Alternative Bioenergy: Small Scale Pellet Production from Forest Residues

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AUTHORIZATION TO SUBMIT THESIS

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ABSTRACT

Forests can readily supply feedstock for alternative bioenergy production. Feedstock removal has the potential to benefit forest health and provide ecosystem services, while also generating profit for forest owners, contractors and forest managers. However, many forest land owners are faced with the challenge of managing forest residues to meet slash compliances and fire regulations. Currently, most residuals are burned or left on site to decompose. In a time where alternative bioenergy sources are growing in demand, new approaches to utilize these residues for bioenergy production are being examined. One approach is a portable, small-scale wood pellet mill that can be taken directly to the logging site. This study aims to compare the pellet quality produced when using a portable system to a controlled laboratory system, using green and beetle killed lodgepole pine residues. Pellets were analyzed for moisture content, calorific value, ash content, carbon and nitrogen content, mechanical durability, density, and percentage of fines. A completely randomized 2x2 factorial design was implemented to compare treatments: feedstock, mill type and the interaction of feedstock across mill type. The effects of treatments on pellet quality were analyzed by the MIXED procedure of SAS 9.4 (SAS Institute, Inc., Cary, NC). Feedstocks were similar only in moisture content, density, and chemical composition, while mill type was found to significantly affect overall pellet quality with portable mill producing lesser quality pellets. It was observed that pellet durability index was affected across a feedstock by mill interaction. Thus, it is possible to manufacture pellets out of residue feedstock utilizing both mill types, however as long as burning residues is socially and environmentally acceptable, portable pelletization of forest residues will remain an underutilized technology.

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I am extraordinarily lucky to have the most amazing family to support me. They are always behind me in whatever direction I choose to go, and will do just about anything to help me succeed. I wouldn't be who or where I am today without you. Mom, Dad, Casey, Owen, and the rest of the gang, thank you. I love you all.

To my friends, the ones whom I consider extended family, thank you. Jon and Ann, my Cavendish crew, Darci, Cynthia, Jessica, my AVS family, thank you for your continued love, support and encouragement. Also to Sandy; thanks for finally teaching me to read. I guess I shouldn't have doubted you in first grade!

Finally, to the kids that have ever been doubted by society. You matter. Keep dreaming.

DEDICATION

To my spunky, independent, intelligent, and generous boy, Owen. You are going to accomplish great things buddy. Also to Mom, Dad, and Casey. You have earned this as much as I have. I love you all.

TABLE OF CONTENTS

TABLES

FIGURES

CHAPTER 1: LITERATURE REVIEW

1.1 INTRODUCTION

1.1.1 The impacts of logging in Idaho

Since the earliest civilizations, logging and lumber production has been important facets of developing societies. From early uses in home building, heating and cooking, to modern lumber and paper manufacturing, logging and wood products play an important role in the day-to-day lifestyle of nearly every American. The industry has experienced significant advancements in the utilization, technologies and practices over centuries, reaffirming logging as a key component of the economic landscape in Idaho and the Pacific Northwest (PNW). Idahoans rely on jobs in the woods, on the roads, and in the mills. Cook et al. (2016) found in 2015 an estimated 11,980 jobs in Idaho resulted from the forest product industry. Furthermore, inter-industry associations resulted in approximately 22,000 jobs in Idaho from converting timber to manufactured consumer products. As a result, $678 million in income was reported, equal to 1.7% of all worker earnings for the state (Cook et al., 2016). Few other states rely more heavily on forest industry jobs than Idaho (O'Laughlin, 2013).

Much like the industry, the resulting timber dollars are a vital part of Idaho's economic maintenance. Forests in Idaho cover 40.5% of the state, with a majority of that percentage considered usable timberlands (Cook et al, 2016). In 2015, Idaho timber harvest was estimated at 1.05 billion board feet (Scribner scale), a slight decrease from 2014 (Figure 1.1; Cook et al., 2016). As a result of harvesting, the Idaho State Endowment Board received $51.9 million for funding public entities, including public schools and universities, state hospitals, and state penitentiaries (Idaho Dept. of Lands Endowment Fund Investment Board, 2016). These timber dollars significantly impact the state of Idaho. Without these funds, many school districts in Idaho would struggle to fund programs. Thus, timber dollars play a valuable role in communities across the state.

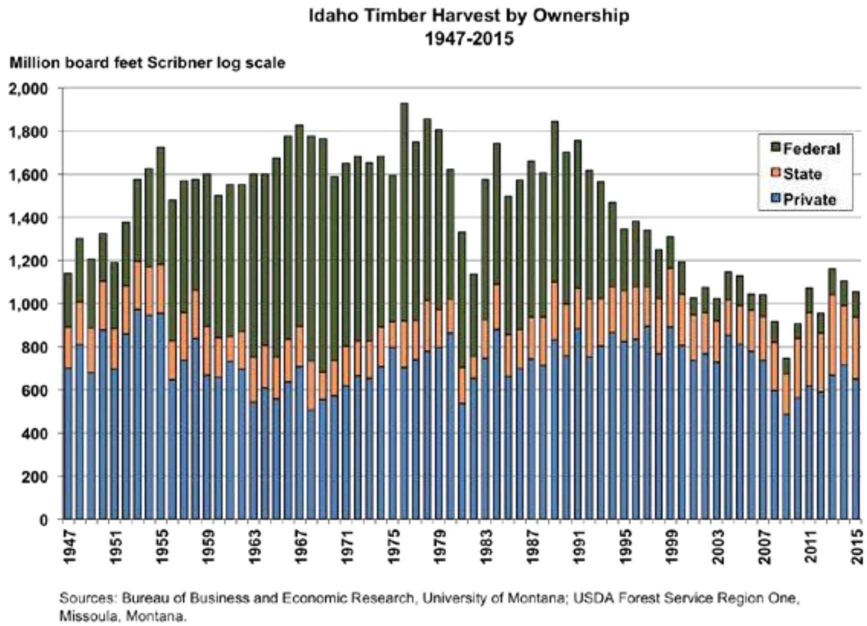


Figure 1.1. Idaho timber harvest by ownership category (Cook et al., 2016)

1.1.2 Forest health and management

Logging is a key aspect to forest health and management. Without timely and sustainable harvest schedules, forests grow too dense, which leads to overcrowding and resource competition among trees, resulting in decreased tree health (Stidham and Simon-Brown, 2011). Increased density among trees can increase the occurrence of insect and/or disease outbreaks or the potential for ignition of catastrophic wildfires; therefore, drastically impacting the overall health of the forest (Brooks, 2015). Despite efforts to manage these situations, a substantial amount of forest residues and dead standing timber exist in Western forest landscapes. If left unmanaged, this timber will only continue to present severe environmental problems.

1.1.3 Mountain Pine Beetle (Dendroctonus ponderosae)

Recently, severe infestations of pine beetles have devastated coniferous forests in the Rocky Mountains and the surrounding western states (USFS, 2010). The mountain pine beetle (*Dendroctonus ponderosae* Hopkins; Figure 1.2) is one of the most destructive and aggressive bark beetle species in the western United States (U.S.), and is especially common in the PNW (Hagle, 2003). As the beetles attack the trees, they inoculate it with a blue-staining fungi (commonly of the *Ceratocystis* and *Europhuim* species), which ultimately results in tree mortality (Woo et al., 2004). This epidemic has been impacting millions of acres of U.S. forests for decades. However, it has recently gained public attention due to the rise uncharacteristic wildfires that devastated many western states during the Summer of 2015. An estimated 300 fires burned nearly 740,000 acres of forests and rangelands in Idaho, costing agencies and taxpayers approximately $60 million in extinguishing efforts (Brooks, 2015). With nearly 80% of the burned acreage overseen by the U.S. Forest Service (USFS) and Bureau of Land Management (BLM), many groups (i.e. landowners, conservationists, etc.) are demanding increased management of federal lands to help prevent future disasters (Healthy Forests, Healthy Communities, 2016). Viable solutions include increasing access to these lands for live and salvage logging opportunities, as well potentially utilizing new and developing technologies for forest slash, or residual, and dead standing timber.

Figure 1.2. (Left) An adult mountain pine beetle chewing through the phloem of a host tree (USFS, 2014); (Right) The resulting damage from a mountain pine beetle infestation (BANR, 2016).

1.1.4 Alternative Energy

With increasing national attention, it will likely be easier to gain public acceptance of using woody biomass (such as forest residues) as a potential source for energy production. Aguilar and Garrett (2009) found people understood that woody biomass utilization could offer an opportunity to produce energy locally, decreasing our dependence on foreign oil, while increasing work opportunities for local communities. Although in recent months the U.S. has seen the lowest fossil fuel prices in nearly a decade (U.S. Energy Information Administration, 2016), alternative energy still appeals to much of the general populace and has left the renewable energy market unscathed. Some speculate that growing global concerns over climate change and a national search for energy security continue to fuel the push for alternatives. Other possibilities include the decreasing costs of renewable energy technologies and their growing feasibility and attainability for the near future. Thus, by continuing to explore the option of utilizing forest residues, new and advancing sources for renewable bioenergy will likely become reality.

1.1.5 Forest residues as renewable bioenergy

New approaches to reducing our dependence on fossil fuels and shifting to renewable bioenergy are being examined. One noteworthy approach is utilizing forest residuals for bioenergy production. Forest residuals (slash) are trees and other woody plants, including limbs, tops, needles, leaves, etc., grown in the forest, woodland, or rangeland environments that are byproducts of forest management activities (Laninga et al., 2015). In light of a search for energy independence, the utilization of forest residuals as a source of bioenergy is worthy of exploration. Forests can readily supply sustainable feedstock for alternative bioenergy production while simultaneously providing economic returns to landowners, contractors and forest managers in addition to benefitting forest health and ecosystem services (Laninga et al., 2015).

Not only are researchers investigating bioenergy from forest residues, but federal agencies are beginning to accept its potential. The Energy Independence and Security Act of 2007 was designed and implemented by the federal government to meet the Environmental Protection Agency (EPA) renewable fuel standards, and to promote energy independence and security ("H.R. 6(110th): Energy Independence and Security Act of 2007," 2007; US Department of Agriculture, 2010). The EPA is "slowly beginning to treat the sector not just as an emitter of particulates, but also as a way to reduce [dependence on] fossil fuels," stated John Ackerly, the President of Alliance for Green Heat (2016). Though the EPA will likely continue to regulate emission standard and monitor particulate emissions for the industry (e.g. newly updated Clean Power Act proposal), they, among others, are starting to view the bioenergy sector as a key approach to reducing our dependence on fossil fuels.

1.1.6 Bioenergy Alliance Network of the Rockies (BANR)

In 2014, the United States Department of Agriculture (USDA) awarded a ten million dollar National Institute of Food and Agriculture (NIFA) Coordinated Agriculture Project (CAP) grant to Colorado State University that established the Bioenergy Alliance Network of the Rockies (BANR). A collaboration of various private industries and educational institutions across Colorado, Montana, Wyoming and Idaho aim to explore the use of beetle killed pine and other forest biomass as a source of bioenergy feedstock in attempts to establish sustainable renewable energy industries across each respective state. The BANR cohort is working to convert woody biomass (i.e. forest management residues, mill residues, harvesting of beetle killed pine, etc.) into advanced renewable biofuel feedstocks, focusing on on-site production in attempts to bypass the logistical concerns (i.e. transportation costs, etc.) (Paustian et al., 2013).

1.1.7 Forest residues management

Utilization of forest residuals for bioenergy production can provide a new management tool to reduce residual accumulation and subsequent fire hazards. Currently, many small forest owners are challenged with managing forest residuals to meet slash compliance and fire regulations. The State of Idaho mandates that residuals be disposed of post harvest to protect reproduction and residual stands (trees remaining post harvest), to reduce the risk of fire and the spread of insects and diseases, and to optimize the conditions for future regeneration of forest tree species (Idaho Department of Lands FPA Handbook, 2015). Traditionally, most residuals are burned or left on-site to decompose. Although this is common practice across the PNW, leaving slash on-site and/or burning it poses risks. Certain species of bark beetles can use green slash piles as breeding grounds, which can potentially increase the risk of a future outbreak of bark beetles in the stand (Schnepf, 2008). Burning emits certain amounts of carbon dioxide and particulate matter into the atmosphere, raising concerns for increased EPA monitoring and regulations in the forestry and logging sectors. In a study by Saul et al. (2015), stakeholders surveyed from multiple communities in the Inland Northwest revealed that air quality was of primary concern. Utilizing slash for renewable energy will likely never eliminate some of these common practices but it can provide the industry an opportunity to be proactive in finding alternative uses for logging waste.

