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Production and Economic Analyses of Woody Biomass Utilization for Energy

John Edward Vance

West Virginia University, jvance11@mix.wvu.edu

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Production and Economic Analyses of Woody Biomass Utilization for Energy

John E. Vance

Thesis submitted
to the Davis College of Agriculture, Natural Resources and Design
at West Virginia University

in partial fulfillment of the requirements for the degree of
Master of Science in Forestry

Jingxin Wang, Ph.D., Chair
Shawn Grushecky, Ph.D.
Joseph Moritz, Ph.D.

Division of Forestry and Natural Resources

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Keywords:
Biomass, Bioenergy, Machine rate, Time-motion study, Cost analysis, Spatial analysis

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ABSTRACT

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John E. Vance

A mechanized harvest system combined with whole-tree chipper producing mixed hardwood chips was investigated on two harvesting sites in the central Appalachian region, USA. Production and machine rate data of the operations were collected through time-motion study, with chipping time elements categorized into feeding, chipping, and loading. Chipping cycles averaged 21.5 minutes to produce 23.54 green tons per truckload, providing an hourly rate of 65.82 green tons/PMH (41.1 dry tons) by the whole-tree chipper. Total cycle time including truck delivery averaged 183 minutes, giving an hourly rate of 7.7 green tons/PMH (4.8 dry tons/PMH). The hourly cost of the harvesting system including one feller-buncher, two grapple skidders, and the chipper was \$376/PMH, the chipper alone has hourly rate of \$ 72/PMH. Given the hourly rate and production chipping alone cost \$ 4.89/cunit or \$ 1.09/green ton (\$ 1.75/dry ton). Combined unit cost including felling, skidding, and chipping gives a total cost of \$ 50.68/cunit or \$ 11.34/green ton (\$ 18.14/dry ton) to produce in-woods chips at the landing. Total operational costs for felling, skidding, chipping, and truck delivery is estimated at \$ 13 to \$ 17 per green ton or \$ 21 to \$ 27 per dry ton dependent upon transportation cost. Chips were sampled from the operations to characterize properties and evaluate whole-tree chips as a bioenergy feedstock according to ANSI Standard AD17225-4:2014 *Solid Biofuels*. Results of properties testing indicated 37.5% green moisture, 0.212 g/cm³ bulk density, 10.5% bark content, 0.49 % ash, and 7,992.5 Btu/lb calorific heating value. These whole-tree chips were found to meet the highest grade A1 requirements of the U.S. wood chip fuel quality standard.

A techno-economic feasibility assessment was conducted for use of woody biomass as an energy source in poultry production, which is one of the largest agriculture industries in West Virginia and also one of the largest consumers of liquid propane in the state. Woody biomass availability and integration was assessed based on wood chip production and characteristics results along with data acquired through a survey of local industrial poultry growers to determine energy and heating requirements of the poultry operations. Average current propane consumption from survey results was 7,036 gallons per year per poultry house. Wood fuel consumption for a wood boiler system to supply heat to a single poultry house was estimated at 85 tons of green wood chips or 45 tons of wood pellets. It was determined that at current local market conditions of \$1.04 per gallon propane an average annual fuel cost savings of \$2,885 could be achieved with \$35 per ton wood chips, while wood pellets at a cost of \$180 per ton were found to have break-even cost with \$1.30 per gallon propane.

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1. Introduction

1.1 Overall Review

West Virginia is the third most heavily forested state in the U.S., and has an ample availability of woody biomass throughout the state as a by-product of forest harvesting and forest product manufacturing (Spong et al. 2017). Currently the majority of this biomass is considered as residue or waste and very little is utilized in any manner. This abundance of wood residue has great potential as an alternative energy source in West Virginia. This research will contain two objectives: the first will be to examine the production rates, harvesting costs, and transportation costs and logistics of a mechanized harvesting system, whole tree chipping operation, and truck transportation in a harvesting system that produces woody biomass in the form of wood chips from mixed hardwood forest. The time-motion study will look for methods to maximize economic feasibility by examining for procedures to maximize efficiency and minimize cost of harvesting, collection, and transportation of forest woody biomass while wood chips will be characterized for physical and energy properties. The second objective will evaluate potential utilization of woody biomass as an energy source in the poultry industry in eastern West Virginia. An assessment of the wood energy potential and biomass availability will serve as the groundwork for further developing a wood energy component in West Virginia.

Woody biomass can be defined as trees and other woody plants, and the parts thereof including limbs, tops, and other woody parts which are grown in a forest or woodlot, and are the by-products of forest harvesting and forest product manufacture. On the other hand, short rotation woody crops (SRWCs) such as hybrid willow has been specifically grown on marginal agricultural land or abandoned mine land for bioenergy feedstocks. Woody biomass has a multitude of potential uses including paper and pulp, engineered lumber, bio-energy and other value added bio-products (Norton et al. 2003). Woody biomass can be processed into many

forms including chips, grindings, and hog fuel. Finding feasible uses for forest woody biomass can help to reduce or offset the cost of forest management and timber stand improvement treatments especially in young stands when little or none of the harvested stems are large enough for the saw-timber market. While there are numerous potential uses for biomass the utilization portion of this research will focus primarily on the potential of bioenergy from woody biomass in the poultry production industry.

Wood fuel is generally in the form of wood chips or wood pellets. Wood chips are wood chipped into small pieces by a machine and are still in a more natural form compared to pellets. Wood chips are generally less expensive and well suited for use in large scale heating systems. Wood chip quality can be affected by the chip variety which is usually considered as “clean” or “dirty”, dirty meaning the chips contain bark and clean meaning the wood was debarked before chipping (Urquhart and Boyce 2008). Chip quality and ultimately the price can also be affected by other factors such as the species composition, moisture content, and for energy usage, the calorific heating value (energy content) is an important factor. Wood pellets are a manufactured form of wood fuel as pellets are a ground wood material densified into a pellet. Pellets are more expensive than chips because of the manufacturing process necessary to produce pellets. While pellets are more expensive there are still benefits to using pellets compared to chips given that pellets are nearly moisture free and contain more energy and heating value per unit than green wood chips. Because pellets are available in both small 40 pound individual bags as well as bulk containers or truckload volumes, pellets are also usable in residential systems, while chips are not since chips are only available in bulk truckload volumes and not smaller individual packages. When choosing a heating system and fuel type one must consider the scale and size of the individual application and weigh the advantages and disadvantages of each fuel type and their

respective fuel system based upon local availability, prices, maintenance requirements, and system operation.

In-woods chipping operations have traditionally been in the form of integrating a chipper as an addition to a mechanized harvesting system producing roundwood. Recently interest has increased in harvesting systems committed exclusively to chipping as the market increases for chips and other byproducts. The addition of the chipper allows for the collection of forest residues such as tops, limbs, and small-diameter stems which would otherwise be left unused. Collecting these forest logging residues also can help to generate additional income and make an impact on the economic feasibility of harvesting in some stands, especially young stands where harvesting is needed for timber stand improvement thinnings but the harvested stems are not of merchantable size for the sawtimber market.

The logistics of whole-tree chipping operations and transportation need to be explored in order to find the most cost effective method to process, transport, and store chips from the fuel source to poultry farm so that the wood heating system can be competitive with traditional propane systems. Some of the logistics that will need to be assessed include the rate at which chips must be produced in order for the harvesting operation to be profitable. Various transportation routes must be explored to identify the most cost efficient route to transport chips in terms of fuel cost, time, and distance. On-site storage structures and capacities must be evaluated in order to maintain a constant supply of available fuel on-site. On-site storage is necessary to allow the poultry farmer to take advantage of favorable pricing of chips and also to ensure adequate fuel supply during winter months when more fuel is required.

Poultry production houses will be targeted for wood energy conversion because the poultry industry is one of the largest agriculture industries in the state of West Virginia and poultry

production houses are large consumers of propane. Poultry production houses require large amounts of energy to produce heat as the interior temperature of poultry houses must remain approximately 80 to 90 degrees Fahrenheit at all times when chickens are being brooded and grown. It is intended that wood energy can be supplemental during the brooding stage when higher temperatures are required, but that during grow-out stage the required temperature can be achieved exclusively by the wood heating system. Addressing something like wood energy for poultry house heating can reduce the moisture content and humidity levels within the house and improve the bird mortality rate and meat quality as well.

1.2 Problem Statement

At current market conditions it is difficult for wood based fuels to compete with traditional fossil fuels, and therefore little of the available woody biomass in the region is utilized in any manner. The objective of this research is to explore and implement feasible methods for harvest, transportation, and utilization of biomass feedstock as an alternative fuel source to traditional fuels. The utilization segment of the study will primarily target the bioenergy uses and specifically poultry production houses, which are the largest agricultural industry in West Virginia and are large consumers of liquid propane and heating oil fuels.

1.3 Objectives

- 1) Evaluate the feasibility and logistics of in-woods whole-tree hardwood chipping operation combined with mechanized harvesting and truck transportation through time-motion study methods. Develop models of harvesting cost, production rate, and transportation cost for chipping operation. Determine wood physical and chemical properties and characteristics of whole-tree hardwood chips sampled from the time study operation and evaluate chips for use as a wood fuel.

- 2) Work in cooperation with the West Virginia Statewide Wood Energy Team on assessment of woody biomass as an energy feedstock, with special interest of wood energy utilization in the poultry production industry.
 - a. Biomass availability and integration assessment
 - b. Transportation and processing logistics
 - c. Techno-economic feasibility of wood energy in the poultry industry

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2. Analysis of Chipping Operation and Chip Quality from Mixed Hardwood Forest

Abstract

A mechanized harvest system combined with whole-tree chipper producing mixed hardwood chips was investigated on two harvesting sites in eastern Ohio, USA within the central Appalachian region. Production and machine rate data of the operations were collected through time-motion study, with chipping time elements categorized into feeding, chipping, and loading. Chipping cycles averaged 21.5 minutes to produce 23.54 green tons per truckload, providing an hourly rate of 65.82 green tons/PMH (41.1 dry tons) by the whole-tree chipper. Total cycle time including truck delivery averaged 183 minutes, giving an hourly rate of 7.7 green tons/PMH (4.8 dry tons/PMH). The hourly cost of the harvesting system including one feller-buncher, two grapple skidders, and the chipper was \$376/PMH, the chipper alone has hourly rate of \$ 72/PMH. Given the hourly rate and production chipping alone cost \$ 4.89/cunit or \$ 1.09/green ton (\$ 1.75/dry ton). Combined unit cost including felling, skidding, and chipping gives a total cost of \$ 50.68/cunit or \$ 11.34/green ton (\$ 18.14/dry ton) to produce in-woods chips at the landing. Total operational costs for felling, skidding, chipping, and truck delivery is estimated at \$ 13 to \$ 17 per green ton or \$ 21 to \$ 27 per dry ton dependent upon transportation cost. Chips were sampled from the operations to characterize properties and evaluate whole-tree chips as a bioenergy feedstock according to ANSI Standard AD17225-4:2014 Solid Biofuels. Results of properties testing indicated 37.5% green moisture, 0.212 g/cm³ bulk density, 10.5% bark content, 0.49 % ash, and 7,992.5 Btu/lb calorific heating value. Size distribution of wood chips were categorized into small (3-16mm), medium (16-45mm), and large (45-63mm). Chip sizes captured 46% for small, 45% for medium, and 3% for large by total mass, respectively. Fines (<2.8mm) composed less than 1% while 4.5% were oversized (>63mm). These whole-tree chips were found to meet the highest grade A1 requirements of the U.S. wood chip fuel quality standard.

