WOOD PELLET PRODUCTION IN THE SOUTHERN UNITED STATES: A QUALITATIVE ECONOMIC ASSESSMENT AND EXPERIMENT TO DETERMINE THE PRODUCTION FACTORS INFLUENCING SELF HEATING DURING STORAGE

By

TODD GLENN BUSH

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2010

To My Family

ACKNOWLEDGMENTS

I would like to acknowledge my committee: Dr. Christina Staudhammer, Jason Smith, and especially Marian Marinescu for their guidance and advice through iteration after iteration of this thesis and associated manuscripts. I would also like to thank my friends and colleagues at Green Circle Bio Energy, especially Greg Martin, Quay Tyus, Olaf Roed, and Morten Neraas, for their support and the initiation of this research project. In addition, I doubt I could have kept my sanity without the advice of my labmates and friends: Sparkle Malone, Nilesh Timilsina, Louise Loudermilk, and Helen Claudio. Most importantly, I want to take the time to appreciate all those that I may be forgetting as I am sure that they are numerous.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Thesis Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Master of Science

WOOD PELLET PRODUCTION IN THE SOUTHERN UNITED STATES: A QUALITATIVE ECONOMIC ASSESSMENT AND A FACTORIAL STUDY OF INTO THE CAUSES OF SELF HEATING DURING STORAGE

By

Todd Glenn Bush

August 2010

Chair: Marian Marinescu
Cochair: Christina Staudhammer
Major: Forest Resources and Conservation

Wood pellet production in the southern United States has more than doubled in the past three years, surpassing western Canada as the region in North America with the greatest production. Most of this increase is caused by a few large plants being built specifically for export to Europe where the pellets are burned for electricity. The economics for producers in the region are helped by the decline in manufacture of traditional wood products including structural panels, lumber, and pulp and paper. Demand for wood pellets is set to continue its rapid rise though some of the traditional wood products are also set to rebound. Of concern for pellet producers is both U.S. made pellets' future position in the world energy market as well as their place in the fiber market of the southern United States.

In addition, when pellets are stored in large volumes, there is a heating effect. This effect is exacerbated by a hot and humid subtropical climate as well as the feedstock of choice of large producers (Southern Yellow Pine). This heating can cause great expense to producers who are shipping overseas as bulk carriers and European buyers

usually have a threshold temperature for biological materials shipped overseas. In addition, this heating often exacerbates convection currents and water deposition inside storage piles before loading. This water can quickly degrade pellets.

The first chapter of this thesis looks at the pellet markets worldwide as well as the state of the wood fiber markets in the southern U.S. which made it possible for wood pellet production to get a foothold in the region. It is concluded that use of wood pellets worldwide will grow, with most growth localized in northern Europe and North America. Production in the Southeast will continue to expand, taking much of the fiber that would have been taken by the now shrinking pulp and paper industries though also utilizing residues from sawmilling and possibly harvest residues.

The second chapter is a factorial analysis in which production factors such as drying temperature and aging are varied between different production runs at the plant of a large wood pellet producer. Quality attributes such as bulk density, durability, and moisture content of pellets going into storage were also monitored. It was then assessed whether these factors had any effect on the temperatures attained in storage. It was found that the most significant factor in the self heating of pellets was the starting temperature of pellets. Therefore, wood pellet producers may do well by investing in consistent and effective methods of cooling pellets after the production runs. Drying temperature also seemed to have a negative correlation to temperature increase though more research is needed as to whether this effect remains when controlling for start temperature.

CHAPTER 1
WOOD PELLET PRODUCTION IN THE SOUTHERN UNITED STATES: A QUALITATIVE ANALYSIS

Introduction

Wood pellets are small cylindrical pieces of compressed sawdust used as a fuel in residential, commercial, and industrial settings. Northern Europe is currently the world's leading consumer of this type of fuel, the majority of which is used in electric power plants instead of coal [1], [2], [3], [4].

Annual wood pellet production capacity in the southern United States (TX, LA, MS, GA, FL, NC, VA, WV, SC, TN, KY, AR, OK) increased from 122,000 tons in 2003 to just over 1.8 million tons in the third quarter of 2009 (Figure 1), with over half of this increase occurring during 2008 and 2009 [5]. This increase allowed the southern U.S. to attain leadership as the region with the highest production capacity of wood pellets in North America . This is still the case even after the closing of the Dixie Pellets plant in Selma, Alabama in September 2009. Dixie Pellets alone counted for about ½ million tons per year of capacity [6].

The developing trend in the southern U.S., compared with other parts of the continent and the World, is to build extremely large wood pellet production facilities. The designed capacity for a plant in the northeastern U.S., for example, averages less than 100 thousand tons per year as compared to newer and planned capacity in the South where it is normal for designed capacity to exceed 200 thousand tons per year [5]. The reason for the large size of these facilities is to take advantage of economies of scale, with the main limiting factor being availability of fiber. The pellets produced in these facilities are destined for bulk shipment to Europe, where they are mainly used as a substitute for a fraction of the coal in industrial power plants [7], [8].

Many have wondered if this growth rate is sustainable or if the current capacity can be maintained if traditional demand for wood fiber resurges or new bio fuels technologies outcompete for what may be a strained supply. Some have seen the closure of Dixie Pellets to be an omen that these large pellet mills may not fully understand that the "availability of raw materials depends on a number of factors, including the amount of timber to be harvested, the weather, the number of loggers in an area and the health of other industries" [9].

Demand and supply for wood fiber are relatively inelastic, meaning that in the aggregate and short term, most incremental increase in demand is satisfied by displacement of current users due to higher prices rather than an increase in harvest [10]. Add to this that half of the cost of delivered pulpwood is comprised of harvesting and transport costs which are directly influenced by fluctuating transport fuel prices [11] and it becomes apparent that predicting the supply and pricing of future wood available for pellet mills becomes daunting.

The purpose of this chapter is to describe the current status of wood pellet production in the southern United States and how it may fit into the future wood fiber portfolio in the region.

Pellet Demand

The main reason to make wood pellets is to make woody biomass more transportable. Wood, in its freshly cut form, is about 50% moisture content. During the pelleting process wood is dried to about 8-12% moisture content and then compressed to nearly 1000 kg/m^3, making it much denser, also in terms of energy content [11], [12].

There are two main markets for wood pellets that are produced in the southern United States. Wood pellets sold domestically for the home heating market are produced almost exclusively from hardwood, at small to medium sized production facilities (<100,000 tons/year pellets), and often utilize the residues from sawmilling operations. Wood pellets shipped in large quantities to northern Europe are mainly produced at large (>200,000 tons/year pellets), stand alone facilities, mainly from species of Southern Yellow Pine. The latter segment accounts for the bulk of the recent growth in the wood pellet industry [5].

Pellet Export

More large plants have been announced, most notably Georgia Biomass has broken ground for an 827,000 ton capacity plant in Waycross, GA that will be the largest in the world if completed [13] and Green Circle Bio Energy plans to build another 550,000 ton plant at an as yet undisclosed location in either Mississippi or Georgia [14]. These and the existing large plants are designed to ship mainly to European power producers.

The high demand for imported pellets in the EU is due mainly to the subsidies granted by European countries and the relatively high cost of coal electricity generation when taking into account the cost of carbon emissions in those countries. This has made it economical to import pellets from as far as the U.S. and Western Canada. However the economics of pellet exportation to the EU are complex due to a variety of factors, such as the cost of wood and wood substitutes in Europe, the fees for ocean bulk freight, which itself is dependent on petroleum prices as well as other factors, and the cost of carbon on the European Market [15].

These factors are all variable, for example: the December 2010 vintage carbon price dropped from a peak of €30 in July of 2008 to €12.83 at the end of March 2010 [16] while the Baltic Dry Index, an indicator of ocean freight costs, crossed the 11,000 point line in May of 2008 but has averaged well under 5,000 points since January of last year [17]. With increased projected demand for wood pellets and the taste for coal generated electricity shrinking in Europe; only a “perfect storm” of these factors could significantly reduce the demand for wood pellets in the near future. Demand is expected to cross the 12 million ton point in 2010, see Figure 2.

Pellet Domestic Consumption

In 2009, 80% of the United States wood pellet production was shipped to domestic destinations [5]. Nearly this entire total was produced from hardwood and destined for heating in residential and commercial applications. The American Clean Energy and Security Act of 2009 (ACES) provided for a 30% tax credit of up to $1500 for the purchase of a 75% efficient biomass stove [19]. This was one of the first subsidies affecting the wood pellet market in the United States and could significantly impact the domestic pellet heating market.

There were a few industrial size shipments of pellets made by large southern mills to some power companies in the U.S in 2009 for trial purposes but no known long term supply contracts materialized as of yet (personal communication). The demand for wood pellets in the industrial sector will depend on subsidies and the government’s definition of qualifying biomass. Nearly all predictions project an increase in demand for pellets for co-firing in traditional coal power plants as it does not require significant retrofit . This is a quick and easy way for coal power plants to reduce their harmful emissions without significantly affecting their total capacity [20]

Prices for wood pellets in either the domestic or export markets are somewhat variable. Flexibility to sell to both the international and domestic markets would probably have significant advantages for both new and existing pellet producers [1].

Fiber Demand

The southern United States has a history of providing lumber, pulp and paper, and, more recently, engineered wood products for the world markets. Species of Southern Yellow Pine have been the main feedstock for most of these sectors. Hardwood still remains a source for fiber, especially in those areas not suitable for the establishment of fast growing pines. The recent decline of the housing market, the decline in demand for printing and writing papers due to electronic substitutes, and increased competition in the pulp and paper industry from tropical plantations in South America have led to a drop in production for nearly all sectors in the region [21].

Delivered prices for the main fiber classes, sawlogs and pulpwood, have remained surprisingly stable over this period, with the exception of softwood sawlogs whose averaged annual southwide averages have dropped in 2009 more than 28% from a peak in 2006 [22] (see Figures 3 and 4) . All delivered fiber prices rose in the first quarter of 2010 but this was mainly attributed to wet weather conditions leading to difficult logging and less fiber on the market [23]. Currently, demand for fiber in the production of wood pellets in the southern U.S. comprises a very small proportion of the total fiber demand in the region. An understanding of what that total demand currently is, will be, and where wood pellet production fits is crucial to understanding the future of the wood pellet industry in the region.

Pulp and Paper

Pulp and paper compete directly for the same feedstock as wood pellets whether whole pulp logs or sawmilling residues. With a total of 86 locations in 13 states, southern pulp mills account for greater than 70 percent of the nation’s total pulping capacity with the majority of the feedstock coming from pine roundwood [24]. Though pulpwood production capacity in the South has been declining for some time, over the past few years both operating rates and pulpwood stumpage prices have remained relatively stable, even increasing to some degree [22] (see figure 3).

The FOEX Ltd. Northern Bleached Softwood Kraft (PIX NBSK) pulp price was recovering from one of its most precipitous drops that lasted through the last two quarters of 2008 and the first quarter of 2009. At its low, prices reached about $580/ton in March of last year and had rebounded to $975/ ton by the end of June 2010 [25]. This price is causing those mills still in operation to increase their production rates and delivered prices for hardwood and softwood pulp are at their highest levels in more than a decade as of the first quarter of 2010 [23].

Regardless, most projections for the region's pulp and paper industry based on recent history and global trends are not optimistic. Operating rates have remained up due mainly to the declining value of the dollar on the world market, increasing the demand for exports. Worldwide the demand for most paper products is declining on a per capita basis as the global economy becomes more digital [26].

Sawmilling

Sawmills, rather than explicitly competing with pellet producers, act as a supplemental feedstock source. Shavings, chips, and sawdust, byproducts of lumber production, offer fiber that is already dry and reduced in size, decreasing processing costs for pellet producers. Also, sawmills purchase roundwood in a different size class than pulp or large pellet producers so they do not compete directly for roundwood. Currently, sawmill closures have reduced total sawmill processing capacities to historic lows in the southern U.S [22].

This is due mainly to a drastic reduction in residential and commercial construction nationwide. In 2009 single family housing starts were the lowest in 50 years, down by 445 thousand compared to a recent high of just over 1.7 million in 2007 [27]. In addition, the Harvard University Leading Indicator for Remodeling Activity (LIRA) remained low in the fourth quarter of 2009 at $115.8 billion from a high in the second quarter of 2007 of $146.2 billion (28). Using a conservative housing forecast, lumber consumption for housing is expected to rebound to 19 bbf in 2013 and total US lumber consumption is expected to increase by more than 50% between 2009 and 2013 [29]. Simply, the sawmilling industry is expected to rebound relatively soon.

