ABSTRACT

HANNUM, LINDSAY CLOUD. Developing Machinery to Harvest Small Diameter Woody Biomass *Transforming a Fire Hazard into an Energy Crisis Solution.* (Under the direction of Joseph Roise and Glenn Catts.)

Energy demands continue to increase despite depleting fossil fuels and growing awareness of global climate changes. Biomass energy will play a vital role as the demand increases for renewable energy. North Carolina State University, the U S Forest Service, FECON, and Craven Wood Energy have partnered to develop the “Kraken” FECON’s Bio- Harvester; a mulcher which cuts, chips, and collects Small Diameter Woody Biomass. This machine removes hazardous biomass fuel loads from the forest and supplies a new source of material to produce carbon neutral wood energy. Unlike agricultural biomass harvesting, the Kraken must harvest natural vegetation diverse in size and composition. Available biomass at each site must be quantified as it varies greatly with species, densities, and age. As we work to develop this piece of equipment efficiently collecting and transporting biomass in the field is our greatest challenge. The testing of the machine did not yield an economically viable system, however it does not subtract from the potential for the equipment especially when fire reduction and habitat restoration are factored into the products. With research and development these machine systems will be improved enabling small diameter woody biomass to become a competitive energy resource.

BIOGRAPHY

Lindsay Cloud Hannum was born on February 15, 1985. Raised in North East, Maryland she grew up traveling throughout the United States with her family, dancing, and playing outdoors at Fair Hill Nature Center.

In 2007 Lindsay graduated from Lafayette College, with a Bachelor of Science in Mechanical Engineering. She spent her time at Lafayette enjoying the Arts Society on Parsons Street, performing at football and basketball games with the dance team and founding Lafayette's first student run dance company Synchromotion.

Realizing that a typical engineering position was not going to satisfy Lindsay's love of the outdoors, she pursued a Masters of Forestry from North Carolina State University. She spent her time at NCSU traveling to the Croatan and Hofmann forests in eastern North Carolina doing field work, as well as interning in Cincinnati, Ohio with FECON Inc. and backpacking in Yosemite National Park with the Forestry Club.

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INTRODUCTION

Literature Review

Population growth and development is increasing our dependency on energy. The world population is expected to double every 20-30 years simultaneously with the development of countries and a reduction in finite fossil fuel and coal supplies (Twidell, 2006). There are five main energy sources available on Earth the sun, motion/gravitational potential, geothermal energy, human induced nuclear reactions, and chemical reactions from mineral sources (Twidell,2006). These energy sources fall into two categories; renewable termed “green energy” and non-renewable termed “brown energy”. Non-renewable, brown energy is currently the cheapest energy available and thus the most dominant form. The use of fossil fuels over time will result in climate changes due to the release of greenhouse gasses. Currently only 14% of the world’s primary energy use is considered bio or green energy (Morris, 2006). There are three main types of renewable, or green energy supply systems; mechanical including hydro, wind, wave, and tidal forces; heat supplies including biomass combustion, geothermal and solar collectors, and photon processes including photosynthesis and photochemistry (Twidell, 2006). Biomass accounts for 80% of renewable energy sources in primary use around the world (Morris, 2006). Biomass has the advantage over wind and solar power that the supply can be more highly controlled, available day and night (Morris, 2006). Biomass has the potential to meet growing energy needs and demands while simultaneously lowering greenhouse gas emissions, increasing soil and water quality, and increasing biodiversity if managed properly and made economically profitable. In order to successfully integrate the use of biomass as an energy source it must be collected and processed in an efficient and profitable manner. This process requires a great deal of attention to identify the available resource and its use, determine the environmental impact, and make production cost-effective.

It is important to define biomass to effectively discuss its potentials. Biomass is any organic material, of plant and animal origin used as feedstock for producing bioenergy and biomaterials. Biomass encompasses a diverse resource of material and for this reason is hard to classify and track. In its most basic bioenergy form, biomass is used for cooking and domestic heating. In the form of open-fire cooking, only 5% of thermal efficiency is achieved (Twidell, 2006). Poor harvesting practices in undeveloped countries often result in deforestation and environmental degradation; this has been observed in Tropical Africa (Brenes, 2006). However biomass includes materials derived from agricultural or forestry production, their by-products, and industrial and urban wastes (OECD, 2004). Biomass can be grouped into two main source categories: energy crops and by-product utilizations, examples of each can be found in Table 1. Biomass plantations are one possible source of biomass energy. Large scale feasibility of energy crops is under research, the mass production of a single crop is not practical in most areas because it would compete with living space and food crop land (Morris, 2006). Single mass crop production would create a monoculture, quickly depleting the quality of the soil and biodiversity. The analysis of energy plantations must take into account the input of energy required to grow and monitor the crop. Biomass sources which take advantage of waste can avoid this input.

Table 1: Biomass Examples

- **Types/ Sources of biomass**
    - **Corn**
    - **Soybean**
    - **Switchgrass-**
    - **Wood**
        - **Waste Wood**- manufacturing scrapes, sawdust
        - **C&D**- with processing produces clean chips
        - **Thinning (PCT and Commercial Thinning)**
        - **Logging Residues**-Slash on deck, tops, branches, bark
        - **Fuel Load Reduction**- under story or undergrowth treatment usually natural vegetation
        - **Diseased or Damaged Trees**- Natural Disaster Recovered, bug infested
        - **Energy Plantations**
            - **Willow**
            - **Poplar**
    - **Rapeseed**
    - **Sugar**
    - **Wheat**
    - **Miscanthus**
    - **Jatropha**
    - **SugarCane**
    - **Sorghum**
    - **Cassava**
    - **Hemp**
    - **Algae**

Biomass is most frequently used in solid form to produce electricity, but the demand for liquid biofuels is increasing the use of non-solid biomass (Silveira, 2005). Technology advances are needed to increase efficiency of biomass use to help conserve and protect domestic energy supplies.

Energy from renewable resources and biomass are global issues and can not be isolated by political boundaries. The effects of greenhouse gas emissions affect the planet as a whole. For this reason efforts to combat these issues must be done jointly world wide, requiring a common language and value system to be effective. The Kyoto Protocol in 1997 created an opportunity for multiple countries to implement mechanisms to achieve their agreed upon necessary objectives (Silveira, 2005). The Clean Development Mechanism (CDM) is currently in operation although it needs full support to be effective. The CDM is an initiative for advanced countries to aide developing countries to develop in an environmentally sound manner, not following in their footsteps becoming fossil fuel dependant. This would help to prevent an increase in fossil fuel consumption world wide, and establish biomass use initially. This would prevent the need for conversion down the road, which industrialized countries are now facing. For example, the CDM has the potential to have a positive economic impact in Bangladesh as their standard of living increases. However, they are not currently part of the program, and fossil fuel dependency will develop if they are not integrated into the host program in a timely manner (Brenes, 2006).

Renewable energy sources have to be locally paired with the surrounding environment for which they are to supply energy. This is a simple question of available resources and a result of the fact that renewable energy is easily produced in dispersed locations but expensive to concentrate (Twidell, 2006). This is the opposite of the current dominant energy supply of fossil fuels which are easily produced centrally but more costly to distribute. This issue presents two major problems; the necessity for site specific plans and a movement away from centralized power plants. Biomass energy encompasses a very diverse market and thus requires a specialized system for each customer (Ferrero, 1988). Biomass energy must take advantage of the available resources of the region. This means using material that is available, even if it does not have the highest energy content (Morris,2006).

Centralized power plants are not efficient for the conversion of biomass. Initial studies have shown that long transportation distances drastically decrease profitability (Ferrero, 1988). While initial creation of smaller biomass facilities will be expensive, long term benefits will include a boost to rural economies providing employment, social cohesion, and energy supply security (OECD,2004). Conversion to a biomass community will take time and technology advancements. During this time Co-firing is a viable option to decrease the use of non-renewable energy. Co-firing involves the integration of biomass fuel into preexisting plants by mixing it, most commonly with coal. It requires minor plant modifications and less approval than new plants, while achieving increased biomass efficiency (Rosillo-Calle, 2007). The potential for biomass energy is available but the means of concentrating and collecting the energy have to be developed. The future holds two main resources for biomass, waste biomass and biomass produced as an energy carrier.

New forest management practices can be a means by which to harvest biomass without having to use a plantation. Lithuania paired with Sweden to study the possible biomass harvest from their existing forests. It was calculated that an annual cut of 6.2 million m^3 could be maintained over the next ten years (Silveira, 2005). In Lithuania biofuels are mainly consumed in the form of firewood, but sawdust briquettes, peat and other primary solid fuels are becoming more prevalent, especially with the export of wood pellets and briquettes. To increase productivity and reduce costs, new technologies and management practices needed to be developed. This study found that chipping costs were the most prevalent operation factors accounting for 38.7% of total costs and transportation costs were the most variable dependent upon extraction distances. Machinery accounted for 60.3% of total input costs, meaning that final fuelwood costs could be reduced with an increase in machinery productivity, longer hours of operation and increased usage (Silveira, 2005). Care was taken as to not deplete the forest resources enabling the process to be sustainable, resulting in an optimal harvest of around 20-30% of the available biomass which was previously non-commercial material. When integrating the use of traditional harvesting with non-commercial biomass the costs for industrial wood extraction were reduced 15%. The work done in this area will help to utilize the available resources.

In France as the transition to wood energy was used to face the energy crisis, new technology had to be developed. Automated heating boilers needed the wood to be chipped, not processed billets as used by previous practices used. J. Morvan explored the many options used to solve this problem (Ferrero, 1988). The simplest option was a fully integrated machine, used for harvest of small softwood poles up to 15cm, which felled, chipped, and hauled chips, by CIMAF, an equipment company. A two machine system was developed for maritime pine thinning, which consisted of a felling machine by ARMEF and a separate BRIMONT machine for chipping. A five machine system consisting of 2 felling machines, one grapple skidder, one clambunk skidder, and a mobile chipper, was found to be advantageous when used on larger acreage. However it was too expensive of an investment for prevalent use in France as their harvests have smaller average cutting areas. To reduce competition between pulp-mills and fuel wood, simultaneous harvesting of pulpwood and chips was proposed. Simultaneous harvesting with sorting of the products when they were cut proved to be advantageous for the pulp-mill. Simultaneous harvesting without sorting of felled products made chip harvesting easier, but produced less pulpwood. Even with these advances in France, biomass energy still could not compete economically with fossil fuels (Ferrero,1988).

The fossil fuel industry has the advantage of experience, infrastructure, and some might argue preferential tax treatment with which biomass energy must compete. Even with rising prices, fossil fuel is still currently cheaper than renewable energy. Comparing the rate at which we are consuming fossil fuels, to the millions of years it takes to regenerate them; eventually the reduction of fossil fuels will become so significant that they will be unable to support humanity’s demands, forcing new energy sources to develop. To prevent reaching this point, the primary way to combat renewable energy costs is to create a sustainable development having both environmental health benefits and increased domestic stability. Benefits of bioenergy use are not always measured in terms of economics as there is currently not a globally established monetary price associated with the reduction in greenhouse gas emission, environmental benefits, or sustainability. With experience, biomass energy will become more efficient and data will be collected to better predict availability of resources. Until this point, bioenergy developers will continue to struggle to make long term commitments to supply energy making competition with fossil fuels difficult (OECD,2004). Advances in biomass and bioenergy will occur on a small scale taking advantage of available resources and wastes, often contributing to the solution of other problems. These may include the risk of forest fires, disposal of wastes, demand for new polymeric materials, and the necessity of fossil fuel producers to advance into a new energy marketplace in order to be competitive in a changing energy industry.

Harvesting Systems

The demand for a small diameter woody biomass harvester is not a new idea. Related harvesting systems have been tested in the past, however only a few are commercially available today in the United States. Nonetheless previous findings with other machines help to define the applications and requirements for new technology.

In the 1970's having exhausted the utilization of wood waste from their plants, Georgia- Pacific recognized the opportunity to utilize forest biomass as an energy source. Georgia-Pacific wanted to simultaneously produce boiler fuel, while performing pre-commercial thinning. This began their work to develop a biomass harvester for material 5 inches diameter breast height (DBH) and smaller (Smith, 1980). Georgia-Pacific contracted N.F.I. Inc to build a proto-type harvester which would cut, gather, and chip the material in the woods. The original design was a cutter head, mounted on a Hydro-Ax 500 with two horizontal rotating hammers which reduced material into chunk form (Smith, 1980). To reduce the horsepower consumption of the original design and increase collection, the machine was modified. The revision included twin cutter wheels each with 8 fixed teeth, which cut and gathered the biomass. A drum chipper with a separate engine was then added to further reduce the material to a more consistent output (Smith and O'Dair, 1980). The final design consisted of a four track hydrostatically powered carrier with two cutter wheels which severe and feed the material onto a ramp toward a series of two in-feed rolls leading to a disk chipper that, blows the chips into an onboard hopper (Smith, 1980). The harvester was able to produce an average 5.2 metric tons per hour, with a max production of 13.7 metric tons (Smith, 1980). While tested with Georgia-Pacific this system was never implemented across operations or commercially produced.

Beginning in 1977, work on the Nicholson-Koch mobile chip harvesting system continued into the early 1980's. The Forest Service, five timber companies, and Nicholson Manufacturing Company partnered on the development of the harvesting system. The system was targeted at material 5 inches in diameter and smaller which could not economically be harvested using standard forestry equipment (Koch, 1980). The basic unit was a 575 hp tracked mobile unit. The harvester used a ground-level cylindrical felling bar 9 ft wide to feed a drum chipper (Koch, 1980). The machine felled and chipped trees up to 12 inches in diameter as well as fed stumps and downed material using two semi-vertical side feed rollers into the chipper (Koch, 1980). Following along with the harvester is a secondary unit to collect the chips and transport them to the roadside, it was estimated a ratio of 2 collection units per harvester were needed (Koch, 1980). Testing was performed on red alder near Seattle. It was estimated that the harvester could deliver the wood chips for approximately $18/ green ton (Koch, 1980). The unit was limited by its utilization rate of 0.468, the machine was only operating 46.8% of the time it was in the field (Sirois, 1982). In order to meet production objectives of 21 tons/hr, it was calculated that the machine should only be applied to sites which have in excess of 20 tons/ ac (Sirois, 1982). There is no current work with this unit.

Comparable work by Texas A&M on a harvester from Brown Bear Equipment was performed throughout the 1980's and 1990's (Felker, 1999). This harvester is able to target natural growth, mixed small diameter woody biomass. The system was a modified John Deere 216 kW silage harvester, with a Brown Bear flail 4200 shredder. Stirrup-type knives were attached to the cutting head in a spiral pattern. In a counterclockwise rotation the material was cut and fed through sized exits slots into an auger. Two different systems were used during the study to move the material from the auger. The first was a set of screw augers used to transport the material under the machine and into a blower behind the unit. The second design was a vertical auger used to move the material into a bin located on top of the cutting head. The harvester was tested in New Mexico and Texas on Pinyon-juniper and salt cedar vegetation. Economic feasibilities of the harvester showed that at current production, fuel consumption, and energy markets the harvester was not self-sufficient, although they were able to reach their target harvesting cost of $1 x 10^{-9}J (Felker, 1999). While it was field tested this harvester was never commercially made available and is not currently being pursued.

The John Deere 1490D Slash Bundler is currently available and on the market in the United States. The harvester is part of a 3 machine system. The first machine is a standard feller/processor, which fells, delimbs, and sorts the trees for the harvester. The second machine is the Slash Bundler which gathers the slash, and bundles the material into desired lengths. The third machine is a forwarder which collects the bundles for transport to the road from the forest. The 1490D uses John Deere's B380 bundling unit to produce the bundles. It targets small diameter waste material after the feller has sorted the marketable timber. The biomass material is compressed reducing its volume by approximately 80%, without crushing the material (JohnDeere, 2008). The bundle is wrapped with ordinary bailing twine for easy transport. These bundles are intended to reduce the burning of slash piles and produce a marketable product. The bundler can produce up to 25 bundles per hour, each with approximately one thermal megawatt of energy (JohnDeere, 2008). The harvester has less than 7psi of ground pressure (JohnDeere, 2008). These bundles can be stored and marketed for renewable energy as long as the consumer has the resources to process the bundles.

FLD Biomass WB55, bio-baler is currently sold in the Unites States under Supertrak Inc. Originally developed by the Canadian company FLD, the harvester was released in the US in 2008. This is a single unit which cuts down, collects, and bales small woody and grass vegetation. A secondary unit is required to collect the bales and transport them to the road side. The bio-baler is pulled behind a tractor, the material is cut using a rotor with FAE fixed teeth and a 7.54 ft cutting width (Supertrak, 2007). The maximum cutting diameter is less than 5 inches. 4 foot netted bales are produced which can be easily transported. The baler can produce 1,102lbs/bale, 2.4795 tons/hr, 4-5 bales per hour in natural vegetation and 10-15 bales or 6.8875 tons/hr in plantations (Supertrak, 2007).

CURRENT MACHINE DEVELOPMENT STUDY

Research Methods

My research was to field test the first generation FECON Bioharvester. The five main project partners are US Forest Service, FECON Inc., North Carolina State

University, Craven County Wood Energy, and North Carolina Forest Foundation. Testing took place on the Croatan National Forest and biomass was marketed to produce bioenergy with Craven wood Energy. Six different project objectives were identified.

