: Morbark 4036 whole-tree chipper from operation A being fed by Barko 595B trailer mounted loader and blowing chips into a chip trailer on the landing.

Table 1 shows a summary of the primary equipment used by operation A during the study period. Operation A's machines had 3,800 hours of use on average. The oldest and youngest machines from operation A were the loader and feller-buncher with 7,300 and 1,500 hours of use respectively.

Machine	Make	Model	Hours	Horsepower
Feller-buncher	Tigercat	720G	1,500	203 – 221
Skidder	Tigercat	620E	2,000	220 – 225
Loader	Barko	595B	7,300	173
Chipper	Morbark	4036	4,400	800

Table 1: Summary of equipment used to harvest biomass on operation A.

4.1.2 Operation B

Operation B (Figure 6) was running a John Deere 643L feller-buncher, CAT 555D grapple skidder, CAT 559D trailer mounted loader, and Bandit 3590 whole-tree chipper (Figures 16 through 19). This operation moved their feller-buncher to the site before the rest of the equipment arrived so that a buffer of downed SDT could be built up. This operation had between 4 and 8 contract trucks each day, with each hauling 2.2 loads per day on average. This allowed them to haul an average of 12.1 loads per day over an eight-day period. The one-way haul distance for their product was 34 miles; about a 50-minute one-way trip.

This operation was performing the first pass of a two-pass system. The understory material was harvested and comminuted before the larger, merchantable trees were harvested for roundwood. However, instead of the same operation conducting both passes, an entirely different operation with its own equipment conducted the second pass. All equipment on operation B was used solely for handling biomass. The biomass operation and the roundwood operations were on the site concurrently, which allowed the residues from the roundwood operation to be comminuted along with the understory material to form biomass wood chips.

The biomass and roundwood operations operated on separate landings 50 yards apart. The landing for the biomass operation was moved once during the observation period to a location approximately 300 yards away from the original landing. The feller-buncher, skidder, and loader operators had 25 years, 20 years, and 1 year experience, respectively. The owner's plan for this site was to turn the stand into horse pasture.

Figure 16: John Deere 643L feller-buncher from operation B setting down a bunch of SDT.

Figure 17: CAT 555D grapple skidder from operation B with a grapple full of SDT on its way to the landing.

Figure 18: CAT 559D trailer mounted loader from operation B feeding a Bandit 3590 whole-tree chipper on the second landing.

Figure 19: Bandit 3590 whole-tree chipper from operation B being fed by CAT 559D trailer mounted loader and blowing chips into chip trailer on the first landing.

Table 2 shows a summary of the equipment used by operation B during the study period. Operation B's machines had 6,175 hours of use on average. The oldest and youngest machines from operation B were the chipper and feller-buncher with 10,000 and 3,100 hours of use respectively.

Machine	Make	Model	Hours	Horsepower
Feller-buncher	John Deere	643L	3,100	219
Skidder	CAT	555D	4,900	275
Loader	CAT	559D	6,700	173
Chipper	Bandit	3590	10,000	755 – 1050

Table 2: Summary of equipment used to harvest biomass on operation B.

The comminuted material from this site was destined to be burned at a Gainesville power plant to produce electricity for the Gainesville area. This power plant utilizes a mix of energy sources, including natural gas. At the time of the study and the preceding months, natural gas was at low price levels not seen since the late 1990's (Macrotrends, 2021). Natural gas was dramatically lower than recent price levels (Figure 20). These price levels were a result of the falling demand for oil during the Coronavirus pandemic. In response to these low prices, the Gainesville power plant was utilizing more natural gas to produce electricity at the time of this study than they typically do. This high utilization of natural gas meant that the power plant required less biomass. Because the power plant required less biomass, they put a quota on the biomass harvesting operations with whom they were contracted. Operation B was held to 50 loads of chips per week; a constraint which had them working 4 days per week.

Figure 20: The five-year price history of natural gas from October 2016 to October 2021. Note the low price seen in July of 2020 and the preceding months *(Insider.com, 2021)*.

4.1.3 Operation C

Operation C (Figure 7) was running a Tigercat 720E feller-buncher, Tigercat 620E grapple skidder, Tigercat 234B track loader, and Bandit 2590 whole-tree chipper (Figures 21 through 24). A John Deere 2154D swing machine outfitted with a Waratah HTH622B harvester head was also on site for the purpose of delimbing and processing roundwood (Figure 25). The feller-buncher started cutting SDT a few days before the rest of the equipment arrived which allowed the feller-buncher to have a buffer of woody material on the ground.

Like operation B, this operation was running a two-pass system. However, unlike operation B, the same equipment was used for both passes. The feller-buncher was used to cut both the SDT and merchantable trees. The skidder skidded the roundwood and biomass material separately. The single loader on site was used for loading roundwood onto log trailers and for feeding woody material into the chipper. This operation had 3 company owned trucks hauling wood chips each day, with each hauling 2.6 loads of wood chips per day on average. This allowed them to haul an average of 7.7 loads of wood chips per day over a three-day period. The one-way haul distance for their product was about 80 miles; about a 1.5-hour one-way trip. All equipment operators had at least 10 years of experience.

Figure 21: Tigercat 720E feller-buncher from operation C amongst SDT.

Figure 22: Tigercat 620E grapple skidder from operation C with a grapple full of low-quality stems.

Figure 23: Tigercat 234B track loader and a pile of SDT on the deck of operation C.

Figure 24: Bandit 2590 whole-tree chipper and Tigercat T234B track loader on the deck of operation C.

Figure 25: John Deere 2154D swing machine from operation C outfitted with a Waratah HTH622B harvester head for delimbing and processing roundwood.

Table 3 shows a summary of the equipment used by operation C for harvesting biomass during the study period. Operation C's machines had 4,975 hours of use on average. The oldest and youngest machines from operation A were the skidder and chipper with 8,700 and 900 hours of use respectively.

Machine	Make	Model	Hours	Horsepower
Feller-buncher	Tigercat	720E	6,400	190
Skidder	Tigercat	620E	8,700	220 – 225
Loader	Tigercat	T234B	3,900	168 – 173
Chipper	Bandit	2590	900	540 – 800

Table 3: Summary of equipment used to harvest biomass on operation C.

4.1.4 Operation Comparisons

Tables 1 through 3 show a summary of the equipment used by each operation during the study period. Operation A had machines with the least amount of use with 3,800 hours per machine on average. Operation B the machines with the most amount with 6,175 hours of use per machine on average. The individual machine with the most use was the Bandit 3590 used by operation B with an estimated 10,000 hours. The individual machine with the least use was the Bandit 2590 used by operation C with 900 hours. The loaders had the highest amount of use on average, followed by skidders, chippers, and feller-bunchers in descending order with 5,967 hours, 5,200 hours, 5,100 hours, and 3,667 hours respectively. Were the chipper with the least hours of use to be excluded, chippers would be the oldest type of machine with 7,200 average hours of use.

Each operation made use of one skidder, one loader, and one chipper. Each operation also had strategies to compensate for low felling capacity. Each operation moved their feller-bunchers to the site before the other machines arrived so that they could build up a buffer of downed SDT. These configurational choices made by the operators indicate that in their experience felling has been the bottleneck in biomass harvesting operations.

