FOREST FUEL REDUCTION AND ENERGYWOOD PRODUCTION USING A CTL / SMALL CHIPPER HARVESTING SYSTEM

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Except where reference is made to the work of others, the work described in this thesis is my own or was done in collaboration with my advisory committee.

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Michael Chad Bolding, son of Michael Hobson and Sherry (Solomon) Bolding, was born September 3, 1977, in Red Bay, Alabama. He graduated from Red Bay High School with honors in 1995. He attended Northwest Shoals Community College in Phil Campbell, Alabama, for two years, then entered Auburn University in September 1997, and graduated with a Bachelor of Science degree in Forestry in June 2000. He then entered Graduate School, Auburn University, in August 2000 to pursue a Master of Science degree in Forestry.

THESIS ABSTRACT

FOREST FUEL REDUCTION AND ENERGYWOOD PRODUCTION

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Currently there is a lack of information concerning mechanical forest fuel reduction. This study examined and measured the feasibility of harvesting to reduce forest fuel buildup and produce energywood. Cut-to-length (CTL) harvesting coupled with a small in-woods chipper provides a low impact way to harvest pre-commercial trees and tops along with merchantable logs. While CTL harvesting systems have been used successfully with full sized chippers, it requires two or three CTL teams. A smaller, less expensive chipper allowed operations to stay small and more efficient.

Productivity and cost results show the system to be capable of harvesting non-merchantable trees and utilizing non-merchantable portions of merchantable-sized trees, which in the past have been normally wasted. The gain from the value of energywood

and merchandized logs makes the system attractive in monetary terms, not to mention the fuel reduction gains received.

Using woody biomass as a fuel source works well in other countries as well as the U.S., especially in areas where alternative sources are scarce. Only a small fraction of the total amount of wood biomass available for fuel is actually used to produce energy. The benefits of energywood will become more important as fuel prices increase.

As fuel reduction systems become more common in the woods, a number of users including landowners, contractors, the forest products industry, equipment manufacturers, and scientists will benefit from this research.

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INTRODUCTION

Public demand for wildfire protection is steadily growing (Anon 1999a). Recent wildfires in the Western US have destroyed millions of dollars of valuable timber and property. "Drought years, tree species composition changes, and declining forest health within fire dependent ecosystems have exposed a large number of communities to a potential for stand-replacement wildfires" (Anon 1999a). For many reasons, including fire exclusion, forests that were once relatively open have become dense with trees and understory brush (Mitchell and Rummer 1999). Fire exclusion has allowed trees to fill stands that were once characterized by widely spaced fire-resistant trees (Anon 1999a).

Forest fuel loads in the United States have been accumulating over the past fifty years due to wildland fire management policies, wildland management practices, and other factors. As a result, the number and size of large, intense fires have grown over the last decade, resulting in higher fire suppression and preparedness costs, and greater damage (Anon 1999a). "Large wildfires can have major ecological impacts on soils, fish, wildlife, water resources, timber resources, recreation uses, air quality, visual quality, archeological sites, homes, developed structures, and human life" (Anon 1999a).

The 2000 fire season was characterized by a dramatic rise in the number of large wildland fires, fire suppression costs, and homes and property at risk in the wildland urban interface (National Fire Plan 2001). "Approximately 123,000 fires burned more than 8.4 million acres" (National Fire Plan 2001). Firefighters from all over the world were deployed on the numerous fire lines. Billions of dollars were spent by federal, state, and local governments for fire suppression (National Fire Plan 2001).

The suppression and stand-replacement costs from these fires could prove to be more expensive than many fuel reduction methods. Fuel reduction is not an easy operation to execute. Traditionally, forest fuels have been reduced by prescribed fire, but this reduction method is becoming a tool of the past due to increased liability concerns and state and federal regulations associated with smoke management.

The use of commercial thinning in dense stands for fuel reduction can also be difficult and expensive within the current merchantability standards. Thinning of a stand for fuel reduction with most stems being of non-merchantable size is expensive for any harvesting method due to low production, and therefore, high cost of wood produced.

The basic problem causing this research is due to the lack of knowledge in the area of mechanical harvesting for forest fuel reduction. Some mechanical systems exist but few have cost and productivity numbers assigned to them. This study examines the feasibility of using low impact mechanical harvesting to reduce fuel loads and produce an alternative energy source. Cost and productivity estimates resulting from the study will determine feasibility.

Possible Solution

In-woods chipping of non-merchantable stems could be a way to recover biomass that has normally been left on the site creating potential fire hazards. In addition, this method may produce a monetary gain through the sale of chips (energywood).

It is recognized that several possible mechanical fuel-harvesting configurations exist. Tree-length operations have traditionally been used for clear-cutting. Reducing forest fuel loads requires a pre-commercial thinning treatment; therefore, tree-length operations are not suitable due to small tree sizes. These operations also require considerable traffic throughout the stand causing more soil compaction and possible residual stand damage. The high production produced with tree-length also requires the use of a large chipper. A large chipper is expensive and also requires large tracts of timber due to high setup and moving costs.

A possible equipment configuration would combine a cut-to-length (CTL) harvesting system with a smaller chipper. A feasibility examination by Bolding and Lanford (2001) of using a small chipper / CTL harvesting system for forest fuel reduction and energywood production shows the system to possibly have promise. CTL systems have been recognized for their low environmental impact and high utilization of merchantable material. CTL systems with only a single harvester and forwarder do not match well with traditional in-woods chippers. Traditional chippers are very costly and require more wood input than a single CTL team can provide. A smaller, less expensive chipper might have reasonable ownership and operating cost and allow operations to stay small and efficient. This system should be able to reduce stocking and remove biomass normally left after most harvesting operations. In overstocked, even-aged stands and multi-storied stands alike, reduction in the number of trees per acre will open the forest canopy releasing the better trees to grow in value. With this approach, previously non-merchantable stems should become merchantable as energywood.

For trees with only energy value, it is anticipated that harvesters will only fell and exclude the processing phase that requires delimbing and bucking. Forwarders will carry entire trees off the ground in full tree form (stem, top, and limbs) along with limbs and tops from merchantable trees, therefore leaving minimal slash for future fire hazards. The larger payload of forwarding is preferred over ground skidding for less ground disturbance and for keeping the material free of dirt, which provides longer life for chipper knives.

With current technology, it is doubtful that pulp quality chips can be produced, but even with a high bark content energy chips will be produced. With increasing fuel and energy prices, energywood from this type operation could be a valuable commodity. Since CTL operations can merchandize small sawlogs, even from overstocked stands, research is needed to determine if the combined value of chips and merchandised products would be profitable. Also, landowners may be willing to accept a reduced stumpage payment if they get the "cleanup" of this type of operation. With rising gas and oil prices, and the positive effects of producing energy from a renewable natural resource this study investigates the CTL/small chipper concept for reducing forest fuel buildups.

OBJECTIVES[1]

The objective of this study was to determine the feasibility of thinning merchantable and previously non-merchantable biomass for forest fuel reduction and energywood production using a small chipper in conjunction with a cut-to-length harvesting operation in a mature pine stand with a dense understory and high fuel loads. Specific objectives were to:

1. Estimate the productivity of
   - A. a harvester cutting merchantable and non-merchantable trees,
   - B. a forwarder moving and feeding non-merchantable material into a small chipper,
   - C. a small in-woods chipper processing non-merchantable material, and
   - D. the entire CTL/small chipper operation along with costs.

2. Estimate the energywood production cost using a CTL / small chipper operation for various non-merchantable volumes per acre.

[1] Funding for this research was made possible by a grant from the USDA Forest Service.

LITERATURE REVIEW

In-Woods Chipping

Over the past 40 years, the forest products industry has become stronger throughout the nation, especially the Southeastern United States (Carte et al 1991). The industry has become an important player in the economy of the region, and also a major consumer of the timber resource (Carte et al 1991). Previously, mills in the Southeast relied mainly on chipping facilities to supply the wood chips needed to produce pulp and paper products as well as fuel for boilers (Carte et al 1991). In recent years, in-woods chipping has proven to be an effective method of producing quality wood chips for pulp (Carte et al 1991). This has led to an increase in in-woods chipping operations.

"The development and use of portable in-woods chippers has significantly increased utilization and allowed recovery of small diameter, low-quality trees at an acceptable cost" (Stokes and Watson 1988). As in-woods chipping systems become more popular for processing wood fiber, information concerning factors affecting the system will become more important (Carte et al 1989). Important factors might include chip quality versus production rates, tree size, species, and capital expenditures of the operation. Reducing the influence of these factors on the production of pulpwood chips should increase the quality of in-woods produced chips, making in-woods chipping more viable to the contractor as well as industry (Carte et al 1989).

The forest industry is becoming more complex and demanding. Increased economic concerns and the fluctuating forest products market make it imperative for companies to successfully manage change. New and innovative ways must be explored to cut costs and increase productivity. Therefore, some companies are interested in purchasing pulpwood chips, whether dirty or clean, directly from suppliers. This enables them to reduce, and possibly exclude, the chipping process from their mill operations and reduce capital expenditures. For the pulpwood market, in-woods chipping also allows suppliers to haul fiber, not bark. Transportation of in-woods-processed pulpwood chips is safer and more cost efficient than alternative hauling methods of roundwood material (Carte et al 1991).

To produce energy from woody biomass the material is most commonly in the form of chips (Christopherson et al 1989). These chips are in the "dirty" form, suggesting that they contain an excessive amount of bark to meet pulp chip requirements. Wood is transformed into chips with a chipper. Chipper selection is influenced by various factors such as (Christopherson et al 1989):

- "Size of trees to be processed
- Amount of wood chips required
- Rate of chip production needed
- Importance of consistent chip size"

Forest Fuel Loading

"Most of the National forests, as well as other federal, state, and private landowners, have problems of overstocked and stagnated stands of trees" (Karsky 1992). Stagnated stands are high in density but low in volume. Most of these stands include a majority of trees that have not yet reached a merchantable or marketable size (Karsky 1992). Stagnation leads to stress, which makes overpopulated stands vulnerable to damaging wildfire or pest attack (Karsky 1992). Thinning of a stand for forest fuel reduction can be costly due to the lack of efficient harvesting methods and under utilization of the resultant biomass produced (Karsky 1992).

In dense stands, small trees can cause fire hazards due to high fuel levels. Small trees tightly spaced in the understory of mature forests create a fire ladder increasing the risk of a possible stand destroying fire. Small trees, limbs, and tops, without current merchantable value, are potential targets for in-woods chipping operations. Stokes (1988) reported, "the advantages of an in-woods chipping system include the ability to recover fiber from limbs, tops, and un-merchantable wood, high productivity, and advanced site preparation". Current in-woods chipping operations also have the disadvantage of requiring large tracts of timber for successful operations due to the high moving and setup costs of large, expensive chipping machines.

Energywood

"U.S. wood energy use has increased steadily since 1972 and is projected to continue to increase" (Kutscha 1999). This increase is partially due to the fact that more industries, including forest products, are beginning to utilize the energy contained in woody biomass. Biomass is being used to fuel boilers and in some cases generate electrical power (Kutscha 1999).

Due to economic and utilization factors, the use of renewable natural resources (biomass), for energy production has not been competitive (Stokes 1997). Congress has discussed possible ways to make renewable energy more competitive. Some proposed responses include specifying minimum levels of electricity to be generated from renewable sources, such as woody biomass (Stokes 1997). Stokes (1997) also found that some utility companies are interested in beginning programs to promote the use of renewable energy.

The possibility of utilizing woody biomass for energy has great potential throughout the Nation. In the forest industry, a large amount of harvested material is left on the site; therefore, wasting its energy application potential. Stokes (1997) reported, "bioenergy use in the South to be 1.6 quads, which is 56 percent of the Nation's use". He also stated, "only 6 percent of energy consumption in the South is generated from wood, and wood is only used to produce about 2.4 percent of the electricity". His study concluded, "by using residues from forestry and agricultural energy products, the bioenergy potential is 4 to 7 quads in the South".

TABLE 1. – "Useful conversion factors for bioenergy" (Stokes 1997).

1 Btu	= 1.055056 joules (J)
1 quad	= 1 quadrillion Btu of energy
	= 1 x 10^{15} Btu of energy
	= 40.82 million metric tons of coal
	= 54.43 million metric tons of oven-dried hardwood
	= 27.10 cubic meters of crude oil

Using woody biomass as a fuel source works well in other countries as well as the U.S., especially in areas where alternative sources are scarce. Only a small amount of the available wood biomass is used to produce energy (Guimier 1989). "Because of technical, economic, and social reasons, the utilization of wood fuel has been slow to gain wider acceptance" (Guimier 1989). In the U.S., fuel chips have been used to fire kilns at lumber mills and digesters at pulp mills. With technology increasing daily, uses for wood fiber as an alternative energy source are expected to expand.

In stands other than southern forests, biomass harvesting is frequently performed in the wintertime. Christopherson et al (1989) reported several reasons for winter harvesting, a few of those are listed below:

- "Lower moisture content in wood (less weight and less subsequent drying necessary).
- Leaves remain in the field for recycling nutrients and reducing possible noxious emissions into the air during combustion.
- Fewer insect/disease problems and less residual tree mortality.

- Frozen ground protects against compaction and root damage by harvesting equipment and reduces erosion."

To better understand the relationship between energy contents of chipped slash and crude oil Guimier (1989) reported, "a metric green tonne of chipped slash at 45 percent moisture content has an energy content of approximately 8,750 mJ and, assuming a 65 percent energy conversion efficiency, it will produce 5,687 net mJ in a furnace. In comparison, a barrel of bunker "C" oil contains 6,508 mJ and, assuming 85 percent energy conversion efficiency, will yield 5,532 net mJ. A metric green tonne of chipped slash is therefore roughly equivalent to one barrel of bunker "C" oil." Based on this conversion, at current oil prices of $24.89 per barrel for crude (Nymex, June 2002), a green ton of energywood is worth $25.29.

Storing merchantable logs to be processed for energy retains quality and fuel value better than storing biomass in chip form (Christopherson et al 1989). At present market conditions, most biomass harvested for energywood is limbs and tops. If energywood prices should exceed pulpwood prices, then storing biomass in roundwood form would be more viable. Currently, handling and transportation systems are setup in a fashion that gives chipped wood an advantage (Christopherson et al 1989). Although, chips, the most common form of fuelwood, have a disadvantage of deteriorating and losing energy quality quickly if not handled correctly (Christopherson et al 1989).

Christopherson et al (1989) reported, "most wood energy facilities maintain on site a 30 to 45 working-day supply of energy feedstock in outside storage". Storage is another unique characteristic of using woody biomass for energy. In contrast, electricity cannot be stored, it must be used; therefore, providing another advantage of renewable energy. But in most cases, the required amount of wood chips require a large area for storage and generally cannot be covered; therefore, speeding chip deterioration (Christopherson et al 1989).

For fuelwood systems in the United States to become more viable, utilization of the finished product must be increased. Much research is needed to explore appropriate harvesting systems as well as processing and consumption possibilities. "Clearly, the harvesting and handling of fuelwood is essential to the future success of using trees for energy" (Christopherson et al 1989).

Cut-to-Length (CTL) Harvesting

Cut-to-Length (CTL) harvesting systems have proven to efficiently harvest a variety of tree sizes including first commercial thinnings (Holtzscher and Lanford 1997). Studies have also shown CTL to be a low impact form of harvesting (Lanford and Stokes 1995).

"Harvesting conditions are changing as the average size of the removed tree continues to decrease, silvicultural prescriptions shift away from clear-cutting, and more emphasis is placed on the reduction of soil impacts from machinery during the harvesting process" (Kutscha 1999). These changes force the North American harvesting community to experiment with different harvesting systems in order to become more productive and better address environmental concerns (Kutscha 1999). Other countries have been paying attention to conditions we term as "new" for decades.

CTL provides minimal residual stand and site damage, requires less manpower, and leaves fewer slash piles than traditional tree-length systems (Lanford and Stokes 1995). CTL operations differ from typical southern tree-length systems because trees are limbed and bucked into log lengths at the stump, leaving limbs and tops evenly distributed throughout the tract (Stokes 1988). This provides a cushion for the harvester and forwarder to travel on while performing their operations in the woods, which in turn reduces soil compaction (Seixas et al 1995). With social and aesthetic concerns becoming increasingly important, CTL operations could become more widely used in the future.

CTL harvesting is the conventional method used in most Scandinavian countries and is also popular throughout parts of Canada and the Northern United States (Tufts and

Brinker 1993). “However, in the southeast the complexity of the machine, high initial cost, availability of financing, lack of service support, and resistance to change by local logging contractors has limited CTL mainly to a few thinning operations” (Holtzscher 1995).

Any harvesting system is driven by cost and productivity. Research is continually investigating new harvesting systems and configurations to aid in reducing costs and increasing productivity. Technology employed from sound research is making harvesting systems more complex and quickly fazing out manual labor. For most CTL systems, chainsaws are not needed. This allows workers to be protected in a machine cab, reducing accidents and injury. “Rising labor rates and need for improvement of working conditions have also prompted the mechanization of timber harvesting” (Stokes 1988).

Most CTL systems employ state-of-the-art equipment, which provides up-to-date technology to maximize timber utilization, and protect water quality (Anon 1999b). In CTL operations, the two-machine system, a harvester and a forwarder, balance to give an efficient operation for smaller tracts.

The harvester provides the felling, limbing, and bucking functions. Harvesters can be mounted on excavator carriers using tracks or purpose-built carriers with bogie rubber tires, tracks, or both which reduces soil compaction especially when a bed of limbs is placed in the tread way. Many harvesters fell and process trees with an attachment mounted on a boom, therefore using a swing-to-tree motion for felling, as opposed to the drive-to-tree method used by most feller-bunchers. The harvester reaches many trees from a single location without moving, which reduces the amount of travel throughout a stand. Less travel means less soil compaction and damage to residual trees.

Currently, harvesters are configured as either "single-grip" or "double-grip" referring to the number of times a stem is gripped or held by the machine (Richardson and Makkonen 1994). "Single-grip harvesters are more popular than the double-grip type because they are faster, more versatile, and often cheaper" (Richardson and Makkonen 1994).

In some cases, contractors mount harvester heads onto excavator style machines to avoid the high cost of integrated harvesters (Richardson and Makkonen 1994). This cost cutting approach can lead to reduced productivity. In most cases, excavators are designed with a heavy boom configuration built for earth moving or loading and not for the finesse required in timber harvesting (Richardson and Makkonen 1994).

In CTL operations, the machine operator can be the limiting factor associated with productivity. CTL equipment is complex and requires much dedication by the operator to reach maximum production. Many different solutions to the operator learning curve are being explored such as operator training schools and the use of simulators to bring an operator up to speed before he actually gets into the woods. "Operator skill, however, depends not only on experience, but also to a great extent on operator motivation, dexterity, judgment, aptitude and depth perception" (Richardson and Makkonen 1994).

The second machine in a CTL system is a forwarder. The forwarding function is the process of transporting wood from the stump to a landing for hauling. The forwarder can have four, six, or eight tires and appears similar to a skidder with a loader and trailer attached. Instead of using a traditional skidder, which drags wood on the ground, a forwarder carries wood clear of the ground. Forwarders are articulated; therefore, requiring less area to maneuver than skidders pulling tree-length stems. Better maneuverability and the shorter length of a forwarder translates into less stand damage (Vidrine et al 1999, Hartsough et al 1997, and Lanford and Stokes 1995). Additionally, forwarders allow for hauling distances of up to one mile (in some cases) without roads, access to most terrain types, and the capability to work both day and night (Lanford 1982).

Due to large payloads, a forwarder can haul wood economically for long distances and needs only minimum skid trails and landings. Lanford (1982) reported a comparison between forwarder and skidder payloads, "forwarders range from 8 to 18 tons, while large skidders can only pull around 2.7 tons per cycle". With larger payloads, forwarders make fewer passes through a stand resulting in lower disturbance and less residual stand damage; therefore, less soil is displaced, rutted, and compacted (Seixas et al 1995). Forwarders also have the opportunity to produce a more consistent wood flow than other systems due to less sensitivity to weather (Lanford and Stokes 1995).