1. Field test FECON Inc. Bio-harvester
2. Collect data on operations, production, and economics
3. Determine economic viability of current and projected bio-harvester
4. Use field testing to recommend 2nd generation modifications
5. Reduce forest fire fuel load
6. Utilize small woody biomass as a renewable energy resource

<u>Biomass Source</u>

The biomass resource of interest in this study is small diameter woody biomass. In eastern North Carolina this is thick underbrush and pocosin vegetation. This biomass source is already in existence and in many areas needs to be removed or treated to reduce the fuel load and fire risk. Historically these areas would have naturally burned on a regular basis, however with United States fire suppression policy over the past 50 years, fire has been eliminated from many ecosystems. In many areas, fuel loads have reached a critical level. Even when controlled burns are an option, permits for these burns are becoming more and more limited with population growth and environmental/safety regulations not to mention limited suitable burning windows based on weather and hydrology.

Our two primary test sites are located in the Croatan National Forest, near New Bern, North Carolina. These sites have dense fire hazardous underbrush, which would threaten neighboring communities if they were to ignite. Due to their location in the wildland-urban interface, it is too risky for the Forest Service to perform controlled burns, given current fire fuel loads. The Forest Service's desire for fuel reduction and the close proximity to Craven Wood energy made this an ideal location for biomass harvesting. Three additional sites on the nearby Hofmann Forest were also used for testing. With the FECON Bio-harvester we are able to mechanically treat an area and recover the material for renewable energy. Fuel reduction and Forest Service habitat restoration plans are both social benefits which are difficult to quantify economically, but critical to the surrounding community. Harvesting the natural vegetation poses a new set of challenges. Unlike a plantation the vegetation is not as homogeneous. By definition, pocosin areas are very wet and thus low ground pressure is needed on any equipment working on these sites. Each site had a different set of conditions with varying materials, densities, and challenges.

After identifying the biomass resource, it was important to quantify the target material. To quantify the potential resource in the Croatan National Forest I went to the field and collected samples, these results are summarized in Table 2. (Raw data in Appendix A)

Table 2: Field Tons/Acre Sample Results

Location	Mean Tons/Acre	95% Confidence Interval	Standard Deviation
Site 1	15.46	7.13 to 23.79	30.04
Site 2	6.02	4.19 to 7.84	6.58

Using GIS software 50 random sample points were generated on each of our two test sites. Using a GPS system I navigated to the plot centers where I collected and weighed the biomass, 6 inches in diameter and smaller to approximately 1 inch off the ground, in a

10 square foot area. These data points were used to predict the quantity of harvestable material. Site maps and sample points for sites on the Croatan National Forest are displayed in Figures 1 and 3.

Figure 1: Site 1 Aerial Map Visual representation of biomass sample sites. Harvesting site was the polygon which contains the sample points; blue represents original sample set, yellow randomly generated sample site, and green is the field collected sample site. County Line Road borders the north east side of the site.

The first site, off of County Line Road, had not been treated for 20 years. A wide range of species and biomass density levels were found on the site. The data had a large variance between points depending on whether or not hardwood, pine, or grass species were present. This averaged to 15.46 tons/acre of harvestable material. See Figure 2 for before and after images of the site.

Figure 2: Site 1 Site 1 flatwoods site. The left image is a before harvesting image of the site. The right image is after harvesting. Notice the small underbrush is removed, leaving the larger timber standing.

Figure 3: Site 2 Aerial Map The allowable harvesting site is interior of the teal polygon. Yellow points indicate randomly generated sample sites. The photo notably illustrates the proximity of the harvesting site to wildland urban interface.

Working in the second site, near Havelock, North Carolina, more consistent biomass fuel loadings with fewer harvestable large trees were observed. This resulted in less variance in the samples. Most samples were small pines, bays, or bamboo grasses, *Arundinaria gigantea*. This site was treated 5 years ago, and thus as expected yielded a lower average of 6.02 tons/acre of biomass, see Figure 4.

Figure 4: Site 2 Sample Plot This image illustrates a sample plot taken from site 2, which was pocosin vegetation. The cleared area is 10 square feet, which was cleared and weighed. Notice the surrounding grassy vegetation contains fewer small diameter trees than site 1.

While these estimates were done in the field, it would be ideal to develop a continuous fuel load model, possibly using Lidar data, which could produce estimates of the density of the underbrush, for each potential harvesting site. In addition this would be a valuable land management tool. Historically understory vegetation has not been a commercially valuable material, and therefore inventory methods and models are not well developed. This type of information could help produce periodic biomass harvesting plans which must vary depending on the density level and distribution of fuel loads at each site.

Statistical Analysis

Statistical analysis was performed on the field data collected. The Wilcoxon rank sum test is a non-parametric significance test, which compares two samples from different populations to determine if they come from the same distribution. It is similar to performing a two-sample t-test. With non-parametric analysis the data do not have to be normal, analysis is relatively insensitive to outlying observations, and results can be easier to understand (Hollander, 1999). The null hypothesis of the wilcoxon rank sum test is that the two populations have the same distribution. To perform the wilcoxon rank sum test there are three underlying assumptions (Hollander, 1999):

1. X's are a random sample from population 1 and are independent and identically distributed
   Y's are a random sample from population 2 and are independent and identically distributed
2. X's and Y's are mutually independent
3. Populations 1 and 2 are continuous populations

The test statistic is W, or the sum of the ordered ranks from the smaller sample size population. If the test statistic is statistically significant then reject the null in favor of the alternative; for a two-sided test the alternative would be that the two populations have different distributions. Statistical significance is determined by the alpha level and the p-value. Alpha is the significance level, or the probability of rejecting the null hypothesis when the null is actually true, this is known as a type I error. The p-value of a test is the probability of obtaining a result as extreme as the one observed. If the p-value determined using the test is smaller than the alpha level the null hypothesis is rejected.

Wilcoxon Rank Sum tests were used to compare Site 1 to Site 2 data on acres per hour treated, utilization rates, and tons per hour collected. Wilcoxon Rank Sum tests were used because normal distributions and identical variances were not present between the two sites, therefore assumptions for the t-test could not be satisfied. All tests were performed with an alpha=.05.

In addition to the Wilcoxon Rank Sum test a general linear model was used to investigate the association between acres per hour treated and tons per hour harvested. To perform this test certain assumptions must be made; normality, homogeneity of variances, linearity, and independence (Quinn & Keough, 2002).

As we look to using biomass as a renewable energy resource there are a few basic questions which must be answered. You must have a source of biomass, a way to cost-effectively harvest the biomass, and a market for the biomass.

<u>Prototype Harvesting System</u>

To utilize the biomass it must be harvested and transported. The forest biomass harvesting system has three main components; cutting the material, transporting the material to a loading deck, and transporting the material to the market. While these components must work together to form one system, they will be analyzed separately in this study.

The main focus of this study is the prototype cutting head for the FECON Bio-Harvester. We are working to develop a single unit to fell, chip, and haul the biomass out of the woods. The unit consists of two parts, the cutting head on the prime mover and the dump wagon to collect the material. The harvester must be able to simultaneously harvest pines and hardwoods up to 6 inches in diameter, along with smaller grasses and shrubs. Most current agricultural equipment is designed to harvest a single row crop in a more controlled environment. Since the land we are working on has not been managed for agricultural production, the machinery developed must work around existing larger trees, pass through unleveled ground conditions, over stumps, downed logs, and root balls. This prevents the use of straight line harvesting plans and requires the use of more durable equipment. The harvester in the study is the FECON Bio-Harvester, see Figure 5; other names for this unit have included the “Kraken”, pick-up mulcher, and biomass harvester. The prime mover is a standard FECON FTX 440 tracked bulldozer with a prototype mulcher head attached. The prototype head is a modified FECON Bull Hog unit, tailored to collect the material it processes. It was originally developed by AHWI, a partner company of FECON located in Germany. Instead of mulching the material into the ground, like the standard Bull Hog unit, the mulcher operates in the reverse direction loading the material into an auger. The auger feeds a paddle material fan, on the side of the head, which sends the chips through a shoot enabling the operator to discharge the material into a collection unit or onto the ground. In our study the harvester was used to tow the collection unit, which is important to note when determining the required harvester horsepower.

Figure 5: FECON Bio-Harvester This is the FECON Bio-harvester, consisting of the harvesting head, FECON FTX 440, and dump wagon trailer on site 1.

Components of the Head

The harvesting head was power take off (PTO) driven by the tractor. The total head width is 264 cm (8 feet 8 inches) however the cutting width is only 183 cm (6 feet). The max PTO speed, always used for operation is 1320 RPM. From the gear box this motion was transferred to power two sets of belts on either side of the harvesting head. One set of belts powered the rotor and the auger. The rotor was driven by two triple belts and operated at a maximum 2066 RPM. The cylindrical rotor with 7 mounting rows, held

48 cutting tools, see Figure 6. The biomass harvesting tests used a combination of double carbide and chipper knife tools, see Figure 7; however the tool bracketing enabled the use of additional tools and unique tool configurations. The screw auger located behind the rotor was powered using one double belt and operated at 135 RPM. The other set of belts, located on the opposite side of the head from the first set of belts, powered the material fan, see Figure 8. Four single belts powered the material fan at 660 RPM. The fan used 7 paddles to transfer the material from the end of the auger into the chute. As the entire system was driven by the PTO, when one component became under load this affected all other components in the system.

Figure 6: Harvester Rotor The rotor had 7 rows with 48 tools. There is a 6 ft cutting width with an 8 ft machine width.

Figure 7: Harvester Tools Features two different tools or "teeth" used on the bio-harvester; left double carbide and right chipper knives.

Figure 8: Harvester Head Belts Belts were used to drive the auger, rotor, and material fan on the harvesting head. On the left is a picture of the auger and rotor belts, the right is the material fan belts.

Additional components of the harvesting head included the trap door, push bar, and chute; see Figure 9. The trap door with 14 pivoting flappers was located in front of the rotor to deflect material thrown forward by the rotor. The operator could hydraulically raise and lower the trap door during operation. The push bar was a metal arm on top of the harvesting head, spanning almost the entire width of the machine which the operator could hydraulically lift and lower during operation to move material. The steel chute received material from the fan and directed it to the collection bin. The chute was self-suspended above the tractor cab. The operator had hydraulic controls to move the chute right and left, pointing to either side of the tractor, and to direct the material up and down the end of chute with a vertical deflection.

Figure 9: Harvester Head The left image illustrates the trap door with the metal flappers, the push bar, and the chute. The right image illustrates the material fan on the harvesting head.

FIELD TESTING

Field testing of the FECON Bio-Harvester by NCSU took place from October 29, 2007 until April 15, 2008. During this time the machine was operated on 55 separate days or partial days, for a total of 93.4 harvesting hours. Testing took place on 5 different sites on both the Croatan National Forest and the Hofmann Forest for a total of roughly 50 treated acres. During field testing, data was collected on activities, use of time, GPS tracks, machine problems, dump wagon weights, and reported Craven Wood Energy weights, see Appendix D. The machine averaged 2.6 tons/ hr production with a maximum production of 7 tons/hr. The machine utilization rate averaged 0.233 ranging between 0.2-0.3. Approximately 150 tons of biomass was marketed to Craven Wood Energy. Testing found that while the system was able to harvest the desired material, it still needs work before the system is marketable.

The operator must learn how to position the head so that the harvester collects the maximum desired woody material, but not the soil. This is critical for two main reasons, too much soil disturbance is not environmentally acceptable and material loads contaminated with high percentages of soil are not marketable. Tilting the head back to increase the exposed teeth to the material enables us to increase our harvesting; however it is limited by the angle of the shoot being able to aim into the dump wagon. The head is material fed thus any biomass that is lower than 6 inches off the ground or is pushed down below this level is not harvested. Reduction in track speed reduces the amount of material pushed over, however results in longer harvesting times for the same amount of material. It is important to fully engage the mulching head before operating to reduce stress on the machine and machine belts. Adjusting operation techniques have enabled us to improve our harvesting material, however there is still concern that too much material is being left on the ground both chipped and unchipped.

There are two main issues to address before the harvester could be commercially marketed. The first issue to address with the harvester is the number of material jams in the head that require shutdown and slow production. When material jams inside the head, nonproductive time is spent to clear the system of debris, see Figure 10. An issue with the harvesting head is that it only averaged 2.1 harvesting hours between problems requiring shutdown. The majority of these problems were jams. Material jammed in the auger, the transition between auger and fan, in the fan housing, and in the chute. Often more than one of these jams would occur before the problem was detected making it hard to find the initial cause of the jam. This resulted in unacceptable maintenance requirements for the harvester to operate; this is reflected in the machine utilization.

Figure 10: Material Jams When material jammed or clogged in the system, it was time consuming to remove the material. The left image is cleaning debris from the door in the chute above the material fan. The right image shows clogged material in the chute.

Second, the system did not collect enough of the material. A common initial concern of the harvester is that it would strip the land; however upon evaluation of treated areas, it is clear that with its current capabilities, this is not a problem. It is estimated that only 1/3 of the potential material was chipped and collected. For profitable production this proportion needs to increase. There are three different areas where material was not harvested. The first is material that was pushed over by the machine or too low to the ground for the machine to harvest or chip. The second is material that is chipped by the harvester and dropped back onto the ground, never reaching the auger. The third area is material lost after being sent through the chute, but missing the collection bin.

As with any new piece of equipment it takes time to optimize and analyze the use and operation of the machinery. Since the harvesting head is a one of a kind piece of equipment it came with very little instruction and information, this resulted in a trial and error approach to operating conditions which was hard on the equipment. In-field modifications to the head were performed as it was deemed necessary during testing. However throughout our testing we found several mechanical design flaws and issues, which need to be addressed in the next generation of the unit.

Machine Utilization

The utilization rate of a machine (μ) is the ratio between the productive machine hours (PMH) to scheduled machine hours (SMH).

$$\mu = PMH/SMH \qquad \text{(Eq 1)}$$

It is a number between 0 and 1, ideally approaching but never reaching 1, this number can also be thought of as a percentage of running time of the machine. Utilization will never reach 1 because time will always be spent during warm-up/ shutdown of the machine as well as fueling the machine and performing routine maintenance. Scheduled machine time was broken down into 9 different categories; harvesting, clean up harvesting, machine travel, maintenance and repair (MR) of the FTX 440, maintenance and repair of the harvesting head, maintenance and repair of the dump wagon, on-site analysis, weighing and dumping of the wagon, and site work. Productive machine hours consisted solely of harvesting time. Field testing of the harvester yielded an average daily utilization rate of 0.233, with a standard deviation of 0.1998. Daily utilization rates graphed for sites 1, 2, and The Hofmann Forest and can be found in Figure 11. Weather was an issue which effected daily utilization rates. When the harvesting material was wet, due to rain or dew material was more likely to clog the machine and often prevented operation.

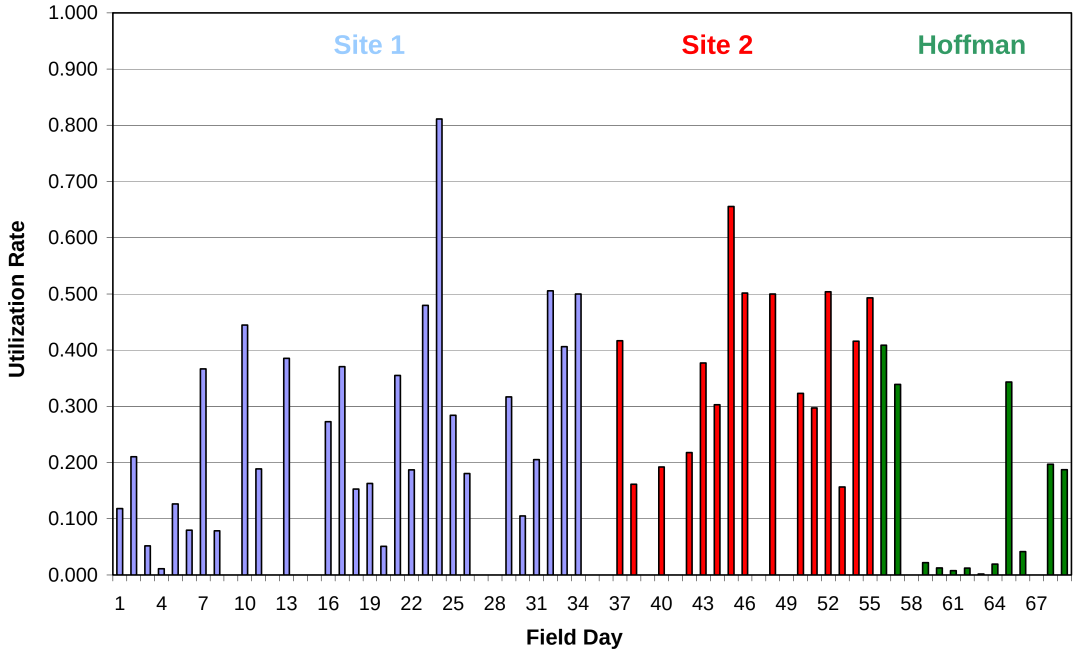

Figure 11: Daily Utilization Rate Daily utilization rate represents the percentages of field days spent harvesting. Site 1 had an average daily utilization rate of 0.218 with standard deviation of 0.195. Site 2 had an average daily utilization rate of 0.275 with standard deviation of 0.202. The overall utilization rate was 0.233 with standard deviation 0.1998. Gaps in the data are observed for days on which no harvesting occurred due to equipment issues. The peak in utilization at site 1 over 0.8 occurred on a day with few SMH. The Hoffman resulted in low utilizations because of increases site work with 3 sites, bridges for ditch crossings, and new operator training.