The operational configurations observed in this study are similar to the configurations observed in past research of logging operations (Bolding et al., 2010; Conrad et al., 2018b). All three operations observed in this study made use of rubber-tired feller-bunchers, grapple skidders, and knuckleboom loaders. Conrad et al. (2018b) found that eighty-six percent of Georgian and 78 percent of South Carolinian logging businesses used feller-bunchers in conjunction with grapple skidders on their logging operations. Additionally, Bolding et al. (2010) found that in the coastal plain of Virginia, the vast majority of logging operations used rubber-tired feller-bunchers (80%), grapple skidders (90%), and some type of knuckleboom loader (98%).

4.2 Stand Characteristics

Cruises were completed on operations A and B; however, a cruise was not completed on operation C as much of the SDT on operation C had already been felled upon arrival of the observers. A small corner of the tract with SDT was in the process of being harvested upon arrival. However, conducting a cruise on that corner was not completed due to the proximity of the feller-buncher. In lieu of a pre-harvest cruise operation C, stem diameters were estimated and recorded for each tree the feller-buncher harvested during felling observational periods.

While this method is non-ideal because it yielded no stand level statistics, this method allowed for estimations of some tree level statistics.

Descriptive statistics of each operation can be found in Table 4. 1/10th acre plots were utilized on operations A and B. Thus, TPA, BA, and volume per acre were ascertained for those operations by multiplying the average TPP, average BA per plot, and average volume per plot by 10, respectively. As operation B was producing both biomass and roundwood, reporting values for all trees on the stand would result in overestimations of biomass volume. Therefore, the values for operation B in the Table 4 are only representative of the trees that were less than or equal to 8 inches DBH. The DBH limit of 8 inches was chosen as trees larger than that would more likely be used to produce roundwood products than biomass wood chips.

Operation	Average DBH (inches) (n, CV%)	Weight/Tree (pounds) (n, CV%)	Trees/acre (n, CV%)	BA (ft^2/ac) (n, CV%)	Weight/Acre (tons) (n, CV%)
A	3.4	120	810	64	48
B	3.3	110	840	60	44
C	4.5	160			
Average	3.7 (3, 17.8%)	130 (3, 20.4%)	825 (2, 2.6%)	62 (2, 4.6%)	46 (2, 6.1%)

Table 4: Stand Characteristics.

As is shown in Table 4, the average size tree across the stands had a DBH of 3.7 inches. Operation B had the smallest average DBH of biomass material at 3.3 inches, while operation C had the largest average DBH of biomass material at 4.5 inches. Across all stands, the average stand density of biomass material was 825 trees per acre. The average tree on all three stands was 130 pounds. Operations B and C again had the smallest and largest values at 110 and 160 pounds per tree respectively. Operations A and B had an average of 46 tons of woody biomass per acre.

DBH distributions for the three operations were biased toward lower DBHs (Figures 26 – 29). Figures 27 and 28 both are descriptive of operation B. Figure 27 shows the DBH distribution of all observed trees on operation B; Figure 28 shows the DBH distribution of the observed trees on operation B that were at or below 8 inches DBH. The DBH distributions for operations A and B were observed during the stand inventory cruise conducted on the sites. The DBH distribution for operation C was estimated during felling cycles. On operation A, 31% of trees had a DBH of 2 inches and 63% of trees had a DBH of 3 inches or less. On operation B, 38% of trees had a DBH of 2 inches and 62% of trees had a DBH of 3 inches or less. On operation C, 16% of trees had a DBH of 2 inches and 36% of trees had a DBH of 3 inches or less.

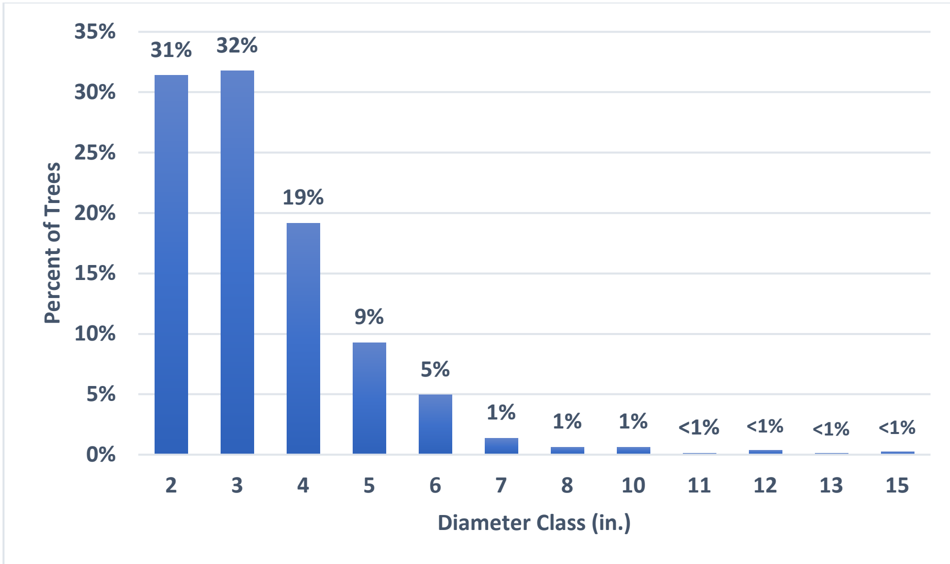

Figure 26: DBH distribution on operation A according to a stand inventory cruise.

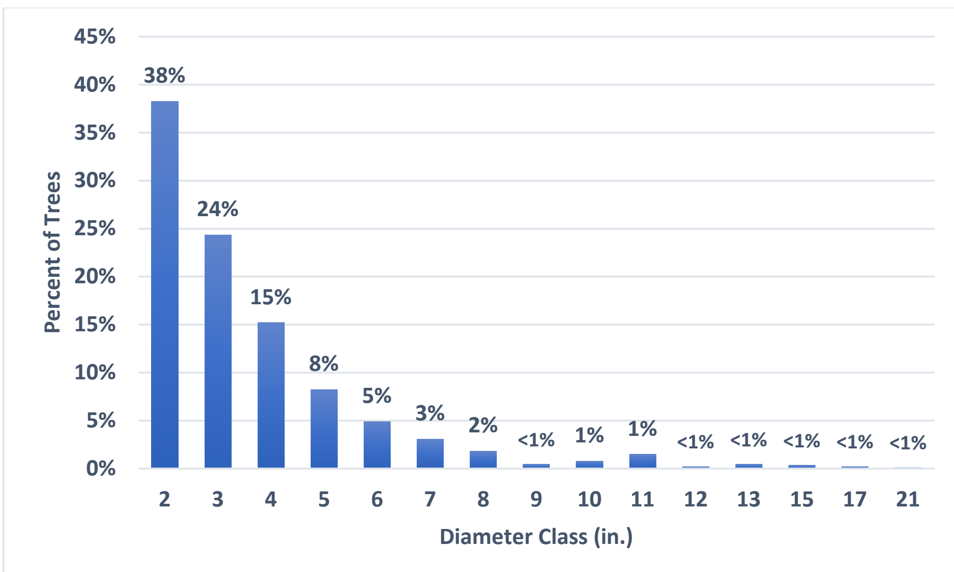

Figure 27: DBH distribution of all diameter classes observed on operation B according to a stand inventory cruise.