Operating a forwarder is less demanding than operating a harvester due to the reduced number of decisions to be made as well as resting time during traveling (Richardson and Makkonen 1994). Operator skill is most important in the loading and unloading phases, and also machine maneuverability. Also, a study by Richardson and Makkonen (1994) found that the number of merchandizing sorts could affect operator productivity. They found that loading and unloading rates decrease as the number of sorts increase.

With the CTL methodology, "cold logging" can be achieved (Holtzscher 1995). "Cold logging" is defined as minimal machine interaction. This means that machines operate separately from each other; therefore, each machine can be utilized to its maximum potential. For example, wood can be piled on the landing for several days or until appropriate trucking is available. This minimizes truck-waiting time at the landing. Trucks can arrive on the site for loading after harvesting is complete. Also, operators have the option of working more convenient hours with cold logging. With hot logging systems, operators must work together on a specified time schedule, to maximize system productivity, and do not have the opportunity to leave the operation for emergencies or other unforeseen occurrences.

METHODS

Preliminary Concept Feasibility

Bolding and Lanford (2001) did a study investigating the feasibility of using a small chipper / CTL harvesting system for forest fuel reduction and energywood production. For their preliminary study only a clearcut harvest scenario was explored. They found harvesting costs to be $334.20 per acre ($39.98 per ton) for the non-merchantable portion. They also found this approach to be feasible only if other values can be included in the process (site preparation savings and energywood income). The feasibility study suggests that if energy equivalent values were obtained, a CTL / small chipper system could provide a positive net income rather than a net loss for site conversion, cleanup operations.

Study Site

In order to determine the fuel reduction benefits of a CTL / small chipper harvesting system this study was performed in mid September 2001 on a stand that represented a high fire hazard. The stand consisted of approximately 10 acres of mature overstory including merchantable loblolly pine and hardwood with a dense non-merchantable hardwood understory. The site was located near Fayette, Alabama.

Equipment[1]

A logging contractor with a CTL operation and some experience cutting small non-merchantable hardwood, was selected. Bandit Chippers, Inc. provided a small chipper and portable axle scales were rented to perform the tests. Equipment manufacturers and details were as follows:

Harvester (Figure 1) – The Timbco T-415C with an 18 inch series 2000 4 roller Fabtek head is a tracked harvester with double grouser tracks, and a 200 horsepower John Deere engine. The harvester weighs 42,000 pounds and applies 6.5 pounds per square inch of ground pressure. It also has a 21 foot 5 inch boom reach.

Forwarder (Figure 2) – The Fabtek 546 B is a six-wheeled machine with a 22 foot 9 inch loader reach and weighs 32,500 pounds. The forwarder has a load capacity of 30,000 pounds.

Chipper (Figure 3) – The Bandit 1850 portable chipper has an 18-inch diameter capacity with 250 horsepower and weighs 12,000 pounds. The chipper also has a moving conveyer deck to aid feed speed.

Axle Scales (Figure 4) – The Intercomp 2 has two 30,000-pound capacity 7 by 3.5-foot weigh pads with a Toledo Lynx Scale Indicator.

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[1] The use of brand or model names is for reader convenience only and does not represent an endorsement by the author, Auburn University, or the USDA Forest Service.

Figure 1. Timbco 415C harvester with an 18 inch series 2000 4 roller Fabtek head.

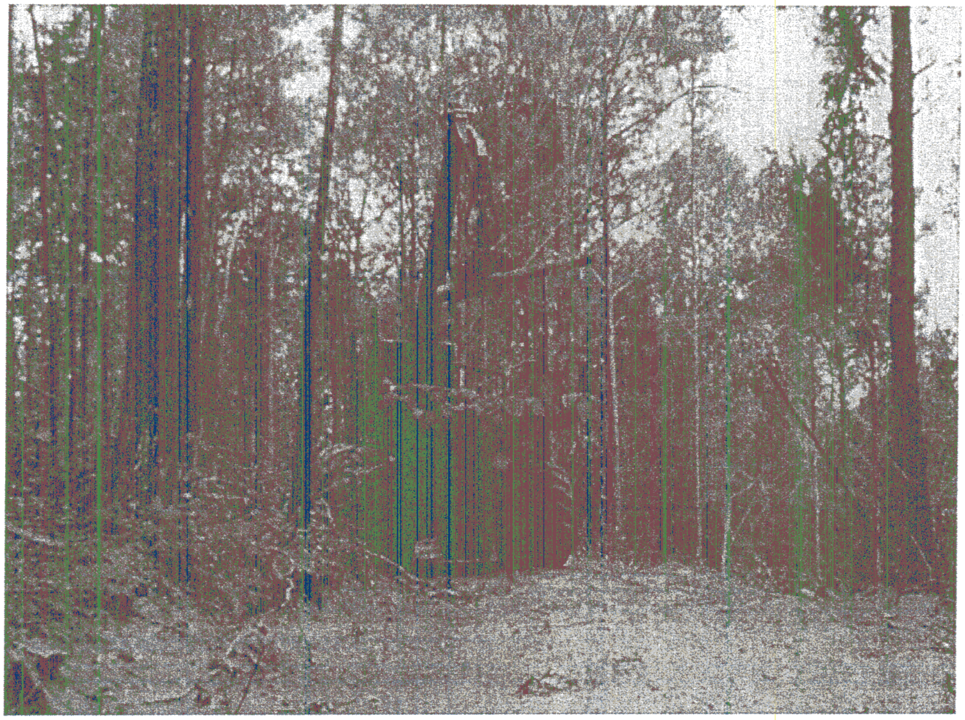

Figure 2. Fabtek 546B forwarder loading merchantable stems.

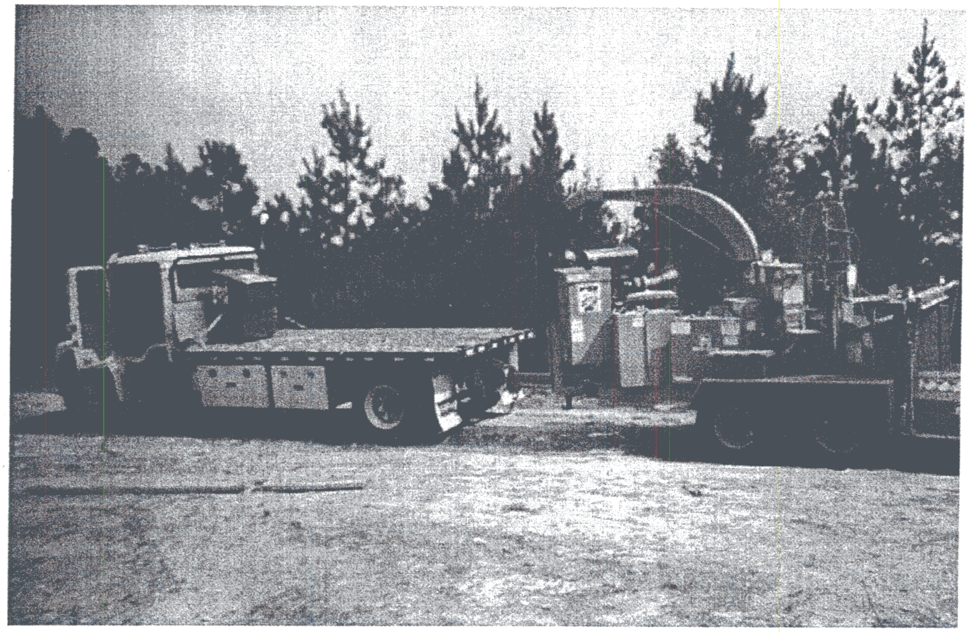

Figure 3. Bandit 1850 whole tree chipper

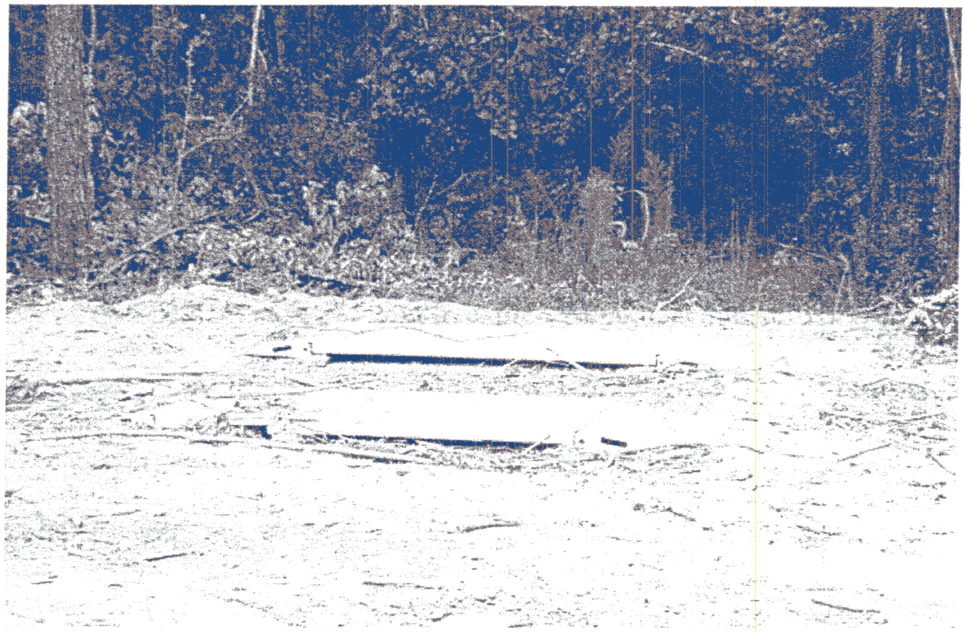

Figure 4. Intercomp portable axle scales.

Data Collection

- Objective 1: Cost and Productivity

Elemental time and production studies were performed on the harvester, forwarder, and chipper. All machines were videotaped for times. Time elements included:

A. Harvester – felling, swing to next tree, processing, machine moving, and delays,
B. Forwarder – traveling empty, loading, travel-while-loading, travel loaded, feeding the chipper, waiting on the chipper, cleaning up around chipper, and delays, and
C. Chipper – chipping, waiting on forwarder, jam-clearing time, and delays.

Various factors, such as tree size, slope, trees per acre, operator effect, and non-merchantable tons per acre that could affect productivity were examined for statistical importance. Least squares regression was used to analyze and model variables affecting productivity. When combined using the Auburn Harvesting Analyzer (Tufts et al 1985) spreadsheet approach, these calculations gave a total system cost to perform this type of treatment. Results of studies gave productive time per ton of chips produced for each of the three machines.

- Objective 2: Energywood Costs

Based on the results of Objective 1, analysis of chipping costs in relation to non-merchantable volume per acre gave energywood production costs while using a CTL / small chipper system.

Harvester Field Procedures and Analysis

The harvester moved throughout the stand harvesting all non-merchantable trees (less than 4 inches DBH). Merchantable trees (greater than or equal to 4 inches DBH) were thinned to a residual 60 ft^2 per acre basal area. At each machine stop the treatment was performed on all trees within boom reach. Time elements for each cycle included move to next group of trees, swing-to-tree, felling, and processing. Processing of non-merchantable trees included only piling with no delimbing. Processing of merchantable trees including delimbing and bucking. Merchantable portions were processed into 20-foot log lengths. The harvester piled non-merchantable trees along with limbs and tops from merchantable trees separate from merchantable stems. The brush material was then picked up by the forwarder.

Harvester studies recovered the cutting of individual trees by videotaping the harvester cutting in six 1-chain by 1-chain study plots (0.1 acres each). All trees on the six plots were measured for DBH, total height, and species. Each tree was then assigned a number so that its recorded measurements could be used during time studies. Tree numbers were audibly recorded during videotaping. Small tree weight equations (Clark et al 1986, Clark and Saucier 1990) were used to determine per acre volume. Merchantable trees were those greater than or equal to 4 inches DBH and non-merchantable trees were greater than 0.5 but less than 4 inches DBH. Trees were measured to the nearest 1-inch DBH. Harvester productivity studies measured and modeled the effects of this range of tree sizes.

Time elements were analyzed statistically using Number Crunching Statistical System (NCSS) 2000. Dependent variables were defined in units of time per tree and are shown in Table 2. All variable significance was determined at a level of 0.05.

TABLE 2. -- Variables determined during harvester study.

Dependent variables	Independent variables
Move	Species
Swing	Slope
Fell	DBH
Process	Total height
Total productive time	Pine tons per acre
	Hardwood tons per acre
	Total tons per acre
	Merchantable pine tons per acre
	Merchantable hardwood tons per acre
	Non-merchantable pine tons per acre
	Non-merchantable hardwood tons per acre
	Tree per acre
	Pine trees per acre
	Hardwood trees per acre
	Merchantable trees per acre
	Non-merchantable trees per acre
	Total non-merchantable tons per acre
	Total merchantable tons per acre

Forwarder Field Procedures and Analysis

The forwarder moved throughout the stand traveling in harvester cutting corridors. The corridors were developed as the harvester performed its operations and bunched and piled harvested material on both sides of the machine. The forwarder loaded and transported, using its onboard loader, non-merchantable harvested material to the chipper and log lengths to setout trailers. Log lengths were forwarded separately from non-merchantable material, and therefore not studied. After forwarding non-merchantable material to the chipper, the forwarder fed its load into the small chipper also with its onboard loader. Each load represented one cycle or observation. Time elements for each cycle included traveling empty from the deck, loading non-merchantable material, traveling between stops, traveling loaded to the deck, feeding the chipper, waiting on the chipper, and cleaning up around the chipper. Each turn was videotaped for times to recover the time elements and number of loading stops. Travel distance was also measured by following the forwarder and recording distance with a Chainman's Hip Chain to account for each machine move.

Weight of non-merchantable material, hauled by the forwarder, was determined with the portable axle scale. After returning to the deck loaded, the forwarder was weighed totaling machine and load weight. After feeding its load into the small chipper, the forwarder was weighed again to account for weight of the machine. Loaded and empty weights were then subtracted equaling the weight of non-merchantable material forwarded. This weight along with time studies determined forwarder productivity.

Time studies were recorded on the loading of 16 forwarder loads of non-merchantable material (entire trees less than 4 inches DBH and limbs and tops from felled merchantable trees). Forwarder time studies were also recorded on the feeding or unloading of 15 forwarder loads of non-merchantable material.

For this study, two forwarder operators were used. Due to the absence of the primary operator, a less experienced operator filled in for 25 percent of the observations. The more experienced operator also had experience forwarding non-merchantable material before this study and the less experienced operator did not. An operator time experience variable consisting of the total time accumulated performing the treatment for each operator during this study and for the observed forwarder loads was analyzed as an independent variable for predicting all dependents associated with the forwarder. Variation between operators was also analyzed by using an operator dummy variable. Dependent variables were defined in units of time per forwarder load and are shown in Table 3. All variable significance was determined at a level of 0.05.

TABLE 3. -- Variables determined during forwarder study.

Dependent variables	Independent variables
Travel empty	Distance traveled
Travel-while-loading	Weight of forwarded material
Travel loaded	Number of stops per turn
Loading	Operator variation
Feeding	Operator experience
Waiting-on-chipper	
Cleanup-around chipper	

Chipper Field Procedures and Analysis

The portable chipper was positioned on the deck so that its out-feed spout could access either of two chip vans. Upon arrival of the forwarder with a full load of non-merchantable material, the chipper's engine was started (engine was shut off between chipping cycles) and thus was prepared to chip. Each forwarder load represented one cycle or observation. The cycle began when the first piece of non-merchantable material entered the chipper and ended when the last piece had been processed. Material was fed into the chipper with the forwarder's boom. Time elements for each cycle included chipping, waiting on the forwarder, jam-clearing, and total cycle time. Each chipping cycle was videotaped for times to recover the time elements, number of waiting-on-forwarder observations, and number of jam-clearing observations. Waiting-on-forwarder observations were recorded when the chipper was idle with no material to process because the forwarder could not feed material fast enough. Chipper jam-clearing observations were recorded when the chipper was idle due to non-merchantable material being jammed in the chipper.

Weight of non-merchantable material brought to the chipper was determined with the portable axle scale by weighing the forwarder loaded and unloaded. Weights were subtracted giving the weight of non-merchantable material chipped. This weight along with time studies determined chipper productivity. Time studies were recorded on the chipping of 14 forwarder loads (one load was not studied due to a scale malfunction) of non-merchantable material (entire trees less than 4 inches DBH and limbs and tops from felled merchantable trees).

As discussed for forwarding, two forwarder operators were used for feeding the chipper. A less experienced operator chipped four forwarder loads (28 percent of the observations). As in the forwarder analysis, an operator time experience variable consisting of the total time accumulated (before the timed observation) performing the treatment for each operator was analyzed as an independent variable for predicting all dependents associated with the chipper. Variation between operators was also analyzed by using an operator dummy variable. Dependent variables were defined in units of time per forwarder load and are shown in Table 4. All variable significance was determined at a level of 0.05.

TABLE 4. -- Variables determined during chipper study.

Dependent variables	Independent variables
Chipping	Weight of material to chip
Waiting-on-forwarder	Operator variation
Jam-clearing	Operator time experience
Total cycle time	

Cost Analysis

Costs of the CTL / small chipper system were analyzed using the Auburn Harvesting Analyzer (AHA) spreadsheet model (Tufts et al 1985). The spreadsheet is capable of determining the productivity and unit cost for a tract of timber based on the type of logging system used, the size of timber being harvested, and other operational variables (Tufts et al 1985).

The top section of the page inputs stand and general information. The stock and stand table is important since it states what size of trees will be harvested as well as the number per acre. The general information contains details such as length of time the crew worked, tract size, commuting distance, and road construction.

Section two of the AHA calculates the productivity of each machine in the system. Results of this section are reported in tons per productive machine hour.

Section three shows input cost data including initial purchase price, economic life of the machine, insurance, taxes, fuel and lubrication, maintenance and repair, and labor costs.

The last section calculates the productivity and cost of the entire system. In this section, the utilization of each function is determined by combining machines in the system. Cost per ton for each function is obtained by combining hourly costs with utilization and system productivity. Finally, the costs of the different functions are combined and the on-board and total costs per ton for the system are calculated (Holtzscher 1995).

For this study, two spreadsheets, one for the non-merchantable portion and one for the merchantable portion, were constructed. Costs were analyzed separately in order to determine the percentage of yearly contribution for harvesting each portion. Tables 5 and 6 outline assumptions used in each model. Formulas used to calculate the percentage of yearly contribution for each model are as follows:

$$\text{NM}^{1}\ \% = \frac{\text{NM system rate}^{-1} * \text{NM tons per acre}}{(\text{NM system rate}^{-1} * \text{NM tons per acre}) + (\text{Merch system rate}^{-1} * \text{Merch tons per acre})}$$

$$\text{Merch}^{2}\ \% = \frac{\text{Merch system rate}^{-1} * \text{Merch tons per acre}}{(\text{NM system rate}^{-1} * \text{NM tons per acre}) + (\text{Merch system rate}^{-1} * \text{Merch tons per acre})}$$

[1]NM = Non-merchantable portion
[2]Merch = Merchantable portion

TABLE 5. -- Auburn Harvesting Analyzer input assumptions for the non-merchantable portion.