2.1 Introduction

2.1.1 Biomass Harvesting Systems

There have been numerous studies of the production rate and associated cost of timber harvesting systems in West Virginia ranging from manual felling operations to mechanized harvesting (Wang et al. 2004a, Wang et al. 2004b). However, there has been little focus in the area of integrating in-woods chipping operations as an addition to roundwood harvesting systems in the Appalachian region. In the southern pine region many studies have shown the ability to capture additional revenue through harvest and collection of material that is otherwise left as a wasted byproduct of timber harvest. Incorporating these forest residue collection methods such as in-woods chipping into timber harvesting practices in the central Appalachian region could help loggers to capture additional revenue during timber harvest and help to further develop a market for wood residues as biofuels or other value-added products.

Baker et al. (2010) found that biomass chipping with a small chipper appears feasible at roundwood to chip ratios between 3:1 and 6:1 where 30 t ha⁻¹ or less is recovered, they concluded that a higher ratio underutilized the chipper and a lower ratio reduced roundwood production. Pairing a small chipper with a roundwood operation was found to be most feasible in a clearcut harvest operation as opposed to thinnings where roundwood production is challenged by tight operating space (Baker et al. 2010). Studies in Echols County, GA examining three combinations of treatments for roundwood and chip harvesting found significant differences between the chip yield for treatments of chipping only tops and limbs, 3.8 tons per acre, compared to chipping tops, limbs, and understory, 10.8 tons per acre, with both treatments being an addition to roundwood harvest, the study concluded that roundwood production is minimally

affected by the addition of a small chipper to a ground based harvesting system (Westbrook et al. 2006).

For small scale operations that cannot fully commit to chip harvesting alone chipping attachments and temporary conversion kits for traditional harvesting equipment have been explored to allow periodical chipping by traditional harvesting crews. Temporary conversion of a John Deere forager with a Pezzolato chipping conversion kit was assessed for performance and cost in comparison to traditional chipping machines (Manzone and Spinelli 2013). Manzone and Spinelli (2013) found that the converted forager proved to be as effective and efficient as an equally sized traditional chipper and could be advantageous to operations that only utilize a chipper part-time.

Aman et al. (2011) compared three biomass harvesting systems including both horizontal grinders and whole tree chippers, concluding that utilization rate of whole tree chippers, 44%, was slightly higher than that of horizontal grinders, 38%. Trucking transportation delays were found to have the most significant impact on production rates across all 3 operational systems (Aman et al. 2011). A data pool of 63 chipping production studies found the average total delay factor to be 38.7% and average machine utilization rate to be 73.8% across 524 hours of pooled observations (Spinelli and Visser 2009). Observation of a drum chipper for chipper knife wear found that knife wear resulted in reduced productivity and deterioration of product quality (Spinelli et al. 2014).

The total delivered cost of producing chips is a function of the fixed and operational costs as well as the machine utilization rate and the production rate. It is widely accepted that the most cost effective method of collecting forest logging residue is to extract the material to a roadside landing at time of primary harvest, for the reason that a secondary harvest to collect the debris

from the felling area results in low productivity and is very cost inefficient. An economic analysis of three roadside chipping operations concluded roadside chipping an economically feasible method of collecting logging residue (Desrochers et al. 1993).

Assessment of bioenergy production from hardwood residues in Appalachia found that wood residues from the region could yield 927 to 1,537 million liters of ethanol production to the bioeconomy development in the region (Adebayo and Wang 2012). Through working with commercial partners for improving harvesting efficiency and biomass quality, a 30% cost reduction was achieved for cut-and-chip biomass harvesting of shrub willow in the Northeast U.S. (Eisenbies 2014). There is great potential to further the bioeconomy through improved efficiency and utilization of biomass harvesting in the Appalachian region.

2.1.2 Wood Chip Properties

An assessment of hardwood red oak and yellow poplar logging residue in Appalachia found no significant difference in heating value of heartwood and sapwood of decayed and undecayed samples (Adebayo et al. 2009). Heat value was reported at 7.71 to 7.99 kJ for yellow poplar and 7.82 to 8.10 kJ for red oak. Volatile matter was 80.27 and 81.5 with ash content of 0.62 and 0.58 for undecayed yellow-poplar and red oak logging residue, respectively. A study of shrub willow traits among cultivars and harvest sites found that ash content was significantly different among genotypes, harvest sites, and the interaction of genotype and harvest site (Serapiglia et al. 2012). A comparison of wood chip piece distribution of poplar stems and tops found that the majority of chips are in the medium size class (8 – 16 mm.) including 55.6 percent of the chips from stems and 52.1 percent of the chips from tops (Assirelli et al. 2013).

2.1.3 Transportation and Storage Logistics

Transportation and storage logistics play an important role in making a biomass feedstock supply chain efficient and economically feasible. It is widely known that maximizing payload is one of the best ways of reducing transportation cost, green wood also has a high moisture content thus reducing the efficiency of transporting long distances. An Australian study found that of the annual savings due to optimizing transport of wood chips from in-woods chipping operations 52% of those savings were a direct result of increasing payload (Acuna et al. 2012). Acuna et al. (2012) determined that a 6-ton increase in payload reduced transportation cost by \$1.2 per ton. A study in southern West Virginia found the average market distance at 123 miles from harvesting sites for biomass residue with transportation cost of \$148.20/cunit for class 3 trucks (Grushecky et al. 2007). Grushecky et al. (2007) simulations found that both skidding and hauling distance had an impact on residue extraction levels and transportation cost.

2.2 Methods and Data for Time-motion Study

Production and machine rate data collection for the time-and-motion study portion of this research was performed in cooperation with a commercial in-woods whole tree chipping operation combined with mechanized timber harvest in eastern Ohio. The field study was conducted during summer and fall 2015 across two harvest locations near Zanesville, OH and Gnadenhutten, OH to analyze whole-tree chipping cost, production rate, and fuel characteristics of the chips. The first harvest site, Zanesville, was a 275-acre private owned farm with two harvest methods, a clearcut of 54 acres and a partial cut of 28 acres. The second harvest site was a several thousand-acre surface mine property using a harvest method of 40 acre clearcut sections ahead of the mining operation. Species composition of both harvest sites was very similar containing mixed Appalachian hardwood species including red maple (*Acer rubrum*), red

oak (*Quercus rubra*), American beech (*Fagus grandifolia*), pignut hickory (*Carya glabra*), white oak (*Quercus alba*) (**Table 2.1**). The whole-tree chipping operation which was evaluated comprised a fully mechanized harvesting system of one Timbco 425 feller-buncher, two grapple skidders, Caterpillar 525C and John Deere 648GIII, and a Morbark 27RXL whole-tree chipper with self-contained knuckle-boom loader. The product is transported from the harvesting site to the destination by three semi-trucks with chip van trailers, and an additional trailer was placed at the harvest site and relocated by the skidder at the Zanesville site in order to subsidize the longer hauling distance. Production and cost for the chipping operation was analyzed using the machine rate method (Miyata 1980).

Table 2.1. Composition of major species by percentage of stem count.

Species	Percent of stems
Red maple (<i>Acer rubrum</i>)	25.3
Red oak (<i>Quercus rubra</i>)	17.7
American beech (<i>Fagus grandifolia</i>)	11.6
White oak (<i>Quercus alba</i>)	8.0
Hickory (<i>Carya glabra</i>)	7.9
Blackgum (<i>Nyssa sylvatica</i>)	7.0
Yellow poplar (<i>Liriodendron tulipifera</i>)	3.2
Sweet cherry (<i>Prunus avium</i>)	2.9
Sugar maple (<i>Acer saccharum</i>)	2.7
Yellow birch (<i>Betula alleghaniensis</i>)	2.6

2.2.1 Chipping

For time study purposes the functions of the chipper will be broken into major cycles and minor cycles. A major cycle for chipping will be defined as each time period in which one chip van trailer of chips is processed by the chipper, loaded, transported, unloaded, and truck returns empty. Data collected for major cycles include the chipping time, trucking time, hauling distance, and payload to determine the hourly production rate of the chipping operation including delivery. There are five elements to compose a major cycle 1) chipping, 2) loading 3) travel loaded 4) unload 5) travel empty. A minor cycle is defined as each knuckle-boom grapple of

stems that is processed through the chipper, each minor cycle starts when the operator begins to lift the stem with the grapple and concludes when the subsequent chips are loaded into the trailer. The chipper was observed for a duration of 49 major truckload cycles of production. Elemental time functions of the chipper consist of 1) *grappling* 2) *feeding/chipping process*, and 3) *loading*. Function 1 *grappling* is defined as the time spent maneuvering stems into the chipper with the attached knuckle-boom grapple, this function begins when the operator begins to lift the stem with the grapple and stops when it is released by the grapple into the feeding mechanism of the chipper. Function 2 *feeding/chipping process* is defined as the time the machine spends feeding stems using the conveyer belt system and the chipping of wood material using internal blades, this element begins as the stem is placed on the conveyor and ends when it comes out the blower chute for loading. Feeding and chipping elements were not separated due to the fact that the chipping blades are internal of the chipping drum on the machine so one cannot see this process to separate it individually, also the feeding and chipping are both mechanically driven processes and must be directly correlated, and where therefore combined. Function 3 *loading* is defined as the time used to blow/load chips into the chip van trailer using the attached chute exiting the chipping drum. The loading element begins as chips start to come out of the chute and stops when all chips are blown into the trailer. For the reason that some or all of these elements will at times be occurring simultaneously a total minor cycle time was recorded, the total minor cycle time is not equal to the sum of the elements since the elements overlap. The weight of chips produced per major cycle was obtained from the delivery tickets from the truck driver as each truck is weighed when unloading then the driver was provided an unloading ticket with recorded weights. Species and volume data were recorded for each stem between the skidding and chipping functions prior to the stems being fed into the chipper. Samples of chips were randomly

collected from numerous truckload cycles and labeled accordingly so that physical and chemical wood properties and characteristics of the chips could be evaluated upon return to the West Virginia University Renewable Materials and Bioenergy Research Center laboratory.