Structural Panels

Traditional plywood mills do not directly compete with wood pellet plants as they purchase from a different timber size class. Oriented Strand Board (OSB), on the other hand, does directly compete in the small diameter tree classes and has seen significant growth since 1980, competing with plywood in the products markets and pulp and paper in the timber markets. The structural panel market is cyclical and, with every fluctuation, a greater amount of relative plywood production capacity is replaced with OSB capacity [30]. OSB overtook plywood production in the southern U.S in the middle of 2005 and hit a high in 2007 of over 3 billion square feet (bsf) on a 3/8" basis. Not long after, and mirroring the decline of the softwood lumber market, a large drop in production began in the 3rd quarter of 2008 starting at 2.8bsf and bottoming out in the first quarter of 2009 around 1.8 bsf. Production has been rebounding and ended the 3rd quarter of last year at 2.17bsf and rising [31].

As the housing market continues to recover, OSB mills will ramp up production to meet demand and new mills will probably be built to replace shuttered and idled plywood mills. By 2011 OSB is predicted to be near 75% of the Plywood/OSB market share [32] and the trend in new OSB facilities is to build large mills that are able to use their waste for energy in the form of heat and steam, thereby being able to more readily use roundwood rather than relying mainly on mill residues.

As a product with high added value, OSB is seen as filling a void in timber demand that many of the pulp and paper producers have left vacant (i.e. can process small diameter logs). It will be effectively able to compete with pulp and paper mills for timber where the cost of transport is similar and could out-compete many producers of bio energy with current technologies and pricing, though this depends on the cost of the finished products.

Wood for Energy

Forest biomass has become the target of much scrutiny as a feedstock for bio energy in a world of increasing real and perceived environmental costs for traditional fossil based energy. The southern U.S., as America’s wood basket, is at the forefront of proposed development. As of April 14, 2010 there were 130 publicly announced wood based energy projects representing 46.6 million tons of incremental wood demand. Technologies range from liquid biofuels, to electricity, to wood pellets [33]. The deployment of much of this demand is unlikely as there are significant hurdles regarding permitting, technology, and financing in a world of tighter credit. Wood Bioenergy South estimated that of this 46.6 million tons, only 18.9 million tons pass what they call “technology and status” screens designed to filter for some of the significant hurdles to establishment [33].

Electricity and co-generation

In the U.S. more electricity is produced from wood than any other renewable source with the exception of hydroelectric. Nearly all of this is generated by the wood processing industries from burning of their waste materials to provide process heat and steam and electricity. Total energy generation from U.S. lumber, paper and allied products industries in the form of electricity and useful heat totaled 1.4 quadrillion BTUs in 2007 [34], this equates to 116.6 million oven dry tons (ODT) of wood fiber and was roughly 25% of the total renewable energy production in the U.S.

The southern US accounted for a large fraction of this energy production, mainly through the reuse of black liquor from the Kraft pulping process. The total generation from paper and allied industries nationwide has been declining for the past 5 years or so [34].

On the other hand, electricity generated by direct combustion of wood is rising. Total demand of all southern wood burning electricity generation slated to be running by 2015 represents 30 million tons of wood [33], given that all these developments pass environmental and financial hurdles. Nearly all of these wood-to-electricity plants that are built will burn wood chips directly due to the cheaper cost and relatively short travel distances. These plants, therefore, will possibly compete with pellets for feedstock if located close together. Utility scale boilers will be able to use waste products such as bark, tops and limbs which are usually cheaper than roundwood [34] though these waste streams are only applicable to utility grade pellets and would not be destined for the home heating markets.

Bio fuels

Of the 10 commercial ethanol plants that are operational or under construction in the southern U.S currently, only one, Range Fuels out of Soperton, GA, explicitly plans to use woody biomass as a feedstock [35]. Each of the other plants, like most ethanol plants around the world, use agricultural products high in starches and sugars which are more easily converted to ethanol. Cellulose, though a sugar macromolecule, is very difficult to breakdown without intensive pretreatment, high enzyme loading, long conversion processes or a gas phase separation. Many recent studies have shown that there may be ways to get past the high recalcitrance of cellulosic materials in order to produce ethanol more economically than starch or sugar ethanol but these are still in the research stage [36], [37].

Fiber Supply

The Southeast holds 44 percent of the nation's forestlands and 31 percent of the nation's energy crop, mill, and urban wood wastes [32]. In 2007 there was over 1.2 billion dry tons of live timber in the southern states and total volume has been increasing for some time [38].

The forests in the southern United States are unique from a resources standpoint in many ways. They have been greatly influenced by the rapid expansion of industrialized human societies, were almost completely cut down and then re-grown in the past 200 or so years, have a tremendous growth rate due to the climate, and predominant species and are almost wholly privately owned [39]. These factors culminate in a forest resource that has been uniquely able to adapt to market forces, which illicit very high demand for its products. Recently though, some of these factors that have helped create one of the largest forest products industries in the world are in a state of flux due to population increase, public sentiment, changing technologies, increasing fuel costs, federal and state regulations.

Forest Structure

Forested lands in the southern US were once greater than that of today. Since about the 1950s, forested land area in the region has stabilized at around 200 million acres even while forested acres in other regions of the country were increasing. At the same time, through better forest management practices and plantations, growth rate on these acres is increasing [39].

Changing ownership of forest lands

Over the past three decades a large-scale divestiture and restructuring of landholdings by vertically integrated forest products companies (VIFPCs) has caused significant changes in forest ownership. Millions of acres have come under the control of timber investment management organizations (TIMOs) and real estate investment trusts (REITs). Between 1980 and 2005 over 60% of the VIFPC owned lands were converted to REIT or TIMO control due to 1) weak financial performance of the forest products industry in this time period, 2) favorable taxing guidelines for TIMOs and REITs, 3) rising forestland values and 4) increased debt burdens. This allowed the VIFPCs to "cash in" on changing investment appetites and increase their liquidity [40].This means that many timberlands will no longer be managed strictly for the benefit of the forest product companies which used to own them and demanded certain product attributes.

In addition, investments by TIMOs and REITS are designed to produce a return in 10 to 15 years, within the timeframe to harvest for pellet production. It is still unclear what the long term consequences and benefits of this change in ownership will really be. Many analysts think that it will cause increased ability for timber markets to adjust quickly; plantations will start to be designed with the bio energy market in mind if demand is present in the area, and annual production contracts may come into play to ensure a steady stream of funds for the shareholders [41].

Planting rate and growing stock

In 2008, 57% of the timber volume growth in the southern U.S. was on plantation tracts, even though only around one quarter of the total area was plantation. Even with a younger age class structure and lower proportion of growing stock contribution, plantations have a significant effect on total timber inventory in the region [39]. Total number of acres planted per year has been decreasing since 1998 in the South as a whole [39]. This is due to 1) changing forest ownership in much of the region, 2) reduced stumpage prices, 3) suspension of subsidies promoting the conversion of marginal farmland to forestland, and 4) increasing development due to population growth.

This is not to say that total acres of plantation land are declining, just that the rate at which the total number of acres is growing is decreasing. Each year many planted acres are harvested and immediately replanted and this does not affect the net area of plantations, though indicates that there may be a changing diameter class distribution of trees growing on plantations. This decline in planting indicates that many plantations may currently be undergoing a longer rotation with timber destined for sawlogs rather than the smaller diameter classes.

Furthermore, the Southeast, which provides more timber products than any other part of the country [42] has also been described as having the highest rate of urban development [43]. Increased housing density on private forest lands can contribute to a decrease in regional timber supply and harvesting, reduced private forest management and investment, and declines in commercial forestry [44].

As prices for smaller diameter logs increase, plantations will most likely be planned with the bioenergy market in mind. Though, to further ensure adequate pricing, and enabled by the changing ownership of forests, it may be beneficial for pellet plants to advocate and promote sustained planting of plantations in order to guarantee a supply of small diameter wood. In addition, supply contracts with landowners or loggers may also help hedge against rising prices and would indeed be welcomed by many REITs and TIMOs which are put into place to generate steady profits for shareholders [45].

Spatial Diversity of Timber Supply

Due to the low bulk density of the biomass going into pellets, the largest cost component of feedstock supply is harvesting and delivery to the mill [11]. In 2009, pine pulpwood stumpage in the southeast averaged $8.14/ton while delivered cost was $21.82/ton, meaning harvesting and transport was about two-thirds of the final delivered price [46]. In a world where transportation fuels are almost certain to increase [34], this causes the economic “catchment area” for a plant (i.e. the radius from which a plant draws its biomass) to shrink. Therefore, the fiber supply closest to the plant is crucial because it is affected by the acreage and productivity of the surrounding forest, road networks, urban encroachment, competing users of small diameter wood, available providers of clean woody residue, and area loggers and competition among them.

Local competition from local producers

The production of the pulp and paper industry has continued to decline since about 1997, as discussed earlier. In the past few years, resulting prices for pulpwood as well as transportation fuels began to decline, allowing those plants that were still operational to produce at a significantly lower cost. In the second half of 2009, pulp and paper production, as a percentage of remaining capacity, increased [26]. Prices for pulpwood would be much higher for areas close to those mills as compared to the southern region as a whole.

Structural panel mills, as discussed previously are in a deep recession due to the severe construction decline tied to the current economic conditions. Production is currently rebounding and much of the shuttered plywood mill capacity is being replaced with OSB production which more directly competes with wood pellets for feedstock sources.

Furthermore, pulp, paper and OSB plants, at least with current final product pricing, manufacture a product with much more value added than wood pellets. There is the possibility for two plants in close proximity to each other to significantly affect the pricing, stability, and timberland planting so that there may actually be an increased amount of wood on the market, thereby lowering the price in a sort of “economy of agglomeration” [47], [48]. The likelihood of this being the perpetual state in the local timber market is unlikely. The pulp, paper, or OSB plants, with higher profit margins (as a proportion of feedstock cost), are likely to set the market price and make it difficult for bio energy players to compete [49], [50].

Wood consuming mills would have to be fairly close to each other to really contend for a major part of their feedstock. As a general rule of thumb, a mill pulling in about 1 million green tons of roundwood per year has a catchment radius of about 50 miles. If a mill advertises a delivered price per ton that it will pay to loggers, as is common, then a probability distribution can be envisioned around a plant from which trees will be pulled.. So while logs will be coming from as far as 50 miles, the great majority of them may be coming from much closer than that [47].

Sawmilling residues

Sawmills demand logs from a completely different size class than pellet mills and therefore they do not directly compete with either pellet or pulp and paper mills [38], [51], [52]. In fact, pellet mills are able to use much of the waste from sawmills such as shavings, dust, and chips to produce pellets. As these materials are already dry and reduced in size, it directly reduces processing cost for pellet production. Many small pellet plants run exclusively as a secondary operation for large sawmills in order for them to bring in extra revenue from their waste stream [5], [53].

Pellet mills producing primarily from roundwood have the advantage of being able to continue running when a lumber production decline occurs, as is the case currently, but can also benefit from sawmilling residues when they come available. Pellet producers must pay a high enough price to offset the real cost of transportation and the opportunity cost of a plant not burning the material for its own energy needs, if it is so equipped [11].

Sawmills can provide supplementary or even the majority of the biomass for a smaller pellet mill, but this may cause the pellet mill to depend on the housing and timber markets too greatly. In addition, proximity to a sawmill affects the land management decisions of the forest owners in the area when deciding rotation ages [54]. Consequently, local forestlands may be managed for higher diameter classes than is ideal for pellets, thereby possibly reducing the supply of pulpwood class timber [55]. The corollary is that the establishment of a sawmilling industry connotes that the infrastructure for a pellet mill is already in place; including roads, timberlands, and loggers. Timing and analysis of how a pellet mill will interact in the local wood market is crucial.

Logging residues

Many studies attempting to assess the total biomass available for bio energy projects have put a significant amount of emphasis on the available biomass that is currently “underutilized” such as urban wood waste and logging residues [56], [57]. These resources may be valuable as they do represent a significant amount of calorific energy that may otherwise be land filled, piled and burned, or left on the site to decay. In the case of urban wood residues this is considered a subpar feedstock more applicable for direct combustion electricity plants. With any residue a significant issue is the cost of transport as they are usually quite bulky.