General Information:				
	Hours/day	9		
	Days/week	5		
	Weeks/year	50		
	Tract size	20 acres		
	Move-to-tract	4 hours		
	Move rate	$2.75 / mile		
	Move distance	110 miles		
	Distance home	5 miles		
Support				
	Pickups	1 @ $.45 / mile		
	Foreman	$2,500 / month		
	Overhead	$2,000 / month		
Machine Productivity[1]				
Harvester[2]				
	Total productive time (min)	$[0.1123 - (0.083*DBH) + (3.824*DBH*TPA^{(-0.5)})]$		
Forwarder[3]				
	Number of landings	1		
	Tons / cycle	5.17		
	Stops / cycle	13.94		
	Travel empty distance	1,654.06 feet		
	Travel-while-loading distance	539.75 feet		
	Travel loaded distance	1,574.06 feet		
	Travel empty time (min)	0.0028*TE DIST		
	Travel-while-loading-time (min)	0.0087*TWL DIST		
	Travel loaded time (min)	0.0028*TL DIST		
	Loading time (min)	[5.3186 + (0.7320* # of STOPS)]		
	Feeding time (min)	0.0010*WT		
	Waiting-on-chipper (min)	0.0005*WT		
	Cleanup-around chipper (min)	0.509		
Chipper[4]				
	Tons / cycle	5.17		
	Chipping (min)	2.4186*WT		
	Waiting-on-forwarder (min)	1.25		
	Jam-clearing (min)	1.5		
	Total cycle time (min)	2.9648*WT		
Hauling				
	Haul distance	94 miles		
	Average speed	45 miles / hour		
	Load size	22 tons		
	Unload time	30 minutes		
Machine Cost				
		Harvester	Forwarder	Chipper
	Initial Cost ($)	193,016	168,000	69,500
	Pay life[5] (yrs)	5	4	5
	Insurance & taxes[5] (% of initial)	0.035	0.04	0.02
	Fuel & lubrication[5] ($ / PMH)	10.44	7.65	11.31
	Maintenance & repair[5] ($ / PMH)	18.23	22.97	6.59
	Labor ($ / SMH)	15	15	0
	Labor overhead (%)	30	30	0
	Availability (%)	85	85	70
	% of work day	100	100	100
	Number of machines	1	1	1

[1]Production equations were generated during productivity analysis.
[2]DBH = diameter at breast height (4.5 feet), TPA = total trees per acre
[3]TE DIST = Travel empty distance, TWL DIST = Travel while loading distance, TL DIST = Travel loaded distance
[3]# of STOPS = Number of stops per turn, WT = Weight of forwarded material per turn (pounds)
[4]WT = Weight chipped per load (tons)
[5]Brinker et al In print

TABLE 6. -- Auburn Harvesting Analyzer input assumptions for the merchantable portion.

General Information:		
	Hours/day	9
	Days/week	5
	Weeks/year	50
	Tract size	20 acres
	Move-to-tract	4 hours
	Move rate	$2.75 / mile
	Move distance	110 miles
	Distance home	5 miles
Support		
	Pickups	1 @ $.45 / mile
	Foreman	$2,500 / month
	Overhead	$2,000 / month
Machine Productivity		
Harvester[1]		
	Total productive time (min)	0.0539*DBH
Forwarder[2]		
	Number of landings	1
	Pounds / cord	5350
	Forwarding distance	1,614.06 feet
	Load size	15 tons
	Cords / stop[3]	[(0.0126*CDS AC) + (1.0750*CDS AC / Merch TPA)]
	Travel empty & loaded (min)[4]	[2*(5.4600 + 0.0013*(FOR DIST-1500))]
	Woods travel (min)[5]	[(CDS CYCLE / CDS STOP) - 1)*0.0480 + (0.0061*WDS DIST) - (0.00000168*WDS $DIST^2$)]
	Load & unload (min)	[(CDS CYCLE / CDS STOP)*(0.2430 + 2.4740*CDS STOP) + (0.2430 + 2.4740*CDS CYCLE)]
Hauling		
	Haul distance	70 miles
	Average speed	45 miles / hour
	Load size	26.75 tons
	Load time	5 minutes
	Unload time	30 minutes

Machine Cost	Harvester	Forwarder
Initial Cost ($)	193,016	168,000
Pay life[6] (yrs)	5	4
Insurance & taxes[6] (% of initial)	0.035	0.04
Fuel & lubrication[6] ($ / PMH)	10.44	7.65
Maintenance & repair[6] ($ / PMH)	18.23	22.97
Labor ($ / SMH)	15	15
Labor overhead (%)	30	30
Availability (%)	85	85
% of work day	100	100
Number of machines	1	1

[1]Production equation was generated during productivity analysis, DBH = Diameter at breast height (4.5 feet)
[2]Production equations are from Lanford et al In review
[3]CDS AC = Total cords per acre, Merch TPA = Merchantable trees per acre (DBH greater than or equal to 4 inches)
[4]FOR DIST = Forwarding distance (feet)
[5]CDS CYCLE = Cords per cycle, CDS STOP = Cords loaded per stop, WDS DIST = Distance between stops (feet)
[6]Brinker et al In print

RESULTS AND DISCUSSION

Harvester Productivity

Productivity of the Timbco harvester was estimated statistically using multiple linear regressions. Descriptive statistics (Table 7) were calculated for each variable associated with harvester productivity. During harvester studies, 352 trees were harvested on 6 study plots. Dependent variables were defined in units of minutes per tree harvested. Percentage of time elements is shown in Figure 5.

TABLE 7. -- Harvester analysis descriptive statistics.

		Mean	Std Dev	Min	Max
Dependent Variables (min/tree)[1]					
	Move time	0.03	0.04	0.000	0.35
	Swing time	0.05	0.04	0.005	0.32
	Fell time	0.04	0.02	0.005	0.15
	Process time	0.08	0.09	0.000	0.90
	Total productive time	0.20	0.13	0.03	1.16
Independent Variables					
Tree Size[1]	DBH (in) (all trees)	3.0	2.2	1	13
	Total height (ft) (all trees)	26	16	10	80
Terrain[2]	Slope (%)	10	3	6	16

[1]Number of observations = 352

[2]Number of observations = 6

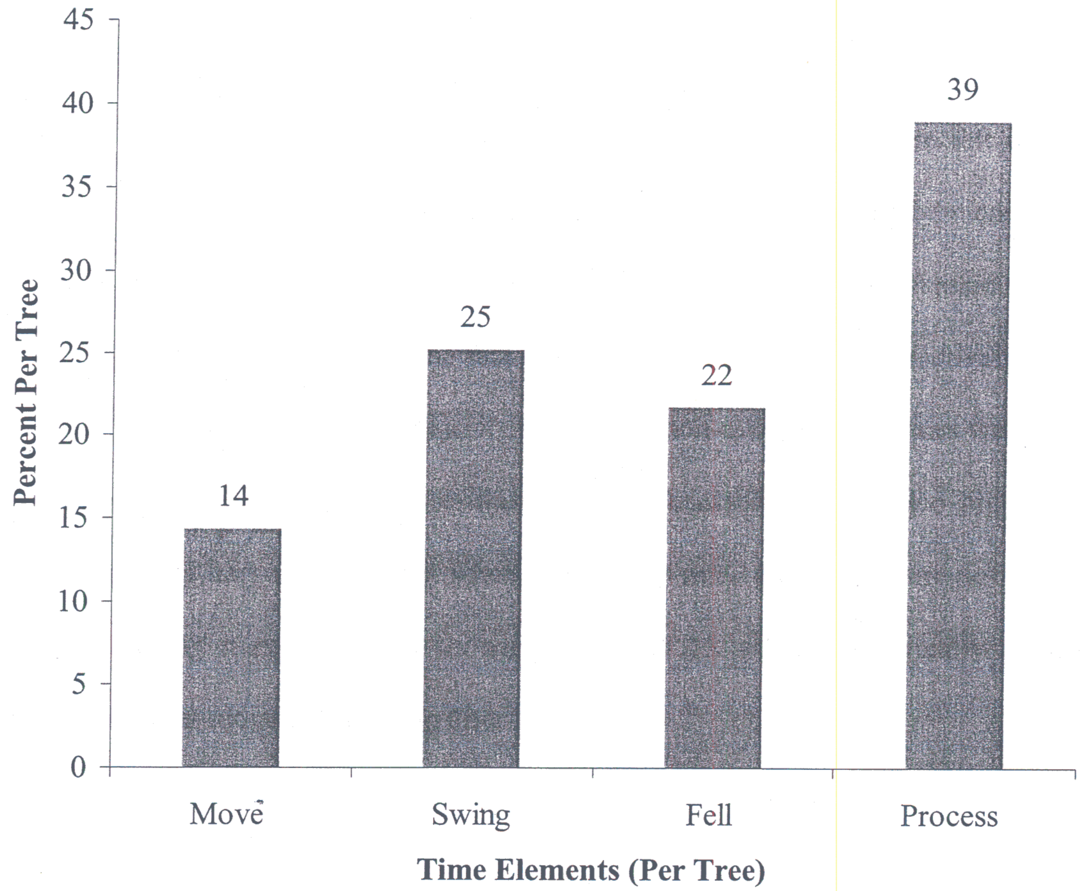

Figure 5. Harvester time elements during CTL / small chipper study.

Table 8 shows stand density statistics for pre-harvest, harvested, and residual trees. Pre-harvest figures came from a 100 percent tree tally on each of the six 0.1 acre study plots. Harvested figures were calculated on the trees that were harvested during time studies. The harvester's boom reach was 21 feet 5 inches; therefore, the machine could reach a total area of 42 feet 10 inches in width, which equates to a plot size of 42 feet 10 inches by 66 feet in length or 0.065 acres. This plot size was used to calculate per acre values for the harvested portion.

The intentions of the harvesting treatment were to thin merchantable trees to a residual 60 ft^2 of basal area per acre and harvest all non-merchantable trees. Table 8 shows that 206.67 non-merchantable and 122.44 merchantable trees were left after the harvest. Residual trees were not measured after the harvest. These numbers came from the difference in pre-harvest and harvested trees. The existence of residual non-merchantable trees is explained by the fact that the harvester could not effectively handle some of the very small trees. The majority of residual non-merchantable trees were in the 1-inch DBH class. The value for residual non-merchantable trees is also higher than actual because the harvester ran over some of the very small trees that were not actually observed as being harvested. As shown in Figures 25 and 26, practically no non-merchantable trees remained standing after the harvest.

TABLE 8. -- Harvester analysis stand density statistics.

			Pre-harvest[4]	Harvested[5]	Residual
Density[3] (per acre)	All Trees	Total tons	155.15	58.69	96.46
		Non-merchantable tons[1]	35.63	17.69	17.94
		Merchantable tons[2]	119.52	41.01	78.51
		Total trees	1,231.67	902.57	329.10
		Non-merchantable trees[1]	873.33	666.66	206.67
		Merchantable trees[2]	358.33	235.89	122.44
	Pine	Total tons	97.98	27.21	70.77
		Non-merchantable tons[1]	15.18	4.26	10.92
		Merchantable tons[2]	82.80	22.94	59.86
		Total trees	146.67	84.61	62.06
		Non-merchantable trees[1]	0.00	0.00	0.00
		Merchantable trees[2]	146.67	84.61	62.06
	Hardwood	Total tons	57.16	31.48	25.68
		Non-merchantable tons[1]	20.44	13.41	7.03
		Merchantable tons[2]	36.72	18.06	18.66
		Total trees	1,085.00	817.95	267.05
		Non-merchantable trees[1]	873.33	666.66	206.67
		Merchantable trees[2]	211.67	151.28	60.39

[1]Trees < 4 inches DBH

[2]Trees >= 4 inches DBH

[3]Number of observations = 6

[4]Plot size = 0.1 acres

[5]Plot size = 0.065 acres

Move Time

Move time per tree was defined as the time it took the harvester to move between harvester stops throughout the stand. Each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating move time per tree.

The best model for estimating move time per tree included the variable of total trees per acre with a square-root inverse transformation ($TPA^{(-0.5)}$) (TPASQIN) that included non-merchantable and merchantable pine and hardwood. The transformation was more significant than trees per acre alone and also more closely follows the trend of the data. Slope was not significant after including TPASQIN in the model.

Best model:

Move time (minutes) per tree = -0.09 + 4.38*TPASQIN

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
INTERCEPT	-0.09	-5.033	0.000
TPASQIN	4.38	6.588	0.000

Analysis of Variance:

Source	DF	SS	MS	F Ratio	Prob Level	R^2	$S_{y.x}$
Intercept	1	0.2891	0.2891				
Model (Corrected)	1	0.0612	0.0612	43.397	0.000	0.11	0.037
Error	350	0.4936	0.0014				
Total (Corrected)	351	0.5548	0.0016				

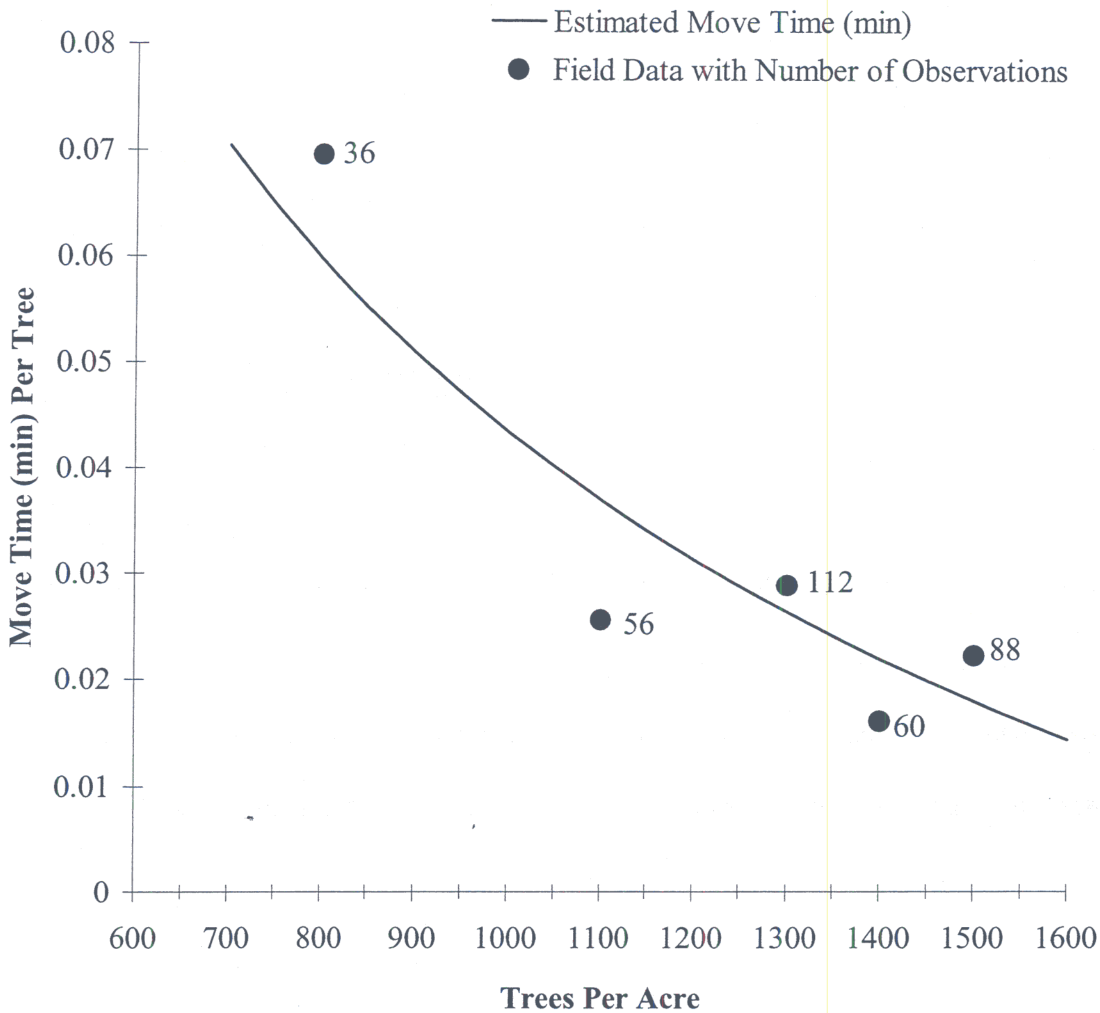

Figure 6. Harvester move time during CTL / small chipper study.

Move time observations in Figure 6 were grouped by 100 trees per acre classes. Next to each data point is the number of observations for the class. The model showed that as trees per acre increased move time decreased. That follows the assumption that if there are more trees per acre then there is less distance between trees and, therefore, less move time as the harvester moves between groups of trees.

Swing Time

Swing time per tree was defined as the time it took the harvester to physically move its boom from the end of a machine move or from a previously processed tree to a new tree to fell. Each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating swing time per tree.

The best model for predicting swing time per tree included the independent variables of DBH (includes all trees non-merchantable and merchantable) and trees per acre with a square-root inverse transformation (TPASQIN) (included all non-merchantable and merchantable trees). Separate terms for DBH and the transformation of trees per acre were tested along with their cross product. The model with DBH and trees per acre was statistically stronger than a model with trees per acre only. The addition of slope in the model was not significant. Species variation was also non-significant.

Best model:

Swing time (minutes) per tree: = -0.08 + 0.006*DBH + 4.16*TPASQIN

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
INTERCEPT	-0.08	-4.861	0.000
DBH	0.006	7.734	0.000
TPASQIN	4.16	6.701	0.000

Analysis of Variance:

Source	DF	SS	MS	F Ratio	Prob Level	R^2	$S_{y.x}$
Intercept	1	0.9238	0.9238				
Model (Corrected)	2	0.1388	0.0694	56.559	0.000	0.24	0.035
Error	349	0.4283	0.0012				
Total (Corrected)	351	0.5671	0.0016				

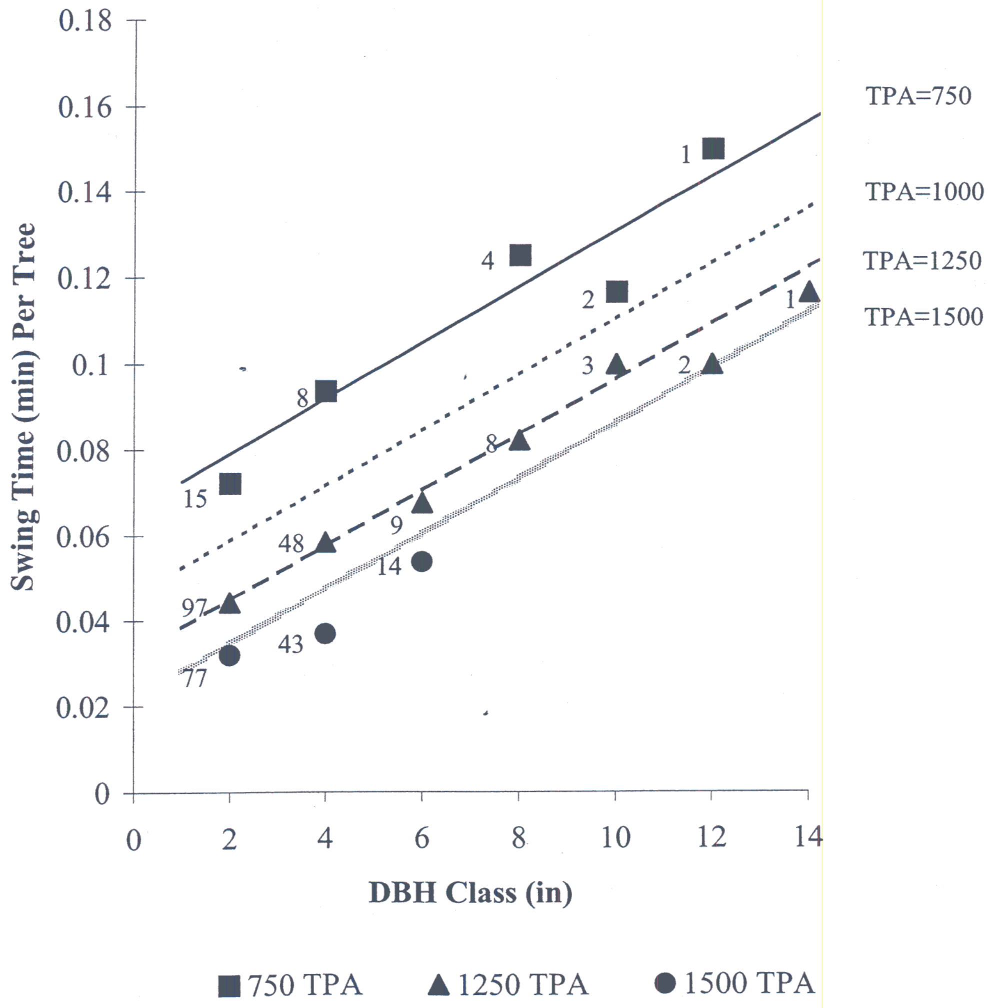

Figure 7. Harvester swing time during CTL / small chipper study.