2.2.2 Trucking

Trucking transportation was observed and directly linked to each corresponding major chipping cycle, a total trucking time was recorded for the major cycle starting when the truck leaves the harvest site and stopping upon the truck's return to the harvest site. The total trucking time includes the elements of traveling loaded from chipping site to destination, unloading, and return trip traveling empty back to the chipping site, however these elements were not observed individually as the researchers did not follow the trucks during delivery or have attached GPS data loggers. For some cycles a total trucking time could not be accurately recorded since on the last load of the day for each truck the trucks did not return to the harvest site, but rather went to the company facility where they parked overnight. Cycles in which the truck did not return were omitted from some analysis where this would create an outlier for cycle times. The origin site location, delivery destination, and hauling distance mileage were also recorded for each major cycle. Payload size in terms of green tons of the chips was determined from the truck driver as each truck was weighed upon unloading at the destination facility and the driver was provided and unloading ticket with the recorded weights. Each payload weight was linked to the corresponding chipping cycle so that an hourly production rate in green tons per PMH of chips can be calculated for each major chipping cycle. A few truckloads of the chips were delivered to an alternative location that did not weigh upon unloading, these cycles were included for time analysis purposes but had to be omitted from the production rate estimates.

2.2.3 Delays

Any delays encountered by any machine during the time study longer than one minute in duration were recorded along with the cause and time duration of the delay. A delay is defined as any amount of time spent by a machine not performing a task within its standard elemental functions. Delay cause is defined into two categories, mechanical or non-mechanical delays. A mechanical delay is considered any delay caused due to machine breakdown or required mechanical maintenance or refueling. Any other type of delay such as those caused by waiting on another harvesting function or by the machine operator performing alternate activities are categorized as non-mechanical delays.

2.3 Methods and Data for Wood Chip Properties Characterization

A collection of thirty-six samples of wood chips were randomly taken randomly from various truckload cycles of the chipper and labeled with the corresponding number to the major chipping cycle and the harvest site from which the sample was taken. Major physical and chemical properties of the wood chips were assessed to determine suitability of the woods run whole tree mixed hardwood chips for use as an energy feedstock for wood boiler system heating or bioproduct purposes. The properties assessed include green moisture content, bulk density, bark content, and calorific heating value, along with elemental and proximate analyses testing to determine chemical composition of the chips in terms of volatile matter, ash, fixed carbon, nitrogen, carbon, hydrogen, oxygen, and sulphur. These properties were determined utilizing the procedures and formulas outlined in the USDA Forest Products Laboratory Wood Handbook (Forest Products Laboratory 2010). Evaluation was based on the ANSI Standard AD17225-4:2014 *Solid Biofuels – Fuel Specifications and Classes – Graded Wood Chips and its Application in the U.S. Market*. Analyses for green moisture content, bulk density, bark content,

piece size, and calorific heating value tests were completed in the WVU Renewable Materials and Bioenergy laboratory utilizing equipment including Thermo-Scientific Lindberg Blue M lab oven, Fritsch Pulverisette cutting mill, Denver Instrument Balance, Parr 6300 Oxygen Bomb Calorimeter, Parr Pellet Press, U.S.A. Standard Test Sieves, and other standard laboratory equipment for properties testing. Elemental and proximate testing was performed by the West Virginia University shared research facilities Analytical Laboratory. All thirty-six original samples were first tested for green moisture content and bulk density. Each sample was then split into two subsamples, one which remained original for further testing as a “dirty” chip sample containing bark while the other subsample was manually debarked in the lab to determine bark content and then further tested as a “clean” chip sample with no bark content. This was done to analyze the benefit of adding a debarking machine to whole-tree chipping operations and determine the effects debarking may have on fuel characteristics of the wood chips. Each subsample was then ground to one millimeter for further analytical testing. Next each subsample of both clean and dirty chips were blended together to create twelve new subsamples of both clean and dirty chips by grouping three of each previous subsamples together, this replicates the typical procedure used at biomass processing facilities where truckloads are dumped and blended together in the pile to create uniformity in the end product. The two sets of clean and dirty twelve blended subsamples were further tested for calorific heating value and then sent to the WVU Analytical Laboratory for elemental and proximate testing. Procedures for each of the chip property test are as follows:

Moisture content: fresh wood chips were collected from the trailer immediately after chipping completed and placed in sealed plastic sample bags for storage and transport back to the laboratory. At the laboratory chips were weighed and wet mass was recorded then chips were

placed in a laboratory oven at 103°C and weighed every twenty-four hours until there is less than 1% change in mass then a dry mass is recorded. Moisture content was calculated on a green basis where $MC = (wet - dry) / dry * 100$

Bulk density: density of chips was determined at an oven dry state using a graduated volumetric cylinder and lab scale balance where a sample of chips was placed in the cylinder then the cylinder is tapped on the lab bench three times to remove air space then volume is recorded chips are then weighed using a lab balance. Bulk density is determined by $BD = mass / volume$.

Piece size: samples were dumped into a set of U.S.A. Standard Test sieves and shaken manually for a period of ten seconds. The portion of chips on each sieve was then weighed and mass recorded. Chips were separated into five piece-size categories; fines, small, medium, large, and oversize using sieves of the sizes 0.11 in.(2.8mm), 0.625in.(16mm), 1.75in.(45mm), and 2.5in.(63mm).

Bark content: each subsample of the whole tree chips was weighed and total mass recorded, then debarked manually using general laboratory hand tools including razor blade and scalpel. Bark was collected and mass recorded then bark content was determined by $BC = (total\ mass / bark\ mass) * 100$.

Calorific heating value: each blended subsample was ground to one millimeter then placed back into oven for minimum of twenty-four additional hours before calorimetry testing so tests are performed at oven dry state. Samples were taken from oven and processed into 0.5-gram pellet using Parr manual pellet press before entering Parr 6300 Oxygen Bomb Calorimeter. Three replicates of each sample was tested to determine average heating value of each sample.

Proximate analysis: Proximate analysis was performed by the WVU shared facilities Analytical Laboratory. Moisture, volatile matter, ash, and fixed carbon by heating the samples in the absence of air. Moisture and volatile matter will vaporize while fixed carbon and ash are residual solids. Each portion is weighted and represented as percentage of total mass. Some components are determined by subtracting from 100 percent those components that have already been determined.

Ultimate analysis: Ultimate analysis was performed by the WVU shared facilities Analytical Laboratory. Ultimate analysis is an analytical test used to determine the elemental chemical composition of the wood chip samples including Nitrogen, Carbon, Oxygen, Hydrogen, and Sulphur.

2.4 Analysis

The generic linear model for analyzing whole-tree chipper cycle times and productivity (Equation 2-1) is expressed as:

$$CT_{ijkn} = \mu + D_i + H_j + S_k + D_i * H_j + D_i * S_k + H_j * S_k + D_i * H_j * S_k + \varepsilon_{ijkn} \quad (2-1)$$

$$i= 1,2,3,\dots,7$$

$$j= 1,2,3,\dots,5$$

$$k= 1,2,3,\dots,5$$

$$n= 1,2,3,\dots,p$$

where:

CT_{ijkn} = nth observation of chipping elemental times, cycle times, or hourly production rate,

μ = mean of each response variable,

D_i = effect of the i^{th} diameter breast height (DBH),

H_j = effect of the j^{th} height,

S_k = effect of the k^{th} number of stems,

ε_{ijkn} = an error component that represents uncontrolled variability, and

n = number of observations within each treatment.

Interactions among diameter, height, and number of stems were also considered in the model.

The generic linear model for trucking cycle times and productivity (Equation 2-2) is expressed as:

$$T_{ijkn} = \mu + S_i + P_j + 2D_k + S_i * P_j + S_i * (2D_k) + P_j * (2D_k) + \varepsilon_{ijkn} \quad (2-2)$$

$i=1,2$

$j= 1,2,3,4$

$k= 1,2,3$

$n= 1,2,3,\dots,r$

where:

T_{ijkn} = n^{th} observation of trucking cycle times or hourly production rate,

μ = mean of each response variable,

S_i = effect of the i^{th} origin site,

P_j = effect of the j^{th} payload size,

D_k = effect of the 2 times the k^{th} hauling distance,

ε_{ijkn} = an error component that represents uncontrolled variability, and

n = number of observations within each treatment.

Interactions among origin site, payload size, and hauling distance were also considered in the model.

The generic linear model for physical and chemical properties (Equation 2-3) is expressed as:

$$CP_{ijn} = \mu + S_i + B_j + S_i * B_j + \varepsilon_{ijn} \quad (2-3)$$

$i = 1, 2$

$j = 1, 2$

$n = 1, 2, \dots, q$

where:

CP_{ijn} = n^{th} observation of wood chip physical or chemical characteristic,

μ = mean of each response variable,

S_i = effect of the i^{th} origin site,

B_j = effect of the j^{th} bark content,

ε_{ijn} = an error component that represents uncontrolled variability, and

n = number of observations within each treatment.

Interactions among origin site and bark content were also considered in the model.

2.5 Results

2.5.1 Whole-tree chipping and trucking operations

The diameter at breast height (DBH) in inches of harvested stems range 2 to 22 in. with average of 6.3 in. while total height ranged 4 to 88 feet with average 35.2 ft (**Table 2.2**). Average volume per tree was 7.6 ft.³ and 1 to 13 stems were processed per minor chipping cycle with average 2.2 stems per cycle.

Total chipping time. Total chipping time is the time to produce one chip van truckload, composed of several minor cycles including the elements of grappling, feed and chip, and loading. Total chipping cycle time ranged from 13.2 to 34.6 minutes with an average cycle of 21.5 minutes (**Table 2.2**).

Table 2.2. Statistics of operational variables of whole-tree chipping and truck delivery.