The supply of logging residues, such as tops and limbs, are applicable to a product called “brown” pellets which are used for industrial purposes due to a high percentage of ash [12]. Data indicates that there may be more than 50 million green tons of recoverable residues available per year [56]. More recently though the debate has started to focus on issues of whether removing this material from the land causes significant harm as it usually requires the addition of supplemental fertilization [58]. In any case, this may be a feedstock that can be utilized for pellets to some degree in the future, but sees very little utilization currently.

Conclusion

The pulp and paper industry in the southern United States is not expected to rebound fully in the next few years from its current historic lows. OSB, wood chip, wood pellet, and wood for electricity plants are expected to replace much of the demand that will be left in the market for small diameter trees and lower value fiber. Lumber production is projected to rebound in the next decade due to a recovering domestic housing market as well as the declining relative value of the dollar helping to strengthen exports. Much of the waste from lumber production can be utilized for the production of pellets when the cost of transport from mill to mill is not prohibitive. Liquid biofuel production from cellulosic feedstock in the region has been somewhat lackluster and, barring a sea change that drastically reduces cost relative to final pricing, is not expected to become a large competitor for woody biomass.

The forests of the southern United States have undergone a radical ownership switch over the past few decades with many of the vertically integrated forest product companies divesting much of their land. Urban encroachment and a decline in programs promoting the conversion of land into forest have resulted in a decrease of total forest lands. In addition, the rate of plantation establishments is decreasing. Conversely, the total growing stock volume is still increasing due to more productive forest management practices. With less of the forested lands being controlled by large forest product companies, forests may be managed for the emerging bio-energy markets, such as wood pellets. The real driver or road block for timber supply for wood pellets is and will continue to be the distance to the pellet mills, especially as transportation fuels become more expensive.

The largest markets for pellets for the next decade will continue to be Western Europe and North America with the latter growing faster than the former, proportionally. The production in Western Europe is very much limited by the supply of fiber. In North America, on the other hand, there is still room for the pellet market to grow but with less reliance on export and greater shipments domestically. Australia and Eastern Europe are projected to become larger players though not to the same degree as Western Europe and North America. South America has many of the factors needed to support pellet manufacturing for export however little to no development has begun or is projected for the near future.

Within North America, Western Canada and the southern United States are currently the largest players in the production and export of pellets. Canada’s boom was stimulated by thousands of acres of wood killed by the Mountain Pine Beetle, leaving wood unsuitable for lumber production. The growth in the southern United States is stimulated by extremely fast growth rate of Southern Yellow Pine in a sub tropical environment combined with the decline of the wood product industries.

In conclusion, the demand for pellets from the southern United States will most likely grow in the coming years both domestically and abroad. The supply of wood fiber for production is less certain as competitors will move in to produce from the cheap fiber and forested land may continue to decline. There is room for pellet producers but some issues must be taken into account: 1) site selection in relation to forest resources, competitors for fiber, infrastructure, and urban areas in order to secure fiber supply is paramount; 2) flexibility in feedstocks will help to hedge fluctuations in the local fiber markets by allowing producers to take advantage of all feedstocks especially if selling primarily to the industrial markets, 3) the ability to sell to a number of markets including international and domestic is needed as the pellet markets mature; and 4) early entrance into both fiber and product markets will allow for early profits before price competition becomes heavy in both.

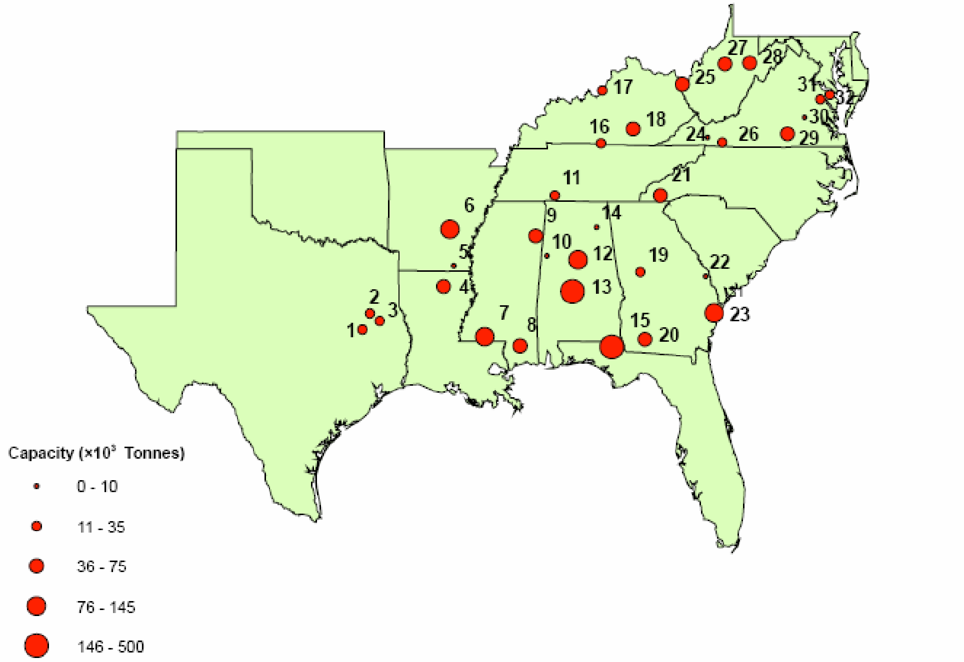

Figure 1-1. Southeastern U.S. Pellet Mills from [5]. Note: 12 and 13 are no longer in operation.

U.S. South

Mill ID	Company Name	Former Name or DBA	Town	State	2003	2004	2005	2006	2007	2008	2009	Comments
							Capacity ($\times 10^3$ tonnes)					
							Closed Mills					
	FutureFuel Chemical Co		Batesville	AR			27	36	36			Open in 2005, now down
							Operating mills					
14	Lee Energy Solutions		Crossville	AL								2009 or 10, 75K tons
10	Nature's Earth Pellet Energy		Reform	AL				5	5	6	6	100 tons/week in 2006
12	New Gas Concepts		Jackson	AL								2010? Eventually 600 stons
13	New Gas Concepts		Selma	AL						45	454	eventually 500 stons
5	Barnes Bros Hardwood Flooring		Hamburg	AR					9	9	9	
6	Fiber Resources		Pine Bluff	AR	67	67	67	90	90	112	112	
15	Green Circle BioEnergy		Cottondale	FL						227	454	Open May 2008
22	Big Heat Wood Pellets	Equustock	Sylvania	GA	9	9	9	9	9	9	9	since 2001
23	Fram Renewable Fuels		Baxley	GA						42	132	started plant 3/2008
19	Rock Wood Prod		The Rock	GA					14	18	18	
20	Woodlands Alternative Fuels		Meigs	GA							68	June 2009, 300 in 2010
17	Anderson Hardwood Pellets		Louisville	KY					18	18	18	started in 2006
16	S Kentucky Hardwood Flooring		Gamaliel	KY				18	18	18	18	available in 2006
18	Somerset Pellet Fuel		Somerset	KY				46	46	46	46	
4	Bayou Wood Pellets		West Monroe	LA						54	54	started Jan 08
9	CKS Energy		Amory	MS				23	44	45	45	since 2007
7	Indeck Magnolia BioFuel Center		Magnolia	MS								2010?
8	Piney Woods Pellets		Wiggins	MS							19	up in july 2009, 50K tons
21	Carolina Wood Pellets		Franklin	NC							62	expected start Q1 2009
11	Hassell & Hughes Lumber		Collinwood	TN					18	18	18	started Jan 2007
2	Good Times Wood Prod		Rusk	TX			9	23	23	23	23	
1	Northcutt Woodworks	Christopher Lum Co	Crockett	TX				14	14	14	14	since 2006
3	Patterson Wood Prod		Nacogdoches	TX					18	18	18	At least since 2007
24	American Wood Fibers		Marion	VA								plant will start in 2009
30	Big Heat Wood Pellets/Equustock		Chester	VA	9	9	9	9	9	9	9	
29	Lignetics Lunenburg			VA						45	45	
31	O'Malley Lum Co		Tappahannock	VA						32	32	since Sep 2008
32	Potomac Supply		Kinsale	VA							18	started 2/09
26	Turman Hardwood Flooring		Galax	VA					14	14	14	started in 2005
25	Hamer Pellet Fuel		Kenova	WV				36	41	41	41	
28	Hamer Pellet Fuel		Garden Grounds	WV					41	41	41	
27	Lignetics		Glenville	WV	36	36	36	36	36	59	59	
					2003	2004	2005	2006	2007	2008	2009	
	Estimated Capacity				122	122	158	344	502	964	1855	
	Estimated 2008 Production									592		

Figure 1-2. Key to Figure 1-1 [5]

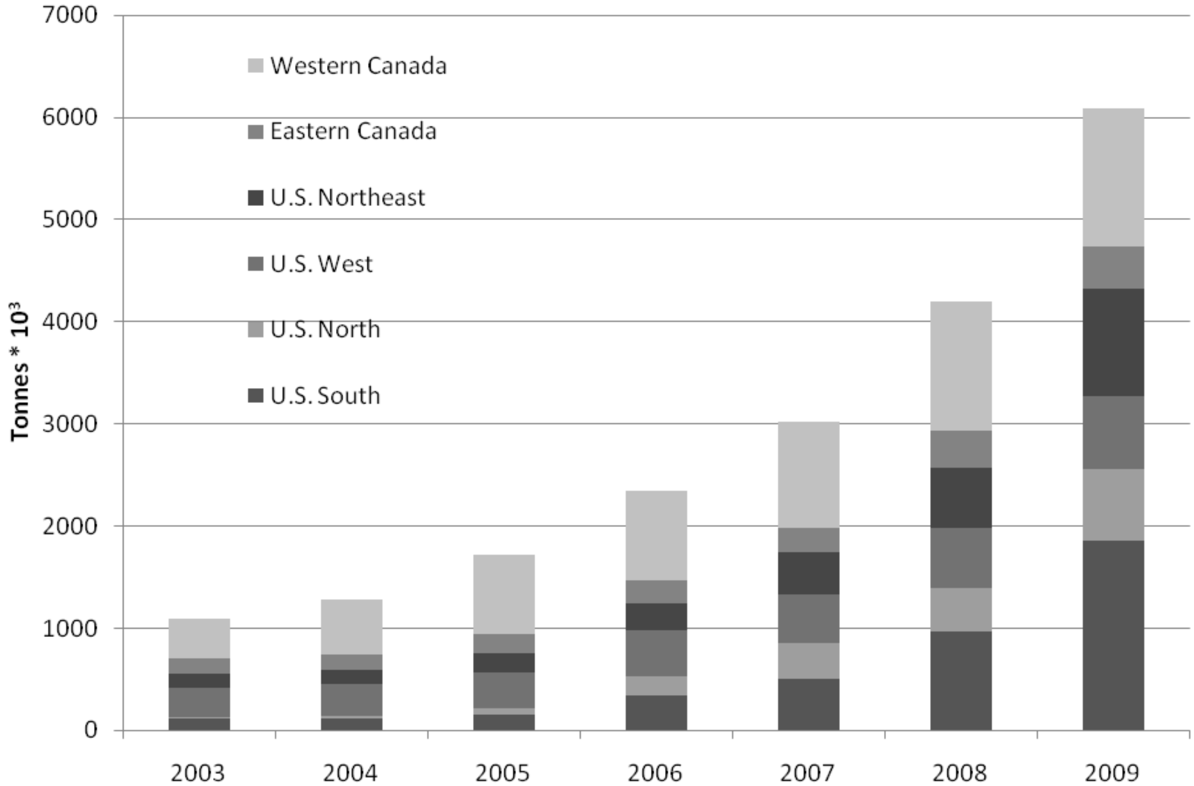

Figure 1-3. North American Pellet Production Capacity (Adapted from [5])