The lines in Figure 7 represent swing time (minutes) per tree predicted values for four different trees per acre classes. There were no trees harvested in the 1,000 trees per acre class. Points on the graph indicate the average swing time at each trees per acre and DBH class. Number of observations is next to each data point. The regression model showed that as trees per acre increased swing time per tree decreased. As for move time per tree; this follows the assumption that as stand density increases there is less distance between trees therefore taking less time to swing to the next tree. Also, the regression showed that as DBH increased swing time per tree increased. This can be explained by the fact that as DBH increases stand density decreases. When stand density is decreased there is more distance between trees therefore taking the harvester longer to swing to the next tree. The larger trees may have taken more time for the harvester head to grip than the smaller ones.

Fell Time

Fell time per tree was defined as the time it took the harvester to position its head onto the tree and physically move its bar saw through the tree. Each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating fell time per tree.

A sum of squares F test was performed to compare a model with only DBH^2 to a model with DBH^2 and a dummy variable to account for non-merchantable trees (less than 4 inches DBH). The test yielded an F ratio of 1.54 (an F ratio of 4 is needed for statistical significance at the alpha equal to 0.05 level) which indicates that no significant difference was detected from this sample for fell time per tree between felling non-merchantable trees (less than 4 inches DBH) and merchantable trees (greater than or equal to 4 inches DBH) after including DBH in the model. Species variation was also non-significant. Although no significant difference was found at the 4 inch DBH break, significance was indicated at the 6 inch DBH break. Therefore, the best model for estimating fell time per tree included only the cross product between the independent variable of DBH^2 and a DBH dummy variable (DBH DUMB) to account for a break in DBH at six inches. To use the model, a zero should be entered for DBH DUMB for DBH less than or equal to six inches. For DBH greater than six inches a one should be entered.

Best model:

Fell time (minutes) per tree: $= 0.04 + 0.00016 * \text{DBH DUMB} * \text{DBH}^2$

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
INTERCEPT	0.04	34.560	0.000
DBH DUMB*DBH^2	0.00016	2.944	0.003

Analysis of Variance:

Source	DF	SS	MS	F Ratio	Prob Level	R^2	$S_{y.x}$
Intercept	1	0.6664	0.6664				
Model (Corrected)	1	0.0044	0.0044	8.668	0.003	0.02	0.022
Error	350	0.1778	0.0005				
Total (Corrected)	351	0.1822	0.0005				

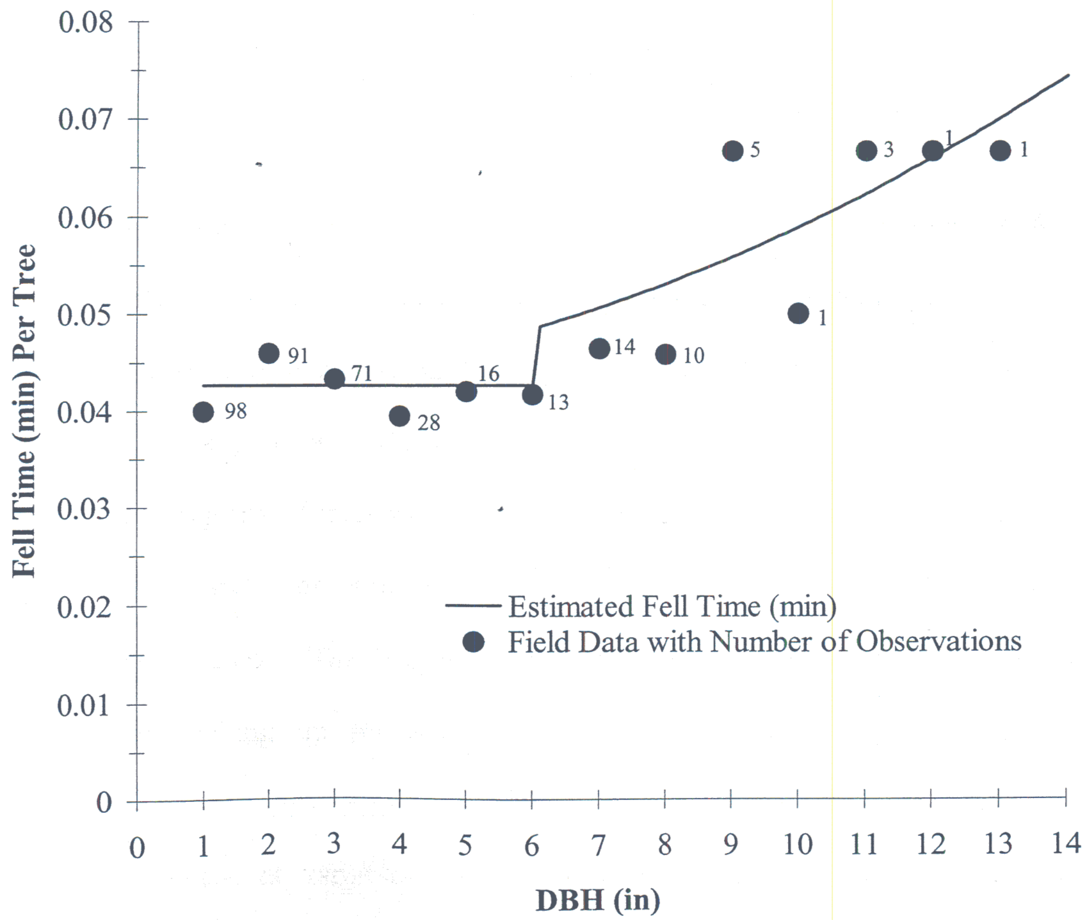

Figure 8. Harvester fell time during CTL / small chipper study.

Data points shown in Figure 8 are for average fell time per tree for all trees felled in each 1-inch DBH class. Number of observations is next to each data point. The regression model showed that as DBH increased fell time increased for trees larger than six inches. This is an expected relationship for fell time per tree explaining the fact that as tree diameter increases it takes longer for the harvester's bar saw to pass through. This relationship is not valid for trees less than or equal to six inches DBH. No significance relationships were found for estimating fell time of the small trees. This is possibly due to the fact that the harvester had difficulty getting its boom on the small trees because of excess slash surrounding the head. This in turn allowed for substantial variation in the data resulting in a low R^2 value.

Process Time

Process time per tree for merchantable trees included time to delimb, buck, and bunch harvested trees. Plots studied included few merchantable felled trees (92 or 26 percent) and consisted of mostly hardwood non-merchantable trees (less than 4 inches DBH) (260 or 74 percent). There were no non-merchantable pine trees harvested. Therefore, the majority of trees harvested were only moved to a bunching location after felling. Limbs and tops from the merchantable trees were also placed in non-merchantable bunches. The bunching procedure helped the forwarder to be more productive in picking up the non-merchantable trees and limbs and tops from merchantable trees.

All independent variables and combinations with their cross products were initially analyzed. The best model to estimate process time per tree included the independent variables of DBH in inches and a dummy variable to account for non-merchantable trees (DBH DUMB). Their cross product (DBH*DBH DUMB) was also significant. Total height, species variation, and slope were non-significant after including DBH, DBH DUMB, and DBH DUMB*DBH in the model. A sum of squares F test was performed comparing a reduced model with only DBH to a full model including DBH and a dummy variable to account for non-merchantable trees. The F test yielded an F ratio of 27.07 (an F ratio of 4 is needed for significance at the alpha equal to 0.05 level). The test indicated a strong statistical difference between the processing time of non-merchantable and merchantable trees.

Best model:

Process time (minutes) per tree for all trees harvested = 0.02 + 0.01*DBH – 0.13*DBH DUMB + 0.03*DBH DUMB*DBH

To apply the model, when DBH is less than 4 inches a 0 should be substituted for DBH DUMB and when DBH is greater than or equal to 4 inches a 1 should be substituted.

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
INTERCEPT	0.02	2.233	0.026
DBH	0.01	3.299	0.001
DBH DUMB	-0.13	-7.069	0.000
DBH DUMB*DBH	0.03	6.894	0.000

Analysis of Variance:

	DF	SS	MS	F Ratio	Prob Level	R^2	$S_{y.x}$
Intercept	1	2.1824	2.1824				
Model (Corrected)	3	2.0771	0.6924	242.277	0.000	0.68	0.053
Error	348	0.9945	0.0029				
Total (Corrected)	351	3.0716	0.0088				

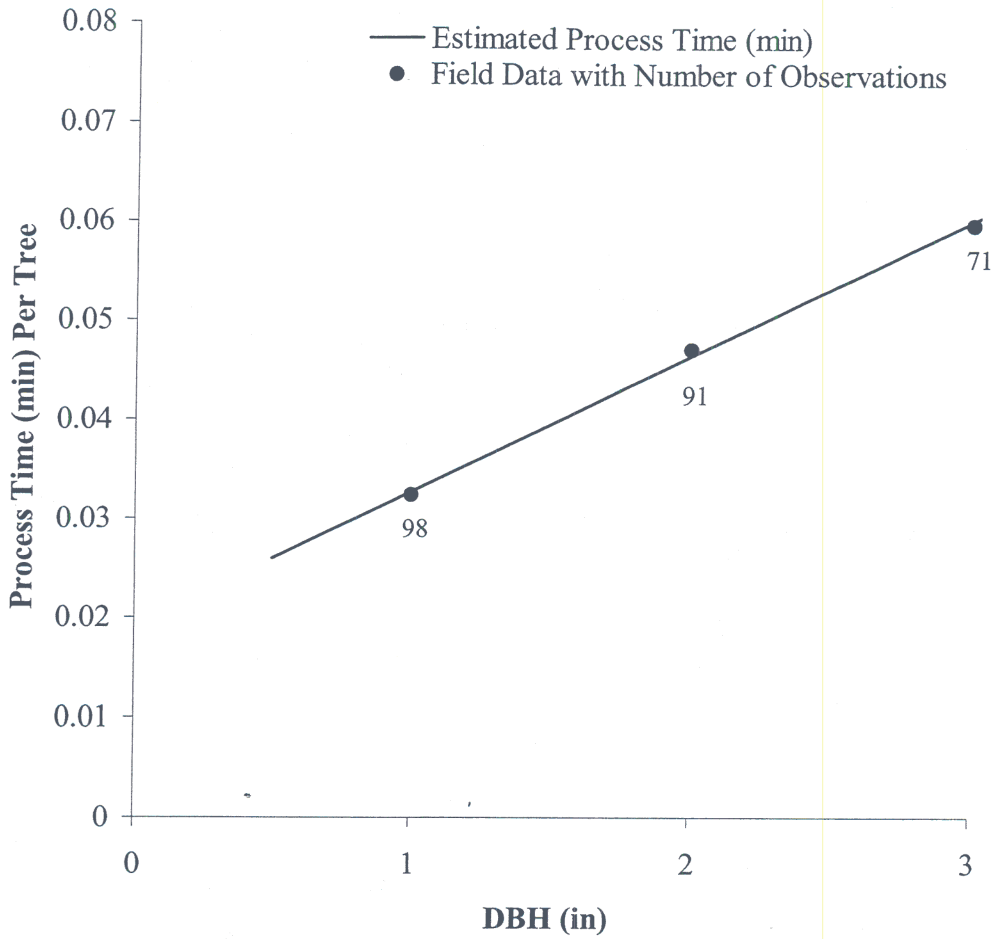

Figure 9. Harvester process time for non-merchantable hardwood during CTL / small chipper study.

In Figure 9 points on the graph are for the average process time per tree at each non-merchantable DBH class. Number of observations is next to each point. The regression model showed that as DBH increased process time per tree increased for the non-merchantable trees. That follows the assumption that as diameter increases the number of limbs and foliage increase. As limbs and foliage increase it takes more time for the harvester to bunch and pile.

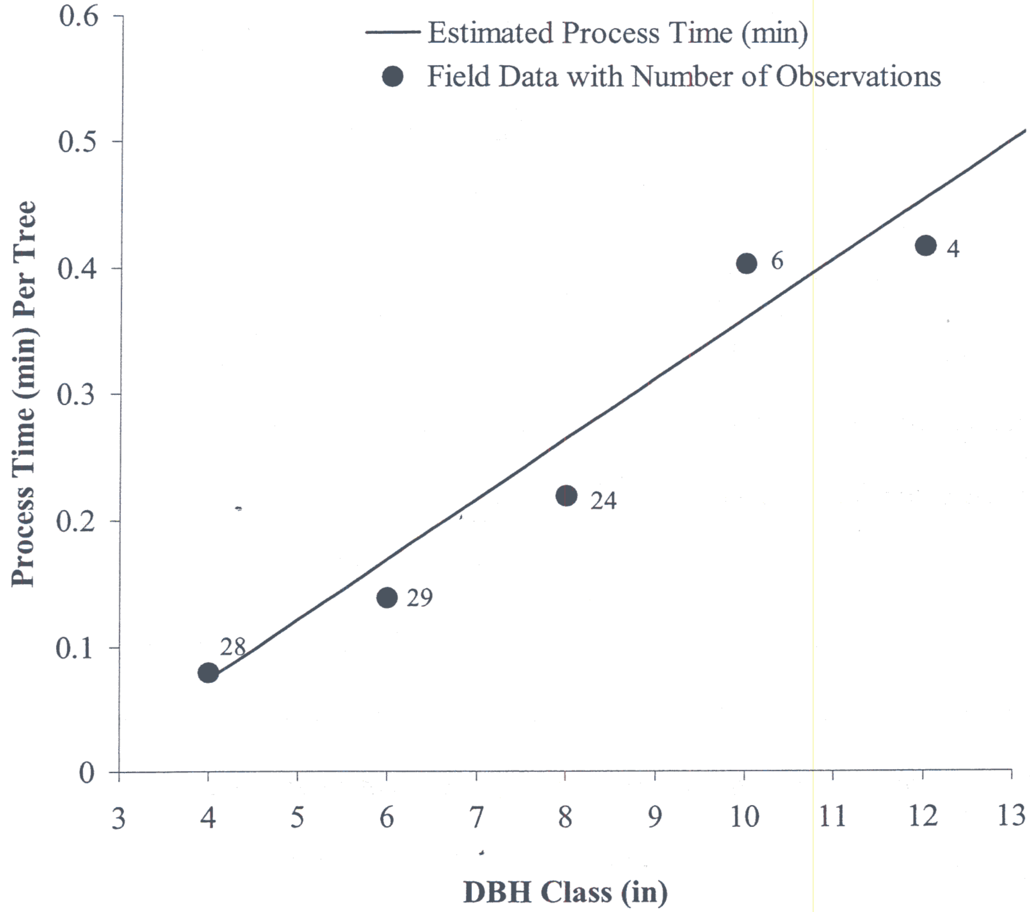

Figure 10. Harvester process time for all merchantable trees during CTL / small chipper study.

In Figure 10 points on the graph are for the average process time per tree at each merchantable 2-inch class. Number of observations is next to each data point. The regression model showed that as DBH increased process time increased. That follows the assumption that as tree size increases process time increases. Therefore, as tree diameter increases bole length and limbs increase which corresponds into more delimbing and bucking.

Total Productive Time

Total productive time per tree is defined as the sum of the harvester's productive time elements that included move time, swing time, fell time, and process time.

All independent variables and combinations with their cross products were initially analyzed. This procedure indicated a strong significant difference between the total productive time of non-merchantable and merchantable trees. The significance led to splitting the data into two sets. Therefore regression models were formulated for non-merchantable trees and merchantable trees.

- Model 1: Hardwood non-merchantable trees only (DBH less than 4 inches)

For this study, 260 non-merchantable hardwood trees were harvested. The best model for predicting the process time of these trees included the independent variables of DBH in inches and the square root inverse transformation of total trees per acre ($TPA^{-0.5}$) (TPASQIN). The cross product of these two terms was also significant, (DBH*TPASQIN). The individual variable of TPASQIN was no longer significant after including the cross product in the model. The addition of DBH^2, total height, and slope were also non-significant after including DBH in the model.

Best model:

Total productive time (minutes) per tree for non-merchantable hardwoods: = 0.11 – 0.08*DBH + 3.82*DBH*TPASQIN

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
INTERCEPT	0.11	10.502	0.000
DBH	-0.08	-3.917	0.000
DBH*TPASQIN	3.82	5.148	0.000

Analysis of Variance:

	DF	SS	MS	F Ratio	Prob Level	R^2	$S_{y.x}$
Intercept	1	6.4987	6.4987				
Model (Corrected)	2	0.2047	0.1024	22.869	0.000	0.15	0.067
Error	257	1.1504	0.0045				
Total (Corrected)	259	1.3552	0.0052				

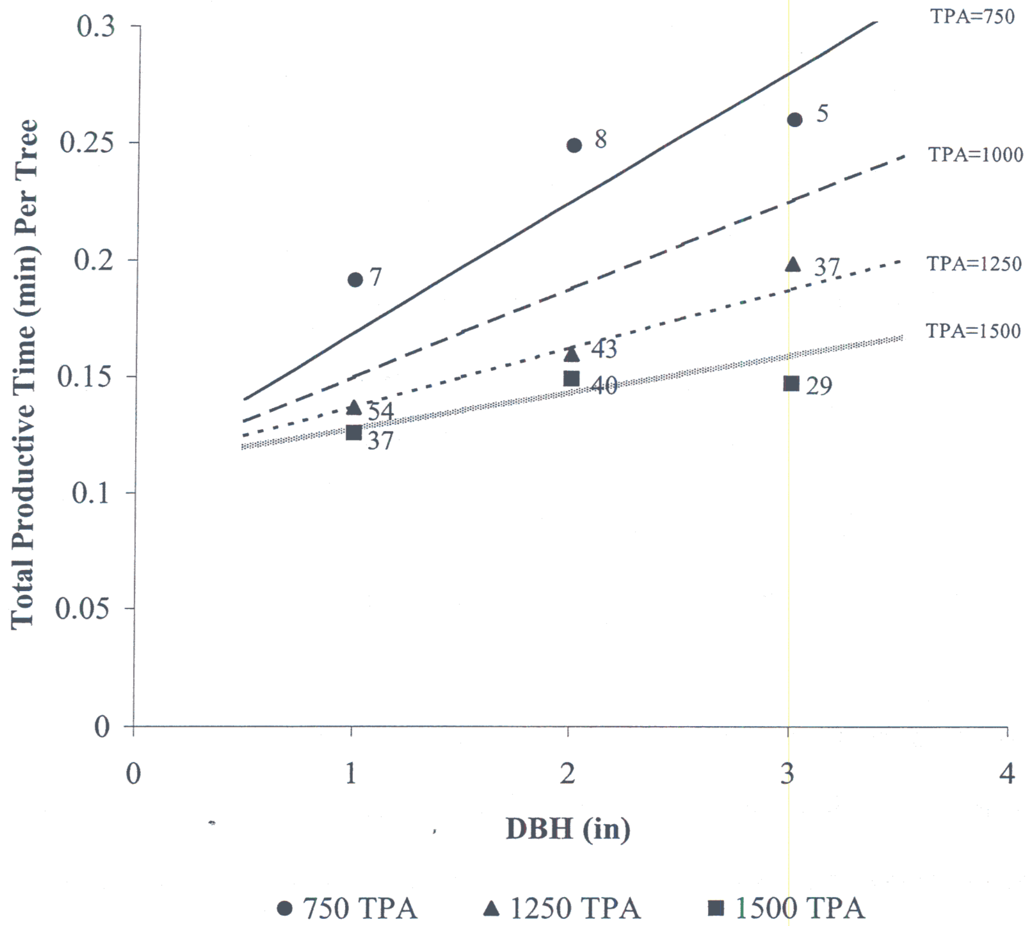

Figure 11. Harvester total productive time for non-merchantable hardwood during CTL / small chipper study.