Variable	Mean	Standard deviation	Minimum	Maximum
Harvest condition				
Diameter (in.)	6.3	3.9	2.0	22.0
Height (ft.)	35.2	15.3	4.0	88.0
Volume per tree (ft. ³)	7.6	8.4	1.7	66.8
Elemental times (min.)				
Minor	0.8	0.4	0.1	3.2
Grapple	0.3	0.2	0.03	1.9
Feed/chip	0.5	0.3	0.08	1.6
Load	0.5	0.3	0.05	1.6
Mechanical delay	9.7	6.8	1.2	23.8
Non-mech. delay	4.1	3.7	1	18.5
Productivity				
Stems per minor cycle	2.2	1.8	1.0	13.0
Minor cycle (ft. ³ /PMH) ^a	1,473.4	1,162.9	95.7	13,9012.9
Major cycle				
Chip time (min.)	21.5	5.2	13.2	34.6
Truck time (min.)	162.0	32.3	106.0	220.0
Major total (min.)	183.0	34.3	124.2	245.6
Haul distance (miles)	45.8	7.9	38.0	57.5
Payload (tons)	23.5	2.1	19.5	27.5

^a PMH = productive machine hour

Trucking time. Trucking time is the time for round trip delivery by truck including elements of travel loaded, unloading, and travel empty. Trucking time was between 106 and 220 minutes for hauling distances of 76 to 115 miles across the two harvesting sites with an average truck time of 162 minutes (**Table 2.2**). Truck times were significantly affected by the harvesting origin site ($F = 44.86$, $df = 1$, $p = <0.0001$). It should be noted that location of the harvesting site of origin will directly impact the hauling distance from harvest site to delivery location. Duncan's Multiple Range test found truck time significantly increased for payloads greater than 26 U.S. tons while it decreased for hauling distances less than 97 miles at the 5 percent level (**Table 2.3**). A regression model was developed to estimate trucking cycle time (**Table 2.4**). Truck cycle times are best estimated from the round trip distance which can be estimated as two times the hauling distance in miles.

Table 2.3. Means and significance levels of statistics for major cycle and truck operations. ^a

	Total major time (min.)	Truck time (min.)	Delivered productivity (tons/PMH) ^b
Origin site			
1	210.0 A	186.9 A	6.8 B
2	154.1 B	135.3 B	9.1 A
Payload size (green tons)			
22	182.2 B	162.2 B	7.3 B
24	184.3 B	163.8 B	7.9 AB
26	175.0 B	152.7 B	8.8 A
28	218.5 A	196.0 A	7.3 B
Haul distance (miles)			
76	154.1 B	135.3 B	9.1 A
97	209.4 A	186.8 A	6.8 B
115	219.6 A	188.0 A	-

^a Means with the same capital letter in a column of the same group are not significantly different at the 5 percent level with Duncan's Multiple-Range Test.

^b PMH = productive machine hour

Table 2.4. Models to estimate times and productivity of chip van truck delivery.

	Models ^a	r ²	RMSE ^b	F-value	p-value
Truck time (min.)	-51.09524 + 2.45238M	0.65	382.43	48.55	0.0001
Total time (min.)	-45.96 + 2.63214M	0.68	389.83	54.86	0.0001
Delivered productivity (tons)	11.1014 – 0.11437M + 0.28915P	0.67	0.8879	24.81	0.0001

^a M = 2 * hauling distance (miles); P = payload (U.S. tons)

^b RMSE = root of mean square error

Total major cycle time. Total major cycle time includes total chipping time and total truck time.

This includes the elements of chipping, loading, travel loaded, unloading, and travel empty.

Major cycle time ranged 124.2 to 245.6 minutes with average time of 183.0 minutes. It differed significantly among the origin site of harvest ($F = 51.26$, $df = 1$, $p = <0.0001$). It was not found to be significantly affected overall by payload or haul distance at the $\alpha = 0.05$ level. However, Duncan's Multiple Range test found it different for payloads greater than 26 U.S. tons and hauling distance greater than 97 miles at the 5 percent level.

Minor chipping time. Minor chipping cycle time is one grapple of stems being processed completely through the chipper including the elements of grappling, feed and chip, and loading. Minor cycle times were between 0.1 and 3.2 minutes with average cycle time of 0.8 minutes. It was significantly affected by average diameter of the stems ($F = 31.15$, $df = 6$, $p = < 0.0001$), number of stems ($F = 9.15$, $df = 4$, $p = < 0.0001$). It was also significantly affected by the interactions of average diameter and height ($F = 1.59$, $df = 23$, $p = 0.0391$), average diameter and number of stems ($F = 2.00$, $df = 15$, $p = 0.0125$), average height and number of stems ($F = 1.89$, $df = 12$, $p = 0.0320$). It was not affected significantly by average height at the $\alpha = 0.05$ level. A regression model was developed for estimating minor chipping cycle time (**Table 2.5**). Total minor cycle time of the chipper is best described by average height in feet, number of stems, the interaction of diameter and height, and the interaction of diameter, height, and number of stems.

Grapple time. Grapple time ranged 0.03 to 1.9 minutes with an average of 0.3 minutes and had the largest range of time among of all chipper elements. Grapple time was significantly different among average diameter classes ($F = 8.61$, $df = 6$, $p = <0.0001$). It was also significantly affected by the interaction of average diameter and number of stems ($F = 1.75$, $df = 15$, $p = 0.0365$). It was not significantly affected by average height or number of stems. The interactions of average diameter and average height, average height and number of stems, and average diameter, average height and number of stems did not significantly alter the minor chipping cycle time at the $\alpha = 0.05$ level.

Feed and chip time. Feed and chip time was between 0.08 and 1.6 minutes with an average of 0.5 minutes. Feed and chip time differed significantly among average diameter classes ($F = 28.29$, $df = 6$, $p = <0.0001$) and number of stems per cycle ($F = 7.63$, $df = 4$, $p = <0.0001$). It was also significantly different for the interactions of average diameter and average height ($F = 1.84$, $df = 23$, $p = 0.0091$), average diameter and number of stems ($F = 2.37$, $df = 15$, $p = 0.0023$), average height and number of stems ($F = 2.76$, $df = 12$, $p = 0.0010$), and average diameter, average height and number of stems ($F = 1.55$, $df = 24$, $p = 0.0448$). It was not significantly different among average height classes. A regression model was developed to estimate the elemental time of feeding and chipping (**Table 2.5**). Feeding time is best described by diameter, height, number of stems, and interactions among these variables.

Load time. Load time ranged from 0.05 to 1.6 minutes with average of 0.5 minutes. Load time was significantly different among average diameter classes ($F = 30.03$, $df = 6$, $p = < 0.0001$) and number of stems ($F = 8.13$, $df = 4$, $p = < 0.0001$). It was also significantly affected by the interactions of average diameter and height, average diameter and number of stems, average

height and number of stems, and average diameter, average height and number of stems. It was not significantly different among average height classes at the $\alpha = 0.05$ level.

Table 2.5. Models to estimate times and productivity of whole-tree chipping.

	Models ^a	r ²	RMSE ^b	F-value	p-value
Minor time (min.)	0.7931 – 0.0085H + 0.02495S + 0.00004086D ² H + 0.00022732DHS	0.16	0.1434	59.25	0.0001
Feed time (min.)	0.43647 + 0.01361S + 0.00053702D ² – 0.00055312DH + 0.00003691D ² H + 0.00013247DHS	0.14	0.0612	41.83	0.0001
Chipper productivity (ft. ³ /PMH) ^c	180.85585 + 50.18026S + 6.59451D ² – 0.08367D ² H + 1.6799DHS	0.31	942044	139.82	0.0001

^a D = diameter breast height (in.); H = total height (ft.); S = number of stems

^b RMSE = root of mean square error

^c PMH = productive machine hour

Productivity. Cycle volume processed through the chipper for minor cycles ranged from 1.7 ft.³ to 78.1 ft.³ with average of 17.0 ft.³ per minor cycle. Number of stems per minor cycle ranged 1 to 13 with average of 2.2 stems per minor cycle. Payload of the truckloads of delivered chips ranged 19.5 to 27.5 tons with average payload of 23.5 tons. Productivity of the chipper ranged 95.6 ft.³/PMH (40.8 green tons/PMH) to 13,912.9 ft.³/PMH (107.4 green tons/PMH) with average hourly production rate of 1,473.4ft.³/PMH (65.8 green tons/PMH). With average payload of 23.5 tons and average total major cycle time of 183 minutes, total delivered productivity is estimated at 7.7 tons/PMH. Productivity of the chipper was significantly different among average diameter classes ($F = 47.16$, $df = 6$, $p = < 0.0001$), average height classes ($F = 21.79$, $df = 4$, $p = < 0.0001$), and number of stems ($F = 84.23$, $df = 4$, $p = < 0.0001$). It was also significantly affected by interactions among diameter and height, diameter and number of stems, height and number of stems, and diameter, height, and number of stems. Total delivered productivity including both chipping and trucking was significantly different among origin sites ($F = 36.67$, $df = 1$, $p = < 0.0001$) and payload sizes ($F = 4.04$, $df = 3$, $p = 0.0205$). Duncan's

Multiple Range test indicated that productivity of the chipper significantly improved at the 5 percent level when more than one stem was processed per cycle and for tree heights greater than 32 ft. (**Table 2.6**). Regression models were developed to estimate total delivered productivity (**Table 2.4**) and productivity of the chipper (**Table 2.5**). Factors that are significant in the total delivered productivity model include the hauling distance and the payload size. Factors that are significant in the chipping productivity model include diameter, height, number of stems, and some interactions of those factors.

Table 2.6. Means and significance levels of statistics for whole-tree chipping operations during time-motion studies. ^a

	Minor time	Grapple	Feed/chip	Load	Cycle volume (ft. ³)	Chipping productivity (ft. ³ /PMH) ^b
Average diameter (in.)						
4	0.77 C	0.35 B	0.51 CD	0.51 CD	10.8 G	980.7 E
6	0.70 C	0.31 B	0.47 D	0.47 D	12.4 F	1,246.7 D
8	0.73 C	0.32 B	0.49 CD	0.48 CD	13.6 E	1,374.4 D
10	0.77 C	0.32 B	0.51 CD	0.50 CD	16.7 D	1,637.3 C
12	0.79 C	0.32 B	0.54 C	0.54 C	21.2 C	2,021.3 B
14	1.10 B	0.44 A	0.70 B	0.71 B	31.1 B	1,928.8 B
16	1.21 A	0.47 A	0.80 A	0.80 A	38.9 A	2,322.2 A
Average height (ft.)						
16	0.79 B	0.33 B	0.51 C	0.50 C	7.81 E	705.4 C
32	0.78 B	0.34 B	0.51 C	0.51 C	12.20 D	1,145.0 B
48	0.77 B	0.33 B	0.51 C	0.52 C	18.18 C	1,732.1 A
64	0.85 B	0.35 B	0.58 B	0.58 B	23.55 B	1,807.5 A
80	1.00 A	0.43 A	0.66 A	0.66 A	29.61 A	1,915.4 A
Number of stems						
1	0.82 AB	0.35 AB	0.54 A	0.54 A	16.6 C	1,345.9 B
2	0.77 BC	0.33 AB	0.51 A	0.51 A	17.3 B	1,644.3 A
3	0.82 AB	0.35 AB	0.54 A	0.54 A	16.8 BC	1,501.9 AB
4	0.73 C	0.31 B	0.51 A	0.51 A	15.3 D	1,544.3 A
5	0.87 A	0.38 A	0.55 A	0.55 A	20.1 A	1,612.8 A

^a Means with the same capital letter in a column of the same group are not significantly different at the 5 percent level with Duncan's Multiple-Range Test.