Performing a statistical analysis using the Wilcoxon Rank Sum test does not show a statistical difference between the distributions of the populations of utilization rates between sites 1 and 2. With 36 samples from site 1 and 19 samples from site 2, the test yielded a p-value of 0.1170, which is not significant at an alpha level of 0.05; see APPENDIX E for a complete output and SAS code. Although there was not a statistical difference in utilization rate populations between site 1 and site 2 this does not conclusively determine a practical difference when using the machine in the field. Field observations can still be valuable to advance this machine into the next generation.

For site 1, the most time consuming practice at 34% was maintenance and repair of the harvesting head. Site 2 logically shows a decrease in the percentage of time spent on maintenance and repair of both the harvesting head and the dump wagon. As initial problems from site 1 were fixed or accommodated for they did not carry into site 2 testing and the largest time percentage, at 27%, was harvesting. The large difference between the flatwoods and pocosin vegetation types on the two sites effected harvesting practices. See Figure 12 for a complete comparison of time between site 1 and site 2.

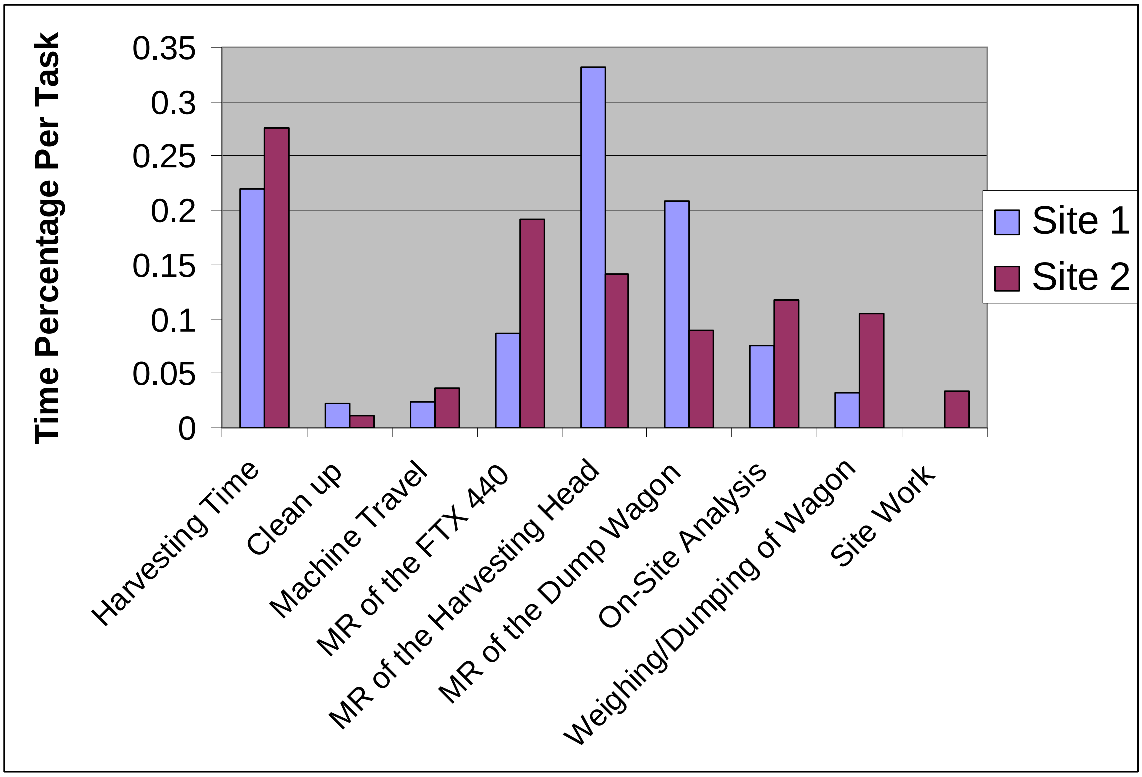

Figure 12: Site 1 and 2 Time Distributions Time distributions are percentages based from the total time at each site. Side by side displays enable a comparison work distribution between sites, showing an increase in harvesting time, maintenance and repair (MR) of FTX 440, weighing/dumping, and a decrease in MR on the harvesting head and wagon. The percentage of time weighing/ dumping and MR of the FTX 440 increased as overall downtime decreased. Maintenance and repair of the harvesting head includes time unclogging jams.

More work still needs to be done to decrease maintenance and down time for all parts of the harvesting system. To be competitively marketable with other standard commercial forestry equipment the harvester needs to reach a utilization rate between 0.7 and 0.8.

Production Rate

Production rates for the harvester were determined on a green ton/hr basis, using harvesting segment times and dump wagon weight loads. Site 1 averaged 1.184 tons/hr, standard deviation 1.32, while site 2 averaged 3.456 tons /hr, standard deviation 1.34, with an overall average of 2.6 tons/hr, standard deviation 1.81. Although site 1 had more potential material to harvest, the vegetation was highly diverse and required slower ground speeds to maneuver through the leave trees on the site. The highest production rates were observed during plantation row thinnings, see Figure 13. Plantations enabled straight-line harvesting in consistent vegetation. While only a few plantation test runs were preformed they showed notably higher production capabilities and potential for the harvester. See Figure 14 for a complete production rates.

Figure 13: Plantation Row Thinning Thinning between plantation rows enabled straight line harvesting of consistent vegetation and yielded the highest production rates. This pine plantation was located near site 1 and was used for demonstrations.

Performing a Wilcoxon Rank Sum test showed a statistically significant difference between the production (tons/hr) populations between site 1 and site 2. With a p-value less than 0.0001, this is highly significant at an alpha level of 0.05. See APPENDIX E for complete test results and SAS code.

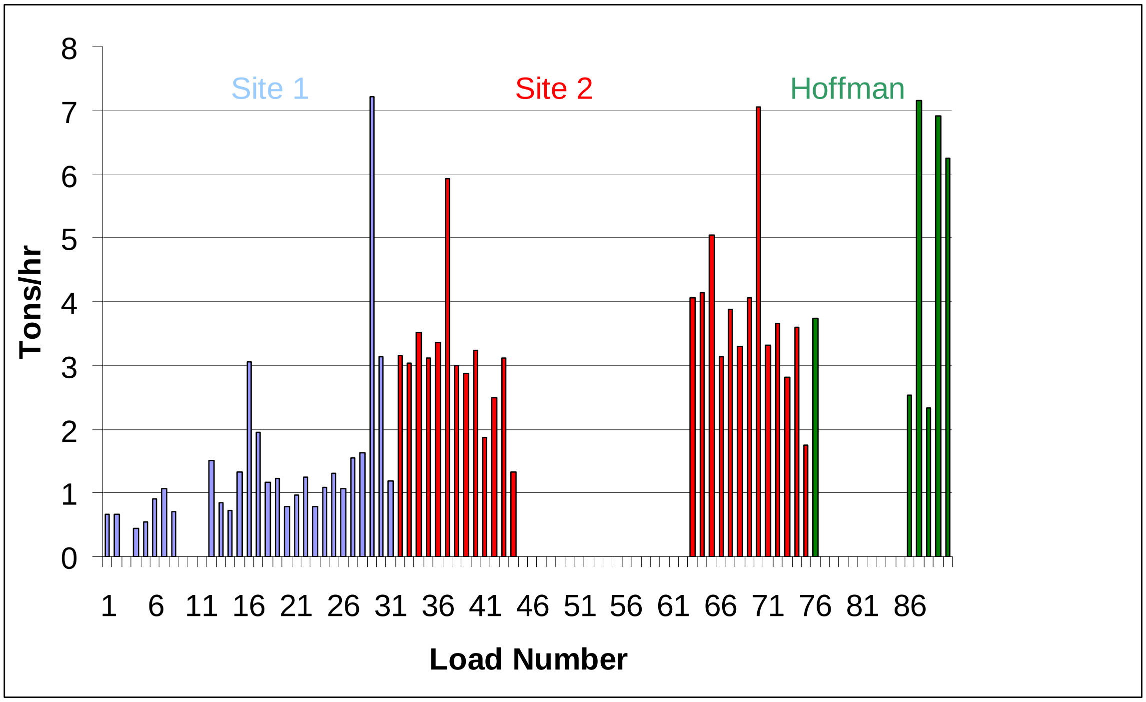

Figure 14: Harvest Production Rate Harvest Production Rate displays the tons/hr harvested for each dump wagon load. Rates vary between sites because of different harvesting conditions. The two peaks in site 1 harvesting rates at 3.05 tons/hr and 7.22 tons/hr are plantation thinnings resulting in higher production rates. Gaps in the data are a result of dump wagon loads which were not weighed. Although site 2 had higher production rates than site 1, it appears the Hofmann consistently had the highest production rates.

<u>Acres per Hour Treated</u>

A Garmin E-Trex unit was used to track GPS logs of the machine paths. Matching this data with the activity time logs enabled the calculation of acres per hour treated. A treated acre consisted of the machine cutting across an area, regardless if the material was collected or blown on the ground. Once GPS distances were matched with harvesting times, a cutting width of 6 ft was used to determine areas. For site 1 this averaged 0.281 ac/hr with a standard deviation of 0.263. Site 2 averaged 0.305 with a standard deviation of 0.089. The overall average was 0.284 with a standard deviation of .195. The Wilcoxon Rank Sum test yielded a statistically significant result when testing the distributions of the two populations, concluding that the distributions are not the same. The acres per hour treated from site 1 have a different distribution than site 2. The resulting p-value was less than 0.0001 and is therefore highly significant at the 0.05 alpha level, see APPENDIX E for SAS code and results.

Acres per Hour vs. Tons per Hour

It is hypothesized that there is an unknown relationship between the acres per hour treated and tons per hour collected. There are a limited number of tons per acre for potential harvest. However from field testing, observational analysis shows that faster ground speeds do not necessarily yield higher productions. If the harvester's ground speed is too slow it will not cover enough acres per hour for high production. On the other hand, if the harvester ground speed is too fast, the biomass is simply pushed over and not collected. In order to obtain sample points for this test, time, weight, and GPS data had to be collected for each segment. This resulted in a total of 33 sample points, 13 from site 1 and 20 from site 2.

To test for an association between acres per hour treated and tons per hour harvested a general linear model was performed. This model shows how much of the variation in tons per hour (Y) can be explained by the linear relationship with acres per hour (X). The null hypothesis of this test is that there is not a linear correlation between acres per hour treated and tons per hour harvested, and thus the slope is zero. The alternative hypothesis is that there is an association between the two variables and the slope of the regression line will not equal zero. If the linear model illustrates a significant correlation between the two variables, association is proved to be significant as well.

Three separate GLMs were generated using the 33 sample points. The first model used all 33 points from both sites. The resulting model of Y=8.45X+.017 showed a positive correlation between the two variables and had an R-Squared value of 0.59. At an alpha level of 0.05 the slope was highly significant with a p-value less than 0.0001. This model explains 59% of the variation in tons per hour harvested using acres per hour treated. The removal of the outlier in the upper right hand corner could not be justified when compared to the complete data set and the range of acres per hour and tons per hour. The second model used only sample points from site 1; Y= 4.86X+.093 with an R-square of 0.69 and a p-value of .0004. Once again this is a highly significant result that there is a correlation between acres per hour treated and tons per hour harvested. The final model using site 2 data alone yielded Y=5.38X+1.53 with an R-squared of 0.34 and a p-value of 0.0071. With this is still a significant result to show a correlation the model only accounts for 34% of the variation in tons per hour. Figures 15-17 show plots of all the models, SAS results and codes are found in APPENDIX E.

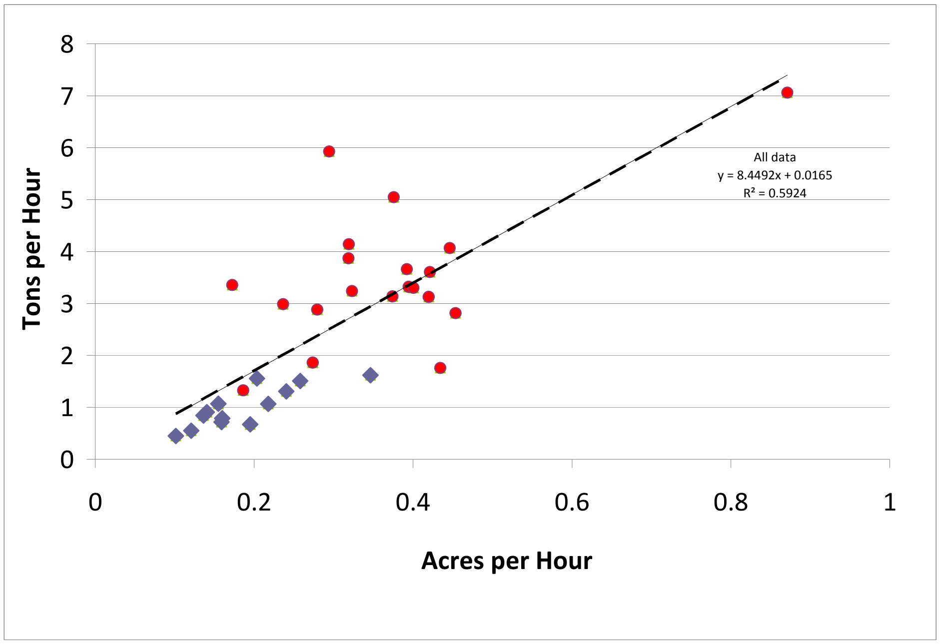

Figure 15: Acres per Hour vs. Tons per Hour Site 1 &2 Plot of all 33 sample points, resulting in a highly significant p-value, there is a significant linear relationship between acres per hour and tons per hour. The model accounts for 59% of the variation in tons per hour using acres per hour.

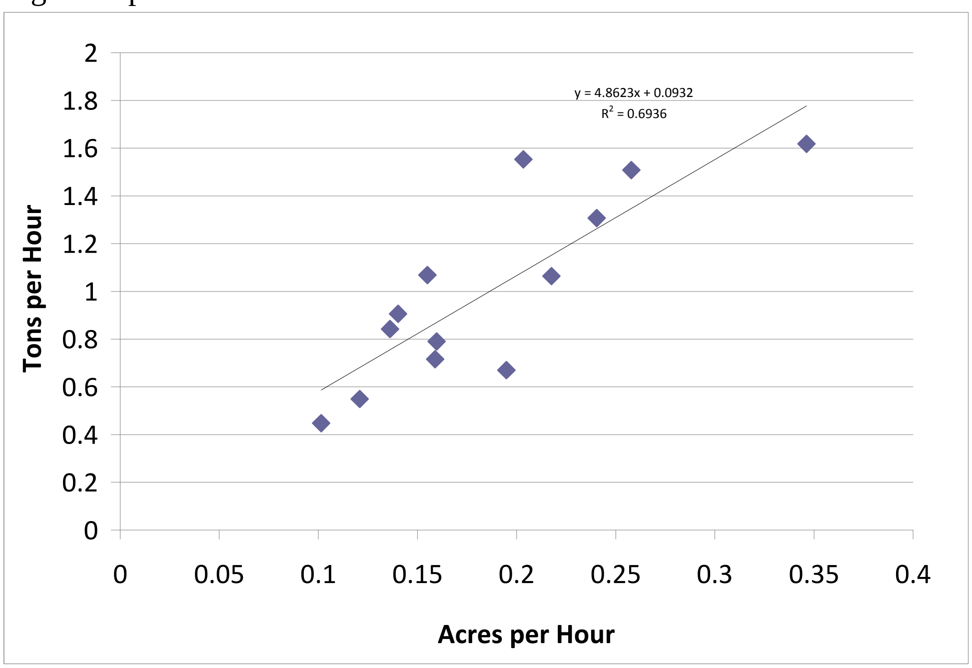

Figure 16: Acres per Hour vs. Tons per Hour Site 1 13 sample points plot. Highly significant slope shows a correlation between the two variables. Model accounts for 69% of the variation in tons per hour using acres per hour.