1.1.8 Forest residues in the Pacific Northwest

Many changes are occurring in the size variations of harvested timber. Advancing technologies in logging equipment and milling systems allow smaller diameter and longer log lengths to be efficiently utilized. This dramatically changes the scope of logging residues left on-site. According to a recent study by Simmons et al. (2014), the average diameter of mill delivered wood has been steadily decreasing over time. Mills are currently receiving increasing amounts of smaller diameter wood to meet the same required volume demands. Increased harvesting of smaller diameter trees results in increased amounts of residues per unit volume of merchantable wood. Whenever significant volumes of timber are removed, be it for fuel reduction or otherwise, large volumes of biomass will be generated (USDA Forest Service, 2005). If this trend continues, then the amount of forest residue produced per logging job will continue to increase (Simmons et al., 2014). Due to high transportation costs associated with transporting green residues out of the woods, it is impracticable to haul the residues to off-site commercial processing facilities. Thus, land managers and the federal government must continue to manage residue accumulation while trying to balance the utilization of these products.

Utilizing logging residues as a fuel source requires estimating the current and future availability of slash locally, as well as a regionally (Casey, 2015). The amount of residual biomass remaining after logging is a function of many factors, including harvest volumes, harvest schedules and methods, silvicultural treatments, and type and location of timberlands (Kersetter and Lyons, 2001). Logging residue is currently a readily available and unused resource in Idaho. Rather than wasting the potential energy contained in this residual biomass through the common practice of burning, it can be converted to a usable fuel and/or energy source. This can offset negative environmental impacts while also potentially bolstering local economies and reducing the import of other energy resources (Idaho Governor's Office of Energy Resources, 2014).

In light of the benefits of using slash as a fuel source, foresters, economists, and biofuel scientists have the ability to quantify the amount of residues that are currently available on logging sites and how they can be most efficiently utilized. Morgan et al. (2012) estimates that 1.6 green tons of logging residues are produced in Idaho per thousand board feet (MBF, Scribner scale) of mill delivered wood. Using the estimate of >1.0 billion board feet harvested in Idaho in 2015, then roughly 1.05 million green tons of slash were produced, most of which will be burned on-site or left to decompose. According to the North American Wood Fiber Review (2014), processed chips from logging residues are priced at $50 per bone dry ton (bdt) ±$30 depending on cleanliness, species, and other factors such as buyer-seller relationships. In the Inland Northwest region, prices are closer to $30 bdt, given location and distance from manufacturing plants. Taking into account the current price of $30 bdt, and 525,000 bdt of logging residue produced per year (i.e., total slash quantity of 1.05 million green tons at 50 percent moisture content) this yields a conservative estimate of $15,750,000 worth of potential energy revenue that was burned in 2015. Capturing as little as a quarter of this value would have significant impacts for the industry and local economies, and suggests a real need for investigating further the use of logging residues for bioenergy production.

1.1.9 Extension benefits to forest owners

In efforts to better assist landowners with forest health management, utilization, and residue disposal, Extension personnel across the U.S. are actively trying to provide information regarding new and innovative technology that can be applied to family forest owners. The University of Idaho Extension Forestry program has procured a portable pellet mill in attempt to provide Idaho family forest owners with an alternative [to burning] residue management option and an optimal source of bioenergy. Of 20 communities in the Inland Northwest that were modeled in a study, Saul et al. (2015) found pellet production to be the most profitable and viable option in 19 of the 20 communities as compared to aviation fuel production and mobile biofuel conversion. Thus, if this mobile mill appears to be applicable, this would equip forest land owners with a new tool to reduce the residual waste on their land. Also, if successful, this technology could potentially help owners generate wood pellets for use in home heating or other energy applications.

1.2 WOOD PELLET PRODUCTION

1.2.1 Wood pellet production and global demand

On-site manufacturing of wood pellets from logging residues is an appealing concept, as it would allow producers to transport a densified product off-site, which would help reduce transportation costs (when compared to hauling the green residue). Wood pellets are densified biomass that has been formed into cylindrical pellets (Carone et al., 2011). In the U.S. wood pellets are primarily used in residential pellet stoves for home heating purposes. Wood pellets can also be used for commercial heating and power generation applications (such as thermal energy; U.S. Energy Information Administration, 2013). In efforts to replace coal for energy generation and space heating, European countries have begun using wood pellets in place of coal as a source of clean energy. The strong demand for wood pellets in Europe has been driving the growth of domestic wood pellet production in recent years (U.S. Energy Information Administration, 2013). From 2012 to 2013, wood pellet exports from the United States nearly doubled, from 1.6 million tons to 3.2 million tons with 98% of the exports being delivered to Europe (U.S. Energy Information Administration, 2013). Moreover, many speculate that this growth demand will only continue to increase in the coming years.

With wood pellets growing demand domestically and abroad, several methods of manufacturing are currently being evaluated in attempts to overcome residues undesirable qualities and yield a viable product. Residues have relatively low output (in comparison to fossil fuels) and high transportation costs. Fasina and Sokhansanj (1996) found that the best way to overcome these obstacles is to densify the product into a form that can be handled and stored much like grain. One approach was to densify the woody biomass via pelletizing. Not only does this aid in handling and storage, but it also decreases transportation costs by increasing the amount of product that could be hauled each load. The most common forms of densified woody biomass products are pellets, briquettes, and cubes (Wilson, 2010).

Pelletization of woody biomass (clean, plant derived organic matter (Laninga et al., 2014)) is understood quite well (Van Loo and Koppejan, 2008); however forest residuals consisting of stemwood with bark and needles and may prove to be a more challenging raw material to work with for desirable quality wood pellet production (Paukkunen, 2015). It is acknowledged that tree length tops and branches with bark and needles are less desirable for feedstock among wood pellet manufacturers due to higher ash content in the bark versus debarked wood (wood devoid of bark, needles, etc.) (Van Loo and Koppejan, 2008). Other factors, like dirt contamination during slash piling, may have a very negative important impact on feedstock quality when logging residues are used as raw material source (Paukkunen, 2015). The Pellet Fuels Institute (PFI) has a Standards Program, which offers third-party accreditation and provides specifications for residential and commercial grade fuel (Table 1.1; Pellet Fuels Institute, 2015). This program defines three densified fuel grades: PFI Premium, PFI Standard, and PFI Utility. Premium pellets are the highest quality graded pellets and are available commercially for home heating, while utility are the lowest graded pellets and used in industrial settings such as boiler-heating systems. It may be difficult to reach these standards with forest residues as bark and needles have increased inorganic contaminant levels and bark also increases ash content yields (Paukkunen, 2015).

Table 1.1. Pellet Fuels Institute standards for residential/commercial densified fuel.

Residential/Commercial Densified Fuel Standards			
Fuel Property	PFI Premium	PFI Standard	PFI Utility
Normative Information - Mandatory			
Bulk Density, lb./cubic foot	40.0 - 48.0	38.0 - 48.0	38.0 - 48.0
Diameter, inches	0.230 - 0.285	0.230 - 0.285	0.230 - 0.285
Diameter, mm	5.84 - 7.25	5.84 - 7.25	5.84 - 7.25
Pellet Durability Index	≥ 96.5	≥ 95.0	≥ 95.0
Fines, % (at the mill gate)	≤ 0.50	≤ 1.0	≤ 1.0
Inorganic Ash, %	≤ 1.0	≤ 2.0	≤ 6.0
Length, % greater than 1.50 inches	≤ 1.0	≤ 1.0	≤ 1.0
Moisture, %	≤ 8.0	≤ 10.0	≤ 10.0
Chloride, ppm	≤ 300	≤ 300	≤ 300
Heating Value	N/A	N/A	N/A
Informative Only - Not Mandatory			
Ash Fusion	N/A	N/A	N/A

1.2.2 Wood pellet manufacturing

A variety of factors in the manufacturing process of densified wood pellets can affect the quality of the pellets, with the biggest factor being type and quality of the pellet mill. Typically two major pellet mill varieties are utilized for manufacturing: ring die mills or flat dies mills (Figure 1.4). Although both mill types are used for wood pellet production, the ring die pellet mill is generally the preferred industry choice. In comparison to flat die mills, ring die pellet mills have greater production capacity and longer equipment lifespans, making them well-suited for large-scale production facilities (Huang, 2014; Zhao et al., 2007; Zhang et al., 2014). However, this mill type initially cost upwards of $500,000, not including pre- and post-processing equipment that is needed in a large-scale operation (Dingman, 2009). Flat die pellet mills still have an application, though on a smaller scale (Gao et al., 1999, US Patent 5,871,802). They are often the cheaper mill choice and have more appeal to small pellet producers (Dingman, 2009).

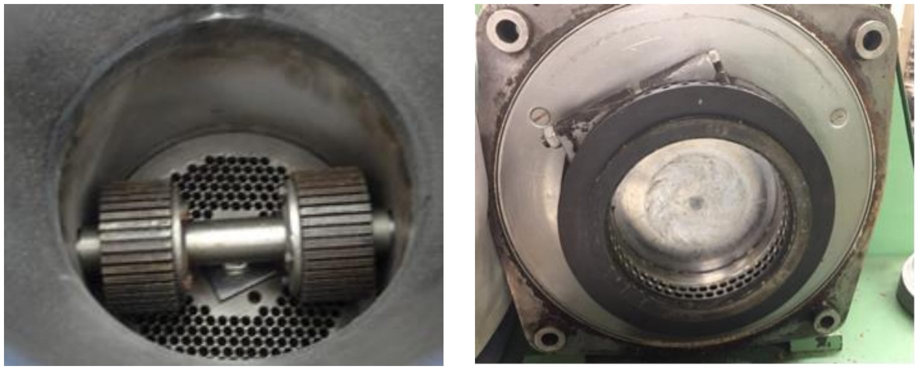


Figure 1.3. Photograph of a flat die (left) and ring die pellet mill (right).

Flat die pellet mills are generally characterized into two categories: rotating die type and rotating roller type (Figure 1.5). The rotating die type has a stationary roller with a die that rotates, while the rotating roller types have a stationary die with rotating rollers (Huang, 2014). Both flat die mill categories create a continuous flow, where rollers apply constant pressure to the feedstock, continuously pushing it down into the die holes. This creates pellets which are immediately and continuously extruded out of the die (Larsson et al.; 2007, Wood, 2010). In contrast, the ring die pellet mill employs a more simplistic design. Feedstock mass is distributed across the inner surface of a rotating perforated die ahead of each roller, which compresses the feedstock mass and compacts it into the dies holes to form pellets (Huang, 2014).

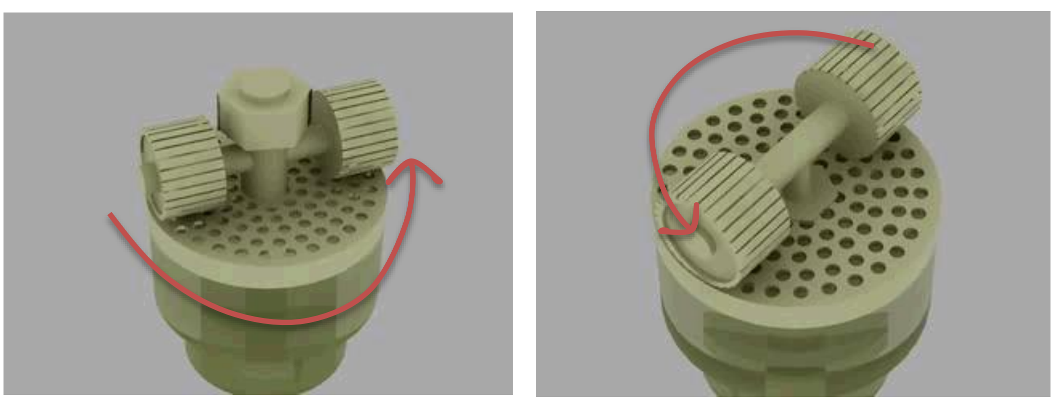


Figure 1.4. Illustrational differences between rotating die type (left) and rotating roller type (right) pellet mills (Amisy, 2016).

The overall design of the pellet mill die also impacts the performance of the mill, utilization of the feedstock, and the quality of the pellets. Often, both flat and ring die mills feature dies with channels that are cylindrical and have beveled openings that are wider than the center portion of the channel and consist of a two series step relief design that allows for the extrusion of the pellet (Figure 1.6 (right); Figure 2.4; Chen et al., 2015; Stark 2009). In a flat die mill, the vertical setup of the dies and rollers allows for the feedstock to gravity feed down into the die channel where it is then compressed by the rollers and extrudes pellets (Figure 1.5; Huang, 2014). Whereas with ring die mills rotational rollers press the feedstock into and through the die channels (Figure 1.6; Chen et al., 2015). In both arrangements, friction between the die and the feedstock creates pressure. This pressure is key to densification as it is what helps push the feedstock through the channels (Chen et al., 2015). As it is building pressure, the friction is also generating heat, which allows the components in the feedstock (waxes, lignin, etc.) to melt and permits for better flow of the material (Nielsen et al., 2009).