^b PMH = productive machine hour

Chipping delays. Delays are any time that is spent on an activity other than those defined elemental functions of the chipper and are classified as either mechanical or non-mechanical delays. Any delays longer than one-minute duration were recorded and included in the analysis. Mechanical delays accounted for 24% of all delays recorded while 76% were non-mechanical. A total of 12 mechanical delays were recorded ranging from 1.2 to 23.8 minutes with an average duration of 9.7 minutes. There were 39 non-mechanical delays recorded ranging between 1.0 and 18.5 minutes with average of 4.1 minutes. The most common type of non-mechanical delay was the chipper operator waiting for the skidder to bring trees to the landing during chipping cycles.

2.5.2 Mixed-hardwood chips properties and characteristics

Samples of mixed hardwood chips were taken from random cycles of the chipping operation across both harvest sites and analyzed for physical and chemical properties with a focus to evaluate potential of these in-woods whole-tree chips as a wood fuel according to ANSI Standard AD17225-4:2014.

Green Moisture. Green moisture was between 32.9 and 45.6 percent with average of 37.5 percent green basis (**Table 2.7**). Green moisture differed significantly among harvest sites ($F = 13.14$, $df = 1$, $p = 0.0009$) with averages of 35.3% and 39.6% for harvest sites 1 and 2, respectively (**Figure 2.1**).

Figure 2.1 Green moisture distribution among harvest site origins.

Bulk density. Bulk density ranged from 0.16 to 0.25 g/cm³ with average 0.21 g/cm³ and was not different among harvest sites at the $\alpha = 0.05$ level.

Table 2.7. Statistics of characteristics of whole-tree mixed hardwood chips.

Variable	Mean	Standard deviation	Minimum	Maximum
Green moisture ^a	37.5	4.1	32.9	45.6
Bulk density (g/cm ³)	0.21	0.03	0.16	0.25
Bark content ^a	10.5	6.2	0.6	25.9
Heat value (Btu/lb)	7,992.5	98.6	7,704.8	8,8185.3

^a Represented as a percentage of total mass.

Bark content. Bark content by percentage mass was between 0.6 and 25.9 percent with average of 10.5 percent. Bark content was not significantly different among harvest sites of origin at the $\alpha = 0.05$ level.

Calorific heating value. Heating value of the hardwood chips ranged from 7,704.8 to 8,8185.3 Btu/lb. with average of 7,992.5 Btu/lb. (**Table 2.7**). Calorific heating value was slightly higher for hardwood chips containing bark compared to the debarked hardwood chips, but heating value

was not found to be significantly different among harvest sites, debarking, or the interaction of site and debarking at the $\alpha = 0.05$ level (**Figure 2.2**).

Figure 2.2. Interaction of calorific heating value among harvest sites and debarking. Bark code 0 is debarked whole-tree chips, bark code 1 is whole-tree chips containing bark.

Piece size. Piece size distribution of whole-tree chips was determined using a set of USA Standard Test sieves with size classifications of fines, less than 2.8 mm(0.11 in.); small, 3 – 16 mm (0.11 – 0.625 in.); medium, 16 – 45 mm (0.625 – 1.75 in.); large, 45 – 63 mm (1.75 – 2.5 in.); and oversize, greater than 63 mm (2.5 in.) (**Figure 2.3**).

Figure 2.3. Piece size distribution of whole-tree hardwood chips.

The small, medium, and large chip size classes captured 46.3, 45.4, and 3.1 percent, respectively of the chips by percentage of total mass. Fines composed less than 1 percent while 4.5 percent of chips were oversized.

Moisture. Moisture ranged from 5.5 to 6.9 percent with average of 6.3 percent (**Table 2.8**).

Moisture was significantly different among harvest sites ($F = 5.29$, $df = 1$, $p = 0.0245$), debarking ($F = 67.44$, $df = 1$, $p = < 0.0001$), and the interaction of harvest sites and debarking ($F = 12.56$, $df = 1$, $p = 0.0007$). It should be noted that this moisture content is determined from proximate analysis and that these samples had been previously oven-dried to determine green moisture and for analytical testing purposes. Therefore, this moisture is that which is absorbed from atmospheric humidity as the samples are taken from the oven for sample preparation for proximate testing.

Table 2.8. Statistics of components of whole-tree mixed hardwood chips.

Variable ^a	Mean	Standard deviation	Minimum	Maximum
Moisture	6.3	0.4	5.5	6.9
Volatile	77.3	1.1	74.5	79.5
Ash	0.5	0.4	0.0	1.6
Fixed carbon	16.0	0.9	14.0	18.5
Nitrogen	0.5	0.1	0.3	1.0
Carbon	45.9	1.3	38.2	48.0
Hydrogen	5.4	0.4	4.7	6.2
Oxygen	48.2	1.4	45.7	56.2
Sulphur	0.0	-	-	-

^a Represented as a percentage of total mass.

Volatile matter. Volatile matter ranged from 74.5 to 79.5 percent of total mass with an average of 77.3 percent. Volatile matter was significantly different among harvest sites ($F = 24.39$, $df = 1$, $p = < 0.0001$). It was not significantly affected by debarking or the interaction of site and debarking at the $\alpha = 0.05$ level.

Fixed Carbon. Fixed carbon ranged between 14.0 and 18.5 percent with average of 16.0 percent. Fixed carbon was significantly different among harvest sites ($F = 22.46$, $df = 1$, $p = < 0.0001$). It was not significantly affected by debarking or site and debarking interaction at the $\alpha = 0.05$ level.

Ash. Ash content was between 0.0 and 1.6 percent of total mass and averaged 0.5 percent. Ash content was significantly different among harvest sites ($F = 38.06$, $df = 1$, $p = < 0.0001$) and debarking ($F = 37.73$, $df = 1$, $p = < 0.0001$) (**Figure 2.4**). It was not significantly affected by the site and debarking interaction. Ash content averaged 0.68 and 0.29 for harvest sites 1 and 2 and averaged 0.68 and 0.30 for whole-tree and debarked clean chips, respectively (**Table 2.9**).

Figure 2.4. Interaction of ash content among harvest sites and debarking. Bark code 0 is debarked whole-tree chips, bark code 1 is whole-tree chips containing bark.

Table 2.9. Means and significance levels of statistics for whole-tree mixed hardwood chips. ^a

	Heat (Btu./lb)	Volatile	Ash	Fixed Carbon	Nitrogen	Carbon	Hydrogen	Oxygen
Harvest site								
1	7,986.7 A	76.71 B	0.68 A	16.43 A	0.52 A	45.70 A	5.32 B	48.45 A
2	7,998.3 A	77.84 A	0.29 B	15.55 B	0.47 A	46.10 A	5.57 A	47.90 A
Chip type by bark content								
Clean	7,982.6 A	77.32 A	0.30 B	15.90 A	0.48 A	45.78 A	5.22 B	48.53 A
Dirty	8,002.4 A	77.23 A	0.68 A	16.08 A	0.52 A	46.02 A	5.67 A	47.79 B

^a Means with the same capital letter in a column of the same group are not significantly different at the 5 percent level with Duncan's Multiple-Range Test.

Nitrogen. Nitrogen content was between 0.3 and 1.0 percent with average of 0.5 percent of total mass. Nitrogen was not found to be significantly affected by harvest site or debarking at the $\alpha = 0.05$ level.

Carbon. Carbon ranged from 38.2 to 48.0 percent with an average of 45.9 percent. Carbon did not differ significantly among harvest sites or debarking at the $\alpha = 0.05$ level.

Hydrogen. Hydrogen content ranged from 4.7 to 6.2 percent with average of 5.4 percent.

Hydrogen was significantly different among harvest sites ($F = 17.06$, $df = 1$, $p = 0.0001$), debarking ($F = 59.99$, $df = 1$, $p = < 0.0001$), and the interaction of site and debarking ($F = 30.61$, $df = 1$, $p = < 0.0001$).

Oxygen. Oxygen content was between 45.7 and 56.2 percent with an average of 48.2 percent. It was significantly affected by debarking ($F = 5.34$, $df = 1$, $p = 0.0239$). Oxygen content was not significantly different among harvest sites at the $\alpha = 0.05$ level.

Sulphur. Sulphur content was included in the proximate analysis but no content was found for any of the hardwood chips.

2.6 Cost assumptions and analysis

Estimates of hourly cost for the feller-buncher, grapple skidders, and chipper were calculated using the machine rate method (Miyata 1980). Since detailed observations and data were not recorded for felling and skidding functions some assumptions are based on a previous study of feller-buncher and grapple skidder production in the region (Wang et al. 2004b). Labor rate was \$15.65 per scheduled machine hour (SMH) plus 40 percent additional fringe benefits cost. Fuel and lubrication cost were determined based upon daily consumption rates and local fuel and oil unit costs given by the machine operators during the time study. Salvage value of all equipment is assumed at 20 percent of the purchase price with an economic life of 5 years. Interest, insurance, and taxes were assumed at 20 percent (**Table 2.10**).

Table 2.10. Machine specifications and cost assumptions.

	Timbco 425 feller-buncher	Morbark 27 RXL chipper	Caterpillar 525C grapple skidder	John Deere 648GIII grapple skidder
Operation	Felling	Chipping	Skidding	Skidding
Purchase price (\$)	225,000	96,600	212,000	175,000
Economic life (years)	5	5	5	5
Salvage value (\$)	45,000	19,320	42,400	35,000
M&R% of D ^a (%)	50	80	60	60
MA ^b (%)	65	84	70	70
Total fixed (\$/PMH)	51.23	17.02	44.82	37.00
Total variable (\$/PMH)	31.34	28.90	22.80	20.26
Total labor (\$/PMH)	33.71	26.08	31.30	31.30
Total Hourly (\$/PMH)	116.28	72.01	98.92	88.56

^a Maintenance and repair as a percent of depreciation.

^b Mechanical availability of machine.