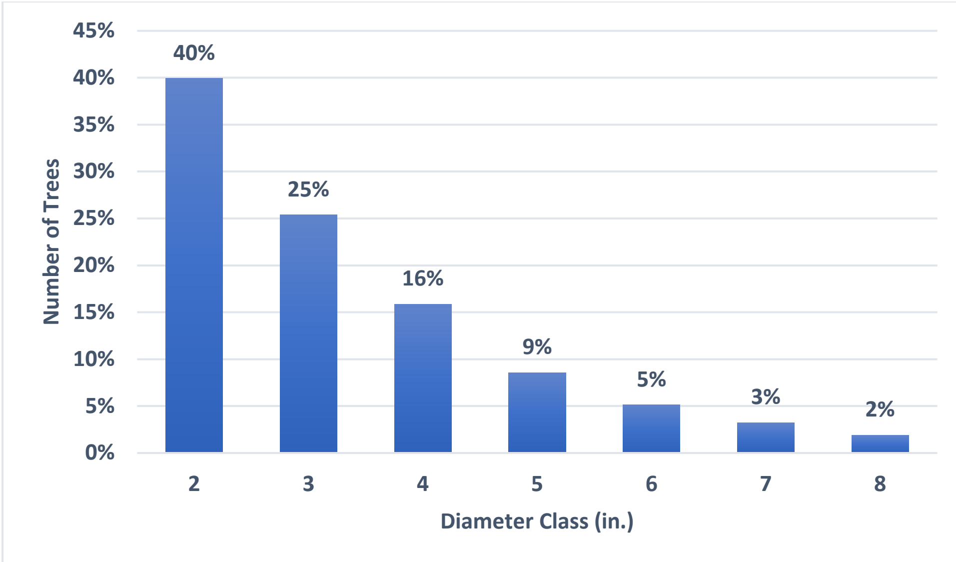

Figure 28: DBH distribution of diameter classes up to 8 inches observed on operation B according to a stand inventory cruise.

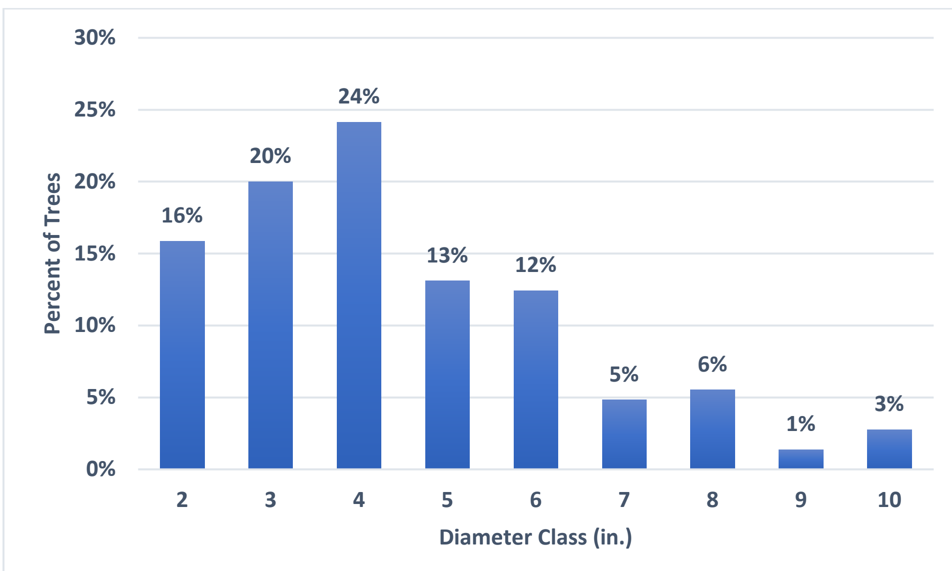

Figure 29: DBH distribution on operation C according to estimates made during felling observational periods.

To verify the volume information estimated from the cruises on operations A and B, the estimated volume values were compared to load tickets provided by the harvesting crew. From the load tickets, operations A and B yielded a total of 3,615.24 and 3,849.69 tons of biomass wood chips, respectively. Given that operations A and B were 80.9 and 92.7 acres respectively, the load sheets would indicate that there was an average of 44.7 and 41.5 tons of biomass material per acre on the respective operations. For operation A, the weight per acre calculated from the load tickets closely aligns with the predicted weight per acre from the stand inventory cruise, with the predicted volume being only 7.3% higher than the calculated volume. For operation B, the weight per acre calculated from the load tickets also closely aligns with the predicted weight per acre from the stand inventory cruise, with the predicted volume being only 6.0% higher than the calculated volume.

For operation C, stand volume was calculated from the load sheets. Operation C yielded 1,029.65 tons of biomass wood chips. Given that operation C was 10.2 acres, its calculated volume comes out to 101 tons of biomass per acre. Operation C's volume per acre is 120% higher than the average calculated volume per acre of operations A and B. This relative higher volume per acre on operation C than operations A and B could be due to the higher proportion of medium sized trees on that operation, whereas operations A and B were dominated by the smallest DBH classes.

4.3 Felling

The descriptive statistics for felling can be found in Tables 5 and 6. Table 5 details feller-buncher activity on a per bunch basis; Table 6 details feller-buncher activity on a per pile basis. Stems per bunch or per pile refers to the number of stems the feller-buncher accumulated in the average bunch or pile. Weight per bunch or per pile results from the multiplication of average stems per bunch or per pile by the average tree weight found on the tract. Time per bunch or per pile results from the number of bunches or piles observed divided by the total time of the observational periods.

Operation	Stems/Bunch (n, CV%)	Weight/Bunch (pounds) (n, CV%)	Time/Bunch (minutes) (n, CV%)	Time/Stem (minutes) (n, CV%)
A	8.70 (96, 53.6%) a	1,040 (96, 53.6%) a	1.3	0.14
B	8.03 (30, 49.5%) a	884 (30, 49.5%) a	2.2	0.27
C	3.72 (39, 48.6%) b	595 (39, 48.6%) b	0.90	0.24
Average	6.82 (3, 39.6%)	840. (3, 26.9%)	1.5 (3, 45.4%)	0.22 (3, 31.0%)
p-value	< 0.0001	< 0.0001		

Table 5: Felling statistics on a per bunch basis.

The feller-bunchers across the operations accumulated on average 6.82 stems per bunch. Feller-buncher C accumulated significantly less stems per bunch (3.72) than operations A (8.70) and B (8.03). The feller-bunchers averaged 840 pounds per bunch. Feller-buncher C also accumulated significantly less weight per bunch (595 pounds) than operations A (1,040 pounds) and B (884 pounds) (Table 5). Feller-bunchers handling multiple stems of small material has also been observed in previous research. For instance, Stokes (1992) noted that handling multiple stems increased feller-buncher productivity.