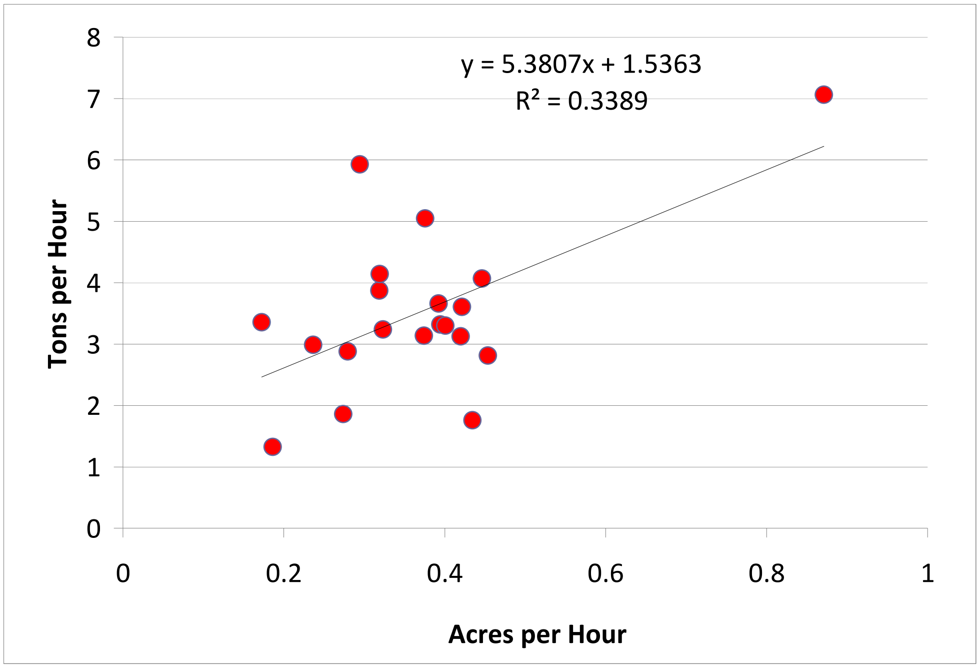

Figure 17: Acres per Hour vs. Tons per Hour Site 2 Plot of 20 sample points from site 2. Significant slope in model shows correlation between the two variables. Model only accounts for 33% of the variation in tons per hour using acres per hour. Removal of outlier could not be justified when compared to the complete data set.

Energy Potential

It is important to understand all energy inputs to estimate a potential energy source. In order to make the system feasible you must be able to produce more energy than is consumed during production. To ensure a net gain in potential energy a BTU (British Thermal Unit) analysis was performed on the harvester. BTU is a measure of heat value or energy. While the harvester was the only controlled energy consumer in this project it is important to note that energy is also consumed transporting the material to market and during the conversion process to electrical power.

The harvester produced more energy than it consumed making it a viable option for renewable energy. Energy, in the form of diesel, went into the harvester, which produced wood chips for use as an energy source. The harvester consumed an average of 12.65 gallons of diesel/ PMH at a rate of 138,700 BTU/gal totaling 1,754,555 BTU/PMH. The harvester produced an average 2.6 tons/PMH at a rate of 9,218,000 BTU/ton (Appendix B), generating 23,966,800 BTU/PMH. At this rate the harvester is generating the potential energy material 13.7 times of which it consumed.

<u>Testing Issues</u>

The major issue encountered during field testing that caused us the most problems, was that the range of motion of the flappers on the trap door, which allowed them to intersect with the cutting teeth. When the trap door was fully closed, in the down position, the flappers could be pushed back into the cutting surface. Not only did we destroy a set of cutting teeth, but the stress on the cutting surface caused by the teeth intersecting the flappers relayed throughout the entire PTO system. This flaw weakened the auger and fan belts within the machine, ultimately contributing to their failure. In addition to wearing the belts it caused hiccups in material flow within the auger and material fan resulting in jamming the head. The safety trap door must be opened to prevent the flappers on the gate from interfering with the teeth on the mulching head. However operating with the gate fully open, as well as posing a safety issue in front of the machine, allows too much material to enter the head and results in jamming the auger. As a result of operating with the gate partially open the sides of the gate were not properly supported and parts of the welding started to break, bending the sides back and toward the blower fan. This threatened the integrity of the material fan housing, which is critical to material flow. To enable us to close the gate we had to straighten the bent pieces and trim the flappers so that they could no longer intersect with the chipper knives. This was the largest permanent modification to the head preformed.

Field testing totaled 165 individual harvesting segments. 53% of the segments concluded as part of normal operating procedures. The rest of the shutdowns were a result of a problem with either the harvesting head, wagon, or FTX 440 with an average problem shutdown every 1.2 PMH, this would be over 8 problem shutdowns in a 10 hour day assuming instantaneous restart. 27% of the shutdowns were caused by a problem with the head, and of these 77% of the time the head was jammed or clogged. The machine averaged a head shutdown every 2.1 PMH, over 5 per 10 hour day. 14% of the total shutdowns were wagon problems and 6% of the shutdowns were a result of problems with the FTX 440. The main concern of this study is with the shutdowns due to issues with the harvesting head as these were the most critical to system operation and often the most time consuming to fix.

During our testing we had total of 5 different belt sets on the material fan, three of which were tracked from application to removal. The Original Belts completely sheared. We made the decision, based on the wear in the belts, to change the second set of belts in preparation for the December demo day. The third set of belts sheared upon startup without a jam. The fourth set was replaced based on wear and experience. Monitoring and maintaining these belts was time consuming in the field as they were not easily accessible on the machine. The belts wore through normal operation, however they experienced increased stress whenever the machine jammed or experienced increased load. Under stress, the belts would slip and begin to smoke, periodically requiring them to be manually tightened.

The best way to track these belt sets is by the harvest times they were in operation and problems causing shutdowns from the head. The current belt life as it appears would mean changing the belts once a week if you could operate 30-40 hours a week, see Figure 18. However if you were successfully running 30-40 hours a week, this would not allow you the time to jam the machine as frequently, the belts would slip less often, and the end result would be a longer belt life. The graph in Figure 6 leads to the conclusion that some of the periods with very short harvest times between head problems are a result of the clog not fully being cleaned or fixed, before harvesting recommenced. Some of these resulted in another immediate problem during start up, while some would allow harvest for 10 min or so. During this time the problem would build, for example a piece remaining in the chute would permit some material to pass through, giving the allusion the problem was fixed, but in a short time would cause another jam. The symmetry of the two large peaks when we changed the belts while observed does not logically lead to an operational cause. However it does make sense that after changing the belts they would run for a longer time without any problems.

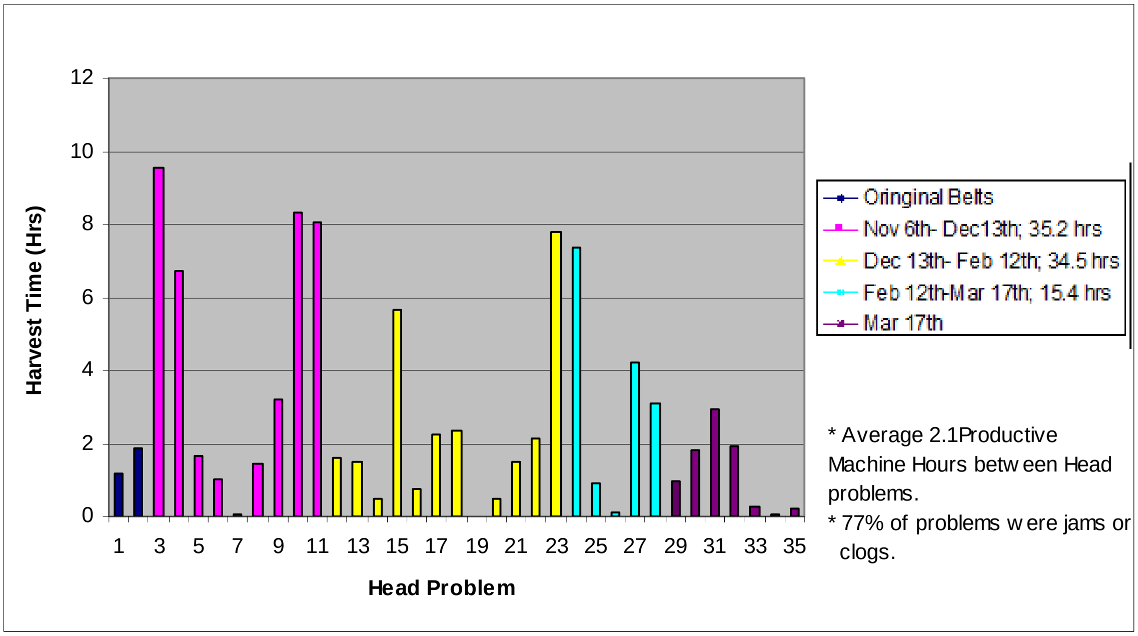

Figure 18: Harvest Time Between Head Problems by Fan Belts Harvest hours between machine shutdowns due to a problem with the head. The head problems are divided by the 5 fan belt sets used during testing.

The arm on the front of the head, which is often called a push bar, was not strong enough to be used as a push bar. Currently it is utilized as a guard to keep material off of the cab and also to direct some material from the sides of the machine into the head of the machine. If the push bar were stronger it could be used to push trees to the proper angle to feed them into the cutting head. The range of motion of the push bar enables it to intersect both the gate and chute during operation. The intersection of the push bar with the gate immediately resulted in bending the push bar arms, compromising the structural integrity of the push bar, see Figure 19. This damage occurred as a result of the hydraulic pressure as the push bar came down into the gate. As the gate was opened to attack a larger tree, the push bar was used to push the tree forward, as the head drove into the tree to chip the material, resulting in the push bar bending over the top of the gate or trap door.

Figure 19: Push Bar The image on the left was taken when the machine arrived, before harvesting took place, notice the straight arms of the push bar. The image on the right was taken after harvesting and the bends in the push bar are now evident.

As we tested the head, we needed to take it apart to fix it and at the same time study how it functions. A total of 22 grease points on or within the head were identified. The most problematic of these are the 8 grease points located behind bolted-on plates within the head. In order to access these grease points the back panels of the head must be removed. This is time consuming and impractical if these points need to be addressed on a daily basis. While eliminating these points does not appear to be an option, they need to be more accessible to conduct maintenance efficiently.

Collection System

Once the material is cut and chipped it must be collected, transported out of the woods, and delivered to the potential buyer. The infield collection unit is a major part of the harvesting system. In our study we used a United Farm Tools agricultural dump wagon pulled behind the FTX 440. Though not the focus of this study our current 4 wheeled dump wagon trailer system proved to be another problem area in the project. It is a standard agriculture wagon and is not designed to withstand rugged forestry conditions. The wagon is pulled by the FTX 440 tractor, collects the material in the field, and then lifts to dump it into a bin which can be transported by truck to the market, see Figure 20.

Figure 20: Dump Wagon The dump wagon lifts and dumps to the side into a roll on roll off bin.

Ideally the wagon would reach a dump height of 15ft to enable it to dump into a 13ft high chip van, maximizing state highway carrying capacity. However, it only reaches 10ft, forcing us to utilize smaller bins for delivery, increasing transportation costs, see Figure 21.

Figure 21: 40 cubic yard Roll-on Roll-off Bin Filled Bin used to deliver material to the end user.

The wagon was also wider than the bioharvester and hard to maneuver through the woods. While the wagon does follow along behind the 440 well in straight lines and is able to withstand variable ground conditions, problems occur when the machine must turn or large stumps damage the undercarriage. When turning the operator loses site of the dump wagon wheels which can then easily catch on a tree or stump bending or breaking the tie rods, making the wagon immovable and resulting in operation down time. Communicating with the operator by radio can enable someone outside of the unit constantly watching the dump wagon tires to warn of potential wagon hazards, reducing damage. Operator experience was able to decrease these problems and eventually eliminate the use of the external spotter.

Once the chips make their way through the shoot they must make it into the dump wagon. Currently this system is operator controlled, so the operator must watch both the dump wagon and chute, manually adjusting the chute to aim into the dump wagon, see

Figure 22. With operator experience we were able to reduce the amount of material which missed the dump wagon and fell to the ground; however we would like to eliminate this loss. Field testing proved the concept of adding a piece of flexible hose or duct work to span the 10-16 foot gap which is in-between the end of the shoot and the dump wagon opening to eliminate this loss, but this modification was not implemented in this study.

Figure 22: Hydraulically Controlled Chute View of hydraulics on the end of the chute which allowed the operator to control the direction of the material into the dump wagon opening.

Material Market

The market for harvested biomass in this study was Craven County Wood Energy. It is a 45MW wood burning facility which produces electrical power. It is part of the larger Decker Energy Inc which manages 4 other wood energy and several natural gas facilities in the United States. The biomass was used in a carbon neutral process to provide energy. The facility is approximately 17 miles from the first harvest site and 27 miles from the second site. Close proximity to the biomass harvesting sites is important for reducing transportation costs. The mulched forest biomass is an ideal product for

Craven Wood Energy as it is less likely to be contaminated with metal or other non-wood material than construction debris or railroad ties and has less mineral soil content. Material specifications depend on the individual facility, and can vary widely with region and technology. Craven Wood Energy does not have a chipper; therefore all purchased material must be chipped small enough to flow through their system. The price per ton that Craven Wood will pay for the material varies with material availability. The market potential at the time of the study was $18/green ton, with preliminary estimates of 10 tons of harvested biomass/hr to break even.

Once we are able to successfully harvest the material we can begin to market it to other potential buyers, including but not limited to bagged mulch distributors, the pulp and paper industry, or potential oil extraction production. The future potential market which would drastically increase the demand for this material is biofuels. The type of biofuel production and marketable regions for this material will depend on the infrastructure to produce the biofuels. Notably using understory biomass does not interfere with food or with traditional forest product markets. As cellulosic ethanol facilities go into production in the United States it will increase the demand for woody material, with corresponding increases in price.

Cost Analysis

In any forestry operation minimizing machine cost is critical to the ability to make a profit. I performed a machine cost analysis for the biomass harvester. The machine cost consists of two main components; fixed and variable or operating costs. Fixed Costs are ownership and set up expenses. The variable or operating costs include maintenance, labor, fuel, lubricants, and tires if applicable. In addition to these costs I also included a cost for the transportation of the biomass which is a critical component to biomass production and cost analysis.

The estimated purchase price of the equipment from FECON Inc. is $473,100. To determine equipment cost an equipment life of 5 years and 2500 SMH per year was used. Equipment cost was calculated per PMH.

$$\text{Equipment Ownership Cost} = \frac{\text{Purchase Cost}}{\text{SMH}*\text{Years}*\mu} \qquad \text{(Eq 2)}$$

The equipment ownership cost results for each site as well as a projected utilization rate of 0.7 are found in Table 3.

Table 3: Equipment Ownership Cost Summary

Site 1 μ=0.218 Equipment Ownership Cost $173.61/PMH
Site 2 μ=0.275 Equipment Ownership Cost $137.62/PMH
Overall μ=0.233 Equipment Ownership Cost $162.6/ PMH
Projected μ=0.7 Equipment Ownership Cost $54.07/PMH

The operating costs for the bioharvester included maintenance, fuel, labor, lubricants, and parts (Eq 3). Values for each of these components were calculated from data collected in the field and based on productive machine hours. Fuel consumption was based on the fuel used throughout the project, which averaged 12.65 gal/hr at a rate of $3.11 per gallon. A single operator was used at a rate of $30/SMH.Total operating costs for the site 1, site 2, overall and projected values are found in Tables 4-7. Projected values are based from data collected by FECON Inc. on the FTX 440. A complete record of field operating costs are in appendix C.

$$\textit{Operating Costs} = \textit{Maintenance} + \textit{Fuel} + \textit{Labor} + \textit{Lubricants} + \textit{Parts} \quad \text{(Eq 3)}$$

Table 4: Operating Costs Site 1

Lubricants	$3.94	PMH
Fuel (12.65 gallons/PMH)	$39.37	PMH
Parts	$11.42	PMH
Maintenance Labor	$129.87	PMH
Labor	$137.61	PMH
Total Operating Cost	$322.21	PMH

Table 5: Operating Costs Site 2

Lubricants	$3.94	PMH
Fuel (12.65 gallons/PMH)	$39.37	PMH
Parts	$11.42	PMH
Maintenance Labor	$55.39	PMH
Labor	$109.10	PMH
Total Operating Cost	$219.22	PMH

Table 6: Overall Operating Costs

Lubricants	$3.94	PMH
Fuel (12.65 gallons/PMH)	$39.37	PMH
Parts	$11.42	PMH
Maintenance Labor	$101.98	PMH
Labor	$128.76	PMH
Total Operating Cost	$285.47	PMH

Table 7: Projected Operating Costs
Using a target utilization rate of 0.7, projected operating expenses are displayed. The harvester will not be commercially viable until the utilization rate is increased. Lubricant and fuel values are from field testing. Maintenance Labor/Parts are from FECON FTX 440 testing. Labor Costs per PMH decrease as utilization increases, bases from $30/SMH.

Lubricants	$3.94	PMH
Fuel (12.65 gallons/PMH)	$39.37	PMH
Maintenance Labor/ Parts	$46.52	PMH
Labor	$42.86	PMH
Total Operating Cost	$132.69	PMH

The difference between the 4 operating costs is primarily found in the maintenance labor cost. The first site has the largest maintenance labor cost, this is a result of the time spent working out the initial bugs in the system. This significantly decreased at the second site and is projected to decrease more as the design flaws of the system are worked out. Other cost differences are due to variable utilization rates.

In today's markets the transportation cost of any material is becoming increasingly important, and this is no different for biomass. Currently we are using 40 and 45 yd roll-on roll-off bins, and paying $90.00 per bin to transport. Ideally we would be using 80yd chip vans but are limited by the dumping height of the dump wagon. Because of the relatively short haul distances our transportation costs were not a function of miles, thus the transportation cost is based on the tons/ bin transported and tons/hr harvested. Haul distances over 42 miles would be charged on a per mile basis. Average values for tons/ bin and costs are found in Table 8.

Table 8: Transportation Bin Average
Bin transportation costs from site to market based on cost/ton and cost/PMH. Average and projected utilization rates for each site were used to determine cost/PMH. $/PMH are based from a 2.6ton/hr production rate.