The chipper was purchased in used condition for \$96,600, after an anticipated economic life of 5 years the salvage value would be at \$19,320. The chipper has mechanical availability of 84 percent based on mechanical delays recorded during the time study. Total hourly cost of the chipper is estimated at \$72.01/PMH, when combined with hourly production rates of 1,473.4ft.³/PMH (65.8 green tons/PMH) this gives a unit cost of \$ 4.89 per 100 cubic feet (cunit) or \$1.09 per green ton for chipping alone. When considering moisture content of 37.5 % the productivity of the chipper is 41.1 dry tons and cost would be \$ 1.75/dry ton for chipping. Felling productivity is assumed at 56.6 green tons/PMH based on the previous study giving a felling cost of \$ 2.05/green ton (\$ 3.29/dry ton). Skidding productivity is assumed at 22.9 green tons/ PMH based on the previous study giving skidding cost of \$ 8.19 per green ton (\$ 13.1/dry ton). Total hourly cost of the entire harvesting system including felling, skidding, and chipping is \$375.77/PMH or combined per unit cost gives a total cost of \$ 50.68/cunit or \$ 11.34/green ton (\$ 18.14/dry ton) to produce in-woods chips at the landing. Trucking productivity is estimated at 7.7 tons/PMH and average hauling distance is 45.8 miles with average payload of 23.5 green tons (14.69 dry tons). If transportation cost is assumed from \$1.00 and \$ 3.00 per loaded mile this adds \$ 1.95 to \$ 5.85 per green ton (\$ 3.12 to \$9.35 per dry ton) for trucking cost. Total operational costs for felling, skidding, chipping, and truck delivery is estimated at \$ 13.28 to \$ 17.18 per green ton or \$ 21.25 to \$ 27.49 per dry ton dependent upon transportation cost.

2.7 Discussion

Harvesting of woody biomass can be economically feasible, but higher production rates must be obtained in comparison with traditional roundwood harvesting due to the value of the end product being considerably less for woody biomass products such as chips compared to traditional sawtimber markets. Combining chipping operations with fully mechanized harvesting

systems is essential to achieve acceptable production rates. Currently, there is not a large market for woody biomass in the region, therefore it is rare to find harvesting crews committed solely to biomass harvesting operations such as whole-tree in-woods chipping, but as more uses of biomass feedstock are identified and developed market activity will increase for woody biomass products potentially leading to more incorporation of chipping operations by logging crews.

For in-woods chipping of whole-tree mixed hardwoods cycle volume processed through the chipper per minor cycles averaged 17.0 ft.³ while processing a range of 1 to 13 stems with an average of 2.2 stems processed per minor cycle. Hourly production rate of the chipper ranged 95.6 ft.³/PMH (40.8 tons/PMH) to 13,912.9 ft.³/PMH (107.4 tons/PMH) with average hourly production at 1,473.4ft.³/PMH (65.8 tons/PMH) at a cost of \$ 4.89/cunit (\$1.09/green ton). Truck payload of delivered chips ranged 19.5 to 27.5 tons with average payload of 23.5 tons and average total major cycle time of 183 minutes, trucking productivity is estimated at 7.7 tons/PMH. Productivity of the chipper was found to be affected by diameter, height, and number of stems as well as the interactions among diameter and height, diameter and number of stems, height and number of stems, and diameter, height, and number of stems. Total delivered productivity including both chipping and trucking was significantly different among origin sites and payload sizes. Hourly cost of the entire harvesting system including felling, skidding, and chipping is \$375.77/PMH, or combined total unit costs of \$ 50.68/cunit or \$ 11.34 /green ton (\$18.14/dry ton) for harvest and chipping. Total operational cost including truck delivery is estimated at \$ 13.28 to \$ 17.18 per green ton or \$ 21.25 to \$ 27.49 per dry ton.

Production rate of this study (65.8 green tons/PMH) was less than the 111 green tons/PMH reported for a dual engine roadside chipper fed by excavator grapple but higher than terrain chipping productivity of 23 green tons/PMH both used for Mediterranean Pine harvest in Italy

(Marchi et al. 2011). Productivity of the whole-tree chipper is also higher than that reported for a chipping truck in central Europe at 13 to 19 metric green tons per hour (Spinelli et al. 2015).

Estimated harvest cost of whole tree chipping (\$ 11.34 /green ton) in the Central Appalachian region is similar to the cost range of \$ 8.67 to \$ 14.44 per green ton reported for clearcut harvest and chipping in the southern pine region of the USA (Baker et al. 2010). Productivity of the integrated roundwood and chipping operation was reported as 13.9 green tons/SMH of chips and 48.2 greentons/SMH total production for a 2:1 roundwood and chip integrated harvesting in the southern pine operation. While overall production is higher when the crew is dedicated to a single product it has been shown that integrated harvesting by adding a chipper to a mechanized harvesting crew to produce both chips and sawtimber is also a viable option.

U.S. wood chip fuel quality standard for Grade A1 requires meeting particle size classification of less than or equal to 10 percent by weight allowance for each the fines and oversized particle size of chips. The standard also requires less than 50 percent green moisture content and less than 1 percent ash content. Characterization of these woods run whole-tree chips indicate average green moisture of 37.5 percent and calorific heating value 7,992.5 Btu/lb. Ash content was 0.68 and 0.30 for whole-tree and debarked chips, respectively. Piece size classification indicated 4.5 percent of chips were oversized while only 0.7 percent were fines. With these characteristics for in- woods processed whole-tree mixed hardwood chips, the standard requirements for Grade A1 is met. Since the ash content of less than 1 percent is met with the whole-tree chips there is not a large incentive for debarking of chips, when the intended use is fuel, as it would add additional cost to the harvesting system and is not necessary to meet the requirements of the fuel standard.

2.8 Conclusion

Production and cost are major considerations for loggers or harvest managers when considering investment into new or additional equipment for their harvesting systems. From this research it can be concluded that a whole-tree chipper could be added to a mechanized harvesting system at an estimated cost of \$72 per productive machine hour. It has been shown that there are vast amounts of logging residue and woody biomass available throughout the central Appalachian region and loggers could benefit from addition of a chipper to their operations to capture additional revenue from this material that is typically left behind as waste. Though it is rare to find dedicated chipping operations it has been shown in other regions with similar cost and production levels that integrated harvesting to produce both chips and roundwood products can be a feasible option for harvest crews. Characterization of the properties for in-woods processed whole-tree hardwood chips found that the chips were able to meet the grade A1 requirements for the U.S. wood chip fuel quality standard. This indicates that the material is highly suitable for use as a potential boiler fuel by achieving the highest grade requirements. In-woods chipping could play an increased and important role to the future of forest harvesting operations in central Appalachia as a means to supply an alternative fuel choice and to benefit loggers with an opportunity to completely utilize harvested wood material and capture additional revenue in the process.

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3. Economic and Environmental Analysis of Woody Biomass as an Energy Source for Poultry Production

Abstract

A techno-economic feasibility assessment was conducted for use of woody biomass as an energy source in poultry production, which is one of the largest agriculture industries in West Virginia and also one of the largest consumers of liquid propane in the state. Woody biomass availability and integration was assessed based on wood chip production and characteristics results along with data acquired through a survey of local industrial poultry growers to determine energy and heating requirements of the poultry operations. A compromise programming model was used for spatial analysis to rank the most feasible locations within the study area for wood energy conversion in poultry houses when considering factors of mean Euclidean distance to biomass sources, biomass availability, transport cost, and market competition. Average current propane consumption from survey results was 7,036 gallons per year per poultry house. Wood fuel consumption for a wood boiler system to supply heat to a single poultry house was estimated at 85 tons of green wood chips or 45 tons of wood pellets. It was determined that at current local market conditions of \$1.04 per gallon propane an average annual fuel cost savings of \$2,885 could be achieved with \$35 per ton wood chips, while wood pellets at a cost of \$180 per ton were found to have break-even cost with \$1.30 per gallon propane.

3.1 Introduction

3.1.1 Compromise programming model

A Compromise programming model is a distance based technique based upon a point of reference that uses a compromised solution to find the ideal solution based upon which option is the closest to the preferred. The Compromise programming model has many uses and can be combined with a geographic information system (GIS) for spatial analysis and modeling applications. The compromise programming model is very useful in land use planning

applications when trying to find a suitable location in the landscape and multiple variables need to be considered in the model.

Compromise programming was used to model agricultural land use suitability to check erosion tolerance, runoff, accessibility, and proximity to water (Baja et al. 2007). Parcel areas of high-priority for conservation were identified through compromise programming of landscape characteristics and the parcel ownership to find areas most suitable for easements (Strager and Rosenberger 2007). The biomass supply chain for district heating plants was assessed for optimization in Florence Italy. The compromise program model was based upon both technolistics and environmental factors to establish the optimized relationships between the bio-energy sources and the demand terminal at the heating plants (Bernetti et al. 2014). There are numerous potential uses in many study areas for compromise programming models. In the natural resources study area, the model is especially useful for techno-economic assessments and land use planning. In this study a compromise programming model is used to evaluate techno-economic feasibility of wood energy conversion of poultry production houses in West Virginia, USA.

3.1.2 Poultry production

Maintaining a healthy production house environment can be one of the most important aspects for poultry producers. A healthy house environment helps to minimize the mortality rate of the chickens and leads to increased body weight of the chickens, both of these factors ultimately affect the profit earned by the poultry grower. Use of an alternative energy source such as wood energy for heating of poultry production houses can help control factors such as moisture and humidity, greenhouse gas (GHG) emissions, and ammonia reduction all of which result in a healthier environment in the production house as compared to burning fossil fuels.

Comparison of a geothermal heat pump (GHP) to conventional diesel fuel heating system found CO₂ and NH₃ contents were significantly less in the GHP house, also mortality rate was decreased and total energy cost was significantly reduced in the GHP house (Choi et al. 2012). Bruzual et al. (2000) found warm brooding temperatures and 53% relative humidity to be optimal brooding conditions. These optimal conditions can be achieved by using efficient heating systems.

Large amounts of poultry waste are accumulated in poultry production operations and finding ways to market this material for additional revenue to the farmer could assist to offset the cost of conversion to alternative energy. Poultry waste is the byproduct removed from poultry productions houses before new flocks of birds arrive and is a combination of litter and an absorbent bedding material, typically wood sawdust, wood chips or peanut hulls. Poultry waste is generally used in one of two methods, as crop field fertilizer or burned as a bio-fuel. An assessment of the co-combustion of natural gas and poultry waste found the carbon combustion efficiency to be 92% for sawdust and 81% for poultry litter (Zhu and Lee 2005). Gasification of poultry litter into poultry litter biochar was found to provide some essential nutrients when included back into the poultry diet as an alternative to land application (Evans et al. 2015). Use of wood energy could reduce moisture and improve the quality of the poultry waste, potentially improving the value. Marketing of the poultry waste byproduct could prove essential in the feasibility of wood energy in the poultry production houses because the litter byproduct could reduce transportation cost of hauling in the wood fuel by having a back-haul of poultry waste.

3.1.3 Wood energy and emissions of wood versus propane

Most commercial poultry production houses in the region are currently using liquid propane fuel through direct combustion within the poultry house for heating purposes, thus directly emitting

GHG emissions and moisture into the house environment. Use of a wood boiler system will move combustion to an exterior portion of the house then a hot-water to air heat exchange system is used to provide heat to the interior. Through reduction of emissions and moisture into the bird living environment there is potential to improve the bird mortality rate and improve weight gain and meat quality by improving the environmental and air quality conditions of the poultry house.