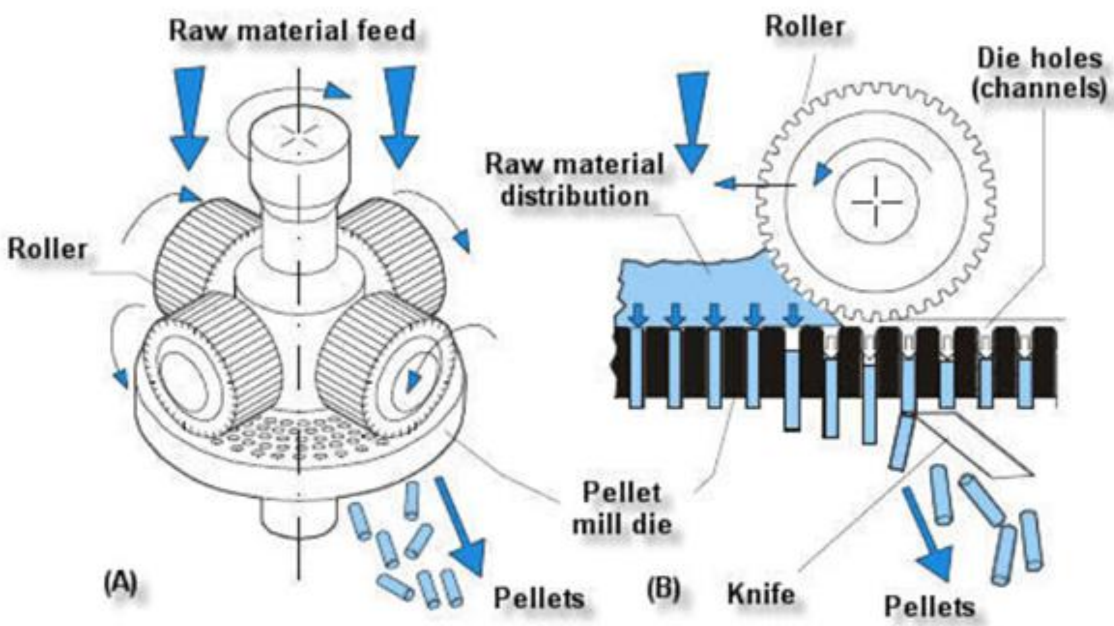


Figure 1.5. Designs and operating principles of a flat die pellet mill (Huang, 2014).

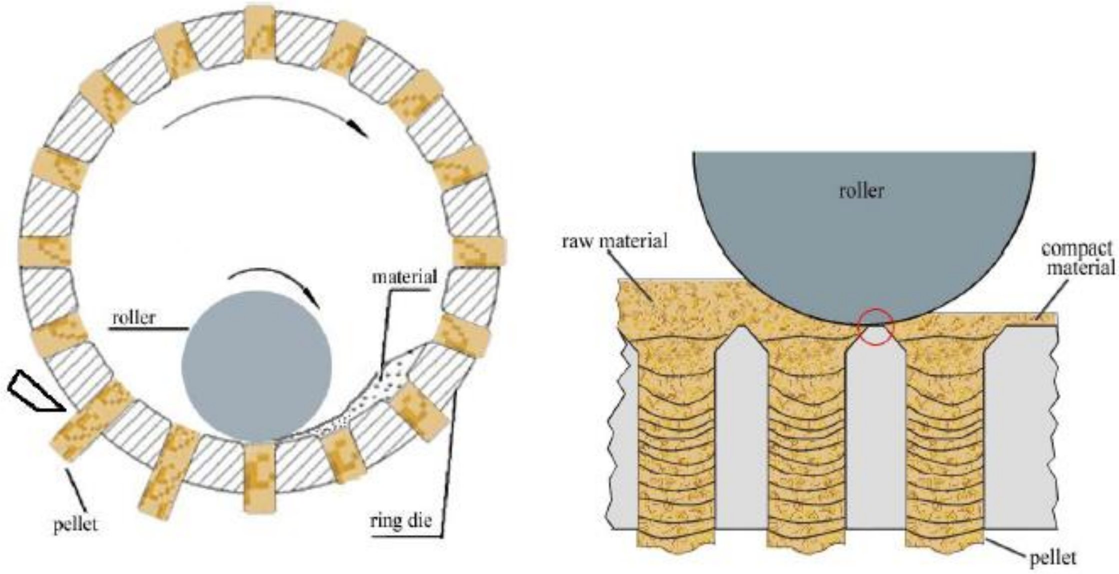


Figure 1.6. Design (left) and operating principles (right) of a ring die pellet mill (Chen et al., 2015).

Both mill types produce pellets that are cylindrical in shape and range in sizes from 4.8-19 mm in diameter and 12.7-25.4 mm in length (Kaliyan and Morey, 2006). A variety of feedstock materials have been used to make fuel pellets, including woody biomass, grasses, grains, etc. During the pelletizing process, attractive forces between feedstock particles and interlocking mechanisms created during feedstock compression are key to the bonding of particles (Wilson, 2010). Regardless of feedstock type, these factors are important for quality pellet production. Pelleting technology is commonly used throughout the U.S. and Europe for its application in processing animal feeds to improve palatability and increase consumption (Wilson, 2010). However, with renewable bioenergy gaining momentum, wood pellets are becoming a dominant player in the marketplace for home heating applications. Though many people and manufacturers are accomplished at the art and science of pellet manufacturing, the pelletizing process has an inherent amount of variability which can lead to lowered production rates and higher variability in the pellet quality (Larsson et al., 2007).

1.2.3 Pellet properties and quality

Many factors can affect the strength and durability of pellets. Strength is an indication of the compression, bendability, and impact resistance of the pellets, whereas durability refers to the abrasive resistance of the pellet (Wilson, 2010; WoodWorks, 2011). Other rheological properties that can affect the overall pellet quality include compressibility (compacting stress to density relationship), compatibility (ability of a material to form strong bonds), and resistance to flow (influence pellet performance), which can vary significantly between feedstock types (Salas-Bringas, et al. 2010; Schulze, 2007). The PFI standards parameters that affect the strength and durability of graded fuel pellets include: pellet density (g/cm^3), diameter (mm), pellet durability index (%), fines (%), length (% greater than 38 mm), and moisture (%) (PFI, 2015). Other significant factors to consider include mill type and milling processes, preheating/steam conditioning, feedstock composition, and addition of lubricants/binders (Wilson, 2010).

1.2.4 Density

Density is an important parameter since it gives insight into how well pellets will hold together during transport and storage (Böhm and Hartmann, 2005). In the PNW, it is not uncommon for woody biomass feedstock to travel large distances from the collection site to a conversion facility (Laninga et al., 2014). Because of this additional stress of transportation, it is important to know how well pellets will transport and store. Pellet density is determined by die hole size (width and length) and compression of the feedstock. Standard pellet mill die hole openings range in size from 4.8-19 mm (Wilson, 2010). Common die sizes for smaller mills range from 6-6.5 mm. Assuming the feedstock is appropriately prepared, pellets should range between those sizes. If the pellets come out looking flaky and break easily, the mill is likely not producing enough torque and/or improperly preheating, leading to less dense pellets (Dingman, 2009).

1.2.5 Pellet durability index

The pellet durability index (PDI) is a standardized parameter for specifying the ability of the fuel pellets to resist degradation caused by shipping and handling (PFI, 2015). The PDI tests the ability of pellets to be handled without generating excessive fines and is also a good indicator of overall pellet quality (Fahrenholz, 2012). As with density, if PDI is too low the pellets will not sufficiently hold together during transport and will be more susceptible to crushing and breakage. Durability is commonly measured in accordance to standard that are set forth by the PFI Annex A.1: Standard Operating Procedure for: Durability Testing—Residential/Commercial Pellet Fuels (Pellet Fuels Institute, 2015).

1.2.6 Feedstock particle size

Feedstock particle material size, moisture content and pellet length are considered the most critical factors affecting overall pellet quality (Fahrenholz, 2012; Kaliyan and Morey, 2005; Wilson, 2010). Particle size can affect all aspects of pellet quality, from overall durability and pellet structure strength, to the percent of fines produced during production and/or transportation. A predominant theory from researchers (Fahrenholz, 2012; Robinson et al.,1962; Wilson, 2010) suggests that small particle sizes leads to better compaction and compression. This produces less fracture points in the pellets and thus increases durability. Similarly, by producing more durable pellets with less fracture points decreases the percentage of fines (Fahrenholz, 2012).

1.2.7 Feedstock moisture content

Moisture in pellet feedstock is necessary for the pelleting process as it helps with the development of intermolecular forces and also acts as both a binder and a lubricant (Kaliyan and Morey, 2005; Wilson, 2010). Folk et al. (1988) suggested that hammermilled feedstock be transferred to a rotary drum where moisture content could be uniformly reduced to a range of 16 to 28% (oven dry basis). In contrast, Kaliyan and Morey (2005) found the optimal moisture content to be between 10 to 15% (wet basis). Li Liu (2000) and Obernberger and Thek (2004) suggested an optimal moisture range for woody biomass between 6 to 12% (wet basis) and 8% to 12% (wet basis) respectively. Wilson (2010) tested a range of moisture content from 10 to 14% (wet basis), ultimately utilizing 10% for most of his work. As is evident from previous work, the reported moisture contents for optimal pellet quality span a broad range. This variability in feedstock moisture contents can be attributed to the differences among the studies, such as feedstock species differences, feedstock particle size, and/or differences in mill and die types. Although moisture content is a critical component in pellet manufacturing, there is not one clearly defined ideal moisture content as no two pellet manufacturing systems are exactly the same. Thus, ranges of appropriate moisture contents for different materials and systems are reported in the literature.

1.3 STUDY RATIONALE

Many have tried to master the "art and science" of pellet production from endless options of feedstock varieties. From woody biomass and prairie grasses harvested to reduce fuel loading, to alfalfa and cereal grains for livestock feed improvements, much research has been conducted around the pellet production idea. With every experimental procedure more knowledge is gained regarding the process and the mechanisms involved in manufacturing the "perfect" pellet. Despite best efforts, there are questions that remain unanswered. The objectives of this study was to produce wood pellets from 1) green lodgepole pine (*Pinus contorta* var. *latifolia*) and 2) beetle killed lodgepole pine that the Rocky Mountains and surrounding landowners are burdened with managing. Wilson (2010) found that lodgepole made the least durable pellets, however this study is optimistic that by utilizing a portable pellet mill the value and carbon energy available in this species can be captured. Additionally, the opportunity to create a value added source of bioenergy for landowners across the region by producing their own wood pellet fuel for home heating is noteworthy.

1.4 STUDY OBJECTIVES

The objectives of this study were to: (1) examine the feasibility of utilizing residual lodgepole pine generated from logging and salvage operations to assess the practicability of using these residuals as a source of raw feedstock material (2) incorporate the use of a new technology into the utilization of this residue by comparing the usage of an on-site portable flat die mill and indoor ring die mill for potential usage for family forest owners, and (3) evaluate the technology's effectiveness and usefulness in utilization by evaluating differences in the pellet quality between pellets manufactured from green and beetle killed lodgepole feedstock on the two mill types.

1.5 STUDY HYPOTHESES

The hypotheses of this study are: (1) both residual green and beetle killed lodgepole pine from logging operations will be a viable feedstock source for pelletization and will efficiently utilize a waste product which will effectively reduce the fuel load left on site post-harvest, (2) both ring and flat die mill types will be successful at manufacturing pellets from both green and beetle killed lodgepole residues, and (3) there will be no significant difference among pellet quality between the two mill types, but a significance difference between green and beetle killed lodgepole feedstock will be observed.

1.6 REFERENCES

Aguilar, F., and Garrett, H. E. G. (2009). Perspectives of Woody Biomass for Energy: Survey of State Foresters, State Energy Biomass Contacts, and National Council of Forestry Association Executives. *Journal of Forestry.* 297-306.

Ackerly, J. (2016). Wood stoves and Washington lobbyists. *Biomass Magazine,* January. Retrieved on April 21, 2016, www.biomassmagazine.com/articles/12793/wood-stoves-and-washington-lobbyists.

Associate Loggers Contractors, Inc. (2016). Homepage. Retrieved on March 28, 2016. http://www.idahologgers.com.

ASTM International (ASTM Standard D 1102 -84) Standard test method for ash in wood.

ASTM International (ASTM Standard D 4442-92) Direct moisture content measurement of wood and wood-based materials.

ASTM International (ASTM Standard E 711-87, Reapproved 1998) Standard test method for gross calorific value of refuse-derived fuel by the bomb calorimeter.

Böhm, T., and Hartmann, H. (2005). Bulk density determination of solid biofuels. *Landtechnik*, 60(3); 158-159.

Brooks, R. (2015). What's bugging our forests? It's a hot topic. PowerPoint Presentation. Presented on February 29, 2016 at "Latah Wildlife Federation."

Carone, M. T., Pantaleo, A., and Pellerano, A. (2010). Influence of process parameters and biomass characteristics on the durability of pellets from the pruning residues of *Olea europaea* L. *Biomass and Bioenergy,* 1-9.