The average time per bunch was 1.5 minutes, with the feller-bunchers from operations B and C having the maximum (2.2 minutes) and minimum (0.90 minutes) values, respectively. The feller-buncher from operation B had the maximum minutes per bunch possibly because it was operating on the first pass of a two-pass system and thus had to maneuver around the merchantable trees in seeking out the SDT, much like what was described by Stokes et al. in 1985 and Watson et al. in 1986. The feller-buncher from operation C was also working the first pass of a two-pass system, however, its time per bunch was low due to the fact that its bunches were made up of less than half the stems than the average of the feller-bunchers on operations A and B.

Operation	Stems/Pile (n, CV%)	Weight/Pile (pounds) (n, CV%)	Bunches/Pile (n, CV%)	Time/Pile (minutes) (n, CV%)
A	32.8 (26, 58.8%) b	3,940 (26, 58.8%) b	3.69 (26, 47.1%)	4.6
B	62.4 (8, 73.2%) a	6,860 (8, 73.2%) a	3.75 (8, 34.2%)	8.1
C	13.2 (11, 46%) b	2,110 (11, 46.2%) b	3.55 (11, 44.4%)	3.2
Average	36.1 (3, 68.5%)	4,300 (3, 55.7%)	3.66 (3, 2.8%)	5.3 (3, 47.6%)
p-value	0.0003	0.0026	0.9570	

Table 6: Felling statistics on a per pile basis.

The feller-bunchers across the operations accumulated on average 36.1 stems per pile. Feller-buncher B gathered significantly more stems per pile (62.4) than operations A (32.8) and C (13.2). The feller-bunchers averaged 4,300 pounds per pile. Feller-buncher B's piles were significantly heavier (6,860 pounds) than operations A's (3,940 pounds) and C's (2,110 pounds) piles (Table 6). Feller-buncher B's weight per pile arises from its number of stems per pile. The feller bunchers averaged 3.66 bunches per pile across the stands, with none of the feller-bunchers' bunches per pile value being significantly different from each other.

The average time per pile was 5.3 minutes, with the feller-bunchers from operations B and C having the maximum (8.1 minutes) and minimum (3.2 minutes) values, respectively. The feller-buncher from operation B had the maximum minutes per pile for a few possible reasons: (1) it accumulated the most stems per pile, (2) it had the most minutes per bunch while having roughly the same bunches per pile as the other two feller-bunchers, and (3) likely had to travel farther to previous piles than the feller-buncher on operation A, which produced smaller and more numerous piles. As will be shown in Table 11, feller-buncher B has the lowest hourly productivity out of all the feller-bunchers observed.

4.4 Skidding

The descriptive statistics for skidding can be found in Table 7. Turns were defined as starting when the skidder was moved off the landing and ended when the skidder was leaving the landing again following its traverse. Defining a turn from leaving to leaving ensures continuous cycles. In Table 7, both distance and time per turn were established using the onboard GPS unit. Distance and time per turn values reflect entire turns rather than just incoming or outbound portion of turns. Methods which would quantify how many stems the skidder carried per turn were not employed. Because these methods were not used, skidder productivity estimates (Table 13) were calculated from chipper productivity values (Table 16).

Skidders were assigned a weight per turn that yielded a daily productivity roughly the same as each chippers' daily productivity. Skidder and chipper productivity rates were assumed to be balanced, as the landings never piled up with wood and the chippers were able to effectively process all the wood brought to the landing each day. Thus, it was possible to calculate weight per turn values that would yield the productivity values shown in Table 13.

Operation	Weight/Turn (tons) (n, CV%)	Distance/Turn (yards) (n, CV%)	Time/Turn (minutes) (n, CV%)
A	4.2	570. (670, 38.2%) a	7.0 (670, 67.8%) b
B	5.2	327 (141, 50.5%) b	9.7 (141, 75.8%) a
C	2.2	246 (105, 47.6%) c	3.1 (105, 45.8%) c
Average	3.9 (3, 39.5%)	381 (3, 44.3%)	6.6 (3, 50.8%)
p-value		< 0.0001	< 0.0001

Table 7: Skidder turn statistics.

The three skidders averaged 381 yards per turn. Skidder A had a significantly longer distance per turn (570 yards) than skidders B (327 yards) and C (246 yards). Even though skidder A had the longest turns in yards by 92% over the average turn distance of the other two skidders, it did not have the longest turns in minutes. Skidder B took a significantly longer time per turn (9.7 minutes) than skidders A (7.0 minutes) and C (3.1 minutes). This could be due to the fact that the feller-buncher from operation A was more productive than the feller-buncher from operation B. This advantage in feller-buncher productivity would result in the accompanying skidder not having to wait as long on the feller-buncher to produce piles. If a skidder spends a portion of its turns waiting for the feller-buncher to create piles, that skidder's turn time will increase[1]. Accordingly, skidder B's turns took longer than skidder A's turns by 2.7 minutes. Since the skidder from operation C was working on the smallest site by over 70 acres, its pulls were the shortest in length and time.

From the skidder productivity estimates laid out in table 13, it was estimated that skidder B had the heaviest average payload, at 5.2 tons per turn. Skidder C was estimated to have the lightest average payload, at 2.2 tons per turn. The average payload of the three skidders was 3.9 tons per turn.

The skidder from operation C was utilized for bringing roundwood and SDT to the landing in separate pulls. The roundwood laden turns were excluded from the analysis to isolate biomass turn data. The type of material being skidded on each turn was discerned by observing the GPS data. Skidder C was deemed to be skidding biomass material on a specific turn if that turn ended near the chipper. Likewise, that skidder was deemed to be skidding roundwood material on a specific turn if that turn ended near the location where roundwood was processed and loaded onto trucks.

4.5 Loading & Chipping

The descriptive statistics for loading and chipping can be found in Tables 8 and 9. Table 8 details all loads for which there is information. Table 9 details only those loads which had no delays. Weight per load was found from load sheets which were supplied by the harvesting

[1] This is an example of one machine's poor productivity rate affecting the productivity rate of another machine.

crews in the weeks following each production study. Time per load was recorded by the on-site observer and supplemented by the KED activity recorder placed on the chipper. Loads were timed from the moment that the chipper began blowing chips into the chip van to when the chipper stopped blowing chips on account of the van being full. If there was a delay during the load, the time for that delay was included in the overall time of a load. The most common cause of chipping delay was a lack of wood on the deck due to the low felling productivity.

Operation	Weight/Load (tons) (n, CV%)	Time/Load (minutes) (n, CV%)
A	27.59 (129, 8.4%)	35 (129, 55.1%) a
B	28.27 (82, 8.0%)	26 (82, 53.1%) b
C	28.04 (23, 4.3%)	16 (23, 10.6%) c
Average	27.97 (3, 1.2%)	26 (3, 37.0%)
p-value	0.0873	< 0.0001

Table 8: Load statistics for all loads.

The three operations averaged 27.97 tons per load with a coefficient of variation of 1.2% and p-value of 0.0873. The close grouping of values was expected as the chip vans were the same size across the three operations and each operation filled their vans as much as possible. The average time per load across the three operations was 26 minutes. Operation A resulted in significantly longer time per load (35 minutes) than operations B (26 minutes) and C (16 minutes) (Table 8). The values from Table 8 incorporate data from all loads, delayed and delay-free. Operation A experienced delays on 46 of their loads while operation B experienced delays on 9 of their loads. Operation C did not experience any chipping delays. The load data excluding delayed loads is given in Table 9.