The Viking Project in Minnesota was a case study in cooperation with the MN Clean Energy Resource Team where a wood heating system was installed on a broiler chicken barn and tested for two years in comparison with a similar propane barn on the same farm. Benefits found in the biomass heated barn include better feed conversion, better air quality, overall better efficiency due to running the ventilation fans less (Ebinger 2017).

Once a wood boiler system is installed by the West Virginia Statewide Wood Energy Team (WV SWET) project the poultry house environment and air conditions can be monitored on two poultry houses, one heated with traditional propane system and one heated with a wood boiler system. This will provide a direct comparison of the environment and air quality of the heating systems as well as their direct effects on bird health, growth, and mortality rates.

3.2 Methods for Assessment of Wood Energy in Poultry Production

3.2.1 Biomass availability and integration

An initial data collection of the current fuel usage rates of traditional fossil fuels, primarily liquid propane, in chicken house heating systems will serve as a basis for understanding the fuel consumption rates and heating system requirements for poultry production houses. This data was collected through a survey administered by the WV Statewide Wood Energy Team to industrial poultry growers throughout the target region of poultry growers in the state of West Virginia.

This survey data includes propane fuel usage, fuel cost, number of poultry houses on farm, and number of flocks grown per year. Fuel usage data from the survey will then be used to estimate the approximate heating requirements in British thermal units (Btu) per hour. A Btu/unit of fuel conversion from propane to wood is then used to estimate the volume of woody biomass feedstock that will be needed to replace the liquid propane heating system.

Wood fuel delivery and storage logistics was discussed among the WV Statewide Wood Energy Team and industry representatives from wood pellet manufacturers, wood boiler manufacturers, and industrial poultry growers to develop a potential supply chain of woody biomass to poultry production houses (**Figure 3.1**). Logistics of wood chips include transportation by semi-truck in bulk with covered storage required at the farm site. Chips are then fed from storage to the boiler's fuel bin by loader or tractor bucket which is commonly available at the farm.

Transportation and storage of wood pellets is done by one ton packages commonly referred to as "supersacks" or by bulk delivery via vacuum truck into covered storage and moved to the fuel bin by loader or tractor.

Logistics of the transportation and storage processes must be developed to transport and store the biomass economically and efficiently in order for wood energy systems to be economically feasible. Utilizing a backhaul of poultry waste litter from the poultry farm is one method that will be assessed in order to reduce transportation costs. Exploring markets for the poultry waste byproduct will be essential in reducing the transportation cost.

Figure 3.1. Supply chain for transportation and storage logistics of woody biomass to boiler system.

Storage techniques and various infrastructure will be evaluated because proper on-site storage of wood fuel will be essential to ensuring fuel availability at all times and maintaining quality of the wood fuel. It is expected that more fuel is needed in the cold winter months as opposed to the warmer portions of the year and because of the harsh weather in the area during the winter months the production rates of biomass during the winter may prove insufficient to meet the increased requirements of the heating systems during this time.

Through surveys and public outreach, the wood energy team has identified three poultry farms that possess interest and potential as a wood energy conversion site. The farms are located in eastern WV in the Grant, Hardy, Mineral and Pendleton county area. Spatial analysis was used to assess the economic feasibility, biomass availability, and transportation logistics of utilizing biomass feedstock as a fuel source for the three identified poultry farms in eastern West Virginia.

These farm locations were used to represent the entire industry as one is located in each of the towns where multiple poultry houses are clustered.

The spatial analysis was performed through the method of a compromise programming model. Compromise programming is a suitable approach for this analysis as it utilizes a distance-based technique that depends upon a point of reference, and attempts to minimize the distance to find the ideal solution. The closest one to the ideal becomes the compromised solution, in this case the poultry houses are used as the point of reference for the model while distance to available biomass, transportation cost, and market competition are used as the input variables to compromise the optimum solution.

The spatial relationship between potential conversion poultry farms and biomass fuel sources was assessed by building a Euclidean distance grid, this is used as a proximity to fuel source variable in the model. The biomass availability and source location data used in this analysis were obtained from the WVU Appalachian Hardwood Center Wood Byproducts survey (Spong 2017). This data provides a list of wood processors and manufacturing facilities in the state of West Virginia that produce wood byproducts, the entire list was reduced by selecting only sources which had biomass available, not currently under contract, and by only selecting byproduct that is usable for the wood boiler system application which is primarily in the form of wood chips and logging residues. A Euclidean distance was used as a proximity to fuel source variable in the model assessing the spatial relationship between poultry farms and biomass fuel sources. The Zonal Statistics as command was then used to calculate the mean distance from each poultry farm to biomass fuel sources, this value was then placed into the Evaluation Matrix. Other variables in the model include transportation costs, amount of biomass available at each source (tons), and a comparison to location of possible competition such as pulp mills that could

affect the market price of purchasing biomass in the area. The amount of biomass available to each poultry house was determined by selecting all biomass fuel sources within 100 miles of each poultry house. The total tonnage value for each farm was then put into the evaluation matrix as the variable for biomass availability. Transportation cost was estimated at \$3.25 per mile and the calculated for the evaluation matrix by converting the average distance value to miles and multiplying by the 3.25 cost per mile. It was assumed that market competition was present for each area. Weights for variables in the model were set at 0.2 for biomass proximity, 0.3 for biomass availability, 0.3 for transportation cost, and 0.2 for market competition. An evaluation matrix was built indicating the values for the respective variables for each farm and weighting each variable from most to least important to input into the compromise programming model. The evaluation matrix is then normalized to create a payoff matrix. After the evaluation matrix is normalized into the payoff matrix the compromise programming model can be calculated based upon the payoff matrix and the variable weights using the formula seen in Equation (3-1) (Strager and Rosenberger 2007). Mapping of these variables spatially will help to identify poultry farms that are most suitable for wood energy conversion.

$$\text{Min} \left\{ L_p(A_j) - \left[\sum_{i=1}^N (W_i) \left[\frac{(f_i^* - f_{ij})}{(f_i^* - f_i^{**})} \right]^p \right]^{\frac{1}{p}} \right\} \quad (3-1)$$

3.2.2 Techno-economic feasibility and price sensitivity

Utilizing the data collected from the WV Statewide Wood Energy Team project survey and field visits to select poultry houses for pre-feasibility engineering assessments, a techno-economic feasibility analysis was performed along with development of price sensitivity curves to determine break-even cost and fuel savings potential of wood fuels compared to liquid propane.

The propane fuel consumption data from the WV SWET survey was utilized to estimate the

energy requirements of the heating system and wood fuel consumption for a wood boiler system to supply heat to the poultry production house. A techno-economic analysis of a wood boiler system in comparison with traditional propane heating system was conducted to determine at what price levels wood energy can compete with liquid propane in poultry house heating. A fuel cost comparison and price sensitivity analysis was performed for both wood chip and wood pellet fuels to determine break-even prices in comparison with propane fuel. When determining the feasibility of wood energy in the poultry industry, additional indirect opportunity cost factors such as bird health, house conditions, and mortality rates must be considered between houses heated with biomass and traditional fuels.

3.3 Results

3.3.1 Spatial Analysis

The evaluation matrix of the compromise program model indicated mean Euclidian distance of 23,086 meters for Fort Seybert, 55,026 meters for Moorefield, and 81,941 meters for Wardensville to biomass sources (**Table 3.1**). Biomass availability ranged from 7,295 to 11,319 tons within a 100-mile radius of each site. Transportation cost estimates of wood fuel to the poultry farms ranged from \$47 to \$166.

Table 3.1. Evaluation matrix of compromise program model.

	Mean Distance (meters)	Biomass Availability (tons/week)	Average Transport Cost	Market Competition
Fort Seybert	23,085.9	11,319	46.6	1
Moorefield	55,026.0	7,953	111.1	1
Wardensville	81,941.2	7,295	165.5	1
Maximum	81,941.2	11,318.5*	165.5	1
Minimum	23,085.9*	7,295	46.6*	1*

* Indicates preferred value for each parameter

Values from the evaluation matrix are normalized by dividing by the maximum value of each variable to return a payoff matrix value that is between 0 and 1 (**Table 3.2**). The preferred value either minimum (f^{**}) or maximum (f^*) is determined for each value. The minimum value is preferred for mean distance, transport cost, and market competition while the maximum value is preferred for biomass availability.

Table 3.2. Payoff matrix of compromise program model.

	Mean Distance	Biomass Availability	Transport Cost	Market Competition
Fort Seybert	0.7183	1	0.7183	1
Moorefield	0.3285	0.7027	0.3285	1
Wardensville	0	0.6445	0	1
f^*	0.7183	1	0.7183	1
f^{**}	0	0.6445	0	0

The ranking is then determined using the compromise programming model (**Table 3.3**). Fort Seybert site is the best location for wood energy utilization in this model when compromising the variables of biomass availability and proximity with transportation cost and market competition (**Figure 3.2**).

Table 3.3. Compromise program output and final ranking.

	P=1	P=2	Rank P=1	Rank P=2	Sum Rank	Final Rank
Fort Seybert	0	0.3088	1	1	2	1
Moorefield	0.5223	0.5674	2	2	4	2
Wardensville	0.8	0.9588	3	3	6	3

Figure 3.2. Biomass availability and proximity to poultry house locations.

3.3.2 Techno-economic feasibility and price sensitivity

Average propane usage by commercial poultry farms in the region is 29,857 gallons per year with a ranging of 2 to 8 poultry houses per farm with average of 3.3 houses giving a propane consumption rate of 7,036 gallons per year per house (**Table 3.4**).

Table 3.4. Survey response of commercial poultry growers in WV.

	Propane Usage (gal/yr)	Propane Price (\$/gal)	Number Houses	Number Flocks/yr	Propane Usage (gal/yr/house)	Propane Usage (gal/house/flock)
Average	2,9857.1	1.04	3.3	5.4	7,035.7	1,310.39
Minimum	2,000	0.89	2	2	1,000	500
Maximum	100,000	1.70	8	7.5	13,750	2,333.33

Energy requirements in Btu/hr are estimated based on the assumptions of a duration of 840 hours per flock, determined were broiler chickens are generally grown in five-week flock rotations with the brooding stage temperature at 90 degrees Fahrenheit and grow out stage is at 85 degrees Fahrenheit. Calculations were performed based upon energy content values of 92,500 Btu/hr for propane, 16,000,000 Btu/hr for wood pellets, and 9,600,000 Btu/hr for wood chips (Coffin 2012, Maker 1994). Efficiency assumptions include 80% efficiency and 10% Btu increase for the brooding stage. Total average estimated energy requirements are 178,107 Btu/hr during grow out period and 195,918 Btu/hr during the brooding period (**Table 3.5**).