Casey, J. M. (2015). Using logging residues as biofuel feedstocks in the Pacific Northwest: estimating slash pile volumes with low-cost, lightweight terrestrial LiDAR. Thesis. University of Idaho, Forest, Rangeland, & Fire Sciences, Moscow, ID.

Chen, Z., Guosheng, Y., Xiangyue, Y., Wang, Q., and Kan, J. (2015). Improving the conventional pelletization process to save energy during biomass densification. *BioResources.* 10(4): 6576-6585.

Cook, P. S., Morgan, T. A., Hayes, S. W., Sorenson, C. B., Simmons, E., and Becker, D. R. (2016). Idaho's forest products industry current conditions and 2016 forecast. Station bulletin No. 1087. Idaho Forest, Wildlife, and Range Experiment Station. College of Natural Resources. University of Idaho, Moscow, ID.

Dingman, B. (2009). A guide to understanding and using the flat die pellet machine. Make Your Own Pellets, LLC. Londonderry, NH.

Fahrenholz, A. C. (2012). Evaluating factors affecting pellet durability and energy consumption in a pilot feed mill and comparing methods for evaluating pellet durability. Thesis. Department of Grain Science and Industry, Kansas State University, Manhattan, KS.

Fasina, O.O., and Sokhansanj, S. (1996). Storage and handling characteristics of alfalfa pellets. *Powder Handling & Process.* 8(4):361-365.

Folk, R. L., Govett, R. L., Johnson, L. R., and Lee, H. W. (1988). Manufacturing and marketing of wood fuel pellets. Technical Report No. 20 (revised). Idaho Forest, Wildlife and Range Experiment Station, University of Idaho, Moscow, ID.

Gao, Q., Moechnig, B. W., and Crenshaw, J. D. (1999). Animal feed pelleting process and animal feed pellets produced therefrom. U.S. Patent 5,871,802.

Hagle, S. K., Gibson, K. E., and Tunnock, S. (2003). Mountain pine beetle. Field guide to diseases and insect pests of northern and central Rocky Mountain conifers. U.S. Department of Agriculture, Forest Service, State and Private Forestry, Northern Region. 58. Missoula, MT.

Healthy Forests, Healthy Communities, Homepage. Accessed on April 21, 2016. www.healthyforests.org.

H.R. 6(110th): Energy Independence and Security Act of 2007. (2007). Accessed on March 17, 2016. www.govtrack.us.

Huang, J. (2014). Flat die and ring die pellet mills comparison. Gemco Energy. Accessed on April 27, 2016. www.biofuelmachines.com/flat-die-and-ring-die-pellet-mill-comparison.html.

Idaho Department of Lands (2015). Rules pertaining to the Idaho forest practices act, title 38, chapter 13, Idaho code. Section 070, Slashing Management, subsections 01-03. Office of the Administrative Rules Coordinator, Boise, ID. 28.

Idaho Department of Lands Endowment Fund Investment Board (2016). FY2016 Endowment distributions to beneficiary institutions. Retrieved from http://www.idl.idaho.gov/land-board/lb/documents-long-term/fy16-distributions-school-district.pdf.

Kaliyan, N., and R.V. Morey. (2009). Densification characteristics of corn stover and switchgrass. Proceedings of *ASABE.* 52(3):907-920.

Kaliyan, N., and R.V. Morey. (2006). Factors affecting the strength and durability of densified products. Presented at the Annual International Meeting of the *ASABE*. Portland, OR.

Kerstetter, J. D., and Lyons, J. K. (2001). Logging and agricultural residue supply curves for the Pacific Northwest. Thesis. Washington State University Energy Program, Pullman, WA.

Laninga, T., Millman, S., and Payne, K. (2015). From wood to wing: opportunities to build an advanced biofuels industry in the Pacific Northwest utilizing it timber-based assets. *Western Planner.* 35(5):12-19.

Larsson, S. H., Thyrel, M., Geladi, P., and Lestander, T. A. (2007). High quality biofuel pellet production from pre-compacted low density raw materials. *Bioresource Technology.* 99(2008):7176-7182.

Li, Y., and H. Liu. (2000). High-pressure densification of wood residues to form an upgraded fuel. *Biomass and Bioenergy.* 19:177-186.

Morgan, T. A., Simmons, E. A., Berg, E. C., Gale, C. B., and Hayes, S. W. (2012). Forestry IS rocket science: quantifying logging residues as feedstock for bio-jet and other uses. University of Montana Bureau of Business and Economic Research, Missoula, MT.

Nielsen, N. P. K., Holm, J. K., and Felby, C. (2009). Effect of fiber orientation on compression and frictional properties of sawdust particles in fuel pellet production. *Energy Fuels.* 23(6), 3211-3216. DOI: 10.1021/ef800923v

Obernberger, I., and Thek, G. (2004). Physical characterization and chemical composition of densified biomass fuels with regard to their combustion behavior. *Biomass and Bioenergy.* 27:653-669.

O'Laughlin, J. (2013). Forest biomass: business opportunities and market challenges. PowerPoint Presentation. Accessed on April 21, 2016. https://www.uidaho.edu/cr/pag/presentations.

Paukkunen, S., Sikanen, L., and Ikonen, R. (2015). Ash content of wood pellets made from small scots pine (*Pinus sylvestris*) trees with bark. *Forest Products Journal*. 65(7/8):1-9.

Paustian, K., Cotrufo, F., Evangelista, P., Mackes, K., Moore, J., Reardon, K., et al. (2013). Sustainable biofuel feedstocks form beetle-killed wood. National Institute of Food and Agriculture, U.S. Dept. of Agriculture, Grant no. 2013-68005-21298. 1.

Pellet Fuels Institute. (2016). Accessed on January 4, 2016. http://www.pelletheat.org.

Pellet Fuels Standard Specifications for Residential/Commercial Densified Fuel (PFI 8.1.3). Pellet Durability Index (PDI).

Pellet Fuels Standard Specifications for Residential/Commercial Densified Fuel (PFI 8.1.4). Fines.

Robinson, R., Bartikoski, R., Smith, G. M., Heideman, A. G., Nesseth, K. A., and Stevens, C. (1962). Proc. Chapter 5: Methods Available for Improving Pellet Durability. Proceedings from the *1962 Feed Production School*. Midwest Feed Manufacturers Association.

Salas-Bringas, C., Filbakk, T., Skjevrak, G., Lekang, O., Hoibo, O., and Schuller, R. B. (2010). Compression rheology and physical quality of wood pellets pre-handled with four different conditions. *Annual Transactions of the Nordic Theology Society.* (18), 87-93.

Saul, D., Newman, S., Gray, D., Keefe, R., Metlen, S., Jacobson, R., et. al. (2015). Prosperity and sustainability: socioeconomic impacts of wood-based bioenergy development startegies. Poster. College of Agricultural and Life Sciences, University of Idaho, Moscow, ID.

Schnepf, C. (2008). Bark beetles, slash, and forest fertility. University of Idaho Extension forestry information series; insects and diseases. 6:1-2.

Simmons, E. A., Morgan, T. A., Berg, E. C., Zarnoch, S. J., Hayes, S. W., and Thompson, M. (2014). Logging utilization in Idaho: current and past trends. Gen. Tech. Rep. RMRS-GTR-318. USDA Forest Service. Rocky Mountain Research Station. Fort Collins, Colorado.

Stark, C. R. 2009. Effect of die thickness and pellet mill throughput on pellet quality. Abstr. T89. Southern Poultry Science Society Meeting. Accessed on July 20, 2016. https://www.ncsu.edu/project/feedmill/pdf/E_Effect%20of%20Die%20Thickness%20and%20Pellet%20Mill%20Throughput.pdf

Stidham, M., and Simon-Brown, V. (2011). Stakeholder perspectives on converting forest biomass to energy in Oregon, USA. *Biomass and Bioenergy*. 35(1):203-213.

U.S. Energy Information Administration (2016). Gasoline and diesel fuel update. Accessed on April 12, 2016. https://www.eia.gov/petroleum/gasdiesel.

U.S. Energy Information Administration (2013). U.S. wood pellet exports double in 2013 in response to growing European demand. Accessed May 9, 2016. https://www.eia.gov/todayinenergy/detail.cfm?id=16391

U.S. Forest Service (2005). A strategic assessment of forest biomass and fuel reduction treatments in Western States. Gen. Tech. Rep. RMRS-GTR-149. Rocky Mountain Research Station, U.S. Dept. of Agriculture, Fort Collins, CO.

U.S. Forest Service (2010). Major forest insect and disease conditions in the United States: 2010 update. FS-988. USFS Forest Health Protection Offices, Washington, DC.

Van Loo, S. amd Koppejan, J. (2008). The handbook of biomass combustion and co-firing. *Earthscan,* London, Sterling, VA.

Wilson, T. O. (2010). Factors affecting wood pellet durability. Thesis. Agricultural and Biological Engineering, Pennsylvania State University, State College, PA.

Wood Products Council (2011). Structural properties and performance: wood design and building series. WoodWorks Information Sheet WW-001.

Wood Resources International LLC. (2014). North American Wood Fiber Review. Accessed on February 15, 2016. www.woodprices.com.

Zhang, X., Cai, Z. S., Chen, L. H., Chen, Y., and Zhang, Y. H. (2014). Research on the processing methods of equipments for densified biomass fuel. *Journal of Agricultural Mechanization Research.* 36(11), 214-217.

Zhao, T. L., Shu, W., Deng, D. J., Cao, D. H., and Wang, P. (2007). Present research status and development of biomass briquette technologies. *Agricultural Engineering Technology Renewable Energy Industry.* (4), 29-33.

CHAPTER 2: ALTERNATIVE BIOENERGY: SMALL SCALE PELLET PRODUCTION FROM FOREST RESIDUES

2.1 ABSTRACT

Forests can readily supply feedstock for alternative bioenergy production. Feedstock removal has the potential to benefit forest health and provide ecosystem services, while also generating profit for forest owners, contractors and forest managers. However, many forest land owners are faced with the challenge of managing forest residues to meet slash compliances and fire regulations. Currently, most residuals are burned or left on site to decompose. In a time where alternative bioenergy sources are growing in demand, new approaches to utilize these residues for bioenergy production are being examined. One approach is a portable, small-scale wood pellet mill that can be taken directly to the logging site. This study aims to compare the pellet quality produced when using a portable system to a controlled laboratory system, using green and beetle killed lodgepole pine residues. Pellets were analyzed for moisture content, calorific value, ash content, carbon and nitrogen content, mechanical durability, density, and percentage of fines. A completely randomized 2x2 factorial design was implemented to compare treatments: feedstock, mill type and the interaction of feedstock across mill type. The effect of treatments on pellet quality was analyzed using multivariate analysis of variance in the MIXED procedure of SAS 9.4 (SAS Institute, Inc., Cary, NC). Feedstocks were similar only in moisture content, density, and chemical composition, while mill type was found to significantly affect overall pellet quality with portable mill producing lesser quality pellets. It was observed that pellet durability index was affected across a feedstock by mill interaction. Thus, it is possible to manufacture pellets out of residue feedstock utilizing both mill types, however as long as burning residues is socially and environmentally acceptable, portable pelletization of forest residues will remain an underutilized technology.

2.2 INTRODUCTION

Management of logging residues is an issue every forest manager encounters, not excluding small, private and family forest owners. A family forest can be defined as "lands that are at least 1 acre in size, 10 percent stocked, and are owned by individuals, married couples, family estates and trusts, or other individuals who are not incorporated or otherwise associated as a legal entity," (Butler and Leatherberry, 2004). Of the nearly 2.8 million acres of private timber in Idaho, private lands harvesting accounted for approximately 62 percent of Idaho's timber harvest volume in 2016 (Figure 1.1; Cook et al., 2016). Understandably, family forests provide important environmental, social, and economic benefits, however the management and conservation challenges, such as residue management, are uniquely complex and multifaceted for them. Many state and federal agencies have consulting foresters available for private forest owners' use, but no one agency can provide all the necessary resources to meet residue management issues. Decisions are made solely by the owner as they are confronted with obligations of implementing residue control in accordance to state mandates. Adversely, foresters are left to extend sustainability and suitable disposal practices to safeguard the landscape and forests (private and commercial) from dilapidation. This presents unique challenges and opportunities for both forest owners and agencies.

Each family forest owner is as diverse as the next, resulting in management objectives that are different and obscure for many owners. Forest residue management can be equally as obscure across allotments, but the residues still require attention and clearance to ensure forest health. Idaho State mandates that post-harvest residues be disposed of to mitigate the risk of ground fuels for wildfires and to reduce the threat of insect and disease outbreaks (IDL, 2015). Typically this is done by piling the residue at a central landing and burning them, or performing broadcast burns. Regardless of the technique, forest owners are observing usable product being discarded or wasted that could be potentially useful in a home energy setting.