Operation	Weight/Load (tons) (n, CV%)	Time/Load (minutes) (n, CV%)
A	27.55 (83, 8.7%)	28 (83, 23.9%) a
B	28.20 (73, 8.04%)	21 (73, 10.7%) b
C	28.04 (23, 4.3%)	16 (23, 10.6%) c
Average	27.93 (3, 1.2%)	22 (3, 27.8%)
p-value	0.1780	< 0.0001

Table 9: Load statistics for delay-free loads.

As is shown by Tables 8 and 9, the delay-free loads took a shorter amount of time than the overall loads. This better showcases the abilities of the chippers used on the studied operations when constantly chipping SDT. The average delay-free load took 22 minutes to complete. Operation A resulted in significantly longer time per load (28 minutes) than operations B (21 minutes) and C (16 minutes). On operation A, the delay-free time per load was 20% lower than the same value for all loads on that operation. On operation B, the delay-free time per load was 19% lower than the same value for all loads on that operation. Operation C did not have any delayed chipping loads as their equipment did not have any mechanical malfunctions and the operation was able to keep woody biomass material on the landing. Operation C was able to keep wood in front of the chipper because there were often long wait times between truck arrivals due to their limited number of chip vans. Additionally, operation

C's feller-buncher had a substantial head start on the chipping operations which allowed for time to build up a buffer of downed stems.

A previous study was done by Mitchell and Gallagher (2007) that investigated, among other things, the production rates of a biomass harvesting system. The harvesting system they observed harvested and chipped the understory material on two sites; the largest tree harvested on either site was 8.5 inches DBH. Mitchell and Gallagher (2007) observed that the average time per load on their study was 24.61 minutes with an average delay of 5.5 minutes per load. This suggests that if there were no delays, the average time per load would be closer to 20 minutes. This rough estimate of 20 minutes per load is similar to the average observed delay-free load on operations A, B, and C.

4.6 Productivity and Utilization

SMH and PMH throughout this section has been calculated from data collected from KED Activity Recorders and supplemented by notes taken by in-person observers. SMH includes all the time that a machine is scheduled to work. PMH represent the time during which a machine performs work. PMH was measured by vibration data captured by the activity recorders. However, a harvesting machine can produce vibrations even when it is not being productive. For instance, if a machine is kept idling during delays, vibrations can be picked up by the activity recorders. This could cause estimates of PMH to be higher than actual PMH. To adjust the vibration information, notes were taken in the field by an in-person observer of all delays. Delays included activities such as fueling, breakdowns, moving the deck, or general inactivity. Delay adjustments to the vibration data were made in the accompanying YAMS software to ensure a better fit with reality (*Kinetic Electronic Designs*, 2020). Tables 10, 12, 14, and 15 give details on the utilization of the feller-buncher, skidder, loader, and chipper on each operation. Tables 11, 13, and 16 detail the productivity of the feller-buncher, skidder, and chipper on each operation.

Operation	SMH (hours/day) (n, CV%)	PMH (hours/day) (n, CV%)	Utilization Rate (%/day) (n, CV%)
A	10.2 (9, 13.4%) a	9.09 (9, 15.0%) a	88.8 (9, 7.3%) a
B	10.2 (5, 10.7%) a	8.49 (5, 27.5%) a	83.4 (5, 27.6%) a
C	7.61 (3, 13.2%) b	4.06 (3, 21.0%) b	53.0 (3, 9.12%) b
Average	9.37 (3, 16.0%)	7.21 (3, 38.1)	75.1 (3, 25.8%)
p-value	0.0173	0.0015	0.0044

Table 10: Activity and utilization statistics for feller-bunchers.

The feller-bunchers averaged a 9.37-hour workday, reported as SMH. Feller-buncher C had significantly lower SMH per day (7.61) than feller-bunchers A (10.2 hours) and B (10.2 hours), significantly lower PMH per day (4.06 hours) than feller-bunchers A (9.09 hours) and B (8.49 hours), and significantly lower utilization rate (53.0%) than feller-bunchers A (88.8%) and B (83.4%) (Table 10). The utilization rates of the feller-bunchers on operations A and B are higher than might be expected on a typical harvest. These high utilization rates are a result of minimal breakdowns, never needing to stop for environmental conditions, and working on a single site the entire research period. As the feller-buncher from operation C did not have any major mechanical breakdowns, its lack of utilization could be due to the feller-buncher doing most of the felling before the arrival of observers as most of the SDT was felled before the observational equipment was placed. Although the observed utilization rates vary widely, their average value of 75.1% is similar to the average feller-buncher utilization rate published by Aman et al. (2011). These researchers analyzed three whole-tree chipping operations in Alabama and Georgia and found that the average feller-buncher utilization rate of the operations they observed was 76%.

Operation	Hourly Productivity (tons/SMH) (n, CV%)	Hourly Productivity (tons/PMH) (n, CV%)	Daily Productivity (tons/day) (n, CV%)
A	23	26	230
B	10	12	100
C	11	20	81
Average	15 (3, 49.3%)	19 (3, 36.3%)	140 (3, 59.2%)

Table 11: Productivity statistics for feller-bunchers.

Feller-buncher productivity estimates can be seen in Table 11. Productivity was estimated from the felling activity recordings taken in the field. From the observed felling cycles, an estimate of trees per minute was calculated for the feller-buncher on each operation. Trees per minute was then multiplied by the average tree volume established from the stand inventory cruise (see Table 4) to estimate the productivity for the feller-buncher.

On average, the feller-bunchers were able to produce 140 tons per day. The most and least productive feller-bunchers daily were A and C at 230 and 81 tons per day. On an hourly basis, feller-buncher A was also the most productive feller-buncher per hour at 26 tons per PMH. Feller-buncher B was the least productive feller-buncher hourly, producing 12 tons per PMH.

The feller-bunchers averaged the lowest daily productivity, which is likely due to the small diameter of the stems they were harvesting. Akay et al. (2004) stated that feller-buncher productivity is closely linked with tree size, with smaller trees leading to decreased felling productivity. Low felling productivity can also be due to the feller-buncher having to maneuver around merchantable trees during the first pass of a two-pass system. Stokes et al. (1985) and Watson et al. (1986) both conducted studies on two-pass systems and observed that feller-buncher maneuvering around large diameter stems led to decreased felling productivity. Both feller-bunchers B and C were operating on a two-pass harvest, and thus ran into the inefficiencies about which Stokes et al. (1985) and Watson et al. (1986) found. The observed operations each took steps to mitigate the impact of low felling productivity by having their feller-bunchers begin felling before the other operators arrive on the site.