The lines in Figure 11 represent total productive time per tree predicted values for four different trees per acre classes. There were no non-merchantable trees harvested in the 1,000 trees per acre class. Points on the graph indicate the average total productive time for each non-merchantable DBH class and the four trees per acre classes. Number of observations is next to each data point. The regression model showed that as trees per acre increased total productive time decreased. As for swing and move time per tree, the same assumption is followed that as stand density increases trees are closer together; therefore, taking less time for the harvester to complete a productive cycle. Also, as DBH increased total productive time increased. This follows the same assumption as before, as DBH increases stand density decreases. When stand density is decreased there is more distance between trees and therefore takes the harvester longer to complete a productive cycle. Also, the felling time component increased with larger trees.

- Model 2: All merchantable trees (pine and hardwood) (greater than or equal to 4 inches DBH)

For this study, 92 merchantable trees were harvested consisting of 33 pine and 59 hardwood. The best model for predicting the total productive time of these trees included the independent variable of DBH in inches. The addition of DBH^2, total height, trees per acre, species variation, and slope was non-significant after including DBH in the model. The intercept variable was also non-significant after including DBH; therefore, it was removed. For models without an intercept the R^2 value is no longer valid. The same model including intercept had an R^2 of 0.51.

Best model:

Total productive time (minutes) per tree for merchantable pine and hardwood:

= 0.05*DBH

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
DBH	0.05	27.808	0.000

Analysis of Variance:

	DF	SS	MS	F Ratio	Prob Level	$S_{y.x}$
Intercept	0	0.0000	0.0000			
Model (Uncorrected)	1	11.0809	11.0890	773.297	0.000	0.120
Error	91	1.3049	0.0143			
Total (Uncorrected)	92	12.3939	0.1347			

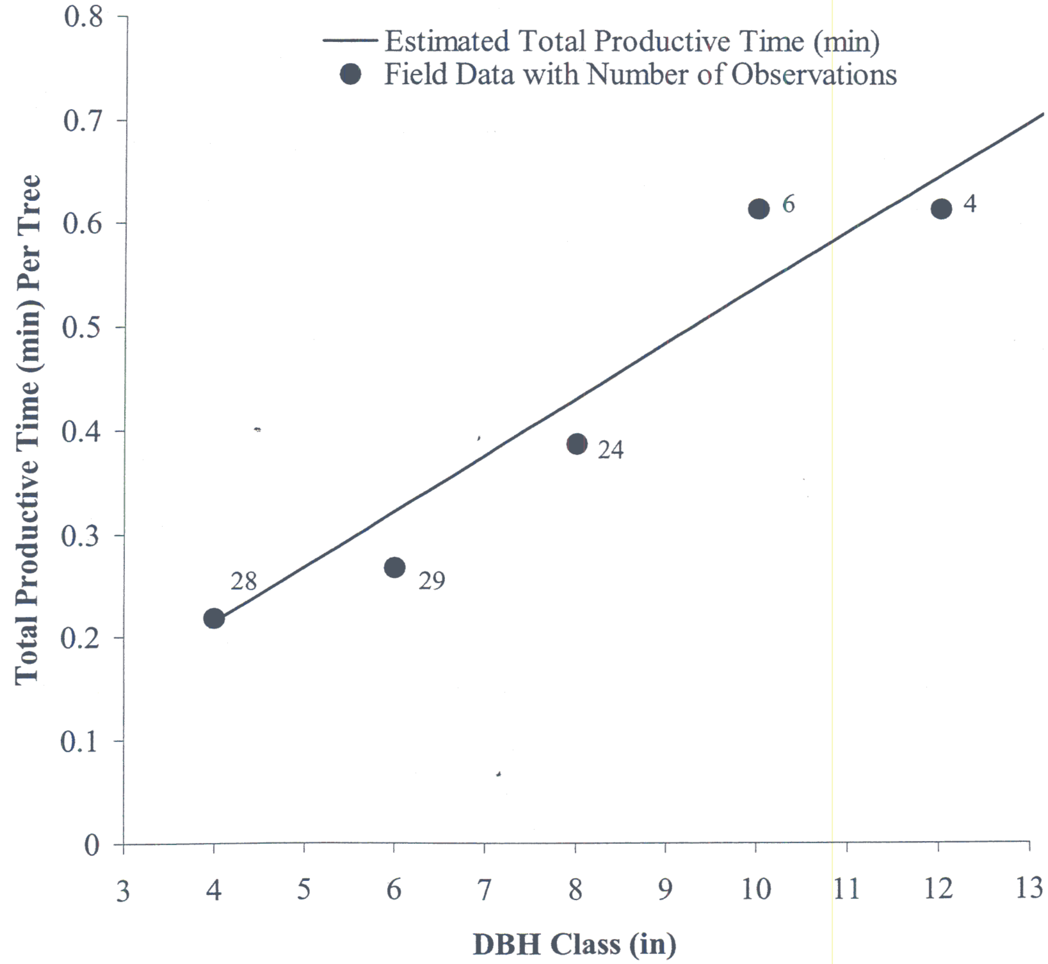

Figure 12. Harvester total productive time for all merchantable trees during CTL / small chipper study.

In Figure 12 points on the graph are for the average total productive time per tree at each merchantable 2-inch DBH class. Number of observations is next to each data point. The regression model showed that as DBH increased total productive time per tree increased. This is explained by the same assumption as for total productive time of non-merchantable hardwood. The predicted line passes closely through the mean points. Again, the regression equation and graph should only be used for merchantable trees, pine and hardwood (greater than or equal to 4 inches DBH).

Forwarder Productivity

Productivity of the Fabtek forwarder was estimated statistically using multiple linear regressions. Descriptive statistics (Table 9) were calculated for each variable associated with forwarder productivity. Dependent variables were classified as moving or stationary and defined in units of minutes per forwarder load of non-merchantable material. Time elements as a percentage of total productive time are shown in Figure 13.

TABLE 9. -- Forwarder analysis descriptive statistics.

		Count	Mean	Std Dev	Min	Max
Dependent Variables (min/load)						
Moving	Travel empty	16	4.7	1.3	1.9	8.0
	Travel-while-loading	16	4.8	2.7	1.4	10.5
	Travel loaded	16	4.5	1.2	2.4	6.4
Stationary	Loading	16	16.5	4.5	10.1	27.0
	Feeding	15	10.8	2.1	7.3	15.0
	Waiting-on-chipper	15	4.6	2.6	0.8	9.9
	Cleanup-around chipper	15	0.5	0.2	0.2	0.8
	Total time	15	46.4	8.7	34.1	70.1
Independent Variables						
(feet)	Travel empty distance	16	1,654.1	414.3	478	2,190
	Travel-while-loading distance	16	539.8	302.3	88	1,052
	Travel loaded distance	16	1,574.1	382.0	997	2,047
	Number of stops	16	13.9	4.5	5	21
	Operator time experience[1] (hrs)	13	4.3	2.7	0	8.2
	Operator time experience[2] (hrs)	4	1.1	1.1	0	2.5
	Weight (lbs) per turn	15	10,365.3	1,747.3	7,600	13,260

[1]Operator 1 (more experienced)

[2]Operator 2 (less experienced)

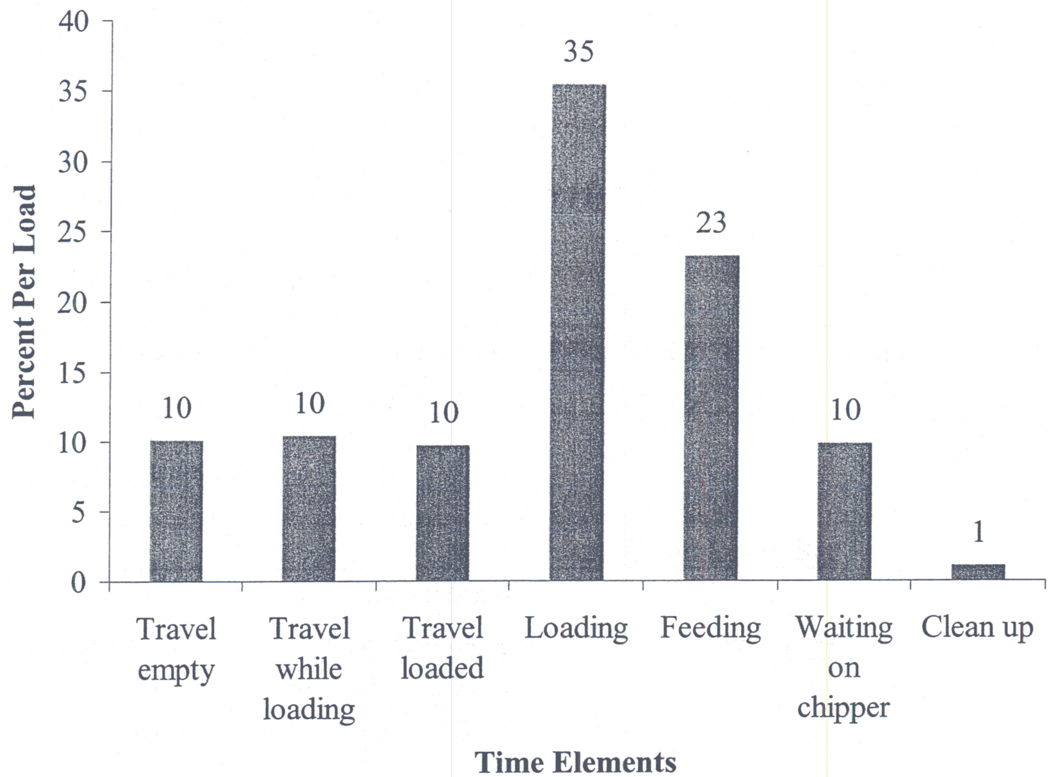

Figure 13. Forwarder time elements during CTL / small chipper study.

Travel Empty Time

Travel empty time per load was defined as the time it took the forwarder to travel empty from the deck to the first machine loading-stop. Each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating travel empty time per load.

The best model for estimating travel empty time per load included the independent variable of travel empty distance in feet. Operator time experience and the variation between operators was non-significant after including travel empty distance per load in the model. The intercept variable was also non-significant; therefore, it was removed. R^2 for the same model including intercept was 0.40.

Best model:

Travel empty time (minutes) per load = 0.003*TE DIST (ft)

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
TE DIST	0.003	18.132	0.000

Analysis of Variance:

Source	DF	SS	MS	F Ratio	Prob Level	$S_{y.x}$
Intercept	0	0.0000	0.0000			
Model (Uncorrected)	1	360.4743	360.4743	328.795	0.000	1.047
Error	15	16.4453	1.0964			
Total (Uncorrected)	16	376.9195	23.5575			

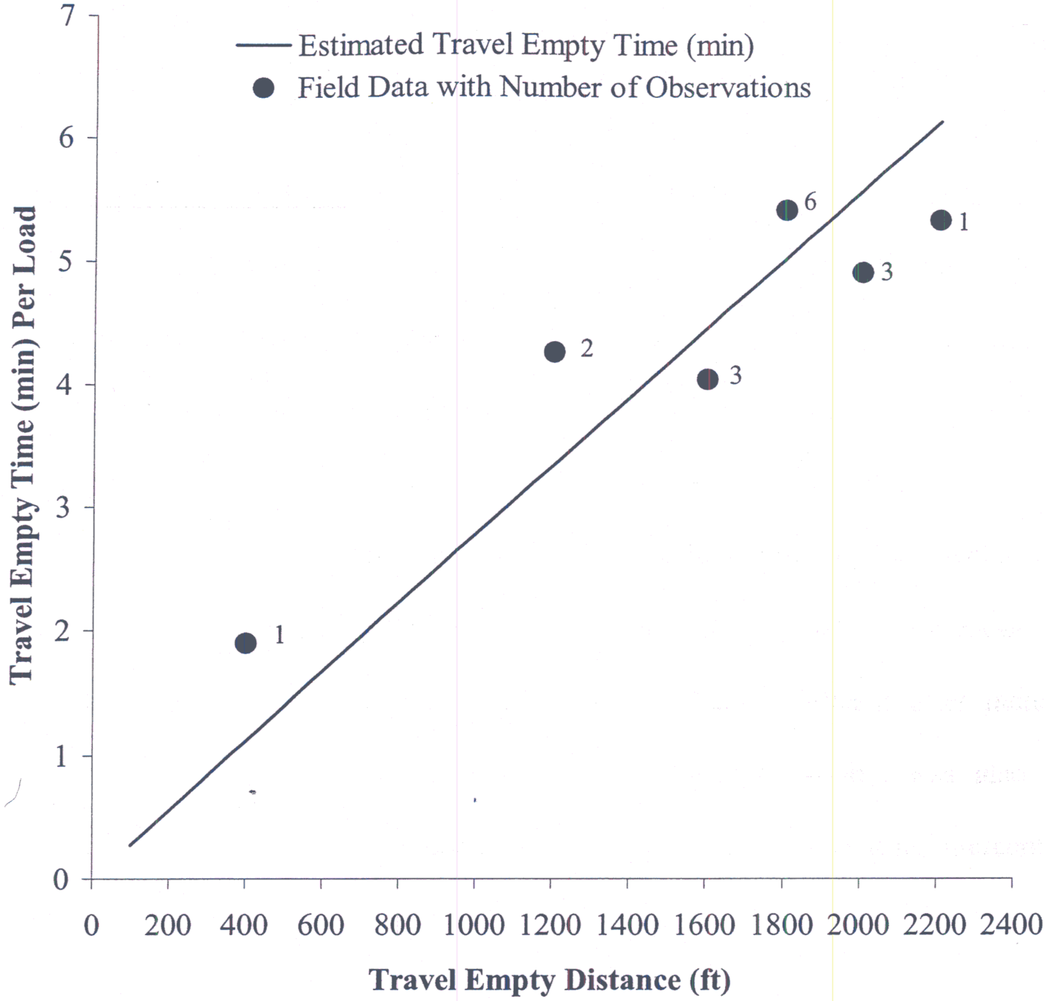

Figure 14. Forwarder travel empty time during CTL / small chipper study.

In Figure 14, points on the graph are for travel empty times at each 200-foot travel empty distance class. Number of observations is shown next to each data point. There were 16 observations averaging 1,654 feet for travel empty distance and 4.7 minutes for travel empty time. The regression model showed that as distance increased time increased. This is in agreement with the assumption that the forwarder traveled approximately the same speed (352 feet per minute) for varying distances.

Travel-While-Loading Time

Travel-while-loading time per load was defined as the cumulative time it took the forwarder to travel between machine loading stops (pickup points) during a single turn. Each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating travel-while-loading time per load.

The best model for estimating travel-while-loading time per load included the independent variable of travel-while-loading distance per load. Operator time experience and the variation between operators were non-significant after including travel-while-loading distance in the model. The intercept variable was also non-significant; therefore, it was not included. R^2 for the same model including intercept was 0.80.

Best model:

Travel-while-loading time (minutes) per load = 0.01*TWL DIST

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
TWL DIST	0.01	17.525	0.000

Analysis of Variance:

Source	DF	SS	MS	F Ratio	Prob Level	$S_{y.x}$
Intercept	0	0.0000	0.0000			
Model (Uncorrected)	1	461.5898	461.5898	307.144	0.000	1.226
Error	15	22.5426	1.5028			
Total (Uncorrected)	16	484.1325	30.2583			

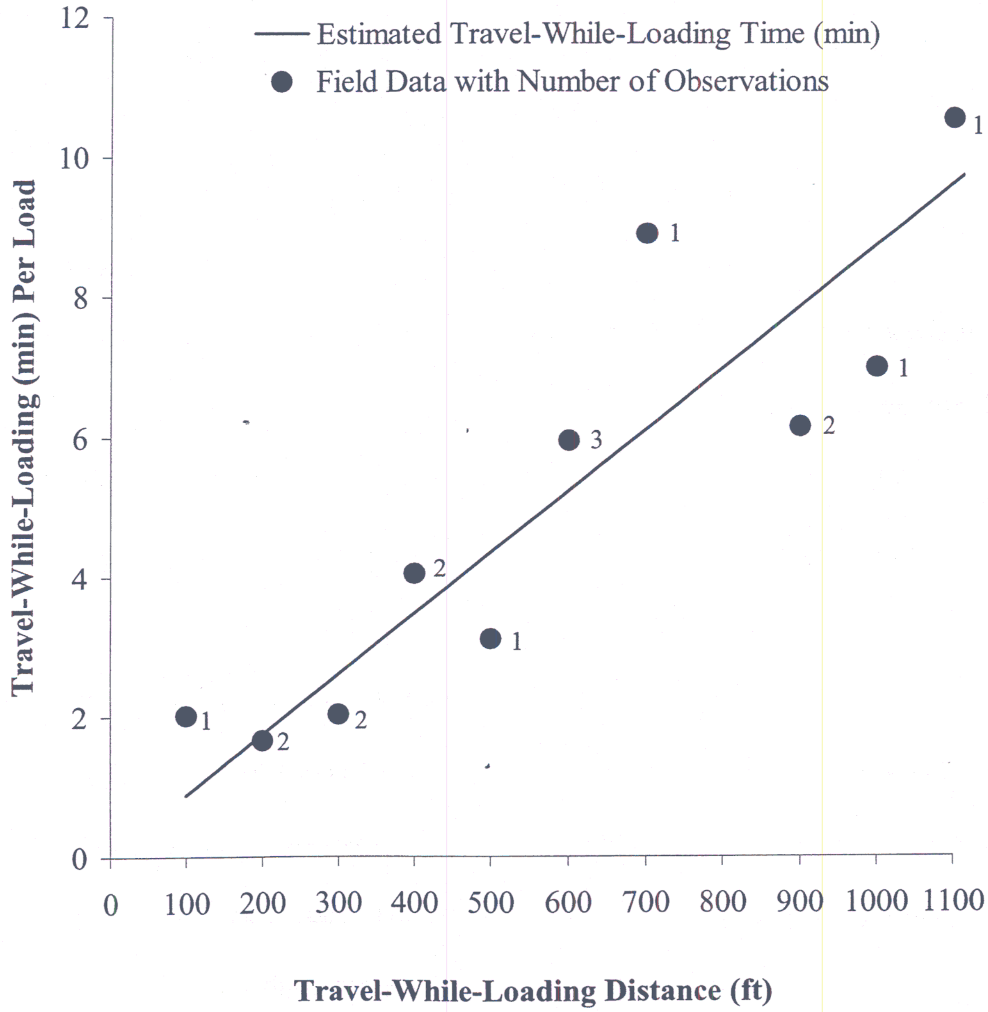

Figure 15. Forwarder travel-while-loading time during CTL / small chipper study.

In Figure 15, points on the graph are for travel-while-loading times at each 100-foot travel-while-loading distance class. Number of observations is shown next to each data point. No observations were recorded for the 800-foot class. There were 16 observations averaging 540 feet for travel-while-loading distance and 4.8 minutes for travel-while-loading time. The regression model showed that as distance increased time increased. This agrees with the assumption that the forwarder traveled approximately the same speed (112 feet per minute) during travel-while-loading times regardless of distance traveled.

Travel Loaded Time

Travel loaded time per load was defined as the time it took the forwarder to travel from the last machine loading stop to the deck. Travel began when the forwarder operator determined his load to be full and wheels began to move. Each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating travel loaded time per load.

The best model for estimating travel loaded time per load included the independent variable of travel loaded distance per load. Operator time experience and the variation between operators were non-significant after including travel loaded distance per load in the model. The intercept variable was also non-significant; therefore, it was removed. R^2 for the same model including intercept was 0.65.