	Tons/Bin	**$/ton**	**$/PMH**
Site 1 Average	10.664	**$8.44**	**$9.99**
Site 2 Average	9.33	**$9.65**	**$33.34**
Overall Average	9.783	**$9.20**	**$23.92**
Chip Van	25	**$3.60**	**$9.36**

Summing the fixed, operating, and transportation costs for each scenario enabled me to calculate total costs. Site 1 resulted in a total cost of $505.81/PMH at 1.184tons/hr, Site 2 cost $390.18/PMH at 3.456 tons/hr, and overall costs of $471.99 at 2.6 tons/hr. With utilization rate of .7 the FTX 440 projected operating data was $196.12/PMH at 2.6 tons/hr. In the current market the system is not cost effective. Note this model does not include interest, insurance, taxes, or expenses to transport the harvester between work sites.

<u>Break Even Analysis</u>

The cost analysis information was then used to calculate the break-even point for the machine. Two ways the system can break even are to increase production or increase the value of the material. Figure 23 shows the relationship between production rate and the market price needed to breakeven. Overall and projected, 0.7 utilization rate, breakeven points can be calculated by dividing the total cost/PMH by the tons produced/PMH to determine the required market price to break even or by dividing the cost/PMH by the current market price of $18/ton to determine the required production to breakeven. At the current overall cost to breakeven the market would have to be $181.53/ton, or the machine would have to produce 26.22 tons/hr. Neither of these values is feasible in the near future. At the projected cost to breakeven the market would need to be $75.43/ton or the machine would need to produce 10.89 tons/hr. Just over ten tons is more realistic for the machine to achieve with modifications, as during testing production peaked at 7.22 tons/hr. With projected costs and this peak production of 7.22 tons/hr the market would need to be $27.16/ton, a high but obtainable market price.

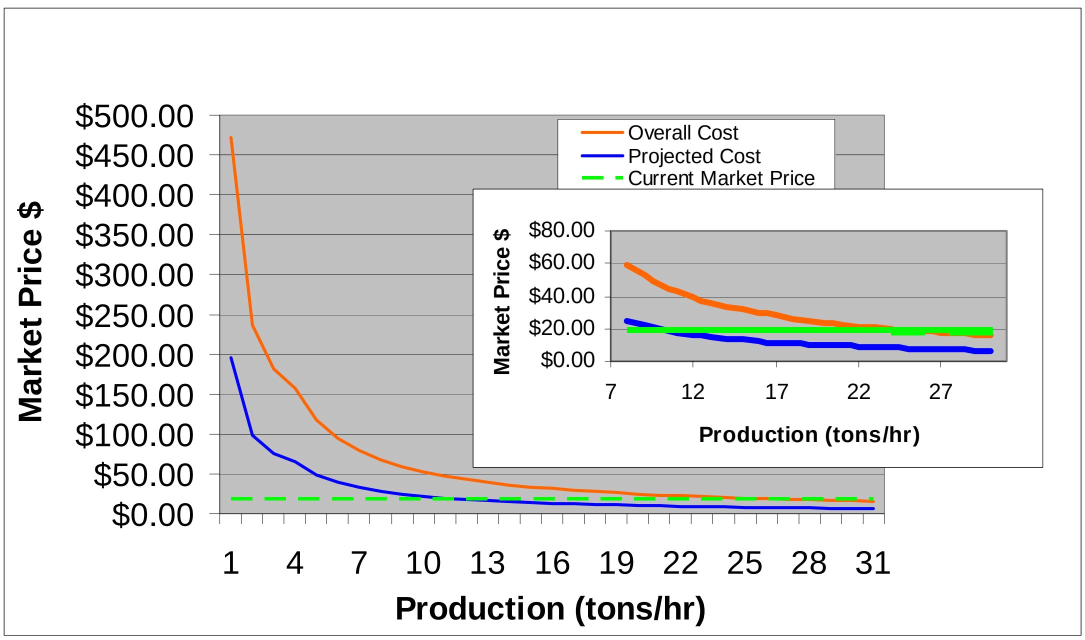

Figure 23: Production vs. Market Price Breakeven Analysis As the biomass production rate increases the required market price to break even decreases. Overall testing costs are greater than projected operating expenses and thus require a higher market to breakeven. The inset graph is an expansion of the breakeven productions given the current market.

Costs are determined on productive machine hours therefore they are a function of machine utilization. This was illustrated by the decrease in ownership costs and operating costs for overall and projected data as utilization increased. Figure 24 models the breakeven relationship of utilization verses production for a given market price of $18/green ton.

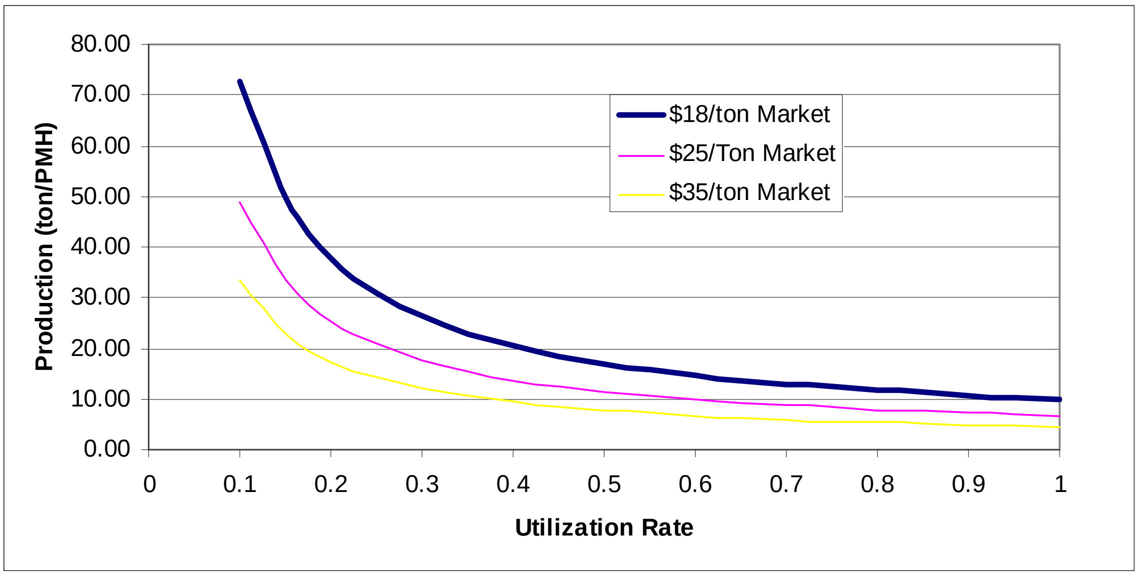

Figure 24: Utilization Rate vs. Production In a constant market, as machine utilization rate increases the required production to breakeven decreases. For $18/ton the break even production approaches 10tons/hr as utilization rate approaches 1. Increasing market prices decrease the required production to breakeven from harvesting.

In reality a combination of machine utilization, production rate, and market price will result in a cost effective machine and harvesting process. Increased production will be achieved by targeting harvesting sites, operator experience, and redesign of the harvesting head. With increasing energy prices I anticipate an increase in the material value used as wood energy for electrical power; nevertheless a dramatic material value increase most likely will not result until chemical extraction is commercially feasible for liquid fuels.

Fuel Reduction Applications

Although not currently cost effective on biomass harvesting alone, the bioharvester does show potential to offset fuel load reduction treatments. Acres which are currently considered a fire hazard due to the potential fuel load from underbrush and thick vegetation are recognized and being treated by the Forest Service and Department of Interior (DOI) and Department of Defense (DOD). Controlled burns, manual, chemical and mechanical mulching treatments are all used to reduce fuel loads. In 2008 the Forest Service and the DOI treated a total of 2,919,000 acres for fuel load reduction through the National Fire Plan and Healthy Forest programs (Healthy, 2009). In 2008 twenty-two percent of the acres which were treated utilized the biomass (Healthy, 2009). However the number of acres treated is still limited by the funds available, resulting in only those acres which are labeled the highest threat to loss of life and property if they were to ignite to be treated. At the same time, the number ofacres on wildland-urban interfaces, which pose a high threat when untreated are increasing with development.

Income from biomass can offset the cost per acre of treatment enabling more acres to be treated. The breakeven market price is no longer only a function of production tons/hr. Including fuel reduction payments, breakeven biomass market price becomes a function of both treated acres/hr and production tons/hr, notably production/hr is related to acres/hr as shown by general linear model analysis. That interdependent relationship, while observed, is not accounted for in this analysis, which is performed at specified ac/hr and ton/hr. Figure 25 shows the fuel reduction with biomass market breakeven analysis for projected costs with 0.7 utilization and field testing average 0.284 acres/hr for 3 different production rates. As production rate increases the total expenses increase per PMH due to biomass transportation costs. The Y intercept is the market price to breakeven without per acre compensation. The X intercept is based on the acres treated per hour and when fuel reduction compensation alone covers all expenses. Figure 26 shows that as treated ac/hr increases for a given production breakeven compensation, the X intercept decreases. Table 9 summarizes the additional acreage treated potential using biomass harvesting.

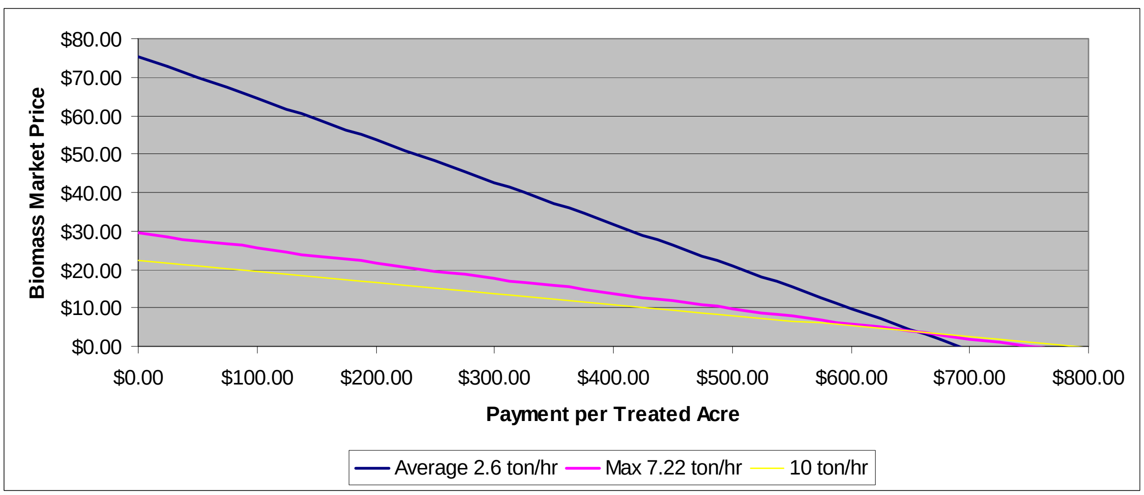

Figure 25: Fuel Reduction with Biomass Harvesting Breakeven Analysis Production Projected cost of 0.7 utilization with an average of 0.284 ac/PMH. Any combination of market price and payment per treated acre along the lines would produce a break even scenario. A biomass market price and payment per treated acre exceeding the line for a given production would yield a profit, below a deficit.

Figure 26: Fuel Reduction with Biomass Harvesting Breakeven Analysis Acres Breakeven analysis of payment per acre vs. biomass market price for 0.7 machine utilization, projected costs of treatment and removal of material, 2.6 ton/hr production and varying acres per hour treated. As time spent to treat each acre decreases the payment per acre to breakeven decreases and the negative slope of the breakeven line increases in magnitude.

Table 9: Potential for Additional Fuel Reduction Treatment Acres. Fuel reduction breakeven prices per acre are determined from Figures 25 and 26. For a set acres/hr as production increases the necessary $/ac decreases and the additional acres which can be treated increases. As acres treated/PMH increases the necessary $/ac decreases. With a budget, $1000 used as an example, this increases the number of acres which can be treated for fuel reduction. For a set production this does not increase the percentage of additional acres treated. Additional acres treated are a ratio between the offset per acre with biomass income to the cost per ac without biomass income. This ratio is not a function of ac/hr.

Fuel Reduction $/ac	Fuel Reduction ($/ac) with $18/ton Biomass market	Production (ton/PMH)	Acres Treated/PMH	Acres Treated/ $1000 Only Fuel Reduction Compensation	Acres Treated/ $1000 with Fuel Reduction and $18 Biomass Market	% increase in Acres Treated
$690.55	$525.76	2.6	0.284	1.45	1.90	31.34
$749.13	$291.52	7.22	0.284	1.33	3.43	156.97
$784.37	$150.56	10	0.284	1.27	6.64	420.95
$784.47	$597.27	2.6	0.25	1.27	1.67	31.34
$599.75	$456.63	2.6	0.327	1.67	2.19	31.34

CONCLUSION

The work on the FECON Bio-Harvester is a positive step in the direction to make small diameter woody biomass a competitive energy source and make fire fuel reduction more affordable. Our goal is to maximize the harvesting potential of this prototype and then make recommendations as to how this process can be improved. In developing this machine we understand that it alone will not solve the energy crisis, but contribute a new untapped energy resource as part of the solution to our energy needs. The potential of this work to open the energy market to hazardous forest fire fuel loads will have even greater social benefits taking a current hazard or problem and turning it into a viable solution for the current energy crisis. Current production rates averaging 2.6 tons/hr are not high enough to make the FECON Inc. Bio-Harvester economically efficient from an energy standpoint alone. However the need for fuel reduction and the development of a system which will reduce the cost for this material removal will enable the harvester to subsidize this material removal while contributing to biomass energy development. Developing a machine which can utilize natural vegetation will expose a plethora of new biomass sources which were previously unharvestable and thus unmarketable, increasing the value of the land. As a new market is opened competition between developing harvesters will result in a more efficient harvesting systems which will increase biomass contribution to solving the energy crisis. Living in a community which is continually increasing energy use, conservation alone is no longer a realistic option to prevent an energy crisis. Research to find renewable energy, such as that provided by the FECON Inc. Bio-Harvester, is critical to the future of the United States economically as well as socially.

REFERENCES CITED

Brenes, Michael. 2006. *Biomass and Bioenergy: New Research.* Nova Science Publishers, Inc, New York.

Felker, Peter. 1999. *Case Study: Development of a swath harvester for small diameter woody vegetation.* Biomass and Bioenergy 17 (1999) 1-17.

Ferrero, G.L., G. Grassi, and H.E. Williams. 1988. *Biomass Energy: From Harvesting to Storage.* Elsevier Applied Science Publishers Ltd, England.

Healthy Forests and Rangelands. 2009 *Healthy Forests Report FY2008 Accomplishments*. USDA/DOI. 1/9/2009. www.forestsandrangelands.gov

Hollander M. and D. A. Wolfe, Wiley. 1999 *Nonparametric Statistical Methods*, 2nd Edition. John Wiley and Sons Inc. United States of America.

John Deere. 2008 *Biomass Harvesting Systems Pamphlet*. JohnDeere. 2008. www.johndeere.com.

Koch, Peter and Thomas E. Savage. 1980. Development of the swathe-felling mobile chipper. J. For. 78(1):17-21.

Morris, Graig. 2006. *Energy Switch.* New Society Publishers, Canada.

Organization for Economic Co-Operation and Development (OECD). 2004. *Biomass and Agriculture.* OECD, Paris, France.

Quinn, Gerry P. and Keough, Michael J., 2002. *Experimental Design and Data Analysis for Biologists*. Cambridge University Press, Cambridge UK.

Rosillo-Calle, Peter. 2007 *The Biomass Assessment Handbook: Bioenergy for a Sustainable Environment.* Earthscan, London.

Silveira Semida. 2005. *Bioenergy-Realizing the Potential.* Elsevier, Great Britain.

Sirois D.L. 1982. *The Nicholson-Koch Mobile Chip Harvester System.* The Sixth International FPRS Industrial Wood Energy Forum ’82. Forest Products Research Society, Madison, WI p.100-105.

Smith, F.M. and J.B. O’Dair. 1980. *A Biomass Harvester*. In, Proceedings of TAPPI 1980 Annual Meeting, pp.391-400.

Supertrak Inc., *WB55 BioBaler*. Supertrak Inc. 2007. CSA corp. August 2008. www.supertrak.com.

Twidell, John and Tony Weir. 2006. *Renewable Energy Resources.* Taylor and Francis Group, London.