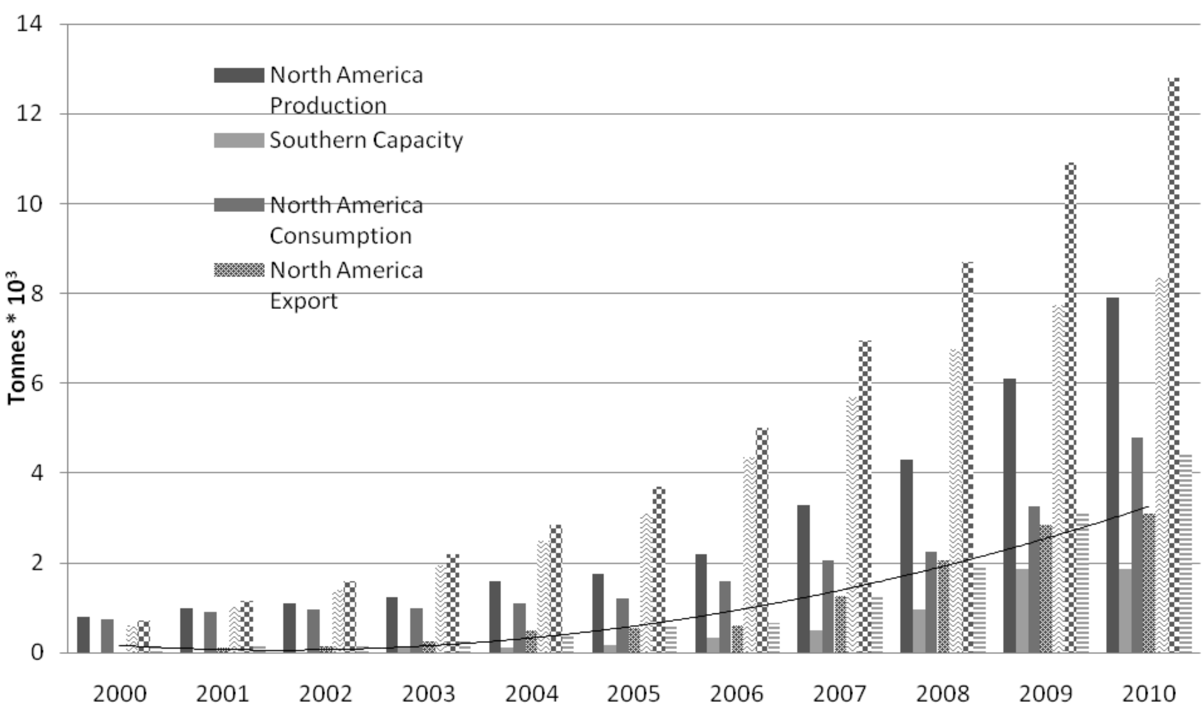

Figure 1-4. Worldwide Wood Pellet Production and Consumption. 2009 and 2010 are projected [18].

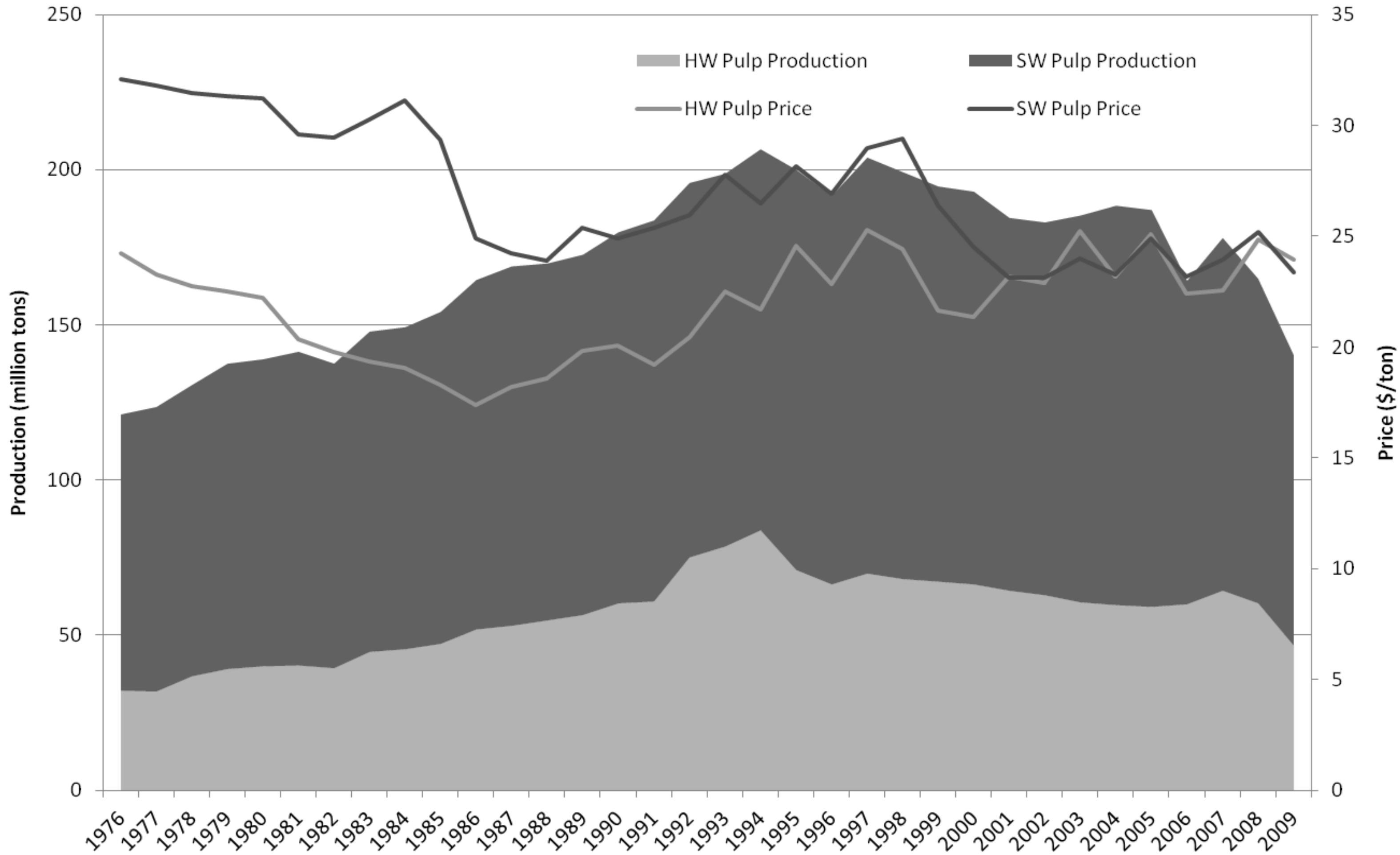

Figure 1-5. Pulp production in the Southeast United States. Production numbers are converted using 2.9 tons = 1 cord for hardwood and 2.68 tons = 1 cord for softwood [59], [26]. Prices are averaged into years from quarterly data [22] and adjusted to 2005 dollars using [74].

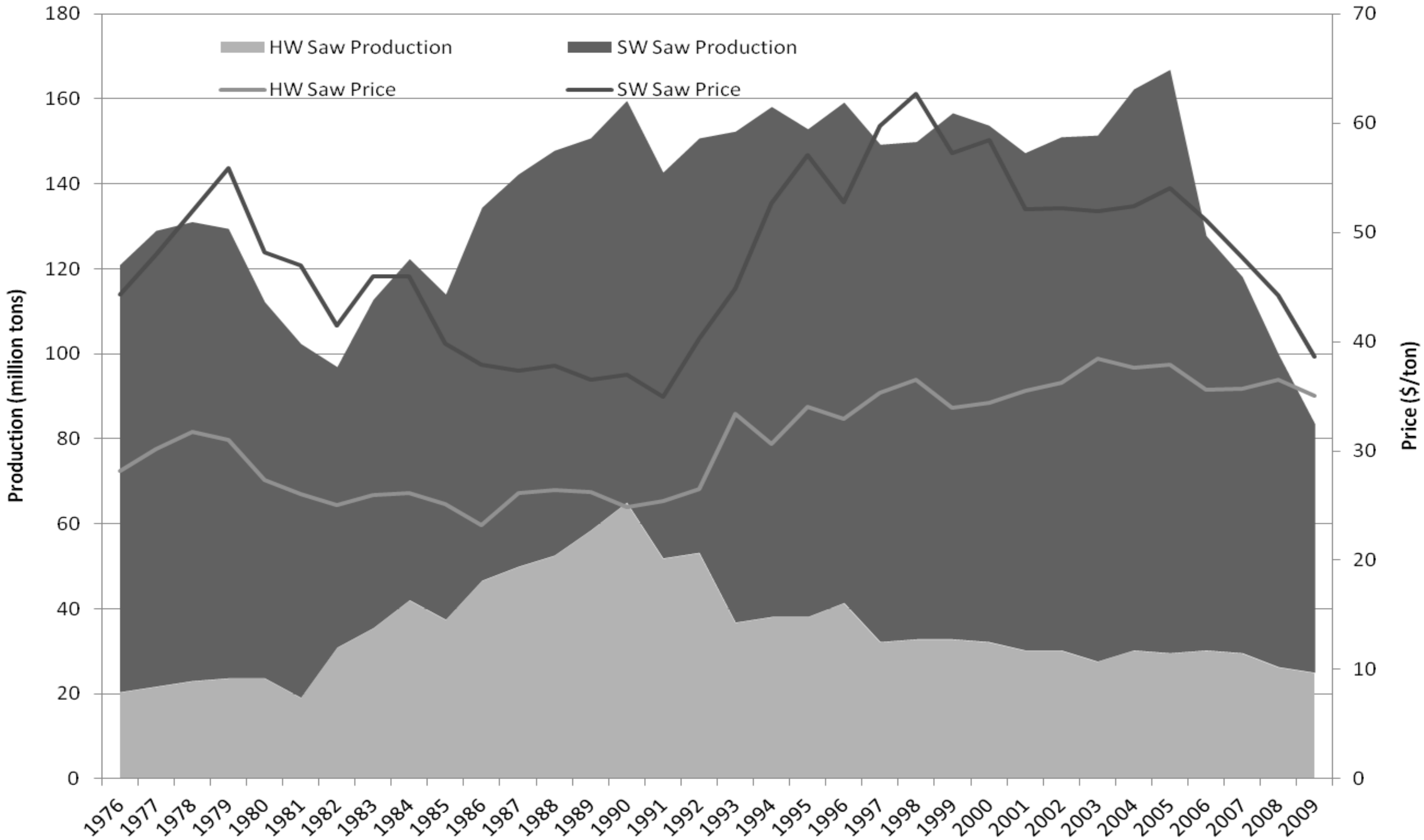

Figure 1-6. Sawmilling in the Southern United States. Production numbers are converted using Scribner rule; 1bbf = 7.5 million tons for softwood and 1 bbf = 6.563 million tons for hardwood [59], [26]. Prices are averaged into years from quarterly data [22]. Prices are averaged into years from quarterly data [22] and adjusted to 2005 dollars using [74].

CHAPTER 2
FACTORS AFFECTING WOOD PELLET SELF HEATING DURING STORAGE

Introduction

During the summer months in Florida, stored pellets made from Southern Yellow Pine (SYP) undergo an exothermic reaction which is leading to the breakdown of some of the pellets. In addition to increased cooling costs and a degraded product, the heated pellets may not meet the contracted delivery temperatures demanded by overseas customers.

The heating begins in rail cars almost immediately after loading from counter flow coolers. After 36 hours, temperatures peak at around 80 degrees Celsius and level off around 70 degrees Celsius, though these conditions are slightly variable depending on ambient weather conditions and properties of the wood pellets.

As wood pellets are a relatively new product on the world market and the large scale production from SYP is even more recent, the body of research is still relatively small. Furthermore, the body of work specifically on the self heating phenomenon in wood pellets is even smaller. In order to understand the possible causes of this phenomenon I drew on literature ranging from the storage of coal, agricultural products, wood products, and all of the recent literature available concerning this specialized topic.

Coal has long been the main solid biologically derived fuel used for large scale combustion. The research into the self heating of coal has long been building, though researchers still disagree on the exact kinetics of the reactions occurring. Overall there are three main mechanisms: 1) physical adsorption; 2) chemical adsorption, and 3) oxidation resulting in the release of gaseous products. Of these three, oxidation is by far the most exothermic [60]. Factors shown to be correlated to the oxidation rate of coals are coal rank, inherent water content, oxidation history, particle size, temperature, partial pressure of oxygen, and moisture content in gas medium [61].