In efforts to protect the health of citizens and prevent environmental and property damage, the Environmental Protection Agency (EPA) implemented the Clean Air Act in 1970 to aid in managing the amount of pollutants that enter the air from many activities including agricultural waste burning (EPA, 2015). By law (Section 110 of Clean Air Act), each state is required to have a State Implementation Plan in place, identifying the sources of air pollution and potential pollutant reduction strategies to meet federal air quality regulations (EPA, 2016). Idaho Department of Environmental Quality (IDEQ) has air quality and burning guidelines in place, and though agriculture waste burning is permitted, fees, monitoring and limitations apply (IDEQ, 2016). Currently, forest residue (slash) burning is not under the jurisdiction of IDEQ (2016), but is instead controlled by the Idaho Department of Lands (IDL). Compliance documents must be filed prior to harvest, and a verification of successful residue disposal is required by the presiding forester post harvest, otherwise fee withholding may result for the harvester or forest owner (IDL, 2015). Although monitoring and management practices are in place, mounting EPA pressures over health and environmental concerns are ever looming and slash burning may one day fall under IDEQ management. Thus, it would be encouraged to have options available that offer alternatives to burning for all forest owners and forest harvesters.

As a method to allow family forest owners to be proactive and self-sustaining, and reduce their carbon footprint, the idea of a portable pelletization unit has become notable. The portable pellet mill is a small-scale production unit, suitable for family forest owners that would like to manufacture wood pellets for home energy uses from waste wood products, including forest and logging residues. This mill has the advantage of being portable, allowing it to be transported to the logging site and maneuvering on-site as needed. This is advantageous to family forest owners, as well as commercial foresters, as it helps to answer the logistical concerns surrounding the use of forest residue for bioenergy. Specifically, by implementing a portable pellet unit on-site, the costs of shipping this forest waste material are dramatically decreased. Instead of transporting green residue, that are upwards of 50% moisture, a densified and usable bioenergy product can be transported instead. Moreover, a family forest owner can possibly utilize the wood pellets for home energy use and be self-sustaining. Not only would the forest owners be able to maintain forest health and integrity while generating supplemental income from the harvesting, but they would also be able to produce a usable bioenergy product from materials that are currently being wasted. Thus, to assist family forest owners with this objective, the use of forest residues for bioenergy production via wood pellets is a viable option.

2.3 MATERIALS AND METHODS

2.3.1 Feedstock Residuals

Residuals were obtained from two locations (Figure 2.1). Green lodgepole pine (*Pinus contorta* var.) residue was obtained from the University of Idaho Experimental Forest located near Princeton, Idaho (46.5026°N, 116.4430°W). Beetle killed lodgepole pine (*Pinus contorta* var.) residue was obtained from a site near Clarkia, Idaho (47.0209° N, 116.1437° W). The two locations are approximately 45 miles apart, but relatively the same elevation (3,000 feet). Residue (slash) materials collected included tree tops (under 25 cm diameter), branches, needles, and bark. The biomass was transported to the University of Idaho Experimental Forest shop, where it was chipped using a gas powered 46 HP Morbark Eager Beaver wood chipper (Morbark, LLC, Winn, MI). The chipped material ranged from 1-8 cm in length, was bagged and marked for identification purposes. Chipped material was dried in a laboratory drying oven at 104°C for 24 hours until the moisture content (MC) reached 0. Dried material was then hammermilled utilizing a 22 HP CF420 diesel powered hammermill with a 6 mm screen (Laizhou Chengda Machinery Company, Shandong, China). Hammermilled material was stored in sealed plastic bags inside plastic bins, which were stored in the shop until further processing occurred.

Figure 2.1. Collecting green (left) and beetle killed (right) residues.

2.3.2 Particle Size Distribution

Particle size distribution was measured for both feedstock types utilizing the sieve analysis method. Both feedstock materials were dried in a drying oven for 24 hours at 104°C until the feedstock reached 0% MC. Five sieve sizes and a collection pan were weighed individually and the weights were recorded. The sieves were then stacked on a sieve shaker in descending order of mesh size; the largest mesh sieve was on top while the smallest mesh sieve was on the bottom with the fines collection pan underneath. Sieve sizes included (largest to small in microns): 6350, 2000, 840, 590, and 420. A 20-gram sample was placed in top screen and a lid was attached. The machine was then started and was allowed to shake for 10 minutes. Once the machine was done, each sieve and corresponding sample was re-weighed and the weights were recorded (done in triplicates for each feedstock type). Mass of wood retained on each sieve (g), percentage of wood on each sieve (%), and cumulative percentage of wood retained on each sieve (%) was then calculated using the following formulas:

$$\text{Cummulative \% retained} = \frac{\text{Mass of wood retained (g)}}{\text{Percentage wood on each sieve (\%)}}$$

$$\text{Mass of wood retained} = (\text{Mass of each sieve} + \text{retained wood}) - \text{Mass of each sieve}$$

$$\text{Percentage of wood on each sieve} = \frac{\text{Mass of wood retained}}{\text{Total mass of wood}} \times 100$$

2.3.3 Pelletizing Residuals

Hammermilled green lodgepole pine and beetle killed lodgepole pine materials were run through a conventional ring die mill and a portable flat die mill. The ring die wood pellets were produced on a California Pellet Mill (CL3) with a 6.4 mm diameter x 44.5 mm die, which is appropriate for pure wood samples (Figure 2.2; California Pellet Mills, St. Charles, MO). Die openings were beveled on the input side of the die and featured a two series step relief design on the output side (Figure 2.4). The openings measured 6.3 mm at the widest opening, narrowing down to 6.0 mm in the center, and widening back out to 6.3 mm. Based on previous literature, a MC range of 15-20% was used. MC percentages were tested (15, 17.5, 20; data not shown) within this range, and based on overall pellet characteristics and quality a MC of 17.5% was found to be optimum. Wood moisture content was determined using a HB43-S Moisture Ananlyzer (Mettler Toledo, Columbus, OH). The MC of the wood particles was adjusted by spraying a calculated amount of water on 3.5 kg of wood particles in a Kushlan Model 350 cement mixer (Kushlan Products, LLC., Sugar Land, TX). Water was applied continuously, using a Central Pneumatic Professional air spray gun at a rate of 0.42 cubic meters per minute (Harbor Freight Tools, Calabasas, CA), while the mixer was ran at 28 RPM. The material mixed for 5 minutes. Once mixed, the wood particles were stored in a heavy-duty plastic bag sealed from the ambient air. The bags were placed in plastic 19 L buckets, sealed with a rubber-lined lid, and stored until pelleting. After pelleting, pellets were arranged in rows to allow for cooling, before they were again stored in the same 19 L buckets.

Figure 2.2. California Pellet Mills laboratory scale ring die pellet mill.

The portable flat die mill wood pellets were produced on a New Michigan Power-Take-Off (PTO) Pellet Machine (Figure 2.3; Make Your Own Pellets, LLC, Londonderry, NH). The flat die measured 28.5 mm thick by 190 mm in diameter. The die openings were again beveled on the input side of the die, and also included a two-step relief design on the output side (Figure 2.4). The openings measured 8.5 mm at the widest opening, narrowing down to 6.0 mm and widening back out to 8.5 mm. The PTO driven mill was powered using a Farmall 560 diesel tractor (Case IH, Racine, WI). The rated revolutions per minute (RPM) speed for the tractor was 1500 RMP, which was also found to be optimal for pellet production. The manual that accompanied this mill suggested wood particles range between 10-15% MC, with an optimal range for most feedstock being between 10 and 12% MC (Dingman, 2009). Similar to the ring die pellets, a range of MC percentages were examined (0, 8, 12), and optimal MC was 8% for the green lodgepole pine feedstock, while 12% was optimal for the beetle killed lodgepole, based on overall pellet quality and characteristics. To convey similar practices used in MC determination, MC adjustments and storage was the same as pellets produced on the ring die mill. Weather data (ambient temperature, relative humidity, precipitation, and pressure) was collected on days when pelleting occurred using the National Oceanic Atmospheric Administration Radar Pro application (U.S. Department of Commerce, Washington, D.C.) for Apple iPhone 6 iOS 9.1 (Apple, Inc., Cupertino, CA).

Figure 2.3. Make Your Own Pellets, LLC., portable PTO driven, flat die pellet mill (Make Your Own Pellets, LLC, 2014).

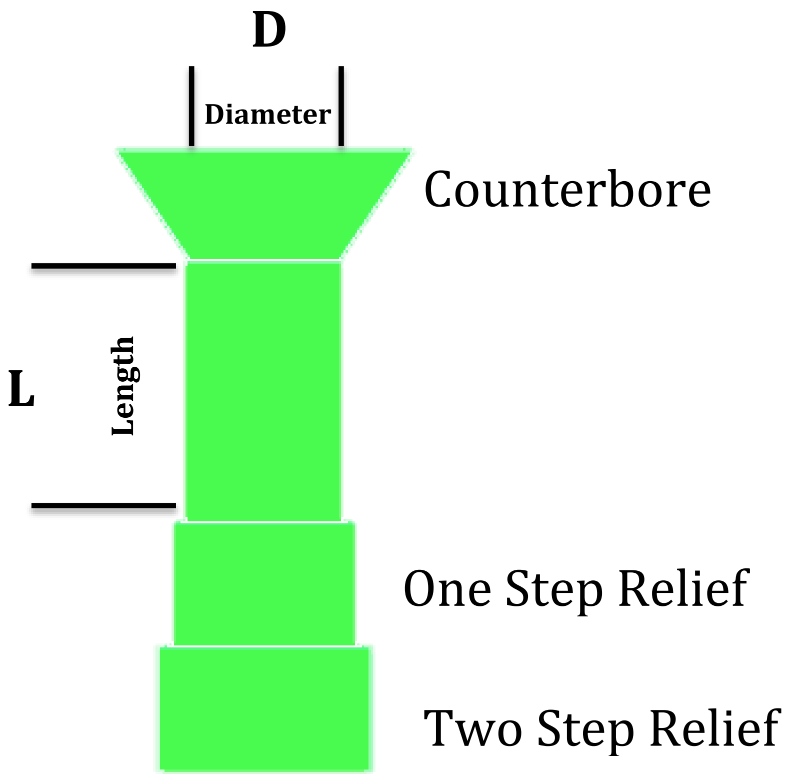


Figure 3.4. Die channel configuration in both the flat and ring die mills (Stark, 2009).

2.3.4 Methods for Pellet Analysis

Pellets (Figure 2.6) were analyzed for moisture content, calorific value (ASTM E711-87), ash content (ASTM D 1102), carbon and nitrogen (CN) content, mechanical durability (PFI 8.1.3), density, and percentage fines (PFI 8.1.4). All samples were analyzed in a random order in each analysis to minimize processing variance.

Pellet MC was performed in triplicate and determined using a HB43-S Moisture Analyzer (Mettler Toledo, Columbus, OH). Depending on pellet size, 2.0 to 5.0 g of pellets were weighed and placed in the aluminum tray. Moisture content data was recorded.

The calorific value was determined in duplicates for each functional pellet replicate using a Parr 6200 Calorimeter, Colby College Version standard bomb calorimeter (Parr Instrument Company, Moline, IL; Figure 2.4). Wood pellets were dried for 24 hours at 104

°C prior to testing. Wood pellet samples varied in weight between 0.38 to 0.65 g. A 10 cm piece of nickel chromium fuse wire was attached to the bomb calorimeter and looped down, just inside of the vessel near the pellet, without touching either. The bomb vessel was pressurized with oxygen to 28 atm. The calorimeter jacket was filled with 2 L of 20°C deionized water. The bomb canister was submersed in the jacket and firing wires were connected. The unit was closed and the unit stirrer was activated. The test began after sample identification and weight was entered on the unit computer. The inside of the bomb canister was cleaned with a damp paper towel after each sample to remove test residues.

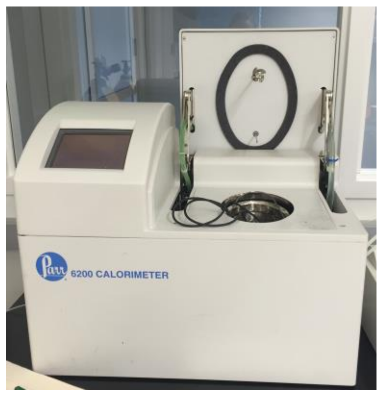


Figure 2.5. Parr 6200 Calorimeter, Colby College Version standard bomb calorimeter.