APPENDICES

Appendix A:

Table 10:Raw Pre-Site Sample Data

Date	Plot	Weight (lbs)	GPS pt	Ton/acre	Comments
9/7/2007	1	3.9	951	8.4942	GPS Pt 960 is a J shaped hole 8'x10'x2'
	2	10.03	952	21.84534	
	3	15.5	953	33.759	
	4	4.5	956	9.801	
	5	0.2	957	0.4356	
	6	0.7	958	1.5246	
	7	45.7	959	99.5346	
	8	15	961	32.67	
	9	5	962	10.89	
	10	4.5	963	9.801	
	11	2.1	965	4.5738	
	12	12.5	967	27.225	
9/14/2007	9	0.375	9T	0.81675	
Jasmine	6	0.875	6T	1.90575	
Lindsay	32	22.25	32T	48.4605	
	40	5.5	40T	11.979	
	5	3.5	5T	7.623	
	29	6.2	29T	13.5036	
9/15/2007	44	18	44T	39.204	Point 17 too wet to access
Jasmine	12	7.1875	12T	15.65438	
Lindsay	38	2.75	38T	5.9895	
	7	0.5625	7T	1.225125	
	24	10.3125	24T	22.46063	
	22	0.3125	22T	0.680625	
	4	0.1875	4T	0.408375	
	30	0.03125	30T	0.068063	
	28	38.9375	28T	84.80588	
	3	3	3T	6.534	
	8	2	8T	4.356	
	37	0.25	37T	0.5445	
	23	6.125	23T	13.34025	
	50	1.0625	50T	2.314125	
	34	0.1875	34T	0.408375	
	14	0.1875	14T	0.408375	
	43	1	43T	2.178	
	18	18.1875	18T	39.61238	
	15	1.6875	15T	3.675375	
9/23/2007	17	83	17T	180.774	drier conditions accessable
Barton	21	2.03125	21T	4.424063	
Lindsay	45	7.1875	45T	15.65438	
	1	4.3125	1T	9.392625	

Table 10 (continued)

	41	5.25	41T	11.4345	
9/24/2007	13	0.03125	13T	0.068063	
Barton	39	2.875	39T	6.26175	
Lindsay	46	0.8125	46T	1.769625	
	27	4.6875	27T	10.20938	
	16	1	16T	2.178	
	25	0.21875	25T	0.476438	
	48	13.96875	48T	30.42394	
	19	5.125	19T	11.16225	
	31	0.375	31T	0.81675	
	2	16.5	2T	35.937	
	26	1	26T	2.178	
9/28/2007	20	4.375	21T	9.52875	
Barton	33	7	33T	15.246	
Lindsay	47	35.5	47T	77.319	
	49	1.5	49T	3.267	
	35	1.6875	35T	3.675375	
	42	4.5625	42T	9.937125	
	36	0.09375	36T	0.204188	
	10	1.1	26	2.3958	
	11	0.1	11T	0.2178	
Mean		7.654717742		16.67198	
Stdev		13.49319613		29.38818	
95% Confidence Interval			8.525987	24.81796	
			Range	16.29198	
Site 2					
10/19/2007	47	3.625	47S	10.34	All Sites Lindsay and Barton
	27	2.25	27S	4.9005	
	8	2.1875	8S	4.764375	
	3	3	3S	6.534	
	48	3.3	48S	7.1874	
	32	2.5	32S	5.445	
	23	1.3125	23S	2.858625	
	25	1.933333333	25S	4.2108	
	45	2	45S	4.356	
	5	3.3125	5S	7.214625	
	7	0.8	7S	1.7424	
	17	1.3	17S	2.8314	
	49	11.5	49S	25.047	
	24	2	24S	4.356	
	29	3.1	29S	6.7518	
	14	0.9	14S	1.9602	
	46	12.6	46S	27.4428	
	43	3.7	43S	8.0586	

Table 10 (continued)

	22	0.1	22S	0.2178
	36	1.4	36S	3.0492
	11	0.8	11S	1.7424
10/20/2007	34	0.25	34S	0.5445
	35	0.09375	35S	0.204188
	9	0.15625	9S	0.340313
	30	2.5	30S	5.445
	13	3.125	13S	6.80625
	10	2.625	10S	5.71725
	19	6.9375	19S	15.10988
	21	5	21S	10.89
	39	4.75	39S	10.3455
	2	1.3	2S	2.8314
	26	1	26S	2.178
	12	2.625	12S	5.71725
	18	2.1	18S	4.5738
	33	1.8	33S	3.9204
	49	1.3	49S	2.8314
	16	1.2	16S	2.6136
10/21/2007	6	2.25	6S	4.9005
	44	1.2	44S	2.6136
	20	15	20S	32.67
	15	2.4375	15S	5.308875
	40	5.7	40S	12.4146
	1	2.7	1S	5.8806
	28	2.125	28S	4.62825
	50	0.8	50S	1.7424
	4	1.7	4S	3.7026
	31	0.1	31S	0.2178
	37	0.8	37S	1.7424
	38	0.8	38S	1.7424
	41	1	41S	2.178
Mean		2.739916667		6.016434
Stdev		3.013160657		6.586384
95% Confidence Interval			4.190781	7.842086
			Range	3.651305

Appendix B:

Table 11: Material Composition

		Hofmann Pocosin Veg	CWE Apr.2006 Fuel Composite
As received:			
	Moisture	47.19	42.8
	%Ash	3.2	6.16
	BTU/Lb	4853	4609
	%Sulphur	0.2	0.05
Dry Basis:			
	%Ash	6.05	10.17
	BTU/Lb	9189	8801
	%Sulphur	0.37	0.09

Appendix C:

Table 12: Operating Costs

Resources Used		Total Machine Hours	78.92	
Item	**Date**	**Quantitiy**	**Price**	**Comments**
Ramp Supplies	5-Sep		$3,145.47	
Hydrolic Oil	29-Oct	5 Gal	$37.00	Heavy Duty Trucks 440 to Dump
Hydrolics	29-Oct		$135.02	Wagon Connection
Fuel	30-Oct	62.4 Gal		Fisher Oil
Drop Light	1-Nov		$13.00	Need to see inside engine compartment
Hydrolic Oil	1-Nov	Bought 15 used 10	$103.98	
Hydrolic Oil	2-Nov	1~2		Sensor showing slightly low, no leak, may not have been refilled
Fan Belt	5-Nov	4	$99.56	Blower Belts
Drive Shaft Support	6-Nov	1		max fixed the support
Grease/ Socket	6-Nov		$16.97	
Cross Tie bolts	7-Nov	4	$5.93	For Wagon 3 spares
Hydrolic Fittings	7-Nov	1		Flapper Fittings
Fuel	7-Nov	73.3	$277.54	Read 80 Gal before 142 after $3.24/gal
Hardware	13-Nov	12	$14.95	
Hardware	15-Nov	10	$28.91	
Fuel	16-Nov	85.9	$314.70	$3.17/gal
Hardware	21-Nov	12	$35.03	
Grease	21-Nov	1 tube	$2.49	
Auger Belts	30-Nov	2	$59.98	
Blower Belts	30-Nov	4	$99.56	
Hardware	30-Nov	5	$34.18	
Fuel	3-Dec	108	$358.55	$3.11/gal
Fuel	11-Dec	113.3	$345.78	$2.859/gal
Cab Air Filter	13-Dec	1	$41.14	
Engine Air Filter	14-Dec	1	$141.04	
Blower Belts	14-Dec	4	$99.56	
Hardware	17-Dec	12	$32.03	
Fuel	19-Dec	105.2	$332.41	$2.96/gal
Fuel	21-Jan	114		
Fuel	6-Feb	116.6	$361.47	$2.904/gal
Hardware	14-Feb	12	$4.70	
Grease	14-Feb	2	$9.98	
Fan Belts	14-Feb	4	$103.96	

Table 12 (continued)

Blower Belts	14-Feb		2	$63.98	
Fuel	20-Feb		127.5	$451.19	$3.315/gal
Fuel	4-Mar		111.6	$408.75	$3.431/gal
Grease	14-Mar		2	$9.98	
Hydrolic Oil	14-Mar	10 gal		$71.92	
Fuel Filter	18-Mar		1	$28.30	
Air Filter	18-Mar		1	$141.04	
Oil Filter	18-Mar		1	$38.09	
Oil	18-Mar		10	$99.90	
Filter	21-Mar		1	$60.76	

Appendix D:

Table 13:Activity Sheets

Date	Start Time	End Time	Activity
30-Oct	10:25	10:35	Test Run 1
	10:35	10:45	idle
	10:46	10:53	loop to ramp
	10:53	11:25	move camera to see wagon
	11:25	11:30	2nd loop to ramp
	3:50	3:53	boundry line
	3:53	3:55	large tree
	4:05	4:24	arch 2 site
	4:34	4:41	stop temp low ignore
	4:42	4:55	travel
		Harvesting Time Total	0.64349155
		Machine Down Time	
		Travel	
31-Oct	9:46	9:58	Test 1 Gate 1/2 open
	10:12	10:26	Test 3 Gate All the way open
	10:30	11:15	out of woods check machine
	11:15	11:48	uncloging auger
	11:48	12:45	install tie rods on dump wagon/ harvester assembled and cleaned
	12:45	1:10	lower skidder tracks
	1:25	1:35	shapren teeth
	2:00	2:07	perimeter starting at gate
	2:07	2:18	idle
	3:20	3:24	idle/metal flagging
	3:25	3:44	resume harvesting
	3:44	3:50	reverse fan needed
	3:59	4:05	
	4:05	4:17	reversing fan
	4:17	4:28	
	4:28	4:34	switch drivers to mark/ clean vines
	4:34	4:36	harvesting
	4:36	4:38	Attach tree at an angle
	4:38	4:48	harvesting
	4:48	4:54	Fan reversing
	4:55	5:15	Travel back to ramp
		Harvesting	1.7897664

Table 13 (continued)

		Machine Down Time			
		Head MR			
		Travel			
		Wagon			
		Research			
1-Nov	8:06		9:15	Wait for Tim with Fluid and Max	
	9:15		11:52	Work on Fluid leak/ Max changed carbid and severely damaged teeth	
	11:52		1:21	Finished repair of hydroulic leak	
	3:40		3:45	Drive non productive	
	3:45		3:51	Harvesting	
	3:51		4:07	Stopped at log hydrolic leak	
	4:07		4:11	Started again/ stopped	
	4:11		4:17	102 paces from start	
	4:17		4:19	stopped because head not turning	
	4:19		4:23	harvesting	
	4:23		4:25	stopped tree in way	
	4:25		4:31	started harvesting	
	4:31		4:32	stopped to clean wound head	
	4:32		4:43	travel non productive back to start	
	4:43		5:02	stopped at start fix hydrolic	
	5:02		5:05	starting travel/ unlaod	
	5:05		5:13	harvesting	
	5:13		5:16	stopped snagged tree	
	5:16		5:17	harvesting	
	5:19		5:31	travel unloaded	
	5:31		6:11	stopped at start with head on blocks	
				End day with 572 Machine hours	
		Harvest			0
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
2-Nov	8:00		10:50	Change Hydroulic hose/ machine check	

Table 13 (continued)

	10:54		11:00	harvesting/ appeared to have blocked shoot jammed in between trees/ when backing up broke dump wagon hitch	
	11:00		11:54	open/check shoot	
	11:54		5:00	get dump wagon out	
				ended day with 4 broken fan belts	
		Harvest			0.04413769
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
6-Nov	8:00		9:16	replaced fan belts	
	9:16		9:20	turned on machine to warm up	
	9:20		9:39	vacumm test- no apparent vacumm, wind from back to front	
	9:39		10:05	started over to dump wagon, cleaning as we go	
	10:05		10:08	hooked up to trailer	
	10:08		10:30	short break to check things out	
	10:31		10:45	harvesting track speed 75%	
	10:45		10:50	stopped tree snagged wagon	
	10:50		11:08	stopped loose belts	
	11:08		11:14	break	
	11:14		11:15	dumps	
	11:15		12:00	walk over pass	
	1:13		1:27	harvest/class demo had to stop when stump b/w head and machine broke drive shaft support	
	1:27		5:30	took drive shaft support to max for strengthing	
		Harvest			0.58016637
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			

Table 13 (continued)

		Weigh/ Dump			
7-Nov	8:00		8:19	installed drive shaft support	
	8:19		8:44	warm up, maintenance move to wagon	
	8:45		8:49	hitched wagon/ 572 machine hours	
	8:49		9:02	walked it back to start	
	9:02		9:22	harvesting	
	9:22		10:57	stopped wagon broke tie rod	
	10:57		11:20	testing without wagon (head tilted all the way back, would not make wagon)	
	11:20		5:10	idle/ fixed hydrolic of chute and new cross ties	
		Harvest			0.47867093
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
8-Nov	8:00		8:30	worked on hydraulic and warm up	
	8:30		9:15	fixed dump wagon-hooked it on	
	9:15		9:36	travel-non productive/ to enage PTO idle just over 100 RPM	
	9:36		10:50	harvesting 50% track speed in hardwoods 3-6" not productive	
	10:50		10:56	travel-non productive to Bin	
	10:56		10:58	Weigh	
	10:58		1:27	Talking with F.S. people (Will, Doug, & Doug)	
	1:27		1:30	warm up	
	1:30		1:34	travel unloads	
	1:34		2:05	harvesting	
	2:05		2:16	snagged a limb on chute	
	2:16		2:43	harvesting	
	2:43		2:53	shut down to clean vines off machine	
	2:53		3:23	harvesting	
	3:23		3:31	gear box temp light when on/ light went off	
	3:31		4:51	harvesting	

Table 13 (continued)

	4:51		7:02	broke wagon wheel connection End of Day Machine Hours 588 Fuel 117 gal	
		Harvest			3.12199211
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
9-Nov	7:45		9:55	Max fixing Dump Wagon (fix/ raise tie rods) weld dump wagon	
	9:55		10:30	Take apart dump wagon hydrolic	
	10:30		10:50	Sharpen Teeth (Max)	
	10:50		12:30	hydrolic O-rings/ waiting on Tim to look/ Max ordered	
	12:30		12:47	lunch/ idle Fuel 116 MH 588	
	12:47		12:50	moving w/o cutting	
	12:50		1:23	harvesting 40% track speed - broke dump wagon wheel caught on tree	
	1:23		3:32	switch/replace tie rod in field	
	2:32		2:39	reattach wagon	
	2:39		2:47	travel back to work area	
		Harvest			0.19377382
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
12-Nov	11:15		11:26	warm up/idle	
	11:26		11:35	loop to bin to dump wagon	
	11:35		11:45	scales under tires/ dump	
		Harvest			
		Clean Up			
		Travel			
		MR 440			

Table 13 (continued)

		MR Wagon			
		Research			
		Weigh/ Dump			
13-Nov	1:30		2:18	reassemble tongue of wagon machine warm up bolts added to front	
	2:18		2:33	gate MH 591, Fuel 108	
	2:33		2:35	Travel to Min Perimeter flagging w/o harvesting	
	2:38		3:58	harvesting (20% track in pines near road/ 40% track/55% track for tight turn near metal)	
	3:58		4:22	Clean machine Align Scales	
	4:22		4:30	Weighing and Dumping/ MH594 Fuel 97	
		Harvest			0.52717177
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
14-Nov	8:11		8:19	machine idle	
	8:19		10:01	harvesting	
	10:01		10:30	look at gate call roise	
	10:30		10:40	weigh	
	1:45		5:30	Decide to remove gate / MH 596/ Fuel 85 gal	
		Harvest			0.78207993
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
15-Nov				Reinstall front Gate/ Rain	
		Head MR			

Table 13 (continued)

16-Nov	8:40		9:07	idle MH 600 Fuel 89
	9:07		9:08	harvesting
	9:08		11:50	take apart auger, clean out, reassemble, clean up tools/ operating at 50% track speed
	11:50		12:12	idle/move and attach wagon/ head tilted forward
	12:12		1:46	harvesting
	1:46		1:54	bent tie rod cut stump down
	1:54		2:04	harvesting
	2:04		2:35	move to weigh and dump wagon cut tree in way
	2:50		3:00	Fueling 61 gal on gage before fueling, Took 85.9 gal, reads 142 gallons
	3:35		5:18	harvesting
	5:18			stuck on root w/ dump wagon/ MH 605/ Fuel 137
		Harvest		2.71778089
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
11-19 Till 11-26		No Harvesting Thanksgiving		
27-Nov	2:35		4:05	Harvesting
		Harvesting Time		0.23641976
28-Nov	8:34		9:50	idle/dump
	9:50		10:47	harvesting
	11:04		11:40	harvesting
	11:40		12:30	Change Tie Rod
	12:30		12:43	harvesting
	12:43		1:07	Dumping/Moving Trailer had to disconnect hitch to get around bin
	2:35		2:37	Start up
	2:37		3:39	Fan Belt's Smoking Blower Clogged
	2:39		3:01	Clean Blower

Table 13 (continued)

	3:01		3:02	Start Blower
	3:02		3:05	Travel-dead head
	3:05		4:28	harvesting
	4:28		4:30	approach bin
	4:30		4:38	
	4:38		4:39	Dump
	4:39		5:00	Cool Down
		Harvest		1.97915582
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
29-Nov	8:00		10:15	Talk with Max
	10:15		12:00	Weekly Maintenance
	2:10		2:27	Harvesting
	3:00		3:18	Fix Blower
	3:18		3:20	warm-up/ move to site
	3:20		4:03	harvesting
	4:03		4:06	vines on shoot/check front
	4:06		4:24	harvesting
	4:37		4:40	weigh and dump
		Harvest		1.09987627
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
30-Nov	8:00		9:45	Oil in Engine, Tighten Fan Belts, Missing Bolt inside Head, screws offset
	9:45		10:10	shoot design
	10:10		11:23	Time Getting supplies cleaning tractor, improving site, install shoot
	11:23		11:37	idle/move to site
	11:37		11:40	harvesting
	11:40		12:45	Cleaned fan

Table 13 (continued)