In the case of heating for wood stored in piles, the reaction mechanisms differ from coal. This is mainly because of the chemical makeup of the substrate and is also dependent on the moisture content in the pile. In wet chip piles, much of the chemical changes occur from microbial activity and related heat development in the central parts of the pile. As the temperatures of the pile rise above about 45°C, degradation occurs less due to microbial factors and more due to thermo-chemical reactions [62]. The conditions described above though are observed for wood that is still relatively high in moisture and, therefore, can support microbial communities.

In studies of the gaseous emissions in wood pellet storage warehouses, home pellet storage rooms, and lumber drying kilns, high levels of volatile organic compounds (VOCs) and carbon monoxide were detected. These were often associated with the general degradation process of wood at high temperatures and were formed due mainly to the auto-oxidative degradation of fatty acids that were present in the extractive fraction [63]. Aldehydes, such as pentanal and hexanal, were found to be the main constituents of the VOCs emitted during self heating of pellet stocks and drying temperature was found to greatly affect the composition of these off-gasses [63].

When using pellet feedstock mixes of fresh Norway Spruce, Scots Pine, and stored pine it was found that increasing the proportion of the stored pine and fresh spruce was related to lower aldehyde generation during pellet storage. This is most likely related to the lower fatty acid concentration in these feedstocks [64].

Recent studies have been conducted in sealed containers where ambient air quality could be monitored and controlled. Tumuluru et al. (2008) found that CO and CO_2 concentrations in pellet storage vessels were high at room temperature though increased exponentially with temperature [65]. Kuang et al. (2008), in an extension of [65], concluded that storage temperature is a critical factor in the off-gassing of wood pellets and that chemical decomposition, mainly oxidation, is the dominant mechanism for off gassing [66]. The latest paper associated to the previous two confirms the previous findings but also finds that headspace and humidity in the reaction vessel are positively correlated to off-gas emissions [67]. Svedberg et al (2008) performed a similar but unrelated study employing FTIR spectroscopy and found that a significant amount of the O_2 consumed in a sealed bulk pellet ship was bound by the oxidative degradation of the fatty acids and other chemicals present in the wood [68].

It is clear from this review that the primary mechanism behind the off gassing and related self heating is the oxidation of fatty acids present in the wood. Some research has been done regarding means to reduce this off gassing and heating by altering some of the production parameters. As mentioned before, changing the feedstock source to those with a lower proportion of fatty acid has been shown to alter the composition of the off gasses but may also reduce the self heating effect during storage [64]. Arshadi et al. (2008)[69] performed a controlled industrial study and found that there was a negative correlation in fatty acids with increasing fraction of spruce or stored pine in relation to fresh pine. A latter study by the same research team further supported the connection between feedstock composition and aldehyde emission but also showed that for freshly made pellets, drying gas temperature was significantly negatively correlated to the emissions during storage [70]. This study was also the first and, to date, only study which explicitly linked emissions of fatty acids to temperature rise during storage, noting that spruce with a lower fatty/resin acid content had a less significant temperature rise. The assumption behind this research is that the main cause behind the self heating of wood pellets during storage is the auto-oxidation of unsaturated lipids and this research will attempt two questions.

First, what are the production factors that are (most) significantly correlated to the heating of pellets? Second, how can production factors and pellet attributes be controlled in order to minimize the self heating of wood pellets in storage? Many production variables can be monitored but in this study drying temperature and aging of wood are hypothesized to have the most significant effect on the self heating of pellets during storage. The former may have an inverse effect on the self heating propensity (higher drying temperature = lower self heating propensity) as high heat during drying has been hypothesized to trigger auto oxidation reactions that persist after processing [64]. The latter may help as aging times have long been thought to remove many of the extractives that are thought to be the main source of self heating. As hypothesized by [64] and shown to some degree by [70]; drying temperature, aging of wood prior to processing, and species of wood may have an effect on the heating and off gassing of pellets in storage.

Materials and Methods

Evaluation of Production Factors

Prior to the commencement of this study it was found that similar temperature profiles to those observed in rail cars could be obtained using double wall insulated 1m^3

plastic shipping containers customarily used for transporting solid carbon dioxide (dry ice); these are henceforth referred to as “blue bins” and are pictured in Figure 2-3.

A twelve run factorial experiment was performed. Each run consisted of varying two production factors and monitoring the temperature profiles using data loggers and K style thermocouples.

The factors used in the analysis were selected based on whether they were already collected during the normal production day, the feasibility of adjusting them during the production process, and whether the observed values were represented in the samples collected. The factors are by no means comprehensive.

Controlled production factors

Dryer Inlet Temperature (C^o) - Drying temperature is assumed to have an effect on the oxidation of fatty acids resident in the wood. Runs were performed at three different temperature levels – 400, 500, and 600 Celsius. Inlet temperature is controlled by many factors and keeping it stable was difficult; however, in test runs we were able to maintain inlet temperature long enough to assure that what is being produced by the pellet mills at a given time was dried at a given inlet temperature.

Aging of wood (weeks) – Aging of raw logs is also assumed to have an effect on self heating of pellets due to the breakdown of the fatty acids during log storage. There were two aging periods:0 and 2 weeks. Aged logs were aged in windrows for two weeks then chipped four days before processing and stored in a chip pile of 80 to 100 wet short tons. Non-aged logs were taken directly from the feed that contained trees brought into the plant and chipped immediately.

In total, there were three levels of the inlet temperature factor and two of the log aging factor (a total of six factor combinations). The experiment was designed so that we had three replicated bins in each of 12 runs (two runs per factor combination). For many of the bins there were mechanical issues or the data was unusable; therefore data from 23 of the bins was available.

Uncontrolled pellet attribute factors

Bins were filled from the supply line after the counter flow coolers. Two samples were taken from each bin, before and after the storage period using 3l buckets. One bucket was taken from the top of the pellet mass in the bin and one was taken from half way through filling or emptying, depending on the stage. The following measurements were taken of these samples.

Pellet Bulk Density (grams/liter) – taken from each bin both before and after the storage period. Bulk density was measured using a Seedburo filling hopper, stand, and 1 liter measuring cup. The measuring cup was filled to overflowing, cleared flat across the top with a straight edge, and then the contents were weighed on a calibrated digital scale. This was repeated three times for each sample and then averaged.

Percent Fines (%) – Each three liter sample was weighed and then sieved through a 4mm screen. Those pellets that did not pass through the sieve were then weighed and divided by the previous weight to get a percentage.

Pellet Durability (% not passed) – 500g of the pellets sieved for percent fines were run in a rotary durability tester (Figure 2-4) for ten minutes at 60 rotations per minute (total of 600 rotations) and then sieved through a 3.15mm sieve. The weight of the pellets that did not pass through was then divided by the original weight to get a percentage. This was performed twice for each 3l sample and averaged. (Note: If variation between the two samples was greater than 5% then another two samples were run in the same manner. The second samples were always within the stated threshold)

Initial Pellet Moisture Content (%dry content) – This was measured using a Mettler-Toledo HR83 Halogen Thermo-gravimetric moisture analyzer. Two moisture readings were taken for every 3l sample and then averaged.

Temperature of Pellets (degrees Celsius) – This was collected using data loggers that recorded the temperature of the core of the pellet mass every 1-30 minutes for the entire period that the pellets were stored.

Response variables

Each of the dependent variable was modeled as a function of the temperatures attained in storage. The rates below were chosen for analysis as they help compare bins which started out at different temperatures, and start temperature tended to have a significant effect on the behavior of pellets in storage. The response variables are as follows:

Max Temp = Maximum temperature attained during storage

Rate to 40 = (40 – Start temp)/(Time at 40 – Start time)

Rate to 45 = (45 – Start temp)/(Time at 45 – Start time)

Rate to 50 = (50 – Start temp)/(Time at 50 – Start time)

Rate to 55 = (55 – Start temp)/(Time at 55 – Start time)

In these variables the "Start temp" is the temperature at which data logging was started. "Start time" is the time at which data logging started as a Julian date. The Time at 40, Time at 45, Time at 50, and Time at 55 are the times (in days) at which those temperatures were reached.

Linear regression analysis

Linear regression is a means of modeling the relationships between one or more dependent variables denoted *y* and one or more independent variables denoted *x,* such that the model of *y* depends linearly on a linear combination of the *x*'s. In the models with no interaction effects, *y* is a function of *x*'s in the form:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_p x_{im} + \varepsilon_i \quad (1)$$

for i = 1,2,…,*n* where *n* is the number of observations, *m* is the number of explanatory variables, and ε_i is the error or deviation from the model for each *i*th observation. The parameters to be estimated, β_0, β_1,…, β_m,, were determined using the least squares method [71].

For models with interaction effects the process was similar though a multiplicative interaction effect was added (i.e. if $\beta_{1*2}x_1x_2$ is included in the regression model along with the simple effects for x_1 and x_2 then β_{1*2} estimates the effect of the interaction) [71].

All analyses were performed with the JMP software package [72]. Exploratory statistical methods were first used to assess whether the explanatory variables were significantly correlated. All explanatory variables were mean centered (i.e. subtracted from the mean) in order to reduce the effects of multicollinearity. Variance inflation factors (VIF) were also reported for each parameter estimate. VIFs greater than 10 were considered problematic [72], though this was not the case in any of the analyses.

A series of models were then fit separately for each of the response variables using each of the main effects in a base model, as follows:

$$max\ temp = \beta_0 + \beta_1 start\ temp + \beta_2 dryer\ inlet + \beta_3 aging + \beta_4 moisture + \beta_5 moisture + \beta_6 bulk\ density + \varepsilon \quad (2)$$

Plots of the residual versus predicted values were analyzed in order to ensure that the assumptions of homoscedasticity and normality of the residuals were met.

Next, in order to estimate the best models possible, it was necessary to assess the effects of interaction terms. This was done by taking the model in Equation 2 and adding each of the possible interaction terms one at a time and re running the model with the new term, as follows:

$$response = \beta_0 + \beta_1 start\ temp + \beta_2 dryer\ inlet + \beta_3 aging + \beta_4 moisture + \beta_5 moisture + \beta_6 bulk\ density + \beta_7 interaction + \varepsilon \quad (3)$$

The p-value of the interaction term in the model was then recorded for each run. Second order quadratic terms (squared factors) were also assessed; except for aging, as this was a binary variable. P-values less than 0.05 were considered significant. Significant interaction terms were passed from the last step and then included in an expanded model which included all of the main effects plus the new interaction terms. The coefficient of determination for this model, as well as the p-value for each variable was reported.

This model was then restricted by removing the term with the lowest p-value unless that variable was included in an interaction term, in which case the term with the second lowest p-value was removed. This process was repeated iteratively until all terms were significant or the adjusted coefficient of determination dropped by greater than 0.05. This was performed for each response variable in order to get an optimized prediction model.

Results

When analyzing the data for relationships between explanatory variables, it was found that there was significant linear correlation among *Bulk Density, Durability,* and *Moisture* as can be seen in Table 2-1. Also included is a scatterplot matrix all factors (Figure 2-7). All variables were mean centered as described in Methods to reduce the effects of multicollinearity.

Not all observations were available for each of the response variables as some bins did not reach the required temperature or began at a higher temperature than expected. This is discussed at the beginning of each section. Results are presented sequentially for each of the response variables: *Max Temp, Rate to 40, Rate to 45, Rate to 50,* and *Rate to 55.*

Response: Max Temp

All 23 of the observations were available for analysis for *Max Temp.* There is replication for each of the controlled factor level combinations as can be seen in Table 2-2. The residuals and interactions are illustrated in Figure 2-8 and the process for coming to the optimized model is illustrated in Table 2-3.

$$max\ temp = 20.46 + 1.04 start\ temp + 0.002 dryer\ inlet + 5.45 aging - 0.003 start\ temp * dryer\ inlet + 0.086 dryer\ inlet * aging \quad (4)$$

Significant in the final model were *Start Temp, Aging,* and the interactions of *Start Temp * Dryer Inlet*, and *Dryer Inlet * Aging. Dryer Inlet* remained in the final model despite being statistically insignificant due to its involvement in both significant interactions. Moreover, when *Dryer Inlet* was removed from the model the value of the coefficient of determination decreased considerably.