Table 3.5. Estimated energy requirements and efficiency assumptions.

	Survey Average
Number of flocks/yr	5.44
Propane usage (gal/yr/house)	7,036
Total Btu/house/yr	650,803,571
Estimated Btu/Hour requirement (840 hrs/flock)	142,486
80% efficiency (Btu/hr)	178,107
10% increase for brooding stage (Btu/hr)	195,918
Wood chip fuel consumption (tons/yr/house)	84.7
Wood chip fuel consumption (tons/month/house)	7.1
Wood pellet fuel consumption (tons/yr/house)	45.2
Wood pellet fuel consumption (tons/month/house)	3.8

Based on the conversion of Btu per hour energy content between propane and wood fuels it is estimated that 45.2 tons of wood pellets or 84.7 tons of wood chips would be consumed per poultry house per year. Inquiry was made with a wood boiler manufacturer and two wood boiler types were considered for poultry house applications. First is a wood pellet boiler capable of utilizing pellet fuel only, the other option is a biomass boiler capable of utilizing wood chips, sawdust, or wood pellets (**Figure 3.3**). The biomass boiler has an output of approximately 310,000 Btu/hr with 80% efficiency while the pellet boiler has an output of approximately 273,000 BTU/hr with a 93% efficiency rating. The tradeoff between the two wood boiler systems is that the pellet boiler requires less initial capital investment but requires the more expensive pellet fuel while the biomass boiler requires a more expensive initial capital investment but accepts a wider range and cheaper fuel types.

Figure 3.3. Boiler systems and fuel type capabilities.

At current market conditions of \$1.04/gallon propane cost annual fuel cost savings of \$2,886 could be achieved with \$35/ton wood chips. Using wood fuel pellets at a cost of \$180/ton would result in an annual fuel cost increase of \$1,552 at current market conditions (**Table 3.6**). Wood pellets at \$180/ton were found to break-even with propane at a cost of \$1.30/gallon.

Table 3.6. Fuel cost analysis for current and break-even market conditions.

	Current Market	Break-even Market	Units
Propane Usage	7036	7036	gal/yr/house
Propane Price	\$ 1.04	\$ 1.30	\$/gal
Propane Efficiency	1.00	1.00	% eff
100% Propane Cost	\$ 7,513.13	\$ 9,146.43	\$/yr
Wood Pellet Usage	45.2	45.2	tons/yr/house
Wood Pellet Price	\$ 180.00	\$ 180.00	\$/ton
Pellet Efficiency	0.90	0.90	% eff
Remaining Propane Use	704	704	gal/yr/house
Propane Price	\$ 1.04	\$ 1.30	\$/gal
90% Pellet 10% Propane Cost	\$ 8,866.76	\$ 9,049.69	\$/yr
90% Pellet 10% Propane Cost	\$ 738.90	\$ 754.14	\$/month
Fuel Savings w/pellets	\$ (1,551.63)	\$ 96.74	\$/yr
Wood Chip Usage	84.7	84.7	tons/yr/house
Wood Chip Price	\$ 35.00	\$ 35.00	\$/ton
Chip Efficiency	0.80	0.80	% eff
Remaining Propane Use	1407	1407	gal/yr/house
Propane Price	\$ 1.04	\$ 1.30	\$/gal
80% Chip 20% Propane Cost	\$ 4,429.33	\$ 4,795.19	\$/yr
80% Chip 20% Propane Cost	\$ 369.11	\$ 399.60	\$/month
Fuel Savings w/chips	\$ 2,885.80	\$ 4,351.24	\$/yr

Price sensitivity was analyzed for wood chips ranging from \$35 to \$65 per ton and for wood pellets ranging from \$140 to \$200 per ton. Pellets have a break-even price ranging from \$1.00 to \$1.50 per gallon propane for \$140 and \$200 per ton wood pellets, respectively (**Figure 3.4**).

Figure 3.4. Wood pellet price sensitivity.

Wood chips have a break-even price ranging from \$0.50 to \$1.00 per gallon propane for \$35 and \$65 per ton wood chips, respectively (**Figure 3.5**).

Figure 3.5. Wood chip price sensitivity.

3.4 Discussion

Woody biomass is vastly available from wood manufacturing facilities, forest residues, or whole-tree chipping operations in the West Virginia area for use as an energy source for poultry house wood heating systems. The economic feasibility of utilizing woody biomass feedstock as an energy source in the poultry production industry is driven by the competing price and availability of traditional fuels such as liquid propane or natural gas pipelines. Even in the scenario that biomass is the cheaper fuel source compared to propane, poultry farmers must consider that wood energy conversion is a significant renovation in order to utilize a woody biomass feedstock and in most cases a completely new heating system must be installed. With many parts to a wood boiler system including the boiler, thermal water storage tank, water-to-air heat exchangers, fuel storage and feeding system an engineering assessment and installation schematics is often necessary for success. Wood energy conversion requires significant capital investment ranging \$30,000 for a single poultry house to \$200,000 for multi-house poultry farms, therefore long-term benefits must be identified in addition to lower fuel cost. Studies have shown benefits of wood biomass heated barns to include better feed conversion, better air quality, and overall better

efficiency (Ebinger 2017). Upon system installation by the WV Statewide Wood Energy team we intend to investigate house environment conditions of wood versus propane heated poultry houses and expect to find that wood energy can also result in better bird health therefore reducing mortality and increasing the yield in bird weight of the poultry farm. It is expected that these benefits can be obtained through a wood boiler system by removing the direct combustion of gas fuels and emissions into the house. Spatial analysis modeling has shown there is adequate wood biomass available within a 100-mile radius of the poultry industry sites in West Virginia with Fort Seybert being the optimum location within the study area for wood energy utilization by poultry growers. Fuel cost analysis determined that at current market conditions of \$1.04/gallon propane cost annual fuel cost savings of \$2,886 could be achieved with \$35/ton wood chips while \$65/ton wood chips are equal to \$1.00/gallon propane. Wood pellets at \$180/ton were found to break-even with propane at a cost of \$1.30/gallon. These analysis show that it is opportunistic for poultry growers to consider wood energy when propane prices are greater than \$1.00 per gallon.

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4. Summary

This research will be a valuable asset for further development of wood biomass fuels as an alternative energy source in the state of West Virginia and throughout the central Appalachian hardwoods region. Production rate and cost estimate models developed from this research are applicable to in-woods chipping operations and wood energy utilization across the region. Wood biomass fuel sources have been identified in adequate volumes and procurement radius to be considered for wood energy utilization by commercial scale wood boilers especially in the poultry industry of eastern West Virginia.

Woody biomass harvesting has been shown to be economically feasible, but higher production rates must be obtained through combining chipping operations with fully mechanized harvesting systems to achieve acceptable production rates. For in-woods chipping of whole-tree mixed hardwoods hourly production rate of the chipper ranged 95.6 ft.³/PMH (40.8 green tons/PMH) to 13,912.9 ft.³/PMH (107.4 green tons/PMH) with average production at 1,473.4ft.³/PMH (65.8 green tons/PMH). Total cycle time including truck delivery averaged 183 minutes, with average hauling distance of 45.8 miles, trucking productivity is estimated at 7.7 green tons/PMH.

Productivity of the chipper was found to be affected by diameter, height, and number of stems as well as the interactions among diameter and height, diameter and number of stems, height and number of stems, and diameter, height, and number of stems. Delivered productivity including both chipping and trucking was significantly different among origin harvest sites and payload sizes. The hourly cost of the harvesting system including one feller-buncher, two grapple skidders, and the chipper was \$376/PMH, the chipper alone has hourly rate of \$ 72/PMH. Given the hourly rate and production chipping alone cost \$ 1.09/green ton, while combined unit cost including felling, skidding, and chipping gives a total harvest cost of \$ 11.34/green ton to

produce in-woods chips at the landing. Total operational costs for felling, skidding, chipping, and truck delivery is estimated at \$ 13 to \$ 17 per green ton dependent upon transportation cost.

Characterization of these woods run whole-tree chips indicate average green moisture of 37.5 percent and calorific heating value 7,992.5 Btu/lb. Ash content was 0.68 and 0.30 for whole-tree and debarked chips, respectively. Piece size classification indicated 4.5 percent of chips were oversized while only 0.7 percent were fines. With these characteristics for in- woods processed whole-tree mixed hardwood chips, the U.S. wood chip fuel quality standard requirements for Grade A1 is met. Ash content of less than 1 percent in whole-tree chips indicates there is not a large incentive for debarking of chips, when the intended use is boiler fuel, as it would add additional cost to the harvesting system and is not necessary to meet the requirements of the highest grade fuel quality standard.

Woody biomass is vastly available from wood manufacturing facilities, forest residues, or whole-tree chipping operations in the West Virginia area for use as an energy source for commercial scale wood heating systems such as those which could be used for poultry production houses.

The economic feasibility of utilizing woody biomass feedstock as an energy source in the poultry production industry is driven by the competing price of traditional fuels such as liquid propane or proximity to natural gas pipelines. Wood energy conversion requires significant capital investment ranging \$30,000 for a single poultry house to \$200,000 for multi-house poultry farms, therefore long-term benefits must be identified in addition to lower fuel cost. Upon system installation by the WV Statewide Wood Energy team I intend to investigate and expect to find that wood energy can also result in better bird health therefore reducing mortality and increasing the yield in bird weight of the poultry farm. It is expected that these benefits can be obtained

through a wood boiler system by removing the direct combustion of gas fuels and emissions into the house.

Spatial analysis has shown there is adequate woody biomass resources available within a 100-mile radius of the poultry industry sites in eastern West Virginia. Fuel cost analysis determined that at current market conditions of \$1.04/gallon propane annual fuel cost savings of \$2,886 could be achieved with \$35/ton wood chips while \$65/ton wood chips are equal to \$1.00/gallon propane. Wood pellets at \$180/ton were found to break-even with propane at a cost of \$1.30/gallon. These analysis show that is opportunistic for poultry growers to consider wood energy when propane prices are greater than \$1.00 per gallon.

With total harvest and truck delivery cost estimated at \$13 to \$ 17 per green ton of wood chips for a 46-mile average hauling distance it is reasonable to believe that considering an acceptable stumpage cost and profit margin whole-tree chips could be produced and delivered within a 50-mile radius for \$35/ green ton. At this delivered price poultry growers can achieve annual fuel cost savings compared to current propane prices. Development of this market could therefore be beneficial to both poultry growers and forest harvesting crews. I hope that this research can collectively support and promote forest harvesting practices in which there is an increase of forest logging residue collection through integration of in-woods chipping operations in order to further utilize these renewable resources for energy at a commercial scale across the central Appalachian region.