Operation	SMH (hours/day) (n, CV%)	PMH (hours/day) (n, CV%)	Utilization Rate (%) (n, CV%)
A	11.3 (9, 17.4%)	9.54 (9, 11.6%) a	85.2 (9, 8.4%) a
B	11.0 (5, 4.3%)	7.90 (5, 18.8%) b	71.5 (5, 16.3%) b
C	8.57 (1)	6.22 (1)	72.6 (1)
Average	10.3 (3, 14.5%)	7.89 (3, 21.0%)	76.4 (3, 10.0%)
p-value	0.7485	0.0364	0.0171

Table 12: Activity and utilization statistics for skidders.[2]

P-values in Table 12 reflect only the data from operations A and B, as operation C only had a single sample day. The KED Activity Recorder failed to pick up vibrations for skidder C except for one full day. The skidders averaged an SMH per day of 10.3 hours. SMH per day for skidders A (11.3 hours) and B (11.0 hours) was not significantly different. The average PMH per day across the operations was 7.89 hours. Skidder A had a significantly higher PMH per day (9.54 hours) than skidder B (7.90 hours). The average utilization rate across the operations was 76.4%. Skidder A had a significantly higher utilization rate (85.2%) than skidder B (71.5%) (Table 12). The utilization rates of the observed skidders are higher than expected on a typical harvest. These high utilization rates are a result of minimal breakdowns, never needing to stop for environmental conditions, and working on a single site the entire research period.

[2] The data from operation C was omitted from the comparison as that operation had only a single sample day.

Operation	Hourly Productivity (tons/SMH) (n, CV%)	Hourly Productivity (tons/PMH) (n, CV%)	Daily Productivity (tons/day) (n, CV%)
A	31	36	340
B	23	32	250
C	31	43	270
Average	28 (3, 16.3%)	37 (3, 15.0%)	290 (3, 16.8%)

Table 13: Productivity statistics for skidders.

Methods which would quantify how many stems the skidder carried per turn were not employed. Because of this, skidder productivity estimates had to be made from chipper productivity values. It was observed that on each operation, the skidder and the chipper were well balanced. This balance indicates that the two machines had similar daily productivities. Thus, it was possible to estimate hourly productivity values for each skidder that would yield daily productivity values comparable to that of each skidder's respective chipper. The estimated skidder productivity values are shown in Table 13.

It was estimated that skidder A had the highest daily productivity with an estimated 343.08 tons per day while skidder B had the lowest daily productivity with an estimated 253.06 tons per day. While skidder A had the highest daily productivity, it was skidder C that had the highest hourly productivity at 43.00 tons per PMH. Skidder C had the highest hourly productivity because its turns were short due to the size of the tract it operated on. The length of its turns can be seen in Table 7. Skidder B had the lowest hourly productivity at 32.03 tons per PMH. This low productivity is due in part to the fact that it had the longest turns measured in minutes out of all three skidders. As was discussed in section 4.4, the long turns measured in minutes taken by skidder B could be due to the low productivity of feller-buncher B.

Site	SMH (hours/day) (n, CV%)	PMH (hours/day) (n, CV%)	Utilization Rate (%/day) (n, CV%)
A	11.2 (9, 14.8%)	8.14 (9, 16.5%)	72.7 (9, 11.4%)
B	9.98 (5, 8.8%)	5.24 (5, 13.9%)	52.5 (5, 18.4%)
C	8.66 (3, 8.7%)	2.54 (3, 18.2%)	29.3 (3, 18.2%)
Average	9.95 (3, 12.8%)	5.31 (3, 52.8%)	51.5 (3, 42.2%)
p-value	0.2918	0.7267	0.2382

Table 14: Activity and utilization statistics for loaders.

P-values in Table 14 reflect only the data from operations A and B. The KED Activity Recorder failed to pick up vibrations for loader C. To formulate an estimate of loader C's utilization data, chipper C's SMH, PMH, and utilization rate were inserted into the table as a proxy for loader C's activity. Because the loader and chipper work as a unit, the loader's actual utilization data should be close to the given chipper data. Thus, the values were deemed interchangeable. As a result of using the chipper's activity data for loader C, none of the time spent producing roundwood was included in PMH. Only the time that the loader was being utilized to feed wood into the chipper was included in PMH. The loaders averaged a utilization rate of 51.5%. The loader on operations A had a utilization rate of 72.7% while the loader on operation B had a utilization rate of 52.5% (Table 14). There were no significant differences between loader A and loader B in terms of utilization data.

Although the observed utilization rates for loaders vary widely, their average value of 51.5% is similar to the average loader utilization rate published by Aman et al. (2011). These researchers found that the average loader utilization rate of the operations they observed was 46%.

Site	SMH (hours/day) (n, CV%)	PMH (hours/day) (n, CV%)	Utilization Rate (%/day) (n, CV%)
A	10.6 (9, 17.0%)	7.38 (9, 23.4%) a	69.7 (9, 12%) a
B	8.18 (5, 39.9%)	3.87 (5, 33.1%) b	47.3 (5, 27.7%) b
C	8.66 (3, 8.7%)	2.54 (3, 18.2%) b	29.3 (3, 18.2%) c
Average	9.15 (3, 14.0%)	4.60 (3, 54.5%)	48.8 (3, 41.5%)
p-value	0.1474	0.0002	0.0001

Table 15: Activity and utilization statistics for chippers.

The chippers across all operations averaged an SMH of 9.15 hours. There were no significant differences between the chippers' SMH per day. Chipper A had a significantly higher PMH per day (7.38 hours) than chippers B (3.87 hours) or C (2.54 hours). The chippers' average utilization rate across all operations was 48.8%. Chipper A had a significantly higher utilization rate (69.7%) than chippers from operations B (47.3%) and C (29.3%). The average utilization rate for the chippers on the biomass only operations, operations A and B, was 58.5% (Table 15). The chipper on operation C had a utilization rate which was 49.9% lower than the average of the other two. This lack of utilization of chipper C stems from the fact that operation C only had three trucks devoted to biomass transport which led to extended periods of non-use.

Additionally, operation C was producing both biomass and roundwood with only one loader, which also led to the loader having to split time between the two activities.

Although the observed utilization rates for chippers vary widely, their average value of 48.8% is similar to the average chipper utilization rate published by Aman et al. (2011). These researchers found that the average chipper utilization rate of the operations they observed was 44%. Aman et al. (2011) also found that on their observed operations the loaders had a slight utilization edge over the chippers. This was due to the loaders having 3% of their overall utilization allocated to adjusting woody material on the deck. This slight edge can be observed in the utilization rates put forward by this study as well. Excluding operation C[3], the average utilization rates of loaders and chippers on operations A and B were observed to be 62.6% and 58.5%, respectively. Thus, loaders A and B observed in this study had 4.1% more utilization than chippers A and B.

Operation	Hourly Productivity (tons/SMH) (n, CV%)	Hourly Productivity (tons/PMH) (n, CV%)	Daily Productivity (tons/day) (n, CV%)
A	33	47	350
B	31	66	260
C	31	110	270
Average	32 (3, 3.6%)	74 (3, 43.5%)	290 (3, 16.8%)

Table 16: Productivity statistics for chippers.

[3] Operation C is excluded here as the chipper utilization values were used as a proxy for loader utilization values. Excluding C ensures that loaders are being compared to chippers.

Chipper productivity seen in Table 16 was estimated from the average weight and time of a load, which can be seen in Table 8. Each chippers' hourly productivity was multiplied by its daily PMH or SMH to find its daily productivity in tons per day. The daily productivity for the chippers ranged from the high of 350 tons per day on operation A to the low of 260 tons per day on operation B. Even though the chipper from operation C only had a utilization rate of 29.3%, which was 49.9% lower than the average of the other two, its daily productivity was 270 tons per day, which was not the lowest daily productivity. This could be because this chipper had the fastest chipping rate; in the small amount of time that it was being productive it maintained a high rate of productivity.