The effect of *Start Temp* is great for low values of *Dryer Inlet* but marginally reduced for higher starting temperatures, while the effect of *Dryer Inlet* is greater at lower levels of *Start Temp* (Figure 2-8). For the interaction of *Aging * Dryer Inlet: Dryer Inlet* has the opposite effect on *Max Temp* depending on whether the wood was aged or not before processing, while *Aging* has much lower effects at lower drying temperatures than higher ones.

Response: Rate to 40

There were only 14 observations (Table 2-4) for this response variable, due mainly to the fact that many of the bins began at a temperature higher than 40 degrees Celsius (8 observations) and one observation that did not attain 40 degrees Celsius and so could not be included in this specific model. All factor combinations are represented, though there is not replication for two of them (500*Aged, 600*Aged). Also, there is a large difference between the two levels for the factor *Aged*. The residuals and interactions are shown in Figure 2-9 and the process whereby the optimized model was determined is shown in Table 2-5.

$$\textit{rate to 40} = -79.44 + 0.275\textit{start temp} + 0.002\textit{dryer inlet} + 3.51\textit{aging} + 0.812\textit{durability} - 0.023\textit{durability} + \textit{dryer inlet} \quad (5)$$

The response variable *Rate to 40* can be interpreted as degrees Celsius per day between the starting temperature and the time that 40 degrees Celsius is attained by the pellets in storage. The samples contained in this subset are, therefore those pellets which were cooled quite a bit before being stored. They are also the pellets that did not attain extremely high temps.

The effects found were *Aging, Start Temp, Durability*, and the interaction of *Durability * Dryer inlet. Dryer Inlet* had the opposite effect on *Rate to 40* at high and low levels of *Durability* and the same was true for *Durability* at high and low levels of *Dryer Inlet.*

Like the results for *Max Temp*, the coefficient for *Aging* is a different sign than would be expected in the model of *Rate to 40* and the magnitude of the coefficient is quite large. A positive correlation (0.2793) was found between *Start Temp* and *Aging* though this is rather weak. The coefficient for *Start Temp* on its own was not very large in the model but *Start Temp* could be rather influential in the model because it can vary more than any other factor. This result showed tht it would be advantageous to cool pellets sufficiently before they go into storage

Response: Rate to 45

The representation in the controlled factor levels was much more robust for the *Rate to 45* response variable than it was for *Rate to 40* with the main concern being that there was no replication for the *Dryer Inlet=600 * Aging=1* combination (see Table 2-6). In total there were 19 observations available and those that weren't included did not attain a temperature of 45 degrees in storage (4 observations). The optimized model is illustrated in Table 2-7 and equation 6 below. The residual and interaction plots are presented in Figure 2-10.

$$\textit{rate to 45} = -177.14 + 0.179\,\textit{start temp} - 0.062\,\textit{dryer inlet} + 7.89\,\textit{aging} + 2.17\,\textit{durability} + 0.165\,\textit{start temp} * \textit{durability} \quad (6)$$

The only significant interaction in this model was *Start Temp * Durability. Start Temp* had the opposite effect on the rate for differing levels of *Durability*. In addition, the effect of *Durability* was much greater for higher starting temperatures than for lower temperatures.

The main effects that remained significant on their own were *Dryer Inlet* and *Aging. Dryer Inlet* had the opposite effect than would be hypothesized from the literature in that the coefficient is negative (see Table 2-7). *Aging,* though the opposite sign of what would be expected, was consistent with the findings for Response = *Rate to 40* in that *Aging* had a positive effect on *Rate to 45.* This was most likely because *Aging* had a positive relationship with *Start Temp.*

Response: Rate to 50

Compared to the observations for *Rate to 45, Rate to 50* has two less total observations, both of which were in the *Dryer Inlet* = 500 * *Aging = 1* factor level combination (See Table 2-8). The lost observations were due to those bins not reaching

50 degrees Celsius. This led to a widening difference between aged and green observations as well as a lack of replication for *Dryer Inlet = 500 * Aging = 1* and *Dryer Inlet = 600 * Aging = 1.*

$$\textit{rate to 50} = -44.11 + 0.626\,\textit{start temp} + 0.069\,\textit{dryer inlet} + 7.12\,\textit{aging} + 1.86\,\textit{durability} - 2.27\,\textit{moisture} + 0.175\,\textit{bulk density} - 3\,\textit{moisture}^2 \quad (7)$$

All main effects aside from *Moisture* remained significant, though *Moisture* remained in the model as a squared term (see Table 2-9). The coefficient for *Start Temp* became much greater for *Rate to 50* than for *Rate to 45* and *Rate to 40. Dryer Inlet* and *Aging* had almost the same modeled effect for *Rate to 50* as for *Rate to 45* and can be interpreted in a similar manner. The coefficient for *Durability* was somewhat higher for *Rate to 50* than for *Rate to 45* and much higher than for *Rate to 40. Bulk Density* is significant and positive in the model for *Rate to 50* but bulk density is an important quality characteristic that a producer would not willingly try to reduce.

The only term besides main effects to prove significant in this model was the quadratic term for *Moisture.* Predicted *Rate to 50* decreased when moisture increased or decreased from about 94.87% dry content. This was the only model in which *Moisture* was a significant factor.

Response: Rate to 55

For the *Rate to 55* response variable one additional observation was lost compared to *Rate to 50* (see Table 2-10): *Dryer Inlet = 400 * Aging = 1.* This led to a still wider gap between the aging levels (see Table 2-10). The optimized model is presented in Table 2-11 and in equation 8 below. Residuals and Interactions are illustrated in Figure 2-12.

$$\textit{rate to 55} = -237.85 + 1.04\,\textit{start temp} + 0.002\,\textit{dryer inlet} + 5.45\,\textit{aging} \quad (8)$$

- 0.003*start temp * dryer inlet* + 0.086*dryer inlet * aging*

The only main effect that did not remain in the final model was *Moisture* (see Table 2-11). *Aging* and *Bulk Density* were left in the model even though the p-values were marginally higher than the critical value of 0.05 because removing them caused the coefficient of determination for the model to decrease more than the threshold of 0.10. This model still has the worst fit of any of the previous models described.

The coefficient for *Start Temp* is the same sign (positive) but had an even greater magnitude than it had in any of the models for any of the other rate based response variables. *Dryer Inlet* was correlated to a drop in *Rate to 55* similar in magnitude to *Rate to 45* and *Rate to 50*. The coefficient on *Durability* was also similar in size and sign when compared to the models for *Rate to 45* and *Rate to 50.*

No interactions were found to be significant in the model for *Rate to 55.*

Discussion

The most consistently influential factor in the self heating of wood pellets in this study was the temperature of the pellets when they began storage. This was not a factor that could be controlled during the industrial scale production runs. In the plant, pellets are cooled using counter-flow coolers which force ambient air through the pellets. These coolers are advertised by the manufacturer to cool pellets to within five degrees Celsius of ambient. Looking over the data, this was not always the case. Data that was collected during the test runs showed that when flows increased and ambient temperatures were high, pellets were not cooled sufficiently. Prior studies have shown that oxygen depletion in sealed containers increases exponentially with increasing temperature, indicating that oxidation increases with temperature [65], [66], [67]. Therefore, it would follow that since oxidation is an exothermic reaction, if the initial temperature of stored pellets was increased, then the maximum temperature and rate of temperature increase would be affected. This finding that temperature can affect oxidation is consistent with the published research.

The drying temperature of wood used for pellets has been linked to the composition of off-gasses during wood pellet storage and emissions of VOCs were linked to the general degradation process of wood at high temperatures. Consequently, lower drying temperatures were thought to have a lowering effect on the oxidation of fatty acids in pellets during storage [63]. This was not seen in this study. *Dryer Inlet* was significant and negative for all models except for those with the responses *Max Temp* and *Rate to 40* where the results depend on the influence of interactions. In the former, the coefficient for *Dryer Inlet* is still negative for high starting temperatures but is positive for low starting temperatures. In addition, when wood was not aged, *Dryer Inlet* had a negative coefficient for the *Max temp* model and vice versa for when wood was aged. This may suggest that lower drying temperatures or a lack of aging may leave more extractives in the wood that can oxidize during storage. In the response *Rate to 40, Dryer Inlet* was negative at high levels of *Durability* and vice versa for low *Durability* but it is difficult to glean any conclusions from this outcome. These results, namely the negative correlation of *Dryer Inlet* and most of the response variables, may be due to the drying temperatures in this study being much higher than previous research. These temperatures may drive out so many of the extractives in the drying process that there are fewer to oxidize from the pellets during storage but this has yet to be proven.

Off gassing of volatile compounds and carbon based gases from pellets, like self heating, is mostly related to the oxidation of fatty and resin acids in the extractives of the wood. Previous studies regarding the off gassing have noted that pellets made from feedstocks with lower extractives levels, such as spruce and aged pine, emitted lower levels of volatile gases than those made from feedstocks with higher extractives, namely fresh pine [64], [69], [70]. As volatile emissions are mainly caused by the breakdown of chemicals in the extractive fraction of wood it could be expected that aging would also decrease the propensity of heating during storage. This was not the case for this study. *Aging* was significant and positive in all models besides that for response *Max Temp,* in which it was moderately negative but only at lower drying temperatures. There is no currently conceivable reason that aging would have a positive effect on the heating propensity of wood in storage. *Aging* was highly correlated to *Start Temp (*see Table 2-12) but the factor passed the VIF test for multicollinearity.

Durability remained significant and positive for each of the rate based response variables with the exception of *Rate to 40.* In the aforementioned model *Durability* was positive at low drying temperatures but vice versa at lower temperatures. The positive coefficient for *Durability* in these models may be because this quality attribute is associated to high pressures in the pellet die. These conditions may lead to extractive breakdown conditions which persist during storage though no literature was found on this. In addition, durability is not a quality attribute which pellet producers would consciously attempt to lower.

Bulk Density and *Moisture* were not consistently significant in each of the models. No published research exists on the effects of bulk density or the moisture content of pellets on the off gassing or self-heating of pellets in storage.

Currently the reigning belief from pellet producers is that as long as pellets are kept dry then the self heating will climax and start to die off long before a runaway reaction occurs. This may be true but to date there have been costs incurred in the form of cooling to meet contract requirements, questions about the safety of working around stored pellets as they are heating and off gassing, and even deaths related to the oxygen depletion of pellets stored in sealed environments [68].

There still exists a great need for research in the self heating and off gassing of pellets. The research in this study further exemplified the connection between temperature and oxidation rate of pellets in storage but is inconclusive as to what the effect of aging and drying temperature are. It would be beneficial to assess the effect of different aging lengths, a larger number of feedstocks, a greater range of drying temperature regimes, and perhaps the effects of various pre treatment methods on the storage stability of pellets.

Conclusions

This research shows that the most consistently correlated factor to the heating of Southern Yellow Pine wood pellets in storage was the starting temperature at which they were placed in storage. Both the rate of temperature rise and the max temperature seemed to be strongly affected.

Both the Aging of wood prior to processing and the inlet gas temperature during drying were significant in most models but in the opposite manner of what were hypothesized by previous research. This may be because the aging period was rather short in this experiment due to time constraints. In addition, the drying temperature range is fairly high compared to other studies.

It would probably be beneficial for wood pellet producers to aim at maintaining fairly low temperatures before pellets are put into storage in order to reduce the propensity for self heating. Additional research is needed on those production factors affecting self-heating, especially while controlling the start temperature of pellets.