To determine pellet ash content (triplicates), 2.0 g of pellets were weighed and placed in a pre-weighed crucible. Pellet + crucible weight was recorded (initial weight) and crucibles were placed in a Lindberg Blue M 794 muffle furnace (Thermal Product Solutions, Riverside, MI) at 600°C for 4 hours. After samples were cool enough to handle, pellet + crucible weight (final weight) were again recorded and ash yield was calculated using the following formula:

$$\% \text{ Ash} = \frac{final\ weight - crucible\ weight}{initial\ weight - crucible\ weight} \times 100$$

Carbon and Nitrogen (CN) content was analyzed for each pellet treatment (triplicates). Pellets were ground through three screen sizes (2 mm, 1 mm, 0.5 mm) using a Thomas-Wiley Model 4 laboratory mill (Thomas Scientific, Swedesboro, NJ), until they resembled a fine powder. Samples were then placed in a drying oven for 24 hours at 104°C.

Once dry, samples were placed in airtight containers and stored in a desiccator until further processing. To prepare the samples for the CN analyzer, 6 mg of sample was placed in a 5x9 mm pressed tin capsule, suitable for solid samples (Code 41061; Costech Analytical, Valencia, CA). Sample and tin were weighed using a Mettler Toledo AT21 comparator microbalance (Columbus, OH). Air was pushed out of the sample tins and they were folded into a round shape. Samples were again stored in a Dry Keeper desiccator (Sanplatec Corp., Osaka, Japan) until further analysis. The CN content was analyzed using a Costech ECS 4010 elemental analyzer (Costech Analytical, Valencia, CA, USA). Certified reference material (Acetanilide, % N = 10.36; % C = 71.09) at varying masses, was used to create calibration curve.

Pellet durability index (PDI) was determined for each pellet treatment in duplicates. A representative sample of the pellets was screened to remove the fines using a 3.18 mm metal screen sieve. The dust tight tumble box was weighed and tared on a Sartorius analytical balance (Sartorius Stedim Biotech, Aubagne, France). A 500 g sample was added to the box. The tumble box was securely closed and attached to 1-1/2 HP Dayton DC motor (Dayton Electric Manufacturing Company, Niles, IL; Figure 2.5). The pellets were tumbled for 10 minutes at 50 RPM (for 500 rotations total). After tumbling, the pellet sample was re-sieved and sample weight was recorded. The PDI was calculated using the following equation:

$$\text{PDI} = \frac{final\ pellet\ weight}{initial\ pellet\ weight} \times 100$$

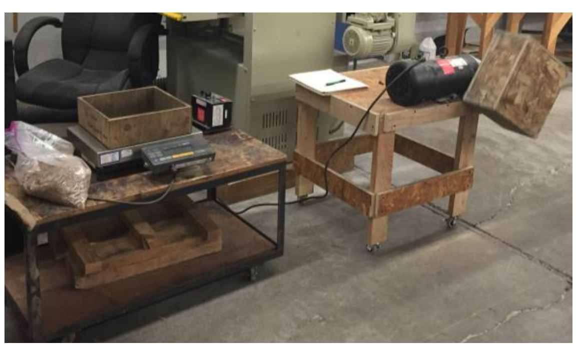


Figure 2.6. Pellet durability index testing system.

The density of each pellet was determined in triplicates. Using a Mitutoyo digital caliper (Code 500-171; Mitutoyo Corp., Japan) to measure length (mm) and diameter (mm), and an analytical balance to measure weight (g) (Fisher Scientific, Waltham, MA), the pellet density was calculated using the following equation:

$$\text{Density} = \frac{weight}{\pi \times length \times 0.25(diameter^2)}$$

Percentage of fines was determined by screening a 3 kg sample through a 3.18 mm wire screen sieve. The sample was added to the screen and the screen was tilted back and forth 10 times. Screened fines were collected in a base pan. Percentage of fines was calculated using the following formula:

$$\%\ \text{Fines} = \frac{Fines\ sample\ weight}{Initial\ sample\ weight} \times 100$$

2.4 EXPERIMENTAL DESIGN

Data were analyzed using multivariate analysis of variance and linear regression using SAS 9.4 (SAS Institute, Inc., Cary, NC). A completely randomized 2x2 factorial design was implemented to compare treatments; feedstock (green lodgepole pine and beetle killed lodgepole pine), mill type (laboratory and portable) and the interaction of feedstock across mill type. The effect of treatments on pellet quality was tested by the MIXED procedure of SAS. Protected least significance difference was used to compare least square means (LSM) and data are reported as LSM ± greatest standard error of the means (SEM). Linear and quadratic contrasts were also tested to detect effects of pelleting order on pellet quality. Experimental unit was declared as each feedstock option by mill type replicated 4 times (n=16). A power analysis was conducted to help determine sample size. With a confidence level of 95% (2-sided) and a nominal power of 80%, it was determined that a minimum of three replicates (12 experimental units) would be required to detect a significant difference among feedstock and mill type. This assumed that each feedstock sample within mill type was independent from one another.

2.5 RESULTS AND DISCUSSIONS

2.5.1. Particle Size Distribution

Particle size distribution was consistent between the beetle kill and green lodgepole pine residues (Figure 2.7). The distribution did not differ when comparing percent retained by sieve size across feedstocks. This consistency between feedstocks was expected, as all feedstock samples were hammermilled using a 6 mm (6000 µm) screen. However, particle size distribution did differ by feedstock across the sieve sizes (*P*=0.0006), with the most notable difference between the 840 and 590 µm sieves. With exception to the 840 µm, green lodgepole had only slightly greater percentages of particles retained per sieve screen. Thus, the overall particle size distribution of both the beetle killed and green lodgepole pine residues were fairly consistent.

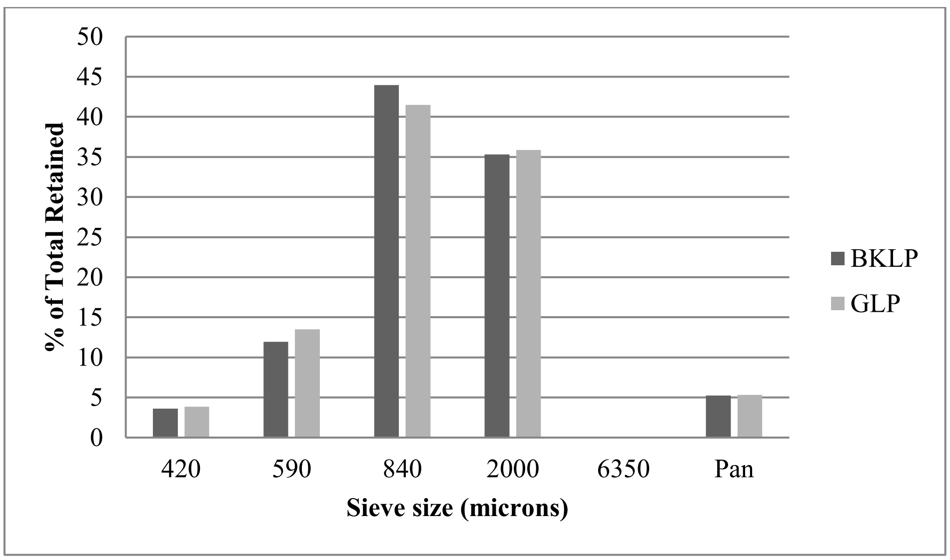


Figure 2.7. Screen analysis results for the beetle killed and green lodgepole pine residue feedstock.

2.5.2 Moisture Content

Pellet moisture content (MC) varied from 2.29 to 8.62%, with pellets from the portable mill having lower MC% (3.13%) as compared with pellets from the ring die mill (7.86%). The feedstock types also differed within each mill type. Green lodgepole consistently had greater MC values than the beetle killed lodgepole (5.70% vs. 5.29% ± 0.14, *P*=0.09; Table 2.1). Ring die mill feedstock had a greater initial MC, which may have increased overall MC in ring die mill pellets (*P*<0.01). As expected, pellet MC varied by mill type (*P*<0.01) and tended to vary by feedstock, though not significantly. Feedstock was pelleted in separate batches but was handled and prepared for pelleting identically to differing final MC as was deemed appropriate for quality pellet production by mill type. It has been found that following beetle infestations, the blue-staining fungi that is left behind by the beetle leads to a decrease in moisture content, as well as specific gravity of the wood, which is thought to be a result of fungal degradation to the cell-wall (Woo et al., 2005; Koch, 1996). Thus, potentially altering the overall MC characteristics of the wood. Also, environment likely influenced the effects of the mill type on MC, as one environment was controlled (laboratory) while the other was not (portable). In addition to environment, the type of die in the mill can also affect conformation. Ring die mills create better quality pellets as compared to flat die mills, and are often the industry standard (Chen, et al., 2015). With exception to the green lodgepole pellets from the portable mill, all of the pellet varieties are within the parameters to meet PFI's Premium pellet specification for MC at ≤8% and all pellet varieties meet the ≤10% specification set for all three PFI pellet categories (Figure 1.3).

Table 2.1. Least Square Means for Pellet Analysis								
	Feedstock		Mill Type			*P*-value		
Analyses	GLP[1]	BKLP[2]	F[3]	R[4]	SEM[5]	Feedstock	Mill	Feedstock × Mill
Density, g/cm^3	1.13	1.15	1.10	1.17	0.014	0.25	< 0.01	0.53
Pellet Durability Index	0.89	0.86	0.78	0.97	0.0048	< 0.01	< 0.01	< 0.01
Fines, %	15.36	19.15	20.41	14.10	1.20	0.05	< 0.01	0.14
Ash, %	0.45	0.34	0.42	0.37	0.023	< 0.01	0.18	0.22
Moisture, %	5.70	5.29	3.13	7.86	0.16	0.09	< 0.01	0.55
Calorific Value, KJ[6]/kg	20750	20430	20664	20516	47.80	< 0.01	0.05	0.32
Chemical Composition								
Carbon, C	51.81	52.51	52.34	51.96	0.41	0.26	0.51	0.35
Nitrogen, N	0.34	0.33	0.32	0.35	0.012	0.64	0.14	0.64
C:N Ratio	0.0025	0.0024	0.0025	0.0024	0.00012	0.41	0.72	0.91
[1]Green lodgepole pine								
[2]Beetle killed lodgepole pine								
[3]Flat die pellet mill								
[4]Ring die pellet mill								
[5]Greatest standard error value of least squared treatment means								
[6]Kilojoule per kilogram								

2.5.3 Calorific Value

Calorific value is a direct measure of heating value possessed in each pellet type. The pellets were rated at similarly reported BTU/lb. as previous studies, regardless of the bark and needles (Piekarski et al., 2009). Interestingly, calorific value differed between the two-feedstock varieties, with pellets from green lodgepole residues having greater heating values than pellets from beetle killed residues ($P<0.01$). This may be due to the green lodgepole residues having a higher percentage of needles still attached during chipping and grinding. The additional branches, needles, and bark likely influenced calorific value due to the presence of additional components (such as waxes) that contributed to increased calorific values. These waxes and extractives likely also aided in the pelleting process, by acting as natural lubricants (Piekarski et al., 2009). Calorific value varied across mill type in the pellets with greater output from the flat die mill pellets as compared with ring die mill pellets ($P=0.05$). Though significant, the variation was negligible at a larger scale (63.34 BTU/lb. or 0.72% increase). Multiple confounding variables were likely influencing this difference, with feedstock MC presumably having the largest impact on calorific value. Feedstock for the ring die mill was altered to 17.5% MC; whereas, feedstock for the flat die mill was altered to 8 and 12% MC for beetle killed and green lodgepole residues, respectively. The greater MC in ring die mill feedstock as compared to the flat die mill feedstock likely had a tendency to affect pellet MC by mill type (7.86 vs. 3.13 ± 0.16 %; $P=0.09$). The MC of the wood can influence pellet calorific value, because part of the energy released during combustion is spent in water evaporation (1049.011 BTU/lb. water), and is therefore not available for thermal use (Krajnc, 2015). As with the other analysis factors, we did not see an interaction effect between feedstock by mill type ($P=0.32$).

2.5.4 Ash

The observed ash content (Table 2.1) for all pellets in this study were well below the standards outlined by the PFI pellet specifications for residential/commercial densified fuels (PFI, 2016). To be branded as premium pellets, the ash content needs to be ≤1.0% (≤2% for standard grade; ≤6% for utility grade). The results of this study show that the ash content of the pellets ranged from 0.26% to 0.54%, which is well below the defined premium standard. Greater ash values were reported in green lodgepole residues than beetle kill lodgepole residues ($P<0.01$), however all values were comparable to those reported in literature (Paukkunen, 2015; Piekarski et al., 2009). Given the utilization of residues (including bark and needles), much higher percentages of ash were expected in all pellets, as bark is a known contributor to higher ash contents (Paukkunen, 2015).

2.5.5 Carbon and Nitrogen

The difference between carbon and nitrogen concentrations among the pellets was considerable (Figure 2.6). Despite having needles in the residue feedstock and resulting pellets, nitrogen concentrations remained low and in some instances, undetectable. In contrast, carbon concentrations were similar to previously reported concentrations for wood residues with bark and needles (Johansson et al., 2003; Johansson et al., 2004). In this study, no significant difference was detected for carbon, nitrogen, or carbon nitrogen ratio. This indicates that chemical composition remained constant across feedstocks, pellet mill types, and the interaction of feedstock and mill. Therefore, combining the residues feedstock for pelleting did not influence the overall characteristics or integrity of the pellets.