Although the chipper productivity rates observed over the course of this study vary widely, the average hourly productivities of 74 tons per PMH and 32 tons per SMH were similar to productivity rates previously published by the aforementioned Aman et al (2011). These authors noted average chipper productivity rates of 71.87 tons per PMH and 32.96 tons per SMH. Additionally, Hanzelka et al. (2016) reported a productivity of 83.7 green tons per PMH. While this productivity is higher than the average of chippers A, B, and C, the value published by Hanzelka et al. (2016) is within the range of the three chippers observed during this study.

4.7 Machine Costs

4.7.1 Operation C Cost Allocation

The feller-buncher, skidder and loader from operation C were all utilized in the production of SDT and roundwood. Since this analysis is purely concerned with the biomass portion of the harvest, only the cost for each machine to harvest biomass was pertinent.

However, methods that would quantitatively yield the percent of time the machines were handling SDT were not employed. Assumptions concerning the portion of time each allocated to handling SDT were established so that the cost to harvest biomass could be estimated. How the assumptions were arrived at is detailed in the following paragraphs.

Of the total number of loads that operation C produced, 59% were biomass wood chip loads. Thus, it can be assumed that at the very least, feller-buncher C spent 59% of its time harvesting SDT. Therefore, it was assumed that 59% of the feller-buncher's PMH was allocated to felling SDT. Thus, 59% of the feller-buncher C's cost has been allocated to harvesting biomass material.

To ascertain the percent of the skidder C's productive time that was devoted to skidding biomass, the skidder's movements throughout the observational period were recorded by the onboard GPS unit. The skidder's turns were later observed in the associated GPS software and classified as either biomass or roundwood turns. The type of turn was differentiated by its endpoint. If a turn ended at the logging side of the deck, it was assumed that the skidder was skidding roundwood material. If a turn ended at the chipping side of the deck, it was assumed that the skidder was skidding biomass material. The skidder spent 322.16 minutes skidding biomass and 307.68 minutes skidding roundwood for a total of 629.84 minutes of skidding activity. The time that the skidder was making biomass turns was divided by the total time that the skidder was making turns. This computation yielded the result that the skidder spent 51% of its time skidding biomass. Thus, 51% of the skidder C's cost was allocated to skidding biomass material.

To ascertain what percent of the loader's productive time was devoted to feeding the chipper, the loader's activity was observed throughout the observational period with an in-person observer. The total time that the loader was either feeding the chipper or loading roundwood onto trucks was 405 minutes. The loader was feeding the chipper for 297 of those minutes. The time that the loader was feeding the chipper was divided by the total time that the loader was either feeding the chipper or loading roundwood onto trucks. This computation yielded the result that the loader spent 73% of its time feeding the chipper. Thus, 73% of the loader C's cost was allocated to handling biomass material.

4.7.2 Machine Rate and Cost Comparison

The machine rate method was utilized to estimate costs for each of the observed operations (Miyata, 1980). Many assumptions are required by the machine rate calculation., Horsepower, economic life, maintenance and repair, and purchase price assumptions for each observed piece of harvesting equipment are displayed in Table 17. Horsepower was found on the equipment manufacturers' websites (Bandit Industries, Inc, 2021; Barko Hydraulics, LLC, 2021; CAT, 2021; Deere & Company, 2021; Morbark, LLC., 2021; Tigercat International Inc., 2021). Feller-bunchers, skidders, and loaders were assumed to have an economic life of 5 years; chippers were set at 10 years (Hanzelka, Bolding, et al., 2016; Spinelli et al., 2017; Townsend et al., 2019). Maintenance and repair rates were varied for each machine according to Brinker (2002) and Wenger (1984). The remaining machine rate assumptions can be found in Appendix A.

Equipment	Horsepower	Economic Life (years)	Maintenance and Repair (%)	Purchase Price (USD)
Feller-Buncher				
A	203 – 221	5	90%	$240,000
B	219	5	90%	$210,000
C	190	5	90%	$225,000
Skidder				
A	220 – 225	5	80%	$225,000
B	275	5	80%	$250,000
C	220 – 225	5	80%	$220,000
Loader				
A	173	5	70%	$200,000
B	173	5	70%	$200,000
C	168 – 173	5	70%	$230,000
Whole-Tree Chipper				
A	800	10	100%	$400,000
B	755 – 1050	10	100%	$275,000
C	540 – 800	10	100%	$450,000

Table 17: Purchase price assumptions of each observed machine.

As the assumptions made for the sake of the machine rate calculation could be inaccurate, the final costs that the machine rate calculation yields may be inaccurate as well. The inaccuracies inherent to the machine rate calculation can be mitigated. If the machine rate calculation is used in a comparison, the effect of faulty assumptions can be reduced. This reduction in the effect of faulty assumptions occurs when consistent assumptions are used on both sides of the comparison. To set up a comparison, three conventional logging operations were theorized and costed out. Each biomass harvesting operation was given a corresponding roundwood operation. These theoretical roundwood operations were assigned the exact same equipment as their corresponding biomass operations, excluding the chipper.

The machine costs from each biomass harvesting operation can be seen in Table 18. Table 18 does not incorporate a comparison, therefore the values held within should be taken as rough estimates.

Costs ($/SMH)	Operation			
	A	B	C	Average (n, CV%)
Felling	$102	$97	$58	$86 (3, 28.1%)
Skidding	$98	$106	$50	$85 (3, 35.8%)
Loading	$92	$92	$71	$85 (3, 14.3%)
Chipping	$108	$101	$106	$105 (3, 3.4%)
Cut & Load	$408	$403	$290	$360 (3, 18.1%)

Table 18: Costs for each harvest activity on a biomass harvest.

Felling biomass had an average cost of $86 per SMH. This average was brought down by the feller-buncher on operation C, as only 59% of that feller-buncher's total cost was allocated to biomass production[4]. The average cost of the feller-bunchers that were devoted only to biomass was $100 per SMH. The costliest feller-buncher was the feller-buncher from operation

[4] Feller-buncher C's total cost of operating was $97 per SMH.

A at $102 per SMH. The least costly feller-buncher was the feller-buncher from operation C at $58 per SMH (Table 18).

Skidding biomass had an average cost of $85 per SMH. This average was brought down by the skidder on operation C, as 51% of that skidder's cost was allocated to biomass production[5]. The average cost of the skidders that were devoted only to biomass was $102 per SMH. The costliest skidder was the skidder from operation B at $106 per SMH. The least costly skidder was the skidder from operation C at $50 per SMH (Table 18).

Loading biomass had an average cost of $85 per SMH. Loaders A and B, which were solely dedicated to biomass production, both had a cost of $92 per SMH. The loader from operation C had a cost of $71 per SMH due to 73% of its overall cost to operate being allocated to biomass production[6] (Table 18).

Chipping had an average cost of $105 per SMH. The costliest chipper was the chipper from operation A at $108 per SMH. The least costly chipper was the chipper from operation B at $101 per SMH (Table 18). Chipper B's low cost is largely a function of its comparatively low purchase price. This chipper had a lower purchase price than the other two chippers because it was much older than the other two (Table 17).