Figure 2-1. Wood pellets cultured on malt agar medium and showing signs of fungal colonization

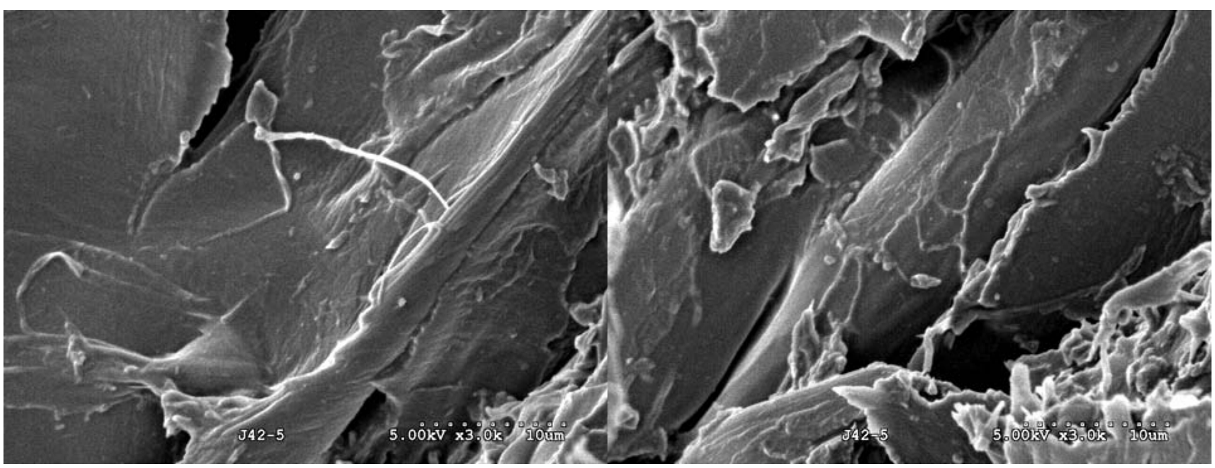

Figure 2-2. Scanning electron micrographs (3000X magnification) of fungal degraded pellets. (Courtesy of Joel Jurgens of University of Minnesota)

Figure 2-3. “Blue Bins” used for the storage of pellets for the purpose of the experiment

Figure 2-4. Filling hopper for determining bulk density of pellets (Source: http://www.seedburo.com/online_cat/categ03/151.asp. Last accessed May, 2010)

Figure 2-6. Tumbler for determining durability of pellets (Source: http://www.seedburo.com/online_cat/categ09/PDT.asp. Last accessed May 2010)

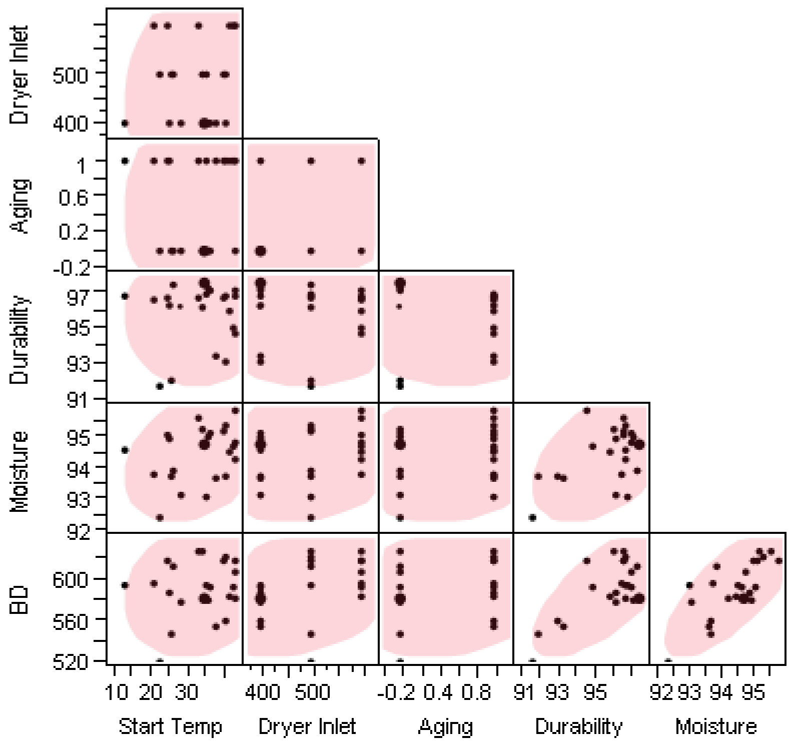

Figure 2-7. Scatterplot matrix of factors for all 23 samples. Ellipses represent α=..95

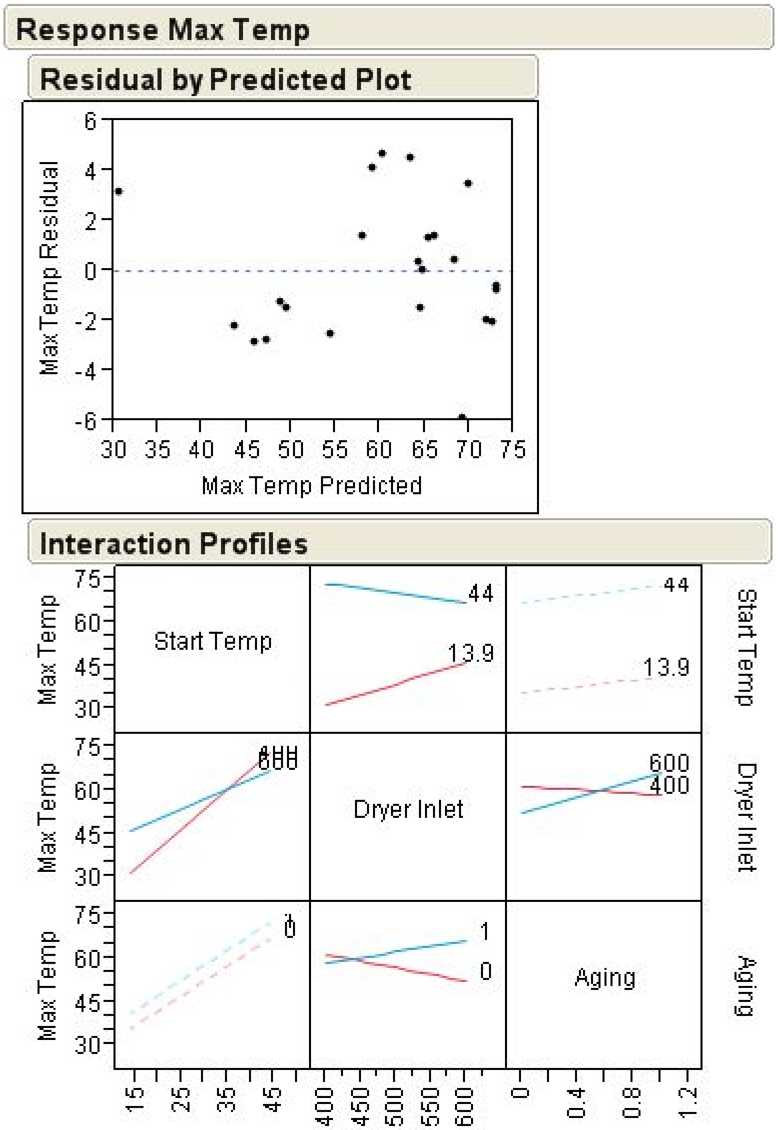

Figure 2-8. Residual and interaction plots for Response = *Max Temp.* Residuals appear to violate the constant variance assumption of Linear Regression though transformation did not yield a more satisfactory model. Note that in the Interaction profiles *Start Temp * Aging* is included only because of the way the chart is constructed and was not found to be a significant interaction.

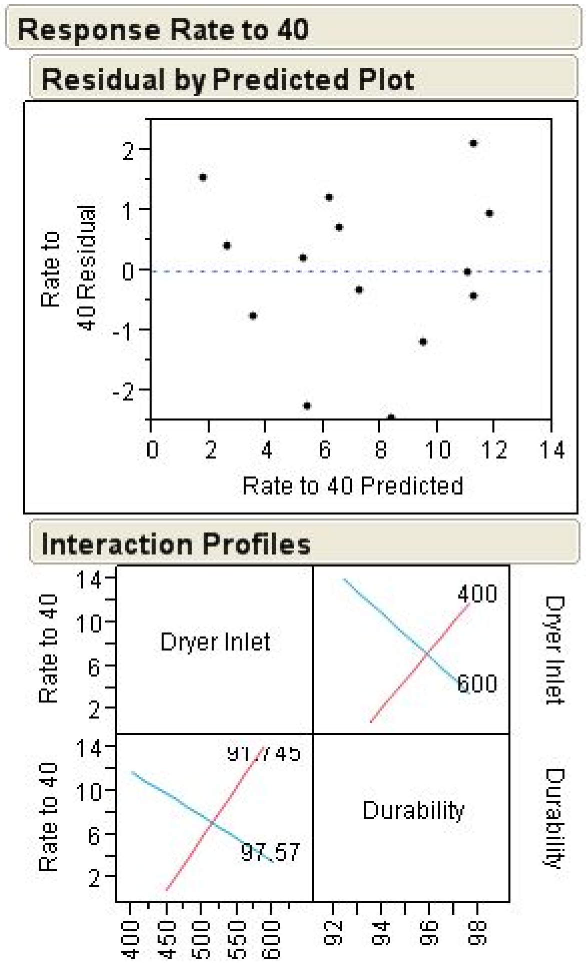

Figure 2-9. Residual and interaction plots Response = *Rate to 40*

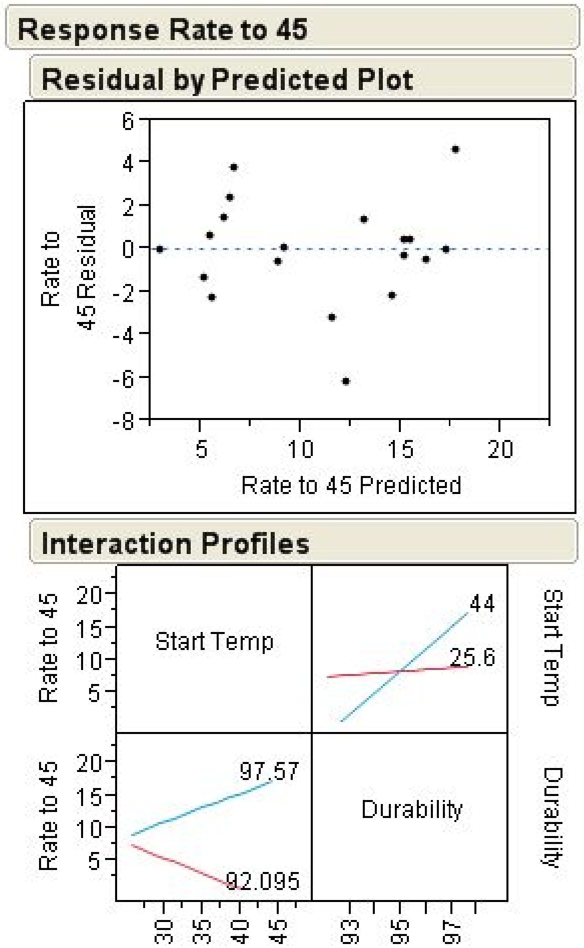

Figure 2-10. Residual and interaction plots for Response = *Rate to 45*

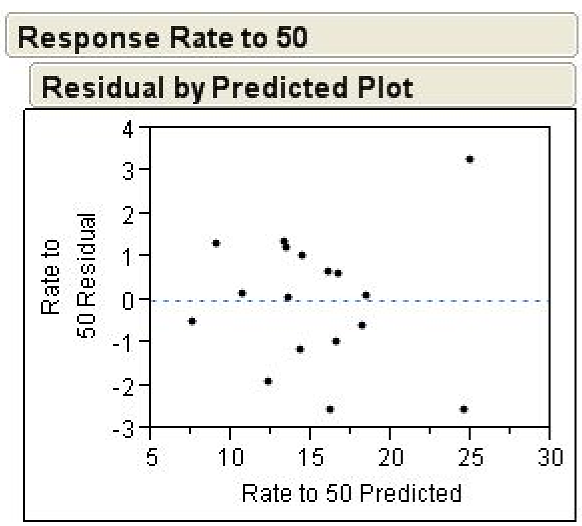

Figure 2-11. Residual plot for Response = *Rate to 50*

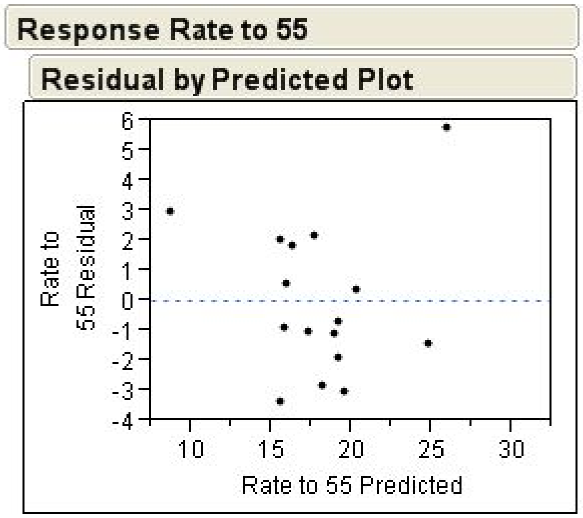

Figure 2-12. Residual plot for Response = *Rate to 55*

Table 2-1. Bi-variate correlations between factors for all available observations