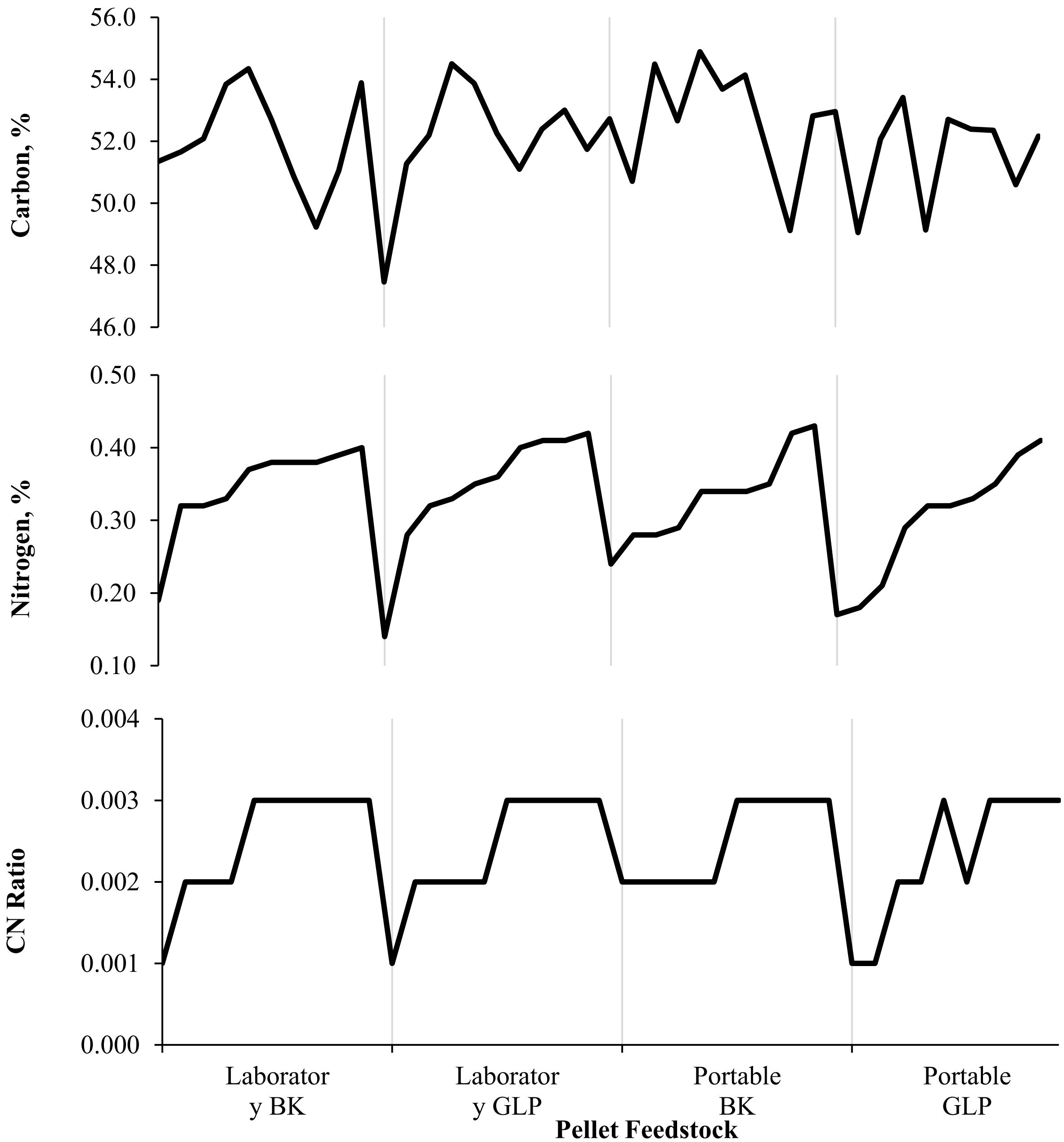


Figure 2.8. Percentage of carbon, nitrogen, and the carbon nitrogen ratio detected in the pellet samples for all treatment levels.

2.5.6 Pellet Durability Index

The pellet durability index indicates of the overall strength and compaction of each pellet variety. This index serves as a conclusive comparison between each feedstock and mill performance, and also indicates how well pellets transport. Results of this study suggest that feedstock (P<0.01), mill type (P<0.01), and feedstock by mill interaction (P<0.01; Figure

2.8) affect pellet durability. Initial observations indicated that pellets manufactured using the flat die mill were visibly inferior to the pellets from the ring die mill. Pellets from the flat die mill were much shorter and appeared fragmented with striations, which previous research has suggested to be synonymous with weakness or breakage points (Figure 2.7; Wilson, 2010). Pellets from the beetle killed lodgepole were also found to be less durable than the green lodgepole pellets (*P*<0.01; Table 2.1). Woo et al., (2004) found that the wood morphology and chemistry is affected after a beetle infestation, lowering the overall quality. This is likely the reason that the beetle kill lodgepole exhibited slightly less durability than the green lodgepole. This indicates that the feedstock, mill type, and the interaction of the two, have a significant impact on the overall pellet quality and durability.

Figure 2.9. Pellets from both residue types, produced on the portable mill (left) and the laboratory mill (right) with varying MC.

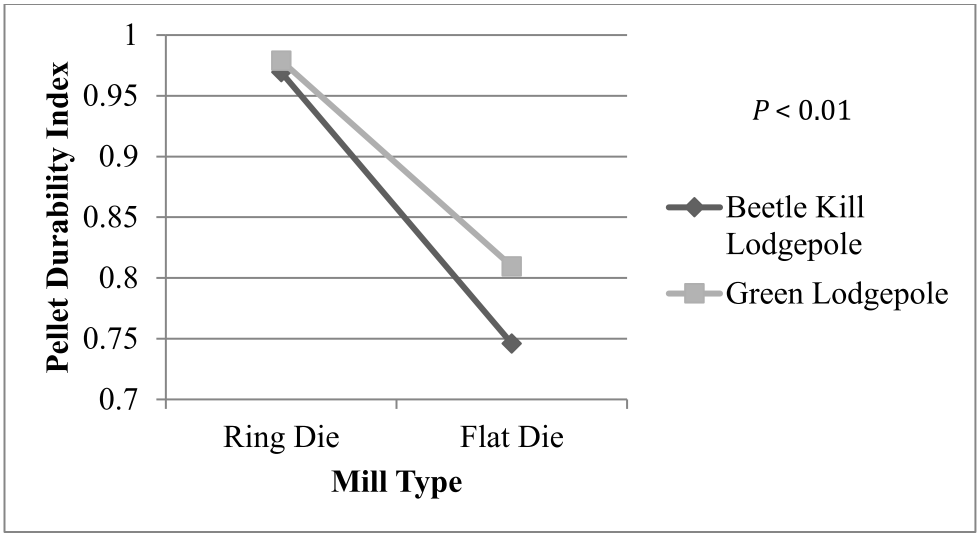
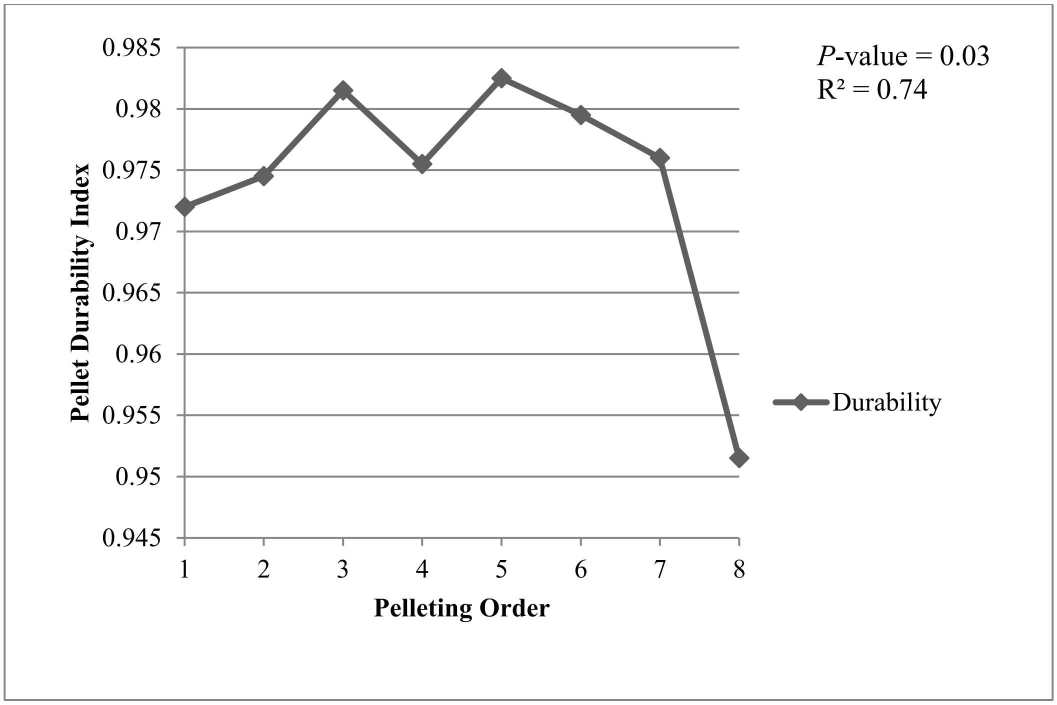


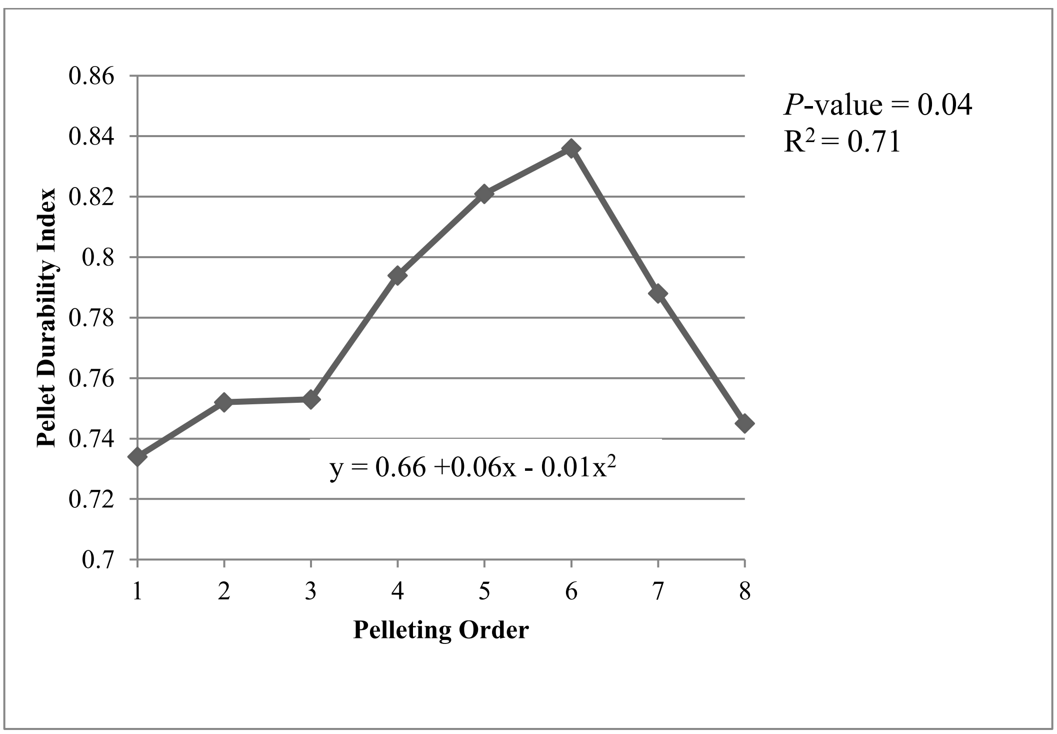
Figure 2.10. Pellet durability of feedstock across mill type.

2.5.7 Regression Analysis

In addition to the main effects, pellet production sequence impacted pellet durability for both mill types and feedstocks (Flat die: P=0.04, r=0.71; Ring die: P=0.03, r=0.74; Figure 2.9). Pellets produced in the middle of the production cycle were found to have the highest PDI value, suggesting that those particular pellets are the most durable and will handle the best. Whereas pellets produced at the beginning and the end of the production cycle resulted in lower PDI values. At the beginning of the production cycle when the mill is cool, pellet quality and durability is expected to be lower because of less heat present to warm up the lubricants (natural or artificial) in the feedstock (Dingman, 2009). However, pellet quality at the end of the production cycle was similar to quality at the beginning of the cycle. Logistically, pellet production and quality would peak at mid-production cycle when the mill is hot and running at full capacity, and would maintain throughout the end of the production cycle. However, pellet quality decreased as the cycle progressed beyond mid-point. Reasons why this may be include outliers, slowed production towards the end of the run or a slight change in weather altering the feedstock characteristics and/or mill temperatures. However a definitive reason why this occurs is unclear.