Best model:

Travel loaded time (minutes) per load = 0.003*TL DIST

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
TL DIST	0.003	25.411	0.000

Analysis of Variance:

Source	DF	SS	MS	F Ratio	Prob Level	$S_{y.x}$
Intercept	0	0.0000	0.0000			
Model (Uncorrected)	1	339.1161	339.1161	645.749	0.000	0.725
Error	15	7.8773	0.5252			
Total (Uncorrected)	16	346.9934	21.6871			

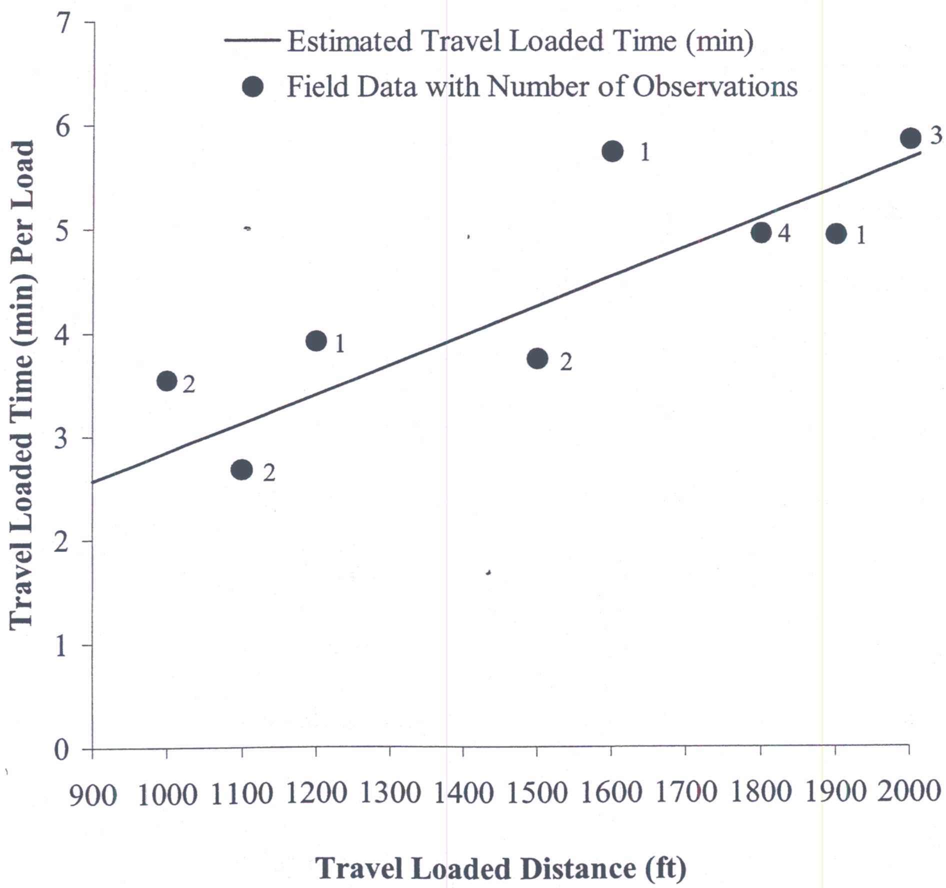

Figure 16. Forwarder travel loaded time during CTL / small chipper study.

In Figure 16, points on the graph are for average travel loaded times at each 100-foot travel loaded distance class. Number of observations is shown next to each data point. No observations were recorded for the 1,300, 1,400, or 1,700-foot classes. There were 16 observations averaging 1,574 feet for travel loaded distance and 4.5 minutes for travel loaded time. The regression model showed that as distance increased time increased. This follows the assumption that the forwarder traveled approximately the same speed (349 feet per minute) over varying distances.

Loading Time

Loading time per load was defined as the time it took the forwarder to fill its bunk with non-merchantable material during machine stops. The material included entire trees less than 4 inches DBH and limbs and tops from felled merchantable trees. Loading time began when the machine stopped traveling at a pile of non-merchantable material and ended when traveling to the next pile began. Loading time was recorded when the machine's tires were stopped, and its boom was in use loading material. Each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating loading time per load.

The best model for estimating loading time per load included the independent variables of number of loading stops per turn, a dummy variable to account for operator variation (OPER DUMB), and their cross product (OPER DUMB* # of STOPS). Weight of forwarded material, operator time experience, and the individual variable of OPER DUMB were non-significant after including number of stops and OPER DUMB* # of STOPS in the model. To use the model, OPER DUMB should be replaced with a zero for an experienced operator and a one for a less experienced operator. For this study, the more experienced operator completed 75 percent of the observations with the less experienced operator completing 25 percent.

Best model:

Loading time (minutes) per load = 5.3 + 0.2*OPER DUMB* # of STOPS + 0.7* # of STOPS

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
INTERCEPT	5.3	3.519	0.004
OPER DUMB* # of STOPS	0.2	3.587	0.003
# of STOPS	0.7	6.730	0.000

Analysis of Variance:

Source	DF	SS	MS	F Ratio	Prob Level	R^2	$S_{y.x}$
Intercept	1	4,340.6060	4,340.6060				
Model (Corrected)	2	264.7933	132.3967	42.543	0.000	0.87	1.764
Error	13	40.4568	3.1121				
Total (Corrected)	15	305.2501	20.3500				

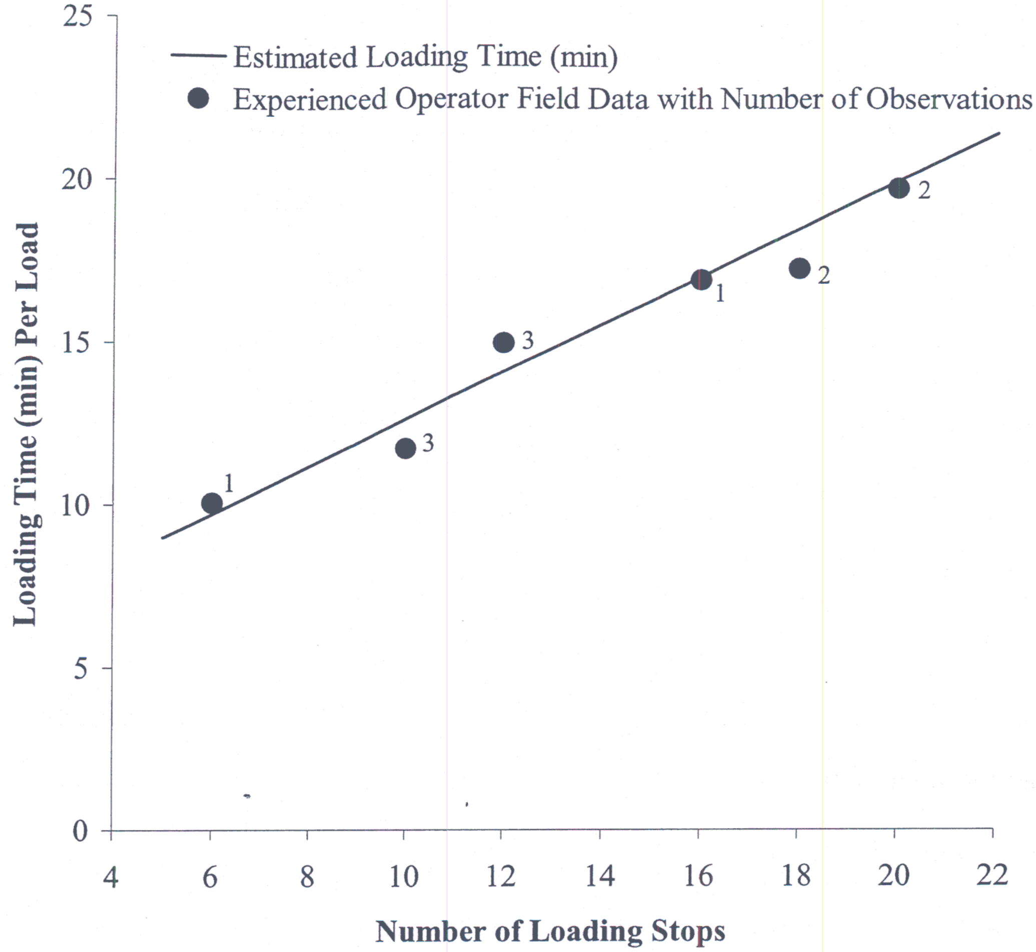

Figure 17. Forwarder loading time for the experienced operator during CTL / small chipper study.

In Figure 17, points on the graph are for average loading times (experienced operator) at each 2 loading stops class. Number of observations is shown next to each data point. No observations were recorded for the 4, 8, 14, or 22 loading stop classes. For the experienced operator, there were 12 observations averaging 14 loading stops and

15.1 minutes for loading time per turn. The regression model showed that as number of loading stops increased loading time increased. This agrees with the assumption that as the forwarder made more loading stops the amount of material forwarded increases. While weight loaded could be expected to influence loading time, it did not due to the consistency of forwarder volumes per turn. Therefore, the number of stops' significance was due to the average pile size being picked up coupled with fixed time required each time the forwarder operator had to stop to pick up. Fixed time might include activities such as turning the machine seat around to travel and time to pick up and set down the loader boom.

Feeding Time

Feeding time per load was defined as the time it took the forwarder to unload and feed its load of non-merchantable material into the small chipper. Feeding time was recorded when the forwarder's boom was in motion. Motion included grappling forwarded material on its load, swinging to the chipper, placing material on the chipper bed, and swinging back to the forwarder for another grapple load.

Each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating feeding time per load. The best model for estimating feeding time per load included only the independent variable of weight (WT) of material forwarded. Operator time experience and the variation between operators were non-significant after including load weight in the model. The intercept variable was also non-significant; therefore, it was not included. R^2 for the same model including intercept was 0.30.

Best model:

Feeding time (minutes) per load = 0.001*WT

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
WT	0.001	20.912	0.000

Analysis of Variance:

Source	DF	SS	MS	F Ratio	Prob Level	$S_{y.x}$
Intercept	0	0.0000	0.0000			
Model (Uncorrected)	1	1,663.5750	1,663.5750	437.329	0.000	1.950
Error	13	49.4512	3.8039			
Total (Uncorrected)	14	1,713.0260	122.3590			

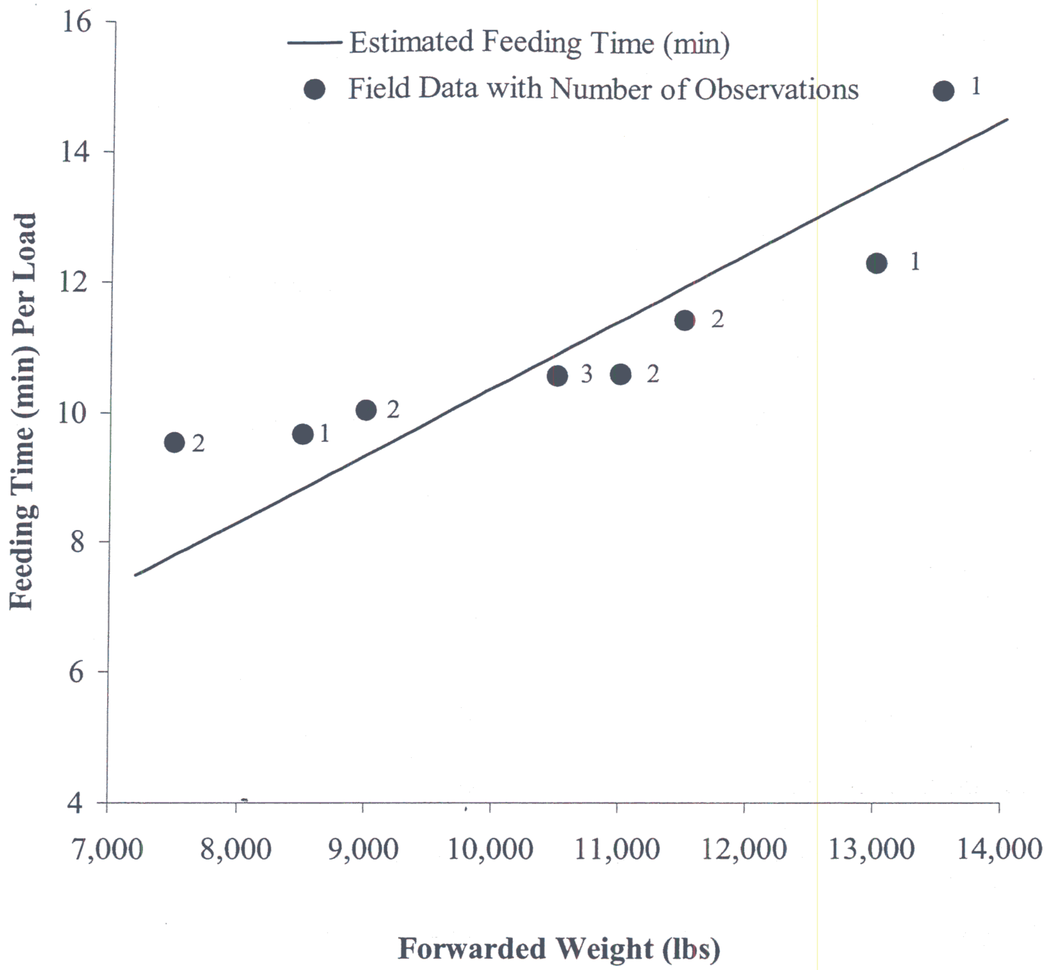

Figure 18. Forwarder feeding time during CTL / small chipper study.

In Figure 18, points on the graph are for average feeding times at each 500-pound weight class. Number of observations is shown next to each data point. There were 14 observations averaging 10,346 pounds of forwarded material and 10.8 minutes for feeding time per load. The regression model showed that as forwarded weight increased feeding time increased. This can be explained by the assumption that as forwarded weight increases more material is present to feed into the chipper. As non-merchantable material increases, the number of grapple bites, swing to chipper cycles, and placement of material on the chipper bed cycles increase.

Waiting-on-Chipper Time

Waiting-on-chipper time per load was defined as the time the forwarder was idle during the chipper feeding process. Waiting time was recorded when the forwarder's boom was not moving. Boom movement became idle when the chipper could not process material as quickly as the forwarder was feeding it. Also, waiting time occurred while the chipper had material hung in the machine and therefore had to reverse the conveyer. This was directly related to the design limits of the small chipper.

Each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating waiting-on-chipper time per load. The best model for estimating waiting-on-chipper time per load included only the independent variable of weight (WT) of material forwarded. Operator time experience and the variation between operators were non-significant after including load weight in the model. The intercept variable was also non-significant; therefore, it was removed. R^2 for the same model including intercept was 0.44.

Best model:

Waiting-on-chipper time (minutes) per load = 0.0005*WT

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
WT	0.0005	8.166	0.000

Analysis of Variance:

Source	DF	SS	MS	F Ratio	Prob Level	$S_{y.x}$
Intercept	0	0.0000	0.0000			
Model (Uncorrected)	1	327.5438	327.5438	66.692	0.000	2.216
Error	13	63.8467	4.9113			
Total (Uncorrected)	14	391.3905	27.9565			

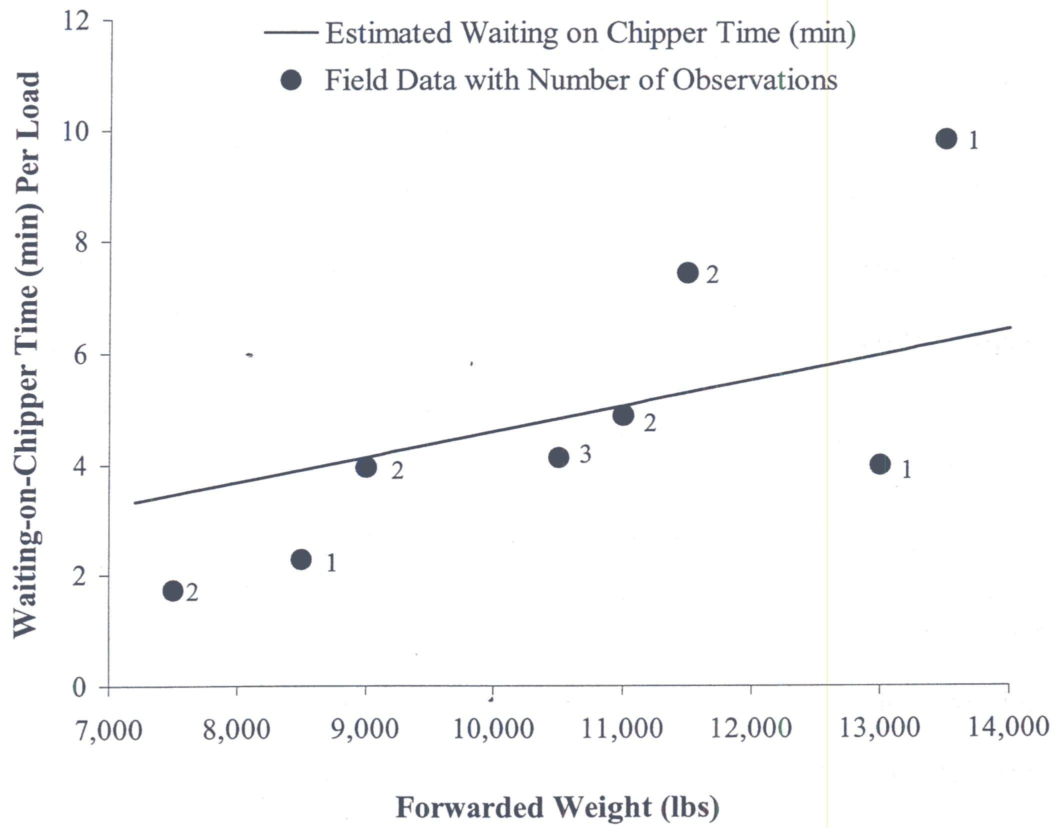

Figure 19. Forwarder waiting-on-chipper time during CTL / small chipper study.

In Figure 19, points on the graph are for average waiting-on-chipper times at each 500-pound weight class. Number of observations is shown next to each data point. There were 14 observations averaging 10,346 pounds of forwarded material and 4.6 minutes for waiting-on-chipper time per load. The regression model showed that as forwarded weight increased, waiting-on-chipper time increased. This can be explained by the assumption that as forwarded weight increases more material is present to feed into the chipper. As non-merchantable material increases, the number of grapple bites, swing to chipper cycles, and placement of material on the chipper bed cycles increases. This gives more opportunity for chipper design limits to slow down the flow of material being placed into the chipper. Also, possibly as load weight increases, the load consists of more full trees (stems less than 4 inches DBH with limbs still attached). Chipping full trees takes more time than chipping limbs and tops; therefore, slowing the chipper and increasing forwarder waiting time.

Cleanup-Around Chipper Time

Cleanup-around chipper time per load was defined as the time it took the forwarder to remove excess leaves, needles, and small limbs or sticks from the chipper's in-feed conveyer. This material was not suitable for chipping, accumulated during the chipper feeding process, and was removed after feeding was complete for each load.

Each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating cleanup-around chipper time per load. This process yielded no statistically significant variables to estimate cleanup time;

therefore, no regression model was formulated. The mean cleanup time over 15 observations was 0.5 minutes per forwarder load.

Chipper Productivity

Productivity of the Bandit chipper was estimated statistically using multiple linear regressions. Descriptive statistics (Table 10) were calculated for each variable associated with chipper productivity. During chipper studies, 14 forwarder loads of non-merchantable material were observed. Dependent variables were defined in units of minutes per forwarder load. Chipper time elements are shown in Figure 20 as percent of total time per forwarder turn.

TABLE 10. -- Chipper analysis descriptive statistics.