When felling, skidding, loading, and chipping costs are added up, the result is the total cost to harvest, process, and load biomass. This total cost is referred to as the cut-and-load cost. Average cut-and-load cost for the three biomass harvesting operations was $367 per SMH.

[5] Skidder C's total cost of operating was $97 per SMH.
[6] Loader C's total cost of operating was $97 per SMH.

The average cut-and-load cost for operations A and B, the two operations dedicated solely to biomass production, was $406 per SMH. The costliest biomass operation was operation A with a total cut-and-load cost of $408 per SMH. The least costly biomass operation was operation C with a total cut-and-load cost of $290 per SMH. Operation C was the least costly biomass operation because a percentage of each machine's cost was allocated to roundwood production (Table 18).

Table 19 shows the costs of the theoretical logging operations. Costing out theoretical roundwood operations allowed for direct comparisons between the costs of running biomass harvesting operations and the costs of running conventional logging operations. Table 19 does not incorporate a comparison, therefore the values held within should be taken as rough estimates.

	Operation			
Costs ($/SMH)	A	B	C	Average (n, CV%)
Felling	$102	$97	$97	$99 (3, 2.9%)
Skidding	$98	$106	$97	$100 (3, 4.9%)
Loading	$92	$92	$97	$94 (3, 2.9%)
Cut & Load	$300	$302	$299	$293 (3, 0.7%)

Table 19: Costs for each harvest activity on a conventional harvest.

The average cost of felling, skidding, and loading roundwood was $99, $100, and $94 per SMH. The average cut and load of the three roundwood harvesting operations was estimated to be $293 per SMH (Table 19).

Table 20 shows the overall cost of each operation on a production basis. The costs shown in Table 20 are derived from the values shown in Tables 18 and 19 using the assumptions provided in Appendix B. Tables 18 and 19 were calculated using the machine rate method; the values in Table 20 were derived from those tables with the use of additional assumptions. As is shown in Appendix B, an overhead and profit of 35% was assumed. Additionally, while the biomass crews were assigned their actual production rates, each conventional operation was assumed to produce 1,500 tons of roundwood per week (Conrad et al., 2018a). This transformation allows for comparisons between the biomass operations and the corresponding reference roundwood operation on a production basis.

Cut & Load ($/ton)	Operation			
	A	B	C	Average (n, CV%)
Biomass	$13.45	$15.93	$16.04	$15.14 (3, 9.7%)
Conventional	$11.83	$10.63	$11.81	$11.42 (3, 6.0%)
Difference	$1.62	$5.30	$4.23	$3.72 (3, 50.9%)

Table 20: Overall system costs of both biomass and conventional harvest operations along with a comparison of the two.

Biomass harvesting operations had an average cost of $15.14 per ton of wood chips that they produced. Biomass operation C was the most expensive operation with a price of $16.04 per ton of production; biomass operation A was the least expensive biomass operation at $13.45 per ton of production. Conventional operations ranged from $10.63 to $11.83 per ton of production (Table 20).

Hanzelka et al. (2016) was able to establish a cut-and-load price for their case study of a biomass only harvest. They reported that the final cut-and-load cost was $13.60 per green ton. This is cheaper than the three biomass operations observed in this study. However, once the cut-and-load that Hanzelka et al. (2016) is adjusted for inflation, the real cost becomes $14.67 per green ton. Adjusting for inflation puts the cut-and-load cost from Hanzelka et al. (2016) within $1 of the average cut and load cost per ton estimated in this study.

In each comparison, the biomass harvesting operations were more expensive on a production basis than their reference roundwood harvesting operation. Biomass operations on average were $3.72 more expensive per ton. Operations B and C saw the highest difference in price, being $5.30 and $4.23 more expensive per ton than their reference roundwood operations, respectively. Operation A saw the least difference in price, being $1.62 more expensive per ton than its reference roundwood operation (Table 20).

5 Conclusions

In this study, 3 biomass harvesting operations were studied in the coastal plain of the Southeastern United States. Each operation ran a rubber-tired feller-buncher, a grapple skidder, and a whole-tree woodchipper. The two of operations (A and B) that were solely devoted to producing biomass utilized a trailer-mounted knuckleboom loader. The operation that produced both biomass and roundwood utilized a track-mounted knuckleboom loader.

The average productivities for the observed feller-bunchers, skidders, and chippers were 19, 37, and 74 tons per PMH. The feller-bunchers were the least productive type of machine on each operation. This low productivity indicates that felling was the bottleneck on each operation. Each operation took actions to mitigate the felling bottleneck by having their feller-bunchers begin felling before the other operators arrived on the site. The low productivity of the feller-bunchers was due to the nature of the material they were felling. Over 60% of the material that feller-bunchers A and B were felling was 3 inches DBH or below. Of the biomass material on operation C, 60% of the material was 4 inches DBH or below. Feller-bunchers B and C were also performing the first pass of a two-pass system and thus maneuvered around the large diameter stems, leading to increased inefficiencies.

One could view the average chipper utilization of 48.8% and erroneously assume that trucking was the bottleneck. If trucking were indeed the limiting factor, one could expect to see large piles of wood stacking up on the landing. However, it was qualitatively observed that when multiple trucks were loaded back-to-back, the operations struggled to keep wood on the landing. Thus, the number of chip vans allocated to an operation must be calibrated to felling capacity rather than chipper capabilities, as the feller-buncher on each of the observed operations limited the productivity of the overall operation.

Costs for the three observed biomass harvesting operations were calculated on an SMH basis and on a production basis. On an SMH basis, chipping was the most expensive on-site activity for each of the biomass operations at $105 per SMH. This is due to the high purchase price of whole-tree woodchippers relative to the rest of the harvest equipment. The costs for felling, skidding, and loading biomass material were estimated to be $86, $85, and $85 per SMH, respectively. On a production basis, operations A, B, and C's cut-and-load costs were calculated to be $1.62, $5.30, and $4.23 per ton more expensive than comparable roundwood harvesting operations' cut-and-load costs, respectively. The operation which was cheapest on a per ton basis was the only operation that was not performing a two-pass harvest (Operation A).

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Appendix A: Machine Rate Assumptions

Salvage value	20%
Economic life:	
Feller-buncher	5 years
Skidder	5 years
Loader	5 years
Chipper	10 years
Interest	8%
Insurance	4%
Taxes	2%
Productive weeks per year	50 weeks per year
Fuel consumption formula	0.037(horsepower) = gallons per hour
Fuel price	$2.40 per gallon
Lube price	$20 per gallon
Maintenance and repair:	
Feller-buncher	90%
Skidder	80%
Loader	70%
Chipper	100%
Labor:	
Feller-buncher	$15
Skidder	$15
Loader	$20
Chipper	$0
Fringe	40%

Machine availability:

Feller-buncher	80%
Skidder	80%
Loader	90%
Chipper	70%

SMH per week:

Operation A	45 hours
Operation B	40 hours
Operation C	45 hours

Appendix B: Cost Comparison Assumptions

Overhead and profit	35%
Productivity per week:	
Biomass operations	Directly from load sheets
Roundwood operations	1,500 tons per week