A



B

Figure 2.11. Regression analysis of pellet production sequence in regards to mechanical durability. A) represents both green lodgepole pine and beetle killed lodgepole pine pellets manufactured on the ring die mill, while B) represents those pellets manufactured using the flat die mill.

2.5.8 Density

Pellet density was found to be highly positively correlated with PDI value (*P*=0.01). This correlation suggests why a significant difference was observed between mill types (*P*<0.01). Despite high correlation, density did not differ across feedstock or feedstock by mill interaction. Mill type did affect pellet density (Table 2.1). This is consistent with previous studies that ring die versus flat die ring produce significantly different pellet quality (Chen et al., 2015). The flat die on the portable mill is considerably thinner than the ring die on the laboratory mill. Therefore, the feedstock is not spending a long time in the die before extrusion. This resulted in less overall heat conduction from the portable mill, lower feedstock compaction, and reduced overall pellet density. In addition to die type, pellet production may have been influenced by the environment where the mills were located. The portable flat die mill was located in an outdoor location, which can be highly variable. As compared with laboratory ring die mill, which was located inside a climate-controlled facility.

2.5.9 Fines

By definition, fines are any particulates that are not consumed during pelletizing or that come from compacted pellets. Fines may accumulate at the mill gate (chute where pellets are extruded), or during transport or handling (Thomas, 1996). In this study, fines were negatively correlated with pellet durability (r=0.70; *P*<0.01) and MC (r=0.73; *P*<0.01). This is logical because when percentage of fines increases, pellet durability, which is highly correlated with MC (r=0.98; *P*<0.01), decreases. Initial visible observations indicated that the pellets produced on the flat die mill had significantly more fines present, both at the gate and after transport and handling, as compared with pellets produced with the ring die mill. Upon analysis, this observation was supported, as fines differed across feedstock (*P*=0.05) and mill types (*P*<0.01). There were no detectable differences of fines by feedstock across mill type (*P*=0.14). Pellet fines were greater for the portable mill as compared with the laboratory mill (20.41 vs. 14.10 ± 1.20%). Fines were also significantly different between feedstock types, with beetle killed lodgepole having a higher overall percentage of fines than green lodgepole (19.15 vs. 15.36 ± 1.20%). Regardless of mill or feedstock type, all variations of pellets exhibited significantly higher fine levels than is acceptable for any standards or accreditation program. Under the PFI low-grade pellets require less than 1.0% of fines be deposited at the mill gate during production. To be branded premium, less than 0.5% of fines at the mill gate is acceptable. Due to the high percentage of fines deposited at the chute gate in this study, it is evident that pellets manufactured on both mill types and from both feedstock variations will not meet commercial or residential pellet standard without further modifications to the mill and/or the feedstock materials.

2.6 CONCLUSIONS

Managing forest and logging residuals will always be an issue for land managers and forest owners. Whether it is performing annual pruning and clearing on family forests, overseeing logging site clean up, or managing stands of dead standing timber, foresters of all divisions will be challenged with evolving forest residual management as new timber harvest strategies emerge and the potential for changing regulations become imminent realities.

The portable pelleting system holds merit as a new resource to utilize forest residue and potentially aid in the reduction of burning residues. Yet, some limitations exist in this system. The portable, flat die mill demonstrated that it was capable of utilizing forest residues and manufacturing pellets, although the pellets were lesser quality than those produced on the laboratory, ring die mill. Pellets from the flat die mill were variable in length, drier, and had numerous striations and breakage lines. Comparatively, the pellets from the ring die mill were more uniform in length, glossy in appearance, and were well compacted. The ring die configuration of the laboratory mill demonstrated that it was better suited for pelleting both varieties of the lodgepole residues in this study. However the flat die mill should not be disregarded, as it was also capable of producing pellets and may excel at pellet production utilizing other feedstock varieties.

Of the variety of feedstock species available, beetle killed pine species were of particular interest for this study. The acres of beetle killed pine in the West are growing rapidly, threatening the integrity forests and creating a fuel source for wildfires. Moreover, beetle attacks have been found to significantly affect the wood morphology and chemistry, affecting the overall quality of the wood fibers (Woo et al., 2004). This lessens the value of the wood, even for energy production, if timely utilization is not enacted (Stennes and McBeath, 2006). Fungal degradation of the wood cell following infestations alters moisture content and specific gravity (Woo et al., 2004; Koch, 1996). Thus, the low density and subsequent high elasticity of the wood likely altered the friction being generated between the die and the feedstock. It is known that denser materials will generate more friction, and thus more heat, during the pelleting process (Wilson, 2010). Heat is vital to quality pellet production and can be achieved with softwood materials by increasing residence time in the die (Wilson, 2010). A modification to increase the die depth (Stark, 2009) of the flat die mill could increase the residence time that the feedstock spends in the die before extrusion, thus increasing the overall compaction and pellet quality. This infers that with minor modifications to the mill, green and beetle killed lodgepole may be better utilized as a feedstock for family forest owners.

Pellets were successfully produced utilizing both the green and beetle killed lodgepole logging residues, however neither feedstock nor mill type yielded pellets that met all the PFI required standards. To be classified in one of the three PFI pellet standard categories for residential and commercial densified fuels (i.e. premium, standard, and utility), it is mandatory that pellets meet all of the fuel property requirements as outlined by each category on the PFI Standards Specification sheet (Figure 1.3). Pellet durability, percentage of fines, and overall pellet length were disqualifying standards for pellets in the present study. Beetle killed feedstock produced slightly lesser quality pellets than the green feedstock and the portable mill was not as well equipped to process the lodgepole pine residue feedstock as the laboratory mill. However, pellets were acceptable in moisture content and percentage ash for all treatment combinations. It is possible to manufacture pellets from logging residues, specifically utilizing beetle kill pine and a portable mill; however the pellets are not suitable for residential or commercial applications based on industry standards. However if family forest owners choose this system to utilize residues on their property, pellet quality may not be as much of a concern. Ultimately, pellet stove owner preference is what dictates the standards of pellet quality. While this portable system may not be appropriate for every pellet stove or forest owner, it may be for some, thus signifying more research is needed to come to a more conclusive answer.

With the portable flat die mill, it is feasible for forest owners to utilize logging residues to manufacture pellets. Though the flat die mill produced lesser quality pellets from lodgepole pine residues, potential to produce pellets for personal household use may be feasible. The portable milling system provides an opportunity for forest owners to be proactive and self-sustaining. However, as long as burning forest residues are permitted pellet production will likely remain an underutilized technology for forest residue management.

2.7 FUTURE RESEARCH

In part, we now have a better understanding of how beetle killed lodgepole pine forest residues and portable milling systems function and the application that all may serve for family forest owners. The initial results were less conclusive than originally anticipated, however we are now provided opportunity for developing this technology. Species selection is a key element during pellet production, as producers often have difficulty making pellets from different tree species. One such opportunity highlighted in this research is further investigation into species selection, specifically a species with a higher known density (i.e. Douglas fir). Investigation into a mixed conifer species is also warranted, as it would better represent the logging residue produced on a logging management site in the PNW. Feedstock preparation is also an important facet in pellet production. It is suggested that a binder be used when working with lodgepole, given its lower density. By applying binders to the feedstock, it may increase pellet quality, which may make this application more viable. Work with binders or other additives would be reasonable, as it may give a glimpse into feedstock properties and pelleting characteristics. Finally, modifications to the flat die mill may make improvements to pellet quality and may also increase feedstock efficiency.

2.8 AUTHOR CONTRIBUTIONS

Audra S. Cochran is the principal investigator and corresponding author. She conducted the field data collection, analyzed the results, and wrote the paper. Dr. Randy Brooks dealt with financial obligations, without which the study would not have been possible. Audra and Randy designed and structured the study, factoring in all contributions from the author's committee members

2.9 CONFLICTS OF INTEREST

The authors have no conflicts of interest.

2.10 REFERENCES

ASTM International (ASTM Standard D 1102 -84) Standard test method for ash in wood.

ASTM International (ASTM Standard D 4442-92) Direct moisture content measurement of wood and wood-based materials.

ASTM International (ASTM Standard E 711-87, Reapproved 1998) Standard test method for gross calorific value of refuse-derived fuel by the bomb calorimeter.

Butler, B. J., and Leatherberry, E. C. (2004). America's family forest owners. *Journal of Forestry.* 3-14.

Chen, Z., Guosheng, Y., Xiangyue, Y., Wang, Q., and Kan, J. (2015). Lower energy pelletization. *BioResources.* 10(4): 6576-6585.

Cook, P. S., Morgan, T. A., Hayes, S. W., Sorenson, C. B., Simmons, E., and Becker, D. R. (2016). Idaho's forest products industry current conditions and 2016 forecast. Station bulletin No. 1087. Idaho Forest, Wildlife, and Range Experiment Station. College of Natural Resources. University of Idaho, Moscow, ID.

Dingman, B. (2009). A guide to understanding and using the flat die pellet machine. Make Your Own Pellets, LLC. Londonderry, NH.

Environmental Protection Agency (2015). Agriculture: agriculture and air quality. Retrieved on May 23, 2016, https://www.epa.gov/agriculture/agriculture-agriculture-and-air-quality#agburning.

Environmental Protection Agency (2015). Clean air act, section110. Retrieved on May 23, 2016, https://www.epa.gov/agriculture/agriculture-agriculture-and-air-quality#agburning.

Idaho Department of Environmental Quality (2016). Air quality in Idaho. Retrieved on May 23, 2016, http://www.deq.idaho.gov/air-quality/.

Idaho Department of Lands (2015). Rules pertaining to the Idaho forest practices act. Office of the Administrative Rules Coordinator, Boise, ID. 28.

Johansson L. S. (2002). Characterization of particle emissions from small-scale biomass combustion. Thesis. Degree of Licentiate of Engineering, Chalmers University of Technology, G'oteborg.

Johansson, L. S., Tullin, C., Leckner, B., and Sjovall, P. (2003). Particle emissions from biomass combustion in small combustors. *Biomass and Bioenergy.* 25: 435-446.

Johansson, L. S., Leckner, B., Gustabsson, L., Cooper, D., Tullin, C., and Potter, A. (2004). Emission characteristics of modern and old-type residential boilers with wood logs and wood pellets. *Atmospheric Environment.* 38: 4183-4195.

Koch, P. 1996. Lodgepole pine in North America. *Forest Products Society*. 35–45, 213–318, 667–695, 927–940, 1029–1041.

Krajnc, N. (2015). Wood Fuels Handbook. Food and Agriculture Organization of the United Nations. Pristina, Kosovo.

Paukkunen, S., Sikanen, L., and Ikonen, R. (2015). Ash content of wood pellets made from small scots pine (*Pinus sylvestris*) trees with bark. *Forest Products Journal*. 65(7/8):1-9.

Paustian, K., Cotrufo, F., Evangelista, P., Mackes, K., Moore, J., Reardon, K., et al. (2013). Sustainable biofuel feedstocks form beetle-killed wood. National Institute of Food and Agriculture, U.S. Dept. of Agriculture, Grant no. 2013-68005-21298. 1.

Pellet Fuels Institute. (2016). Accessed on January 4, 2016. http://www.pelletheat.org.

Pellet Fuels Standard Specifications for Residential/Commercial Densified Fuel (PFI 8.1.3). Pellet Durability Index (PDI).

Pellet Fuels Standard Specifications for Residential/Commercial Densified Fuel (PFI 8.1.4). Fines.

Piekarski, M., Gallagher, L., and McDonald, A., (2009). Assesement of fuel pellets made from forest fuel reduction thinning residues. U.S. Forest Service.

Stark, C. R. 2009. Effect of die thickness and pellet mill throughput on pellet quality. Abstr. T89. Southern Poultry Science Society Meeting. Accessed on July 20, 2016. https://www.ncsu.edu/project/feedmill/pdf/E_Effect%20of%20Die%20Thickness%20and%20Pellet%20Mill%20Throughput.pdf

Stennes, B., and McBeath, A. (2006). Bioenergy options for woody feedstock: are trees killed by mountain pine beetle in British Columbia a viable bioenergy resource? Natural Resources Canada, Canadian Forest Service, and Pacific Forestry Centre. Information Report BC-X-4005.

Wilson, T. O. (2010). Factors affecting wood pellet durability. Thesis. Agricultural and Biological Engineering, Pennsylvania State University, State College, PA.

Woo, K. L., Watson, P., and Mansfield, S. D. (2005). The effects of mountain pine beetle attack on lodgepole pine wood morphology and chemistry: implications for wood and fiber quality. *Wood and Fiber Science*. 37(1): 112-126.