	Count	Mean	Std Dev	Min	Max
Dependent Variables (min/load)					
Chipping time	14	12.5	2.6	7.2	17.9
Waiting-on-forwarder time	14	1.2	0.8	0	2.4
Jam-clearing time	14	1.5	1.7	0	5.0
Total cycle time	14	15.3	3.9	7.9	24.7
Independent Variables					
Weight (pounds) per turn	14	10,346	1,812	7,600	13,260
Operator time experience[1] (hrs)	10	1.1	0.8	0	2.3
Operator time experience[2] (hrs)	4	0.3	0.3	0	0.8
Waiting-on-forwarder observations	14	5.0	3.1	0	11
Jam-clearing observations	14	3.2	2.5	0	8

[1]Operator 1 (more experienced)

[2]Operator 2 (less experienced)

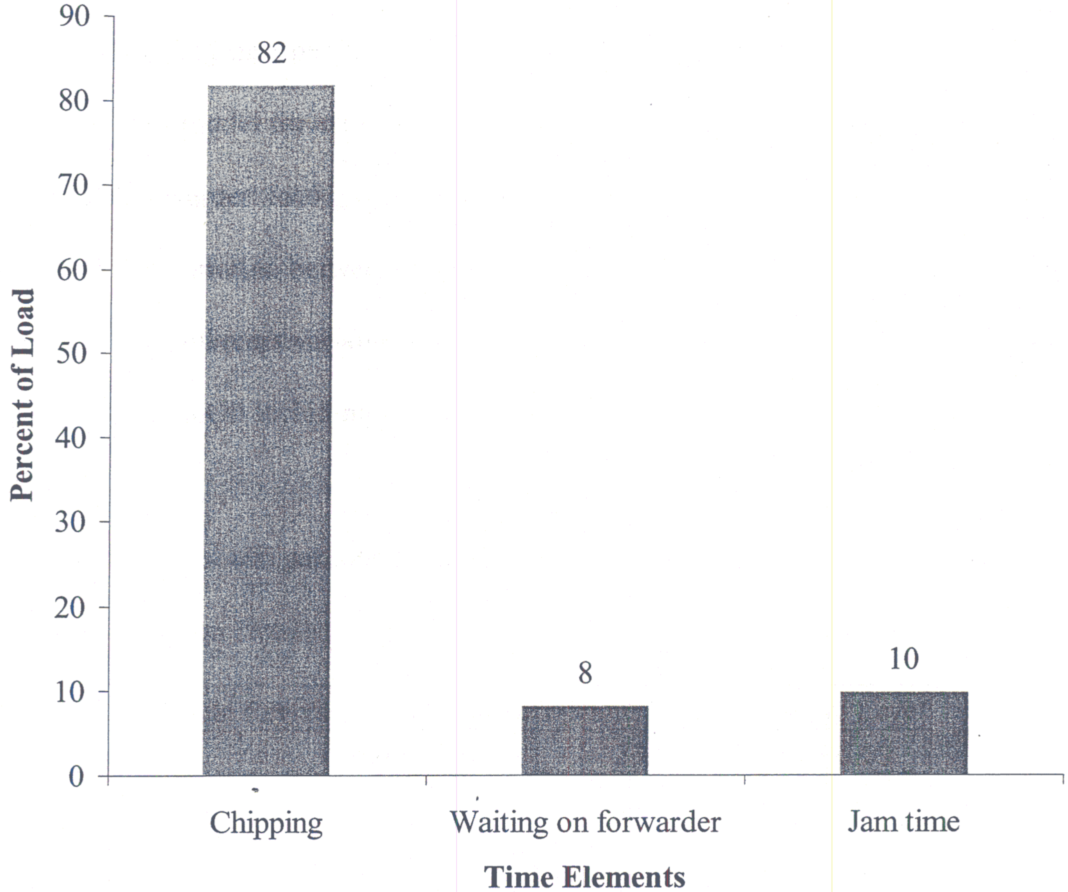

Figure 20. Chipper percentage of time elements for CTL / small chipper study.

Chipping Time

Chipping time per load was defined as the time it took the chipper to actually chip non-merchantable material fed by the forwarder. Chipping time was recorded from the time the first piece of non-merchantable material entered the chipper until no material was being chipped. Chipping activity was halted by waiting on the forwarder for material and material being jammed in the chipper. Each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating chipping time per load.

The best model for estimating chipping time included the independent variable of weight per forwarder load (WT) brought to the chipper in pounds. Operator time experience and variation between operators was non-significant after including weight in the model. The intercept variable was also non-significant; therefore, it was not included. R^2 for the same model including intercept was 0.71.

Best model:

Chipping time (minutes) per load = 0.001*WT

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
WT	0.001	33.925	0.000

Analysis of Variance:

Source	DF	SS	MS	F Ratio	Prob Level	$S_{y.x}$
Intercept	0	0.0000	0.0000			
Model (Uncorrected)	1	2,253.8090	2,253.8090	1,150.901	0.000	1.399
Error	13	25.4579	1.9583			
Total (Uncorrected)	14	2,279.2670	162.8048			

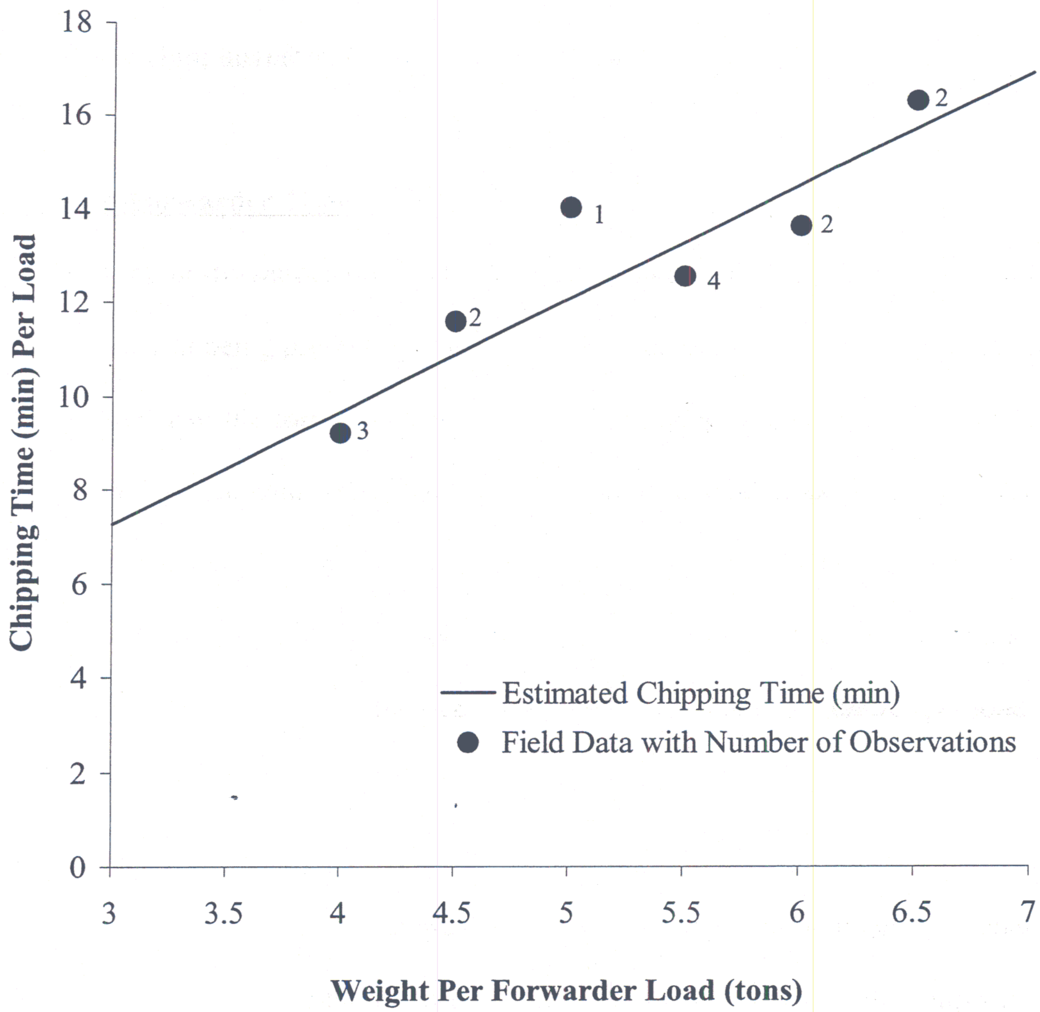

Figure 21. Chipping time during CTL / small chipper study.

In Figure 21, points on the graph are for average chipping times at each 0.5-ton weight class. Number of observations is shown next to each data point. There were 14 observations averaging 5.17 tons (10,346 pounds) of chipped material and 12.5 minutes for chipping time per load. The regression model showed that as chipped weight increased chipping time per load increased. The more material that enters the chipper the more it has to chip; therefore, chipping time increases.

Waiting-on-Forwarder Time

Waiting-on-forwarder time per load was defined as the time the chipper was idle due to no material being present to chip. This time occurred when the chipper processed material faster than the forwarder could feed. Each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating waiting-on-forwarder time per load. This process yielded no statistically significant variables to estimate waiting-on-forwarder time; therefore, no regression model was formulated. The mean waiting time over 14 observations was 1.25 minutes per load.

Jam-Clearing Time

Jam-clearing time per load was defined as the time the chipper was unable to process due to non-merchantable material being jammed or hung in the chipper. This time was recorded while the chipper was reversed forcing out the jammed material. At times, adjusting was necessary because the forwarder operator attempted to feed material faster than the chipper was able to process it. It is likely that jam time is correlated with the type of material being fed into the chipper, but for this study, only weight of non-merchantable material was measured. No variables such as length or diameter of actual stems chipped were recorded. Also, machine design could have affected jam-clearing time. During statistical analysis, each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating jam-clearing time per load. This process yielded no statistically significant variables to estimate clearing time; therefore, no regression model was formulated. The mean clearing time over 14 observations was 1.5 minutes per load.

Total Cycle Time

Total turn time per load was defined as the sum of the chipper's time elements that included chipping time, waiting-on-forwarder time, and jam-clearing time. Each independent variable was analyzed separately and in combinations to determine their statistical importance in estimating total cycle time per load.

The best model for estimating total cycle time included the independent variable of weight (pounds) per forwarder load chipped (WT). Operator time experience and variation between operators were non-significant after including WT in the model. The intercept variable was also non-significant; therefore, it was removed. R^2 for the same model including intercept was 0.63.

Best model:

Total cycle time (minutes) per load = 0.0015*WT

Regression Equation Details:

Independent Variable	Regression Coefficient	T-Value (Ho: B=0)	Prob Level
WT	0.0015	24.186	0.000

Analysis of Variance:

Source	DF	SS	MS	F Ratio	Prob Level	$S_{y.x}$
Intercept	0	0.0000	0.0000			
Model (Uncorrected)	1	3,386.6730	3,386.6730	584.997	0.000	2.406
Error	13	75.2598	5.7892			
Total (Uncorrected)	14	3,461.9330	247.2809			

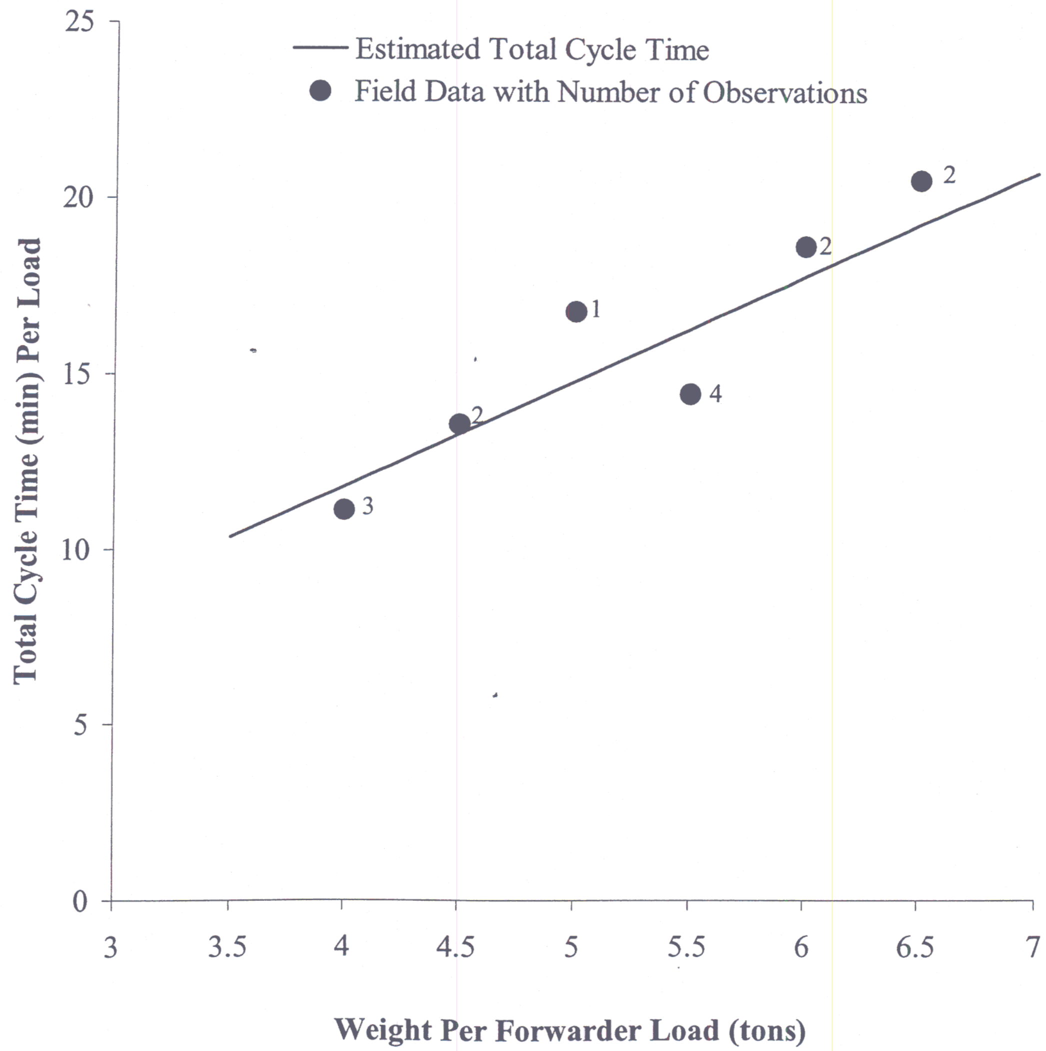

Figure 22. Chipper total cycle time during CTL / small chipper study.

In Figure 22, points on the graph are for average total cycle times at each 0.5-ton weight class. There were 14 observations averaging 5.17 tons (10,346 pounds) of chipped material and 15.27 minutes for total time per load. The regression model showed that as chipped weight increased total time per load increased. The more material that entered the chipper the more it had to chip; therefore, total cycle time increased.

System Costs

Costs for the CTL / small chipper operation were analyzed in two parts. Auburn Harvesting Analyzer (AHA) (Tufts et al 1985) spreadsheet models were formulated for estimating the cost and productivity of

1. harvesting only the non-merchantable portion of the stand, and
2. harvesting only the merchantable portion of the stand.

This approach was taken in order to understand the effects of harvesting non-merchantable material on an operation that was also removing merchantable material and follows the same assumptions used by Bolding and Lanford (2001). Harvesting only the non-merchantable portion consisted of 55.14 percent of the total yearly scheduled hours if stands similar to that of the study site were harvested for an entire year; therefore fixed costs of the total system were proportioned by that same percentage. The same procedure was used for harvesting only the merchantable portion, which made up 44.86 percent of the total yearly scheduled hours.

Non-merchantable Portion

Felling and processing costs for the non-merchantable portion were estimated with the AHA by inputting only the non-merchantable DBH classes for the harvester along with non-merchantable portions (limbs and tops) of merchantable trees. The regression equation, calculated in the productivity section, for the total productive time of harvesting non-merchantable trees (total productive time/tree = 0.11 - 0.08*DBH + 3.82*DBH*TPASQIN) was used to estimate minutes per tree for the harvester. For the variable of TPASQIN (trees per acre$^{-0.5}$) 1,232 trees per acre was used. This value represents the total trees per acre for the entire stand, not just the non-merchantable portion. This procedure allowed the AHA to project costs for actually harvesting only the non-merchantable portion but within the context of a stand consisting of 1,232 total trees per acre. When applying this treatment, the harvester can produce at a rate of 1.79 hours per acre. The harvester's average production was 10.00 tons per productive machine hour (including limbs and tops from merchantable trees). Harvester availability was set at 85 percent; therefore production per scheduled machine hour was 8.50 tons. After combining all machines in the system, cost per ton for the harvesting function was $8.52.

Productive machine minutes per turn for the forwarder were 45.28 and consisted of total travel time, loading time, feeding time, waiting-on-chipper, and cleanup-around the chipper. Regression equations calculated in the forwarder productivity section were used to estimate the time elements. The forwarder's average production capability was found to be 6.85 tons per productive machine hour. Availability was set at 85 percent and production per scheduled machine hour was 5.82 tons. After combining all machines in the system, cost per ton for the forwarding function was $10.07.

For the chipper, productive machine time per cycle was estimated using the regression model for total cycle time constructed in this study (total productive minutes/cycle = 0.0015*WT) and was 15.33 minutes. WT represents the average pounds chipped per cycle. Pounds per cycle were converted into tons and divided by hours per cycle and gave an average production of 20.24 tons per productive machine hour.

Availability was set at 70 percent resulting in a production of 14.17 tons per scheduled hour. After combining all machines in the system, cost per ton for the chipping function was $1.73.

Haul distance used for the non-merchantable portion was 94 miles (actual distance from the study site to the mill). Maximum load size was 22 tons of chips per vanload. Loading time per chip van averaged 192.7 minutes. This time includes the entire time a van was sitting on the deck being loaded and waiting to be loaded. Since only one forwarder was used for feeding the chipper, van-loading time was directly related to forwarder productivity. Loading time was calculated by dividing the average vanload size by the tons per productive machine hour of the forwarder. For the hauling function, tons per productive machine hour were 2.79, and cost per ton of chips was $11.36.

A harvesting operation is only as productive as its least productive function. For harvesting the non-merchantable portion only, the forwarder was found to be the least productive machine (5.82 tons per scheduled machine hour). This is directly related to the small payload size of material forwarded per load and the length of distance forwarded. Utilization for the functions was: harvester 58 percent, forwarder 85 percent, and chipper 29 percent.

All AHA inputs and results for the non-merchantable portion are shown in Table 11. On-board truck cost for harvesting only the non-merchantable portion was $25.70 per ton of chips produced, which equates to $460.96 per acre. With the addition of hauling ($11.36), the cut and haul costs were $37.06 per ton or $664.78 per acre.

TABLE 11. -- Auburn Harvesting Analyzer non-merchantable portion cost projections.