	12:45		1:24	Lunch
	1:24		1:37	move to reattach wagon
	1:37		2:16	nothing blowing open top of blower shoot clogged
	2:16		2:27	harvesting/testing shoot
	2:27		2:54	fixing/improving shoot
	2:54		3:00	harvesting shoot sagging
	3:00		3:15	Remove shoot
	3:16		3:33	Harvest
	3:33		3:46	chainsaw
	3:46		4:37	harvesting
	4:48		5:00	Weigh and Dump
		Harvest		0.65202807
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
3-Dec	8:00		3:38	Prep for Tu Put on rest of new teeth
	3:38		3:42	warm up to make a short test
	3:42		3:46	travel
	3:46		4:12	Harvest
	4:12		4:17	travel
	4:17		4:27	Weigh
	4:27		4:28	
		Harvest		0.22571139
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
4-Dec	10:04		10:35	Harvesting
	10:35		10:54	Weigh and Dump
	10:54		11:14	Travel to plantation to find row
	11:14		11:46	Harvesting row in plantation
	11:50		12:00	Dump Wagon
	12:00		12:30	Talking

Table 13 (continued)

	2:11	2:18	idle machine
	2:19	2:22	harvesting
	2:22	2:25	Release dump wagon
	2:25	3:06	harvesting
	3:20	3:31	Dump Wagon
	3:31	4:00	harvesting
	4:00	4:37	Change Bent Tie Rod
	4:37	4:50	harvesting
	5:00	5:20	Dump Wagon/shut down
		Harvest	0.14632049
		Clean Up	
		Travel	
		MR 440	
		Head MR	
		MR Wagon	
		Research	
		Weigh/ Dump	
5-Dec	7:50	8:10	Load and remove Bin 2
	8:15	9:00	Max sharpen Teeth, Tim air compressor on filter, Lindsay truck signs and add 1/2 gal engine oil
	8:45	12:00	Max attach bumper
	8:10	9:35	delivery time of Bin 2 to return to site
	10:20	10:37	clean up areas w/ tractor, No wagon collection
	10:37	12:30	unjam auger and tighten belts jammed auger both sides smoking 80% track speed
	1:30	1:44	machine start reattach dump wagon
	1:44	2:20	harvesting caught bumper on tree
	2:20	2:50	uncatch wagon remove and back into it at new angle
	2:50	3:55	harvesting caught bumper on tree
	3:55	4:30	dump weigh idle
		Harvest	0
		Clean Up	
		Travel	
		MR 440	
		Head MR	
		MR Wagon	
		Research	

Table 13 (continued)

		Weigh/ Dump		
6-Dec				No Harvesting Last FOR 505 Class
7-Dec	8:00		8:40	maintenance
	8:40		8:46	warm up
	8:46		8:47	Travel
	8:47		8:51	Harvest 24 sec of back up
	8:51		9:04	log wedged in wagon
	9:04		9:24	Harvest 67 sec of back up
	9:29		9:36	stopped to cut down dangerous tree, no break or other problem
	9:36		10:51	Harvest 7.3 min of back up
	10:51		10:53	Stopped to get around pine tree
	10:53		10:57	Harvest/travel 15 sec back up
	10:57		10:59	travel to bin
	10:59		11:10	weigh/dump
	11:10		11:18	Replace string in hip chain
	11:18		11:19	Travel
	11:19		12:46	Harvest 4.9 min of back up
	12:46		12:47	removed log from hoses
	12:47		12:58	Harvest 11 sec backup
	12:58		1:02	travel to bins
	1:02		1:03	weigh/dump
	1:03		3:38	Go to movie theather side to mark area
	3:38		3:43	Warm up machine
	3:43		3:46	Travel
	3:46		4:44	Harvest 4.35 min of back up
	4:44		4:47	Travel
	4:47		5:04	weigh/dump
		Harvest		5.09958208
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
10-Dec				Tim Cleaning Site on his own no data collected no wagon
11-Dec	3:30		3:40	start idle attach
	3:40		4:53	Head on cleanup/ harvest too dark to continue

Table 13 (continued)

		Harvest			0.25715548
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
12-Dec	9:15		9:24	Idle	
	9:24		9:56	Cleanup 10 acres/harvesting	
	9:56		10:15	large tree downed harvesting	
	10:15		10:20	inspect site	
	10:20		10:35	harvesting smoke on red oak	
	10:35		10:50	travel out of woods weigh and dump	
	10:50		12:00	Unplug	
	1:10		2:10	cleanup / start harvesting outside of 10 acres	
	2:10		3:47	Weigh wagon full and empty w/ bumper	
	3:47		3:51	idle/move to harvesting	
	3:51		5:10	harvesting	
	5:10		5:30	travel back to ramp in dark	
		Harvest			3.11122499
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
13-Dec	8:30		11:30	Max helping fix wagon roof	
	11:30		12:30	Fix reversing Fan w/ max, replace cab filter, order C13 filter and 4 new belts	
	12:30		1:00	Rivots in wagon roof	
	2:00		2:15	Weigh Wagon	
	2:15		2:22	Clean up	
	2:22		3:44	harvesting 3.26 min of backup	
	3:44		4:54	stopped snagged a stump with tie rod bent tie rod	
	4:54		5:04	harvesting	
		Harvest			0.7780557

Table 13 (continued)

		Clean Up Travel MR 440 Head MR MR Wagon Research Weigh/ Dump		
14-Dec				Hydraulic leak/ bent shoot no harvesting
	10:35		10:45	time from truck to enter and leave gate to pick up bin
		Head MR		
17-Dec				Too Wet from weekend rain to harvest, do not want to tear up site before demo day
	1:20		2:20	Remove all teeth from machine with max
	2:53		3:35	Put new teeth on machine
		Head MR		
18-Dec	8:13		8:42	idle/warm up machine very cold today
	8:42		8:56	travel no harvesting
	8:56		10:26	harvesting (loop around to arch 2 site)
	10:26		10:30	travel/ clean up to ramp
	10:30		10:45	weigh and dump
	10:45		10:55	Discuss new carbide teeth
	10:55		11:15	disconnect wagon level ramp area
	11:15		12:00	fix teeth which are not fully tightened on head
	12:15		12:35	Lindsay driving down road and up row
	12:35		1:15	Tim site clean up on Plantation Turn
	1:15		1:50	Lindsay travel out of plantation to ramp
	1:50		1:55	Idle
	1:55		2:50	Lunch
	2:50		3:00	idle/ install flag
	3:00		3:15	attach wagon move into site
	3:15		4:02	Harvesting
	4:02		4:14	roots under wagon chainsaw
	4:14		4:48	Harvesting
	4:48		4:51	clean up to ramp
	4:51		5:30	weigh and dump/idle

Table 13 (continued)

		Harvest			2.53473081
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
19-Dec	8:15		9:15	idle warm machine up	
	9:15		9:25	Fueling Took 105 Gallons	
	10:40		11:01	idle machine/travel to site	
	11:01		11:21	Harvesting Plantation row Demo	
	11:21		11:40	Weigh and Dump	
	1:00		1:08	idle move to harvest	
	1:08		1:48	Harvesting	
	1:48		2:00	clean up/ move to weigh and dump BIN FULL some load left in bin	
	4:20		5:30	clean up Hardwood Drain no wagon	
		Harvest			0
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
20-Dec	8:30		9:00	idle/ attach wagon (some material in wagon)	
	9:00		9:47	upon start up clogged fan, need to watch open bottom of auger end	
	9:47		9:55	clean up	
	9:55		10:15	Harvesting Auger smoking jammed right back corner	
	10:15		10:35	unjam auger/ plug shoot	
	10:35		11:11	travel back to ramp/ unclog shoot and fan	
	11:11		11:38	clean up/ travel unloaded/ shoot still clogged	
	11:38		11:45	attemp celan up/ travel	
	11:45		12:18	Harvesting	
	12:18		12:27	pulling vines off of machine	
	12:27		1:12	harvesting	

Table 13 (continued)

	1:12		1:16	clean-up go to ramp
	1:16		1:36	weigh and dump
	1:36		2:57	Lunch
	2:57		3:02	clean-up/ travel
	3:02		3:16	Harvesting till major auger smoke
	3:16		3:28	Auger bad jam
	3:28		3:36	travel w/o wagon to ramp
	3:36		6:00	work to clean auger tighten belts
		Harvest		0.2649224
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
4-Jan	2:20		2:30	start/idle
	2:30		4:01	Harvest
	4:01		5:16	Clean Auger Jam
		Harvest		0
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
9-Jan	11:30		11:50	Move to Wagon Hook up Restart Fan Jam
	11:50		12:30	Back to set remove jam
	12:30		1:00	Harvest
	1:00		1:38	Auger jam and travel back to set
	1:38		2:16	adjusted auger belts
	2:16		4:00	Harvest
	4:00		4:23	Dump "Full Load" no exact weight 2.25 tons estimated
	4:23		5:00	Clean machine
		Harvest		0
		Clean Up		
		Travel		
		MR 440		

Table 13 (continued)

		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
10-Jan	10:30		11:00	warm up and maintenance	
	11:00		1:15	Harvest	
	1:15		2:00	Dump and Level Dump BIN FULL	
	2:00		2:44	Visit with will	
		Harvest			0
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
18-Jan	1:45		2:15	Idle	
		Harvest			
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
21-Jan	8:15		9:00	idle/fuel	
		Harvest			
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
22-Jan	9:00		1:00		

Table 13 (continued)

2ND SITE					
28-Jan	8:00		8:15	Attach trailer and relocate for Bin Placement	
	12:25		12:45	warm up to operate	
	12:45		13:11	Harvest	
	13:36		13:55	harvest head tilted all the way forward	
	13:55		14:45	idle down Weigh and Dump	
	14:45		15:34	Harvest	
	15:34		15:51	Weigh and Dump	
	16:04		16:10	Jam w/ Joe	
		Harvest			0
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
29-Jan	8:00		12:00	Clean Jam	
	12:00		13:00	Maintenance	
	13:50		14:35	Harvest	
	14:37		15:44	Weigh/ Dump Clean chute	
	15:44		15:45	warm up	
	15:45		15:47	travel unloaded	
	15:47		16:22	Harvest	
	16:22		17:05	Weigh/ Dump Level Bin	
		Harvest			0
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
		Site Work			
30-Jan	8:00		9:00	move material to second site	
	9:00		10:30	walk over passes (research)	
	10:30		12:10	landing repair b/c of rain	
	12:10		13:15	Lunch	

Table 13 (continued)

	13:15		14:15	Discussion too wet on ramp to work, end day
		Harvest		
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
		Site work		
31-Jan	8:00		11:20	sand delivery/ramp work
	11:20		11:25	Idle
	11:25		11:40	Harvest
	11:40		12:41	wagon stuck in mud
	11:50		12:08	Harvest no wagon
	12:12		12:22	Harvest no wagon
	12:22		12:42	pull wagon out of mud reattach 440
	12:42		13:10	Harvest
	13:10		13:25	weigh and dump
	13:25		13:55	lunch
	13:55		13:58	idle/warm up
	13:58		14:27	Harvest
	14:27		15:45	auger jammed
	14:27		14:52	weigh and dump
	15:45		16:27	chute jammed at bent neck sides cracked flapper range of motion affected
	16:27		16:29	travel
	16:29		16:52	Harvest
		Harvest		1.58186825
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
		Site work		
1-Feb	8:00		11:20	Get 440 out w/ F.S.
	11:20		11:35	weigh and dump
	11:35		13:00	Clean machine wait on max, max fix chute

Table 13 (continued)

		Harvest		
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
		Site work		
4-Feb	8:45	9:07	Idle	
	9:07	10:00	Harvest	
	10:00	10:17	travel weigh and dump	
	11:30	12:15	Harvest	
	12:15	12:20	weigh and dump	
	12:20	15:30	wheel came off fix	
	15:30	16:50	fix bumper	
	16:50	17:10	idle cool down	
		Harvest		4.81748783
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
		Site work		
5-Feb	10:00	10:20	run for demo, jam and end	
	10:20	10:23	weigh and dump	
	10:25	11:27	clean auger	
	11:27	11:28	Harvest	
	11:28	12:00	clean shoot	
	12:45	13:14	Harvest	
	13:14	14:00	auger jam	
	14:00	14:10	weigh and dump	
	14:10	15:16	Harvest	
	15:16	15:25	weigh and dump	
	15:25	15:50	Harvest	
	15:50	17:20	fan and auger jam	
	17:20	18:00	Harvest	
	18:00	18:10	weigh and dump	
		Harvest		2.23876425

Table 13 (continued)

		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
		Site work		
6-Feb	8:30		8:46	check machine
	8:46		8:52	Idle
	8:52		8:54	head on travel
	8:54		9:09	harvesting
	9:09		9:25	bolt fell out of tie rod, new bolt and good to go
	9:25		9:32	harvesting back to ramp for fuel
	9:32		9:57	Fueling took 116.6 gallons
	9:57		10:00	warm-up/ idle
	10:00		10:11	Harvest
	10:11		10:16	loop to Bin and Dump no scales
	10:16		10:25	idle look at load
	10:26		11:21	harvesting
	11:21		12:18	unjam chute
	12:18		12:25	clean tracks and dump partial load to fill bin
	12:25		12:33	level bin BIN FULL
	12:33		12:54	Harvest to refill wagaon
	12:54		13:00	cool down machine
	13:00		14:30	rock in road/distribute
		Harvest		1.78228193
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
		Site work		
7-Feb	6:15		6:45	Bin Pick up note 4x6 in last load
	7:45		8:00	duimp wagon no scales straighten load
	8:00		8:10	idle-warm up
	8:10		9:06	harvesting
	9:06		9:30	travel back to BIN Dump no scales

Table 13 (continued)

	9:30		10:20	harvesting
	10:20		10:30	dump no scales
	10:30		11:14	harvesting
	11:14		11:25	dump no scales
	11:25		11:52	harvesting
	11:52		11:58	dump no scales
	11:58		12:30	level Bin BIN FULL
		Harvest		2.74397247
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
		Site work		
8-Feb	7:30		9:30	Bin to Craven
	7:30		9:20	machine maintenance
	9:20		10:00	harvesting
	10:00		10:09	dump no scales load 1
	10:09		10:15	Travel
	10:15		10:50	harvesting
	10:50		11:00	dump no scales
	11:00		11:40	harvesting
	11:40		11:50	dump no scales
	11:50		12:30	harvesting
	12:30		12:40	dump no scales
	12:40		12:58	harvesting
	12:58		13:03	dump no scales BIN FULL
	13:03		13:15	machine cool down and level load
		Harvest		2.99407777
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
		Site work		
11-Feb	8:00		16:00	shoot repair
		Head MR		

Table 13 (continued)

12-Feb	9:00		9:45	shovel gravel at turnaround
	9:45		10:10	disconnect wagon move bin
	10:10		10:50	reconnect wagon & check tractor
	10:50		11:30	Harvest
	11:30		11:40	walk out not running
	11:40		11:50	stop 2 phone calls
	11:50		12:00	Dump
	12:00		13:00	Lunch
	13:00		13:15	idle/check tractor
	13:15		14:00	Harvest
	14:00		14:30	dump & level bin
	14:30		14:40	harvest Blower belts sheared w/out jam
	14:40		15:40	repair belts
	15:40		17:00	Harvest
	17:00		17:30	dump & level bin
		Harvest		0.82728231
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
		Site work		
19-Feb	13:55		14:00	Idle
	14:00		14:55	run to crown and harvest
	14:55		15:00	travel & dump
	15:00		15:30	Level bin
		Harvest		1.11846815
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
		Site work		
20-Feb	10:00		10:10	Idle
	10:10		10:15	Travel
	10:15		10:45	Harvest

Table 13 (continued)

	10:45	10:50	travel to set	
	10:50	11:00	dump and level	
	14:00	14:15	"clean up" no wagon	
	14:15	14:44	Fuel	
	14:44	15:17	Harvest	
	15:17	15:23	Travel	
	15:23	15:32	weigh and dump	
	15:32	15:43	move wagon and unhook bumper hitting tire	
	15:43	16:10	clean up no wagon	
	16:10	16:18	cool down/idle machine	
		Harvest		0.55618099
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
		Site work		
21-Feb	8:00	10:00	Max straightening/fixing bumper	
	10:00	10:04	walk over pass	
	10:04	10:16	warm up/idle machine	
	10:16	10:21	travel	
	10:21	11:00	harvesting	
	11:00	11:13	travel	
	11:13	11:19	weigh and dump	
	11:19	11:30	idle/ travel no harvesting	
	11:30	12:05	harvesting	
	12:05	12:13	travel	
	12:13	12:19	weigh and dump	
	12:19	12:50	Lunch	
	12:50	13:00	travel	
	13:00	13:33	haresting 75% track speed	
	13:33	13:42	travel	
	13:42	13:49	weigh and dump	
		Harvest		1.28872024
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		

Table 13 (continued)