SYSTEM: **Small Chipper w/ CTL -- Non-merchantable portion** **Fayette Study**

STAND & STOCK TABLE

DBH	P TPA	HW TPA	P HT	HW HT	Total Tons	Merch Tons	Non-merch Tons
1	0.00	251.21	0.00	10.00	0.40	0.00	0.40
2	0.00	233.26	0.00	20.00	2.52	0.00	2.52
3	0.00	182.00	0.00	30.00	6.03	0.00	6.03
4	7.69	64.08	36.67	36.80	4.74	3.79	0.95
5	5.13	35.89	45.00	44.29	4.84	3.90	0.93
6	12.82	20.51	50.00	48.75	5.74	4.72	1.01
7	20.51	15.38	53.75	58.33	9.04	7.54	1.51
8	15.38	10.53	55.00	50.00	8.04	6.71	1.33
9	7.69	5.13	63.33	55.00	5.12	4.71	0.41
10	2.56	0.00	70.00	0.00	1.55	0.56	1.23
11	7.69	0.00	66.67	0.00	5.42	4.61	0.81
12	2.56	0.00	80.00	0.00	2.57	2.19	0.38
13	2.56	0.00	70.00	0.00	2.69	2.27	0.42
TOTAL	84.59	817.98			58.69	41.01	17.94
	902.57						

GENERAL INFORMATION

SMH per Day =	9		Tract Size=	20	Acres
Days per Week =	5		Move Time =	4	Hours
Weeks per Year =	50		Move Rate $/mile =	2.75	
SMH per Year =	2250		Move Distance=	110	Miles
			Distance home=	5	Miles

Support:				Roads to be built:		
Pkups	1	0.45	$/mi.	Type	Miles/#	$/mi/ea
Foreman:		2500	$/mo.	Permanent	0	10000
Overhead:		2000	$/mo.	Temporary	0	3000
Saws	0	700	$/ea.	Push-out	0	1500
				Entrances	0	1000

Tons/tree =	0.07		
Quad. Mean DBH	3.74	Mill Quota (Tons/WK) =	999

FELLING & PROCESSING | **FORWARDING** | **CHIPPING** | **HAULING**

Machine Productivity

FELLING & PROCESSING

DBH	Min/T	Hr/Ac
1	0.1383	0.5789
2	0.1642	0.6384
3	0.1902	0.5769
TOTAL		1.7942
Tons/PMH=		10.00
Oper Effy=		1

FORWARDING

No. Landings =	1
Tons/Cycle=	5.17
Cycles/Ac.=	3.47
Tons/stop =	0.38
Dist btwn stops (feet) =	30.45
Stops per cycle =	13.94
TE Dist (feet) =	1654.06
TWL Dist (feet) =	539.75
TL Dist (feet) =	1574.06
Tot Forward Dist.=	3767.87
TE time (min) =	4.63
TWL time (min) =	4.70
TL time (min) =	4.41
Tot Travel time (min) =	13.73
Loading time (min) =	15.52
Feeding time (min) =	10.34
Waiting-on-chipper (min) =	5.17
Cleanup-around chipper (min)	0.51
PMM/Cycle=	45.28
	6.85
	1

CHIPPING

Tons/Cycle =	5.17
Chipping (min) =	12.50
Waiting-on-forwarder (min) =	1.25
Jam-clearing (min) =	1.50
Tot cycle time (min) =	15.33
PMM/Cycle =	15.33
	20.24
	1

HAULING

Haul Distance (miles) =	94
Average Speed (mph) =	45
Load Size (tons) =	22
Unload Time (min.) =	30
Load Time (min.) =	192.66
Round Trip Time (hours)	7.89
	2.79
	1

Machine Cost

	Felling & Processing	Forwarding	Chipping	Hauling
% of Fixed Costs =	**55.14**			Interest Rate= 0.09
Initial Cost($)=	193,016	168,000	69,500	
Pay. Life(Yrs)=	5	4	5	
Mon. Payment($)=	4,006.69	4,180.69	1,442.71	Haul Rate (%/mile) = 2.66
I&T(%Initial)=	0.035	0.02	0.04	
F&L($/PMH)=	10.44	7.65	11.31	
M&R($/PMH)=	18.23	22.97	6.59	
Labor($/SMH)=	15.00	15.00	0	
Labor OH (%)=	30	30	0	
Avail (%) =	85	85	70	90
% of Work day	100%	100%	100%	
Number =	1	1	1	2.32

Harvesting Function	Tons /PMH	Avail (%)	Tons/SMH One	Tons/SMH All	UT (%)	Cost per SMH Fixed	Cost per SMH Oper	Cost per SMH Labor	Cost per SMH Total	Cost $/Ton
Fell&Processing	10.00	85	8.50	8.50	58	13.44	16.70	19.5	49.64	8.52
Forwarding	6.85	85	5.82	5.82	85	13.12	26.03	19.5	58.65	10.07
Chipping	20.24	70	14.17	14.17	29	4.92	5.15	0	10.08	1.73
Hauling	2.79	90	2.51		90					11.36
Support	Pickups, Chainsaws, Foreman, and Overhead						47.88		118.36	4.38
Road Work										0
Moving	4 hours spent moving men & equipment to tract									1.00

			On-board truck: * per Ton =	25.70
System Rate tons/SMH) =	**5.82**	2.38 loads per day		
Weekly production (tons) =	262.06		**Cut & Haul: *** per Ton =	37.06
Days required to cut tract =	23.40			

* Profit not included.

On-board Cost/Acre Non-Merch ($) 460.96

Cut & Haul Cost/Acre Non-Merch ($) 664.78

Merchantable Portion

Felling and processing costs for the merchantable portion were estimated with the AHA by inputting only the merchantable DBH classes for the harvester. The regression equation, calculated in the productivity section, for the total productive time of harvesting merchantable trees (total productive time/tree = 0.05*DBH) was used to estimate minutes per tree for the harvester. This procedure allowed the AHA to project costs for harvesting only the merchantable portion. For performing the treatment used in this study on a 20-acre stand like that of the study site, the harvester can perform at a rate of 1.29 hours per acre. The harvester's average production was 31.69 tons per productive machine hour. Harvester availability was set at 85 percent; therefore production per scheduled machine hour was 26.94 tons. After combining all machines in the system, cost per ton for the harvesting function was $2.76.

Productive machine minutes per turn for the forwarder were 46.74 and consisted of total travel time, loading time and unloading time. Since forwarding merchantable trees was not studied, regression equations from Lanford et al (In review) were used to estimate the time elements. The forwarder's average production capability was found to be 19.25 tons per productive machine hour. Availability was set at 85 percent and production per scheduled machine hour was 16.37 tons. After combining all machines in the system, cost per ton for the forwarding function was $3.47.

Haul distance used for the merchantable portion was 70 miles (average distance from the study site to the mills). Load size averaged 26.75 tons of round wood per truck-load. For the hauling function, tons per productive machine hour were 7.24. Cost per ton of round wood was $6.65.

For harvesting the merchantable portion only, the forwarder was found to be the least productive machine (16.37 tons per scheduled machine hour). Utilization for the functions was: harvester 52 percent, and forwarder 85 percent. All AHA inputs and results for the merchantable portion are shown in Table 12. On-board truck cost for harvesting only the merchantable portion was $8.52 per ton, which equates to $349.45 per acre. With the addition of hauling ($6.65), the cut and haul costs were $15.17 per ton or $622.16 per acre.

Cost versus Revenue

Seven vanloads of chips were produced from the non-merchantable portion of the stand. The maximum load size was 22 tons. Each load was sold for energywood at a rate of $14.50 per ton. Cut and haul costs for harvesting only the non-merchantable portion generated by the AHA were $37.06 per ton. Subtracting these costs from the revenue received yields a $22.56 per ton or $404.73 per acre loss.

Based on Guimier's (1989) conversion to crude oil, a metric green tonne of chipped slash roughly has an energy content equivalent of one barrel of crude oil. (One imperial ton is equal to 1.0160 metric tonnes.) At current oil prices of $24.89 per barrel for crude (Nymex, June 2002), energywood is worth $25.29 per ton. Subtracting the estimated costs ($37.06 per ton) from $25.59 per ton equates in an $11.47 per ton loss or $205.77 per acre.

TABLE 12. -- Auburn Harvesting Analyzer merchantable portion cost projections.

SYSTEM: **Small Chipper w/ CTL -- Merchantable portion** **Fayette Study**

STAND & STOCK TABLE

DBH	P TPA	HW TPA	P HT	HW HT	Total Tons	Merch Tons	Non-merch Tons
1	0.00	251.21	0.00	10.00	0.40	0.00	0.40
2	0.00	233.26	0.00	20.00	2.52	0.00	2.52
3	0.00	182.00	0.00	30.00	6.03	0.00	6.03
4	7.69	64.08	36.67	36.80	4.74	3.79	0.95
5	5.13	35.89	45.00	44.29	4.84	3.90	0.93
6	12.82	20.51	50.00	48.75	5.74	4.72	1.01
7	20.51	15.38	53.75	58.33	9.04	7.54	1.51
8	15.38	10.53	55.00	50.00	8.04	6.71	1.33
9	7.69	5.13	63.33	55.00	5.12	4.71	0.41
10	2.56	0.00	70.00	0.00	1.55	0.56	1.23
11	7.69	0.00	66.67	0.00	5.42	4.61	0.81
12	2.56	0.00	80.00	0.00	2.57	2.19	0.38
13	2.56	0.00	70.00	0.00	2.69	2.27	0.42
TOTAL	84.59	817.98			58.69	41.01	17.94
	902.57						

GENERAL INFORMATION

SMH per Day =	9		Tract Size=	20	Acres
Days per Week =	5		Move Time =	4	Hours
Weeks per Year =	50		Move Rate $/mile =	2.75	
SMH per Year =	2250		Move Distance=	110	Miles
			Distance home=	5	Miles

Support:				Roads to be built:		
				Type	Miles/#	$/mi/ea
Pkups	1	0.45	$/mi.	Permanent	0	10000
Foreman:		2500	$/mo.	Temporary	0	3000
Overhead:		2000	$/mo.	Push-out	0	1500
Saws	0	700	$/ea.	Entrances	0	1000

Tons/tree =	0.07	Mill Quota (Tons/WK) =	999
Quad. Mean DBH=	3.74		

FELLING & PROCESSING

DBH	Min/T	Hr/Ac
1		
2		
3		
4	0.22	0.26
5	0.27	0.18
6	0.32	0.18
7	0.38	0.23
8	0.43	0.19
9	0.49	0.10
10	0.54	0.02
11	0.59	0.08
12	0.65	0.03
13	0.70	0.03
TOTAL		1.29
Tons/PMH=		31.69
Oper Effy=		1

FORWARDING

Machine Productivity

No. Landings =	1
Pounds/cord =	5350
Forward Dist.=	1614.06
Load(tons) =	15
Cords/acre =	15.33
Cords/cycle =	5.61
Cycles/Ac.=	2.73
Cords/stop =	0.35
Woods Dist.(feet) =	31.43
Travel E&L (min) =	11.22
Woods Trav (min) =	3.62
Load&unld (min) =	31.91
PMM/Cycle=	46.74
Tons/PMH	19.25
Oper Effy	1

HAULING

Haul Distance (miles) =	70
Average Speed (mph) =	45
Load Size (tons) =	26.75
Unload Time (min.) =	30
Load Time (min.) =	5.00
Round Trip Time (hours)	3.69
Tons/PMH	7.24
Oper Effy	1

Machine Cost

	Felling & Processing	Forwarding		Hauling
% of Fixed Costs =	**44.86**		Interest Rate=	0.09
Initial Cost($)=	193,016	168,000		
Pay. Life(Yrs)=	5	4		
Mon. Payment($)=	4,006.69	4,180.69	Haul Rate ($/mile) =	2.54
I&T(%Initial)=	0.035	0.04		
F&L($/PMH)=	10.44	7.65		
M&R($/PMH)=	18.23	22.97		
Labor($/SMH)=	15.00	15.00		
Labor OH (%)=	30	30		
Avail (%) =	85	85		90
% of Work day	100%	100%		
Number =	1	1		2.51

Harvesting Function	Tons /PMH	Avail (%)	Tons/SMH One	Tons/SMH All	UT (%)	Cost per SMH Fixed	Cost per SMH Oper	Cost per SMH Labor	Cost per SMH Total	Cost $/Ton
Fell&Processing	31.69	85	26.94	26.94	52	10.93	14.81	19.50	45.24	2.76
Forwarding	19.25	85	16.37	16.37	85	11.34	26.03	19.50	56.87	3.47
Hauling	7.24	90	6.52		90					6.65
Support	Pickups, Chainsaws, Foreman, and Overhead						40.83		102.11	1.56
Road Work										0
Moving	4 hours spent moving men & equipment to tract									0.72

			On-board truck: *	**per Ton =**	8.52
System Rate tons/SMH) =	**16.37**	5.51 loads per day			
Weekly production (tons) =	736.46		**Cut & Haul: ***	**per Ton =**	15.17
Days required to cut tract =	8.97				

* Profit not included.

On-board Cost/Acre Merch ($) 349.45

Cut & Haul Cost/Acre Merch ($) 622.16

Energywood Production Costs

To achieve objective 2, the AHA spreadsheet constructed for harvesting only the non-merchantable portion of the stand (Table 11) was used to estimate production costs for harvesting different non-merchantable volumes per acre. The model was run with inputs of 5 through 35 non-merchantable tons per acre to better understand how cost per ton was affected when volume per acre changed. The merchantable portion of the stand was held constant and non-merchantable trees per acre were varied. Non-merchantable tons were generated from non-merchantable trees only (DBH less than 4 inches). Limbs and tops from merchantable trees were not increased.

Thirty spreadsheet models were run to give a smooth prediction line. Assumptions were the same as those used in Table 11 except for a weighting factor applied to the fixed costs of machines used to harvest non-merchantable trees per acre. The weighting factor was calculated by dividing the new non-merchantable tons used to estimate costs by the non-merchantable tons per acre from DBH classes 1 through 3 harvested during this study (limbs and tops from merchantable trees were not included). For example, to estimate costs for a 20-acre stand with merchantable characteristics like that used in this study and 15 non-merchantable tons per acre, the weighting factor was 15 divided by 8.95 (cut non-merchantable tons per acre during the study that came from non-merchantable trees only) or 1.68. This factor allowed harvester productivity to reflect an addition in total trees per acre relative to that of non-merchantable tons per acre. This procedure was also used to adjust forwarder tons per stop, stops per cycle, and travel-while-loading distance.

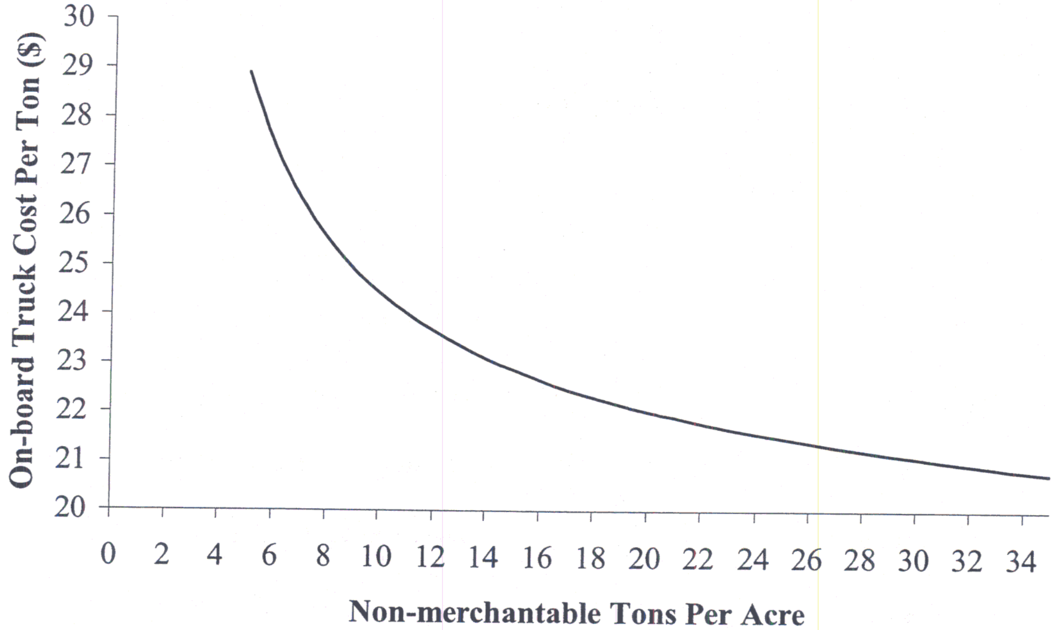

Figure 23. Energywood production costs for various non-merchantable volumes per acre.

Figure 23 shows energywood production costs per ton on-board truck to decrease as non-merchantable tons per acre increase. Also, as non-merchantable tons per acre increased, on-board cost per acre increased. Non-merchantable tons per acre as shown in Figure 23 includes entire trees in the 1 through 3-inch DBH classes but does not include limbs and tops from merchantable trees which was a constant 8.98 tons per acre. Cost per ton does include those limbs and tops of merchantable trees. Number of trees per acre and corresponding tons per acre for the non-merchantable trees were increased for estimation as described earlier (merchantable trees and their limbs and tops were held constant). It should be realized that costs generated by the AHA are only applicable for a stand with merchantable characteristics similar to the one used in this study.

SUMMARY AND CONCLUSION

This study was performed to obtain baseline data and information for productivity and costs associated with mechanically harvesting small diameter trees for the purpose of forest fuel reduction. In addition, with this operation comes an opportunity to benefit from the recovery of previously non-merchantable biomass.

The CTL / small chipper system was considered an environmentally low impact method of harvesting and utilizing small diameter trees. Based on an earlier feasibility study (Bolding and Lanford 2001), the combination of CTL with a small portable chipper seemed to be an efficient method for performing the fuel reduction treatment. The study site used for data collection was chosen because of its high proportion of non-merchantable trees and therefore, fire hazard potential.

Harvester productivity was most affected by DBH and trees per acre. DBH was significant for estimating total productive time for merchantable-sized trees, and both DBH and trees per acre were used for estimating total time to harvest non-merchantable-sized trees. As expected, the harvester and forwarder were more productive when harvesting merchantable trees. At times the harvester was unable to fell small diameter trees (1 to 3 inches DBH) due to the amount of brush surrounding the machine and head. Stand statistics in Table 8, showed that 206.67 non-merchantable trees per acre were left after harvesting. This amount reflects that many of the very small non-merchantable stems could not be effectively handled and processed by the harvester, and therefore were knocked down and/or run over by the machines. In reality, few non-merchantable stems remained standing after the harvest. Figures 24 through 26 show the stand before, during, and after harvesting.

Figure 24. Stand condition before harvesting.

Figure 25. Stand condition during harvesting.

Figure 26. Stand condition after harvesting.

To recover small trees, not effectively processed by the harvester, a possible alternative would be to use a saw-head feller-buncher for felling since the trees require no processing. If forwarders were used for transportation and merchantable trees were to be harvested, a harvester would also be required.

For the most part, forwarder productivity was most affected by travel distance and weight of material forwarded. The chipper feeding process was slowed by waiting and cleanup times. There seems to be room for improvement in this process. A possible alternative would be to use a drop feed chipper. This would allow the forwarder to feed at its own rate with less machine interaction. However, when chipper size and features increase, purchase price also increases. Future studies are needed to investigate the benefits versus costs of a more expensive, but easier to feed chipper. Also, for this study only 14 forwarder loads were observed. More observations might have shown feeding times to decrease due to added experience by the forwarder operator. A time experience variable was analyzed, but found non-significant for estimating any times associated with the forwarder. More observations might have detected significant differences.

Forwarder productivity for the non-merchantable portion was 6.85 tons per productive machine hour. This productivity was lower than that of the other machines causing forwarding to be the least productive function. An operation is only as productive as the least productive function; therefore, a possible solution would be to add another forwarder to the operation. This alternative would again increase capital expenditures as mentioned earlier. Also, another forwarder operator could work an extra shift to aid in balancing the system. Another approach might investigate forwarding non-merchantable material in a cylindrical bale form. This methodology has been studied in the Scandinavian countries and can possibly increase forwarder payloads (Andersson et al 2000). Packing material in bale form allows forwarders to haul neat packages; this in turn could increase forwarder productivity.

Chipper productivity was the highest of all machines in the system. The chipper performed at 20.24 tons per productive machine hour with an average total cycle time of 15.33 minutes. As for the forwarder, chipper productivity was also affected by waiting times. Waiting-on-forwarder time could be reduced or possibly eliminated as forwarder operator experience increases. Jam-clearing time is directly related to the chipper's design limits. The chipper could not effectively handle as much material as the forwarder was capable of feeding. This in turn, harmed chipper and forwarder productivity. Again, these issues could be addressed with a different type chipper. Also, for this study, a representative of the chipper company remained on the site and started the chipper's engine each time the forwarder returned the deck. In an operational setting this would most likely not be possible; therefore, a remote control feature that would allow the forwarder operator to start the chipper's engine prior to arrival would be of great benefit. Without a remote the forwarder operator would have to get off the machine and start the chipper causing a delay.

Hauling costs of chips produced from the non-merchantable portion were $11.36 per ton (the highest of all functions). Chip vans are more expensive than log trailers and therefore hauling costs for chips are higher. During the study, a maximum load size of 22 tons was observed. Load size is a very important factor in this operation and must be maximized due to the current low price of energywood and high hauling cost. Load size increased as the study progressed due to better chip van and chipper out-feed spout positioning. Haul distance was 94 miles, which also contributed to higher costs.

Based on results from the study, there appears to be an opportunity to reduce fire hazards and create income (not profit) from energywood using a CTL / small chipper system. There are a number of questions to be addressed with future studies such as 1) using a drop feed chipper to increase forwarder productivity and decrease feeding time, 2) system balancing aspects by adding another forwarder or operator, 3) forwarding material in bale form, 4) exploration of different stand and species types, and 5) system costs versus fire suppression costs.

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