		Weigh/ Dump			
		Site work			
22-Feb				Bin to Craven, rain	
25-Feb				Rain	
26-Feb				Rain	
27-Feb				too wet	
28-Feb	13:00		13:15	idle/warm up check engine oil	
	13:15		13:20	Travel	
	13:20		13:58	Harvest	
	13:58		14:11	Travel	
	14:11		14:20	weigh and dump	
	14:20		14:25	talk about standing water ok so far	
	14:25		14:33	Travel	
	14:33		15:03	Harvest	
	15:03		15:08	Travel	
	15:08		15:20	weigh and dump	
	15:20		15:26	Travel	
	15:26		16:00	Harvest	
	16:00		16:06	Travel	
	16:06		16:15	weigh and dump	
	16:15		16:20	Travel	
	16:20		16:33	Harvest	
	16:33		16:36	branch caugh on shoot brace	
	16:36		16:57	harvest 100% most of time but difficult through patchy open spaces	
	16:57		17:05	Travel	
	17:05		17:13	weigh and dump	
	17:13		17:30	site clean up/ shut down	
		Harvest			2.87395474
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
		Site work			
29-Feb	10:00		10:07	idle/warm up	
	10:07		10:12	Travel	
	10:12		10:12	Harvest (need small load to fill bin)	

Table 13 (continued)

	10:12		10:32	fan jammed/not moving head back to ramp
	10:32		10:38	Travel
	10:38		11:06	harvest 80% visual imparct harvesting not going as fast
	11:06		11:14	Travel
	11:14		11:29	weight and dump
	11:29		13:50	weekly maintenance (new missing bolt on head)
	13:50		13:55	idle/warm up
	13:55		14:02	Travel
	14:02		14:28	Harvest
	14:28		15:12	auger clogged 1 to 2" material need to slow down
	15:12		15:19	Harvest
	15:19		15:30	travel out of woods aguer jammed
	15:30		16:09	umjam auger tighten belts
	16:09		16:20	weigh and dump
	16:20		16:30	cool down/shut down
		Harvest		1.42623307
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
		Site work		
3-Mar	8:00		9:00	Max fix bumper
	12:40		12:51	idle/warm up
	12:51		12:58	Travel
	12:58		13:34	harvest very windy blowing material away from wagon 75% track speed
	13:34		13:38	Travel
	13:38		13:43	weigh and dump
	13:43		14:17	talking/research
	14:17		14:24	Travel
	14:24		15:14	Harvest
	15:14		15:22	Travel
	15:22		15:28	weigh and dump
	15:28		15:37	talk/research
	15:37		15:42	Travel
	15:42		16:29	Harvest
	16:29		16:35	Travel

Table 13 (continued)

	16:35		17:00	weigh and dump tighten hydraulics on flapper	
		Harvest			3.09462105
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
		Site work			
4-Mar	8:19		8:27	idle/warm up 440	
	8:27		8:34	Travel	
	8:34		9:09	Harvest/clean up final load	
	9:09		9:19	Travel	
	9:19		9:30	weigh and dump	
		Harvest			0.83140053
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
		Site work			
Hofmann Site 1					
5-Mar	12:30		12:39	idle/warm up	
	12:39		14:04	just 440 along roadside b/w bridges no wagon	
	14:04		15:58	auger jammed/cleaned	
		Harvest			0.81881765
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
		Site work			

Table 13 (continued)

6-Mar	12:55		13:02	idle/ warm up	
	13:02		13:06	clean up/ site prep around bridge no wagon	
	13:06		13:12	attach wagon	
	13:12		13:19	site prep by hand	
	13:19		13:39	cross bridge first harvesting pass (harvest one way double track 2nd way)	
	13:39		13:44	Broken shoot hydraulics, travel out of wood/ fix hydraulics (need parts)	
	13:44		13:54	Weigh and Dump	
		Harvest			0.28672991
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
		Site work			
7-Mar	RAIN			Fix Hydraulic	
		Harvest			
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
		Site work			
No harvest 3-10 or 3-11					
12-Mar	13:00		13:15	Warm up Tractor	
	13:15		13:50	Harvest	
	13:50		14:00	Dump	
	14:00		14:20	Try to Remedy computer brightness	
	14:20		14:58	Harvest	
	14:58		15:30	Dump and Level	
	15:30		16:07	Harvest	
	16:07		16:22	Dump and level	

Table 13 (continued)

	16:22		16:54	Harvest/clean up	
	16:54		17:15	Dump and Level	
	17:15		17:30	Tighten Flapper Hoses, Attempt to clean Tracks	
		Harvest			
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
		Site work			
13-Mar	8:20		8:28	Plot Boundary	
14-Mar	10:15		12:15	Bin Delivery to Craven	
	12:30		12:40	idle/ warm up	
	12:40		12:47	Reattach wagon	
	12:47		12:51	Harvest	
	12:51		13:01	hydraulic temp too high engine auto shut down	
	13:01		13:05	Harvest back to set	
	13:05		13:14	idle till hydraulic warning manuel shut off	
	13:21		13:31	use chain to remove stick from Wagon undercarriage	
	14:48		14:51	case hydraulic temp high error code turn machine back on and let it sit	
	14:51		14:53	turn head on sit on road	
	14:53		14:58	travel to woods (head off)	
	14:58		15:14	harvest 60% track speed MAJOR JAM	
		Harvest			0.29682473
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
		Site work			

Table 13 (continued)

17-Mar	9:30		15:30	Remove Jam from fan, New Fan Belts, Grease	
	15:30		15:40	Warm up/idle	
	15:40		15:45	Dump	
	15:45		16:25	Harvest	
	16:25		16:45	Dump &level	
	16:45		17:02	Harvest	
	17:02		17:05	Clean boom Jam and Flap	
	17:05		17:45	Harvest/ clean up	
	17:45		18:00	dump &level	
	18:00		18:20	repair trailer lines/ remove debris from under trailer	
		Harvest			1.71935533
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
		Site work			
18-Mar	10:00		10:20	Warm/ Idle	
	10:20		11:30	Harvest, flapper cylinder leak	
	11:30		11:45	Dump and Level Auger clogged	
	11:45		14:00	Repair Leak and Auger Clogg	
		Harvest			1.15350264
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
		Site work			
24-Mar	7:45		14:45	Max Oil Change, Don (Fecon) computer repair	
	14:45		14:50	Idle/ warm up	
	14:50		15:00	Harvest/ Pass	
	15:00		15:50	Visit w/ Alan Goodson	
	15:50		16:00	Harvest/ Pass	
	16:00		16:20	Remove limb from trailer, Fix Flapper leak	

Table 13 (continued)

		Harvest Clean Up Travel MR 440 Head MR MR Wagon Research Weigh/ Dump Site work		
25-Mar	8:00		8:30	Add 5 Gallons Hydraulic Fluid
	8:30		8:55	Idle/ Warm up
	8:55		9:55	Harvest
	9:55		10:10	Dump
		Harvest Clean Up Travel MR 440 Head MR MR Wagon Research Weigh/ Dump Site work		
Hofmann Airstrip				
25-Mar	10:25		12:45	Move to Airpot
	10:40			Clutch engaged by itself & stopped, shut down for 2 min to disengage
	10:50			run 1300 RPM (any greater clutch self engages), Loop Temp 97, Gear Temp 96 loop PSI 670, Gear box temp low error/ falls to zero
	12:45			Gear Temp back to 95/96
	13:25		13:30	Idle/ Notes
	13:30		13:50	Harvest
	13:50		14:00	clean Head
	14:00		14:16	Harvest-1 pass
	14:16		15:15	Harvest
	15:15		17:30	unclog boom
	17:30		18:45	Harvest
	18:45		18:50	Cool Down

Table 13 (continued)

	18:50		19:00	Clean Machine	
		Harvest			1.84441362
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
		Site work			
Hofmann 3rd Site					
2-Apr	7:45		8:45	Check fluid Levels, Visual Inspect, and Walk Area	
	8:45		13:45	Move and Set Bridges	
	13:45		14:30	lunch?	
	14:30		14:40	idle/ warm up	
	14:40		15:00	Harvest No Wagon	
	15:00		16:30	Out to Road, Shut Down, reset bridges, and Walk cut area	
	16:30			Shut down	
		Harvest			0.18732105
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			
		Weigh/ Dump			
		Site work			
9-Apr	8:00		9:30	Maintenance, including tightening belts	
		Harvest			
		Clean Up			
		Travel			
		MR 440			
		Head MR			
		MR Wagon			
		Research			

Table 13 (continued)

		Weigh/ Dump		
		Site work		
10-Apr	12:57		13:06	Idle
	13:06		13:09	travel
	13:09		13:11	Head on water in fan
	13:11		13:14	head on crossing bridge
	13:14		13:32	Harvesting track speed 55%
	13:32		13:38	Cross Bridge/ idle head off
	13:38		13:52	weigh and dump
	13:52		13:56	weigh w/out load
NEW DRIVER	13:56		14:13	Driver Training
	14:13		14:24	Training Crossing Bridge/ Walking site
	14:24		14:26	harvesting/ training
	14:26		15:35	shoot and fan jammed too much duff layer
	15:35		15:40	travel
	15:40		15:55	Harvest No wagon
	15:55		15:58	Talk
	15:58		16:00	Harvest No wagon
	16:00		16:05	Travel out of woods Shoot clogged
		Harvest		0.4457021
		Clean Up		
		Travel		
		MR 440		
		Head MR		
		MR Wagon		
		Research		
		Weigh/ Dump		
		Site work		
11-Apr	10:33		10:37	idle/ warm up
	10:37		10:42	Travel
	10:42		10:46	Harvest
	10:46		12:58	clean shoot unjam fan
	12:58		13:00	Travel
	13:00		13:12	Harvest
	13:12		15:00	shoot clogged unclog
	15:00		15:30	research/talking
	15:30		15:37	travel/reattach wagon PTO auto turn on
	15:37		15:47	Harvest
	15:47		15:49	log stuck under wagon
	15:49		16:00	Harvest

Table 13 (continued)

16:00	16:19	log under wagon	
16:19	16:25	weigh and dump	
16:25	16:28	tighten hydraulics on shoot (flapper)	
16:28	16:31	Travel	
16:31	16:53	Harvest (PTO would not turn off)	
16:53	17:09	weigh and dump	
17:09	17:12	tighten hydraulics on shoot (flapper)	
17:12	17:15	Research/ Batteries in GPS	
17:15	17:20	Travel	
17:20	17:47	Harvest	
17:47	18:00	weigh and dump	
18:00	18:12	idle Cool Down	
	Harvest		0.92381221
	Clean Up		
	Travel		
	MR 440		
	Head MR		
	MR Wagon		
	Research		
	Weigh/ Dump		
	Site work		

Appendix E: SAS Output

Daily Utilization Rate SAS Code

```
data utilization;
input u site$;
datalines;
0.118 1
0.210 1
...
0.415885553 2
0.492971351 2
;
proc npar1way wilcoxon data=utilization;
var u; class site;
exact;
run;
```

Daily Utilization Rate SAS Output

```
The NPAR1WAY Procedure
                            Wilcoxon Scores (Rank Sums) for Variable u
                                  Classified by Variable site
                                   Sum of      Expected        Std Dev          Mean
               site       N        Scores      Under H0       Under H0         Score
               1         36        919.50        1008.0      56.204551     25.541667
               2         19        620.50         532.0      56.204551     32.657895
                                Average scores were used for ties.
                                     Wilcoxon Two-Sample Test
                               Statistic (S)               620.5000
                               Normal Approximation
                               Z                             1.5657
                               One-Sided Pr >  Z             0.0587
                               Two-Sided Pr > |Z|            0.1174
                               t Approximation
                               One-Sided Pr >  Z             0.0616
                               Two-Sided Pr > |Z|            0.1233
                               Exact Test
                               One-Sided Pr >=  S            0.0586
                               Two-Sided Pr >= |S - Mean|    0.1170
                            Z includes a continuity correction of 0.5.
                                        Kruskal-Wallis Test
                                    Chi-Square         2.4794
                                    DF                      1
                                    Pr > Chi-Square    0.1153
```

Production Rate SAS Code

```
data dumpwagon;
input tonperhr site$ acperhr;
datalines;
0.667911926 1      .
0.669724771 1      0.194877676
...
3.606398325 2      0.421263442
1.757152898 2      0.434421136
;
proc npar1way wilcoxon data=dumpwagon;
```

```
var tonperhr; class site;
exact;
run;
```

Production Rate SAS Output

```
The NPAR1WAY Procedure
                        Wilcoxon Scores (Rank Sums) for Variable tonperhr
                                   Classified by Variable site
                                   Sum of      Expected        Std Dev          Mean
               site        N       Scores      Under H0       Under H0         Score
               1          27        429.0         729.0      56.204982     15.888889
               2          26       1002.0         702.0      56.204982     38.538462
                                     Wilcoxon Two-Sample Test
                              Statistic (S)               1002.0000
                              Normal Approximation
                              Z                              5.3287
                              One-Sided Pr >  Z              <.0001
                              Two-Sided Pr > |Z|             <.0001
                              t Approximation
                              One-Sided Pr >  Z              <.0001
                              Two-Sided Pr > |Z|             <.0001
                              Exact Test
                              One-Sided Pr >=  S          1.519E-09
                              Two-Sided Pr >= |S - Mean|  3.039E-09

                           Z includes a continuity correction of 0.5.
                                       Kruskal-Wallis Test
                                    Chi-Square          28.4900
                                    DF                        1
                                    Pr > Chi-Square      <.0001
```

Acres per Hour Treated SAS Code

```
data activities;
input acperhr site$;
datalines;
0.352694215 1
0.352998819 1
...
0.421261649 2
0.434418654 2
;
proc npar1way wilcoxon data=activities;
var acperhr; class site;
run;
```

Acres per Hour Treated SAS Output

```
                                       The NPAR1WAY Procedure
                         Wilcoxon Scores (Rank Sums) for Variable acperhr
                                   Classified by Variable site
                                   Sum of      Expected        Std Dev          Mean
               site        N       Scores      Under H0       Under H0         Score

               1          65       2981.0        3640.0     167.051786     45.861538
               2          46       3235.0        2576.0     167.051786     70.326087
                                Average scores were used for ties.
                                    Wilcoxon Two-Sample Test
                                Statistic              3235.0000
                                Normal Approximation
                                Z                         3.9419
```

```
                    One-Sided Pr >  Z         <.0001
                    Two-Sided Pr > |Z|        <.0001
                    t Approximation
                    One-Sided Pr >  Z         <.0001
                    Two-Sided Pr > |Z|        0.0001
               Z includes a continuity correction of 0.5.
                          Kruskal-Wallis Test
                    Chi-Square              15.5621
                    DF                            1
                    Pr > Chi-Square         <.0001
```

Acres per Hour vs. Tons per Hour SAS Code

```
data dumpwagon;
input tonperhr site$ acperhr;
datalines;
0.667911926 1       .
0.669724771 1       0.194877676
…
3.606398325 2       0.421263442
1.757152898 2       0.434421136
;
goptions reset=all;
proc gplot data=dumpwagon;
plot tonperhr*acperhr;
symbol v=diamond i=r;
run;
proc glm data=dumpwagon;
model tonperhr=acperhr;
run;
```

Acres per Hour vs. Tons per Hour SAS Output

Site 1&2

```
The GLM Procedure

                             Number of Observations Read          77
                             Number of Observations Used          33
                                        The GLM Procedure
Dependent Variable: tonperhr
                                                  Sum of
       Source                      DF          Squares     Mean Square    F Value    Pr > F
       Model                        1      50.79760388     50.79760388      45.06    <.0001
       Error                       31      34.94795872      1.12735351
       Corrected Total             32      85.74556260
                      R-Square     Coeff Var      Root MSE     tonperhr Mean
                      0.592423      41.95598      1.061769          2.530674
       Source                      DF        Type I SS     Mean Square    F Value    Pr > F
       acperhr                      1      50.79760388     50.79760388      45.06    <.0001
       Source                      DF      Type III SS     Mean Square    F Value    Pr > F
       acperhr                      1      50.79760388     50.79760388      45.06    <.0001
                                                      Standard
                Parameter         Estimate             Error    t Value    Pr > |t|
                Intercept      0.016522148        0.41766442       0.04      0.9687
                acperhr        8.449232490        1.25871007       6.71      <.0001
```

Site 1

```
The GLM Procedure
                             Number of Observations Read          33
                             Number of Observations Used          13
                                        The GLM Procedure
```

Dependent Variable: tonperhr

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	1.26614190	1.26614190	24.90	0.0004
Error	11	0.55931861	0.05084715		
Corrected Total	12	1.82546051			

R-Square	Coeff Var	Root MSE	tonperhr Mean
0.693601	22.48149	0.225493	1.003017

Source	DF	Type I SS	Mean Square	F Value	Pr > F
acperhr	1	1.26614190	1.26614190	24.90	0.0004

Source	DF	Type III SS	Mean Square	F Value	Pr > F
acperhr	1	1.26614190	1.26614190	24.90	0.0004

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	0.093170395	0.19275858	0.48	0.6383
acperhr	4.862306271	0.97439358	4.99	0.0004

Site 2

The GLM Procedure

Number of Observations Read	44
Number of Observations Used	20

The GLM Procedure

Dependent Variable: tonperhr

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	11.47635566	11.47635566	9.23	0.0071
Error	18	22.38510336	1.24361685		
Corrected Total	19	33.86145902			

R-Square	Coeff Var	Root MSE	tonperhr Mean
0.338921	31.64830	1.115176	3.523651

Source	DF	Type I SS	Mean Square	F Value	Pr > F
acperhr	1	11.47635566	11.47635566	9.23	0.0071

Source	DF	Type III SS	Mean Square	F Value	Pr > F
acperhr	1	11.47635566	11.47635566	9.23	0.0071

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	1.536306767	0.70011867	2.19	0.0416
acperhr	5.380739663	1.77126394	3.04	0.0071