	Start Temp	Dryer Inlet	Aging	Durability	Moisture	BD
Start Temp	1.0000	0.2582	0.2793	0.0462	0.3409	0.1914
Dryer Inlet	0.2582	1.0000	0.2103	0.0550	0.2205	0.3879
Aging	0.2793	0.2103	1.0000	-0.0248	0.2660	0.2277
Durability	0.0462	0.0550	-0.0248	1.0000	0.4792	0.7166
Moisture	0.3409	0.2205	0.2660	0.4792	1.0000	0.7494
BD	0.1914	0.3879	0.2277	0.7166	0.7494	1.0000

Table 2-2. Factor level combinations available for Response = *Max Temp.* (Dryer Inlet*Aging)

	400	500	600	Total
Aged	4	3	6	13
Green	4	4	2	10
Total	8	7	8	23

Table 2-3. Model optimization chart for response = *Max Temp*. P-values for each factor and adjusted R- squared are reported for each model. Optimized model, including coefficients, is reported in last column.

	p-values					Coefficients
Intercept					0.0082	20.459303
Start Temp	0.0001	0.0001	0.0001	0.0001	0.0001	1.0377435
Dryer Inlet	0.8456	0.9011	0.8956	0.9372	0.8236	0.0018396
Aging	0.0096	0.0053	0.005	0.0023	0.0014	5.4549584
Durability	0.7387	0.4927*				
Moisture	0.6495	0.4109	0.1897	0.1671*		
Bulk Density	0.8651*					
Start Temp * Start Temp	0.43	0.4219	0.4308*			
Start Temp * Dryer Inlet	0.0068	0.005	0.0045	0.0014	0.0023	-0.003357
Dryer Inlet * Aging	0.0014	0.0006	0.0004	0.0002	0.0001	0.0860795
Adj R Square	0.924253	0.929501	0.931868	0.933335	0.929042	

* factor removed in next iteration

Table 2-4. Factor level combinations for Response = *Rate to 40.*

	400	500	600	Total
Aged	2	1	1	4
Green	4	4	2	10
Total	6	5	3	14

Table 2-5. Model optimization chart for Response = *Rate to 40*.

	p-values					Coefficients
Intercept	0.7406	0.6089	0.3128	0.7536	0.0096	-79.43863
Start Temp	0.024	0.0068	0.0096	0.0125	0.0301	0.2749031
Dryer Inlet	0.4387	0.1548	0.4514	0.8552	0.8108	0.002022
Aging	0.3636	0.0335	0.0222	0.0109	0.0218	3.5130409
Durability	0.2481	0.0163	0.0118	0.0055	0.0127	0.8122682
Moisture	0.2315	0.0844	0.0606	0.1276*		
Bulk Density	0.4778	0.1825*				
Start Temp *Aging	0.1429	0.0968	0.1896*			
Durability * Dryer Inlet	0.6301	0.1608	0.0436	0.0056	0.0113	-0.023249
Durability * Aging	0.922*					
Adj R Square	0.847014	0.877279	0.848761	0.823099	0.779183	

* factor removed in next iteration

Table 2-6. Factor level combinations for Response = *Rate to 45*

	400	500	600	Total
Aged	4	3	1	8
Green	2	3	6	11
Total	6	6	7	19

Table 2-7. Model optimization chart for Response = *Rate to 45*

	p-values					Coefficients
Intercept	0.7406	0.6089	0.3128	0.7536	0.0096	-79.43863
Start Temp	0.024	0.0068	0.0096	0.0125	0.0301	0.2749031
Dryer Inlet	0.4387	0.1548	0.4514	0.8552	0.8108	0.002022
Aging	0.3636	0.0335	0.0222	0.0109	0.0218	3.5130409
Durability	0.2481	0.0163	0.0118	0.0055	0.0127	0.8122682
Moisture	0.2315	0.0844	0.0606	0.1276*		
Bulk Density	0.4778	0.1825*				
Start Temp *Aging	0.1429	0.0968	0.1896*			
Durability * Dryer Inlet	0.6301	0.1608	0.0436	0.0056	0.0113	-0.023249
Durability * Aging	0.922*					
Adj R	0.847014	0.877279	0.848761	0.823099	0.779183	

* factor removed in next iteration

Table 2-8. Factor level combinations for Response = *Rate to 50*

	400	500	600	Total
Aged	4	1	1	6
Green	2	3	6	11
Total	6	4	7	17

Table 2-9. Model optimization chart for Response = *Rate to 50*

	p-values	coeff
Intercept	0.7425	-44.11073
Start Temp	0.0004	0.6259736
Dryer Inlet	0.0001	0.068887
Aging	0.0009	7.115485
Durability	0.0084	1.8603161
Moisture	0.1321	-2.279411
Bulk Density	0.0098	0.1754715
Moisture * Moisture	0.0158	-3.00539
Adj R Square	0.826369	

Table 2-10. Factor level combinations for Response = *Rate to 55*

	400	500	600	Total
Aged	3	1	1	5
Green	2	3	6	11
Total	5	4	7	16

Table 2-11. Model optimization chart for Response = *Rate to 55*

	p-values		Coefficients	p-values	
Intercept	0.1246	0.0089	-237.8524	0.0181	0.0665
Start Temp	0.0037	0.0019	0.7473942	0.0066	0.0128
Dryer Inlet	0.0067	0.0043	-0.047761	0.0191	0.0703
Aging	0.0798	0.0637	4.6231381	0.1113	
Durability	0.0378	0.0297	1.9959846	0.0143	0.0517
Moisture	0.7563*				
Bulk Density	0.2742	0.0753	0.0942415		
Adj R Square	0.529164	0.571429		0.456937	0.366505

* factor removed in next iteration

Table 2-12. Correlations coefficients for response variables and factors.

	Start Temp	Max Temp	Rate to 40	Rate to 45	Rate to 50	Rate to 55	Dryer Inlet	Aging	Durability	Moisture	BD
Start Temp	1	0.9	-0.1751	0.4791	0.7989	0.8681	0.2582	0.881	0.7147	0.7901	-0.6771
Max Temp	0.9	1	-0.0183	0.5764	0.8369	0.8919	0.2826	0.9192	0.787	0.7429	-0.7182
Rate to 40	-0.1751	-0.0183	1	0.7682	0.3982	0.2386	-0.6247	-0.2996	0.2485	-0.4337	-0.0443
Rate to 45	0.4791	0.5764	0.7682	1	0.8856	0.7919	-0.3943	0.3182	0.6853	0.1367	-0.5019
Rate to 50	0.7989	0.8369	0.3982	0.8856	1	0.9835	-0.041	0.6629	0.8797	0.5646	-0.5922
Rate to 55	0.8681	0.8919	0.2386	0.7919	0.9835	1	0.0899	0.752	0.893	0.6857	-0.5872
Dryer Inlet	0.2582	0.2826	-0.6247	-0.3943	-0.041	0.0899	1	0.5254	0.3052	0.6374	0.2414
Aging	0.881	0.9192	-0.2996	0.3182	0.6629	0.752	0.5254	1	0.6498	0.7755	-0.6544
Durability	0.7147	0.787	0.2485	0.6853	0.8797	0.893	0.3052	0.6498	1	0.7575	-0.2958
Moisture	0.7901	0.7429	-0.4337	0.1367	0.5646	0.6857	0.6374	0.7755	0.7575	1	-0.2596
BD	-0.6771	-0.7182	-0.0443	-0.5019	-0.5922	-0.5872	0.2414	-0.6544	-0.2958	-0.2596	1

REFERENCE LIST

[1] Peksa-Blanchard M, Dolzan P, Grassi A, Heinimö J, Junginger M, Ranta T, et al. Global wood pellets markets and industry: policy drivers, market status and raw material potential. IEA Bioenergy Task 40; 2007.

[2] Ericsson K, Nilsson LJ. International biofuel trade—a study of the Swedish import. Biomass and Bioenergy 2004; 26: 205–20.

[3] Vinterbäck J. Pellets 2002: the first world conference on pellets. Biomass and Bioenergy 2004; 27: 513–20.

[4] Hillring B, Vinterbäck J. Wood pellets in the Swedish residential market. For. Products J. 1998; 48: 67–72.

[5] Spelter H, Toth D. North America's wood pellet sector. Madison(WI): U.S Dept. of Agriculture, Forest Service, Forest Products Laboratory; 2008. Res. Pap.: FPL-RP-656.

[6] Faulkner L. Dixie Pellets closes doors Selma Times-Journal. 2009 Sept 2. [Cited 2010 July 1]. Available from: http://www.selmatimesjournal.com/news/2009/sep/02/dixie-pellets-closes-doors/

[7] Olsson O, European bioenergy markets [thesis]. Uppsala (Sweden): Swedish University of Agricultural Sciences, Dept. of Energy and Technology; 2009.

[8] Magelli F, Boucher K, Bi HT, Melin S, Bonoli A. An environmental impact assessment of exported wood pellets from Canada to Europe. Biomass and Bioenergy 2009; 33: 434–41.

[9] Forest2Market. Forest2Mill Newsletter, The impact of Dixie Pellet's closure [internet]. Charlotte: Forest2Market Inc. [Cited 2010 July 1]. Available from: http://www.forest2market.com/f2m/us/f2m1/free/forest2mill-archive/story/2009-Sep-Dixie

[10] Galik CS, Abt R, Wu Y. Forest biomass supply in the southeastern United States: implications for industrial roundwood and bioenergy production. J. of Forestry 2009; 107: 69–77.

[11] Mani S, Sokhansanj S, Bi X, Turhollow A. Economics of producing fuel pellets from biomass. Appl. Engineering in Agriculture 2006; 22: 421–6.

[12] Lehtikangas P. Quality properties of pelletised sawdust, logging residues and bark. Biomass and Bioenergy 2001; 20: 351–60.

[13] Bioenergy production facility coming to Waycross. The Valdosta Daily Times. 2010 Jan 23. [Cited 2010 July 1]. Available from:

http://valdostadailytimes.com/business/x410004956/Bioenergy-production-facility-coming-to-Waycross

[14] Sims S. Green Circle to build new plant. Panama City News Herald. 2010 Oct 14. [Cited 2010 July 1]. Available from: http://www.newsherald.com/articles/plant-78284-build-circle.html.

[15] Junginger M, van Dam J, Zarrilli S, Mohamed FA, Marchal D, Faaij A. Opportunities and barriers for international bioenergy trade. IEA bioenergy Task 40; 2007.

[16] EUA Futures, Historical data – ECX EUA Futures Contract. London: European Climate Exchange Carbon Financial Instruments. [cited 2010 July 1]. Available from: http://www.ecx.eu/EUA-Futures

[17] Baltic Dry Index Ticker, New York: Bloomberg.com. [cited 2010 July 1]. Available from: http://www.bloomberg.com/apps/quote?ticker=BDIY:IND

[18] ISO/TC 238. Business plan- solid biofuels. Second draft. International Organization for Standardization (ISO) Geneva: 2009.

[19] American Clean Energy and Security Act of 2009, 2009, H.R. 2454, 111th Cong. 1st Sess. (2009)

[20] van Loo S, Koppejan J, editors. The handbook of biomass combustion and co-firing. London: Earthscan; 2008

[21] McCarthy P, Lei L. Regional demands for pulp and paper products. J. of For. Economics 2010; 16:127–44.

[22] Timber Mart-South, Timber price dataset. Athens (GA): Frank W. Norris Foundation; 2010.

[23] Timber Mart-South Market News Quarterly 2010; 15(1): 4–5.

[24] Johnson TG, Steppleton CD, Bentley J. Southern pulpwood production, 2008. Asheville (NC): U.S. Dept. of Agriculture, Forest Service, Southern Research Station; 2010. Research Bulletin: RB-SRS-165.

[25] Foex.fi [internet]. Helsinki: FOEX Indexes, Ltd.; [cited 2010 July 1]. Available from: http://www.foex.fi/

[26] Timber Mart-South Market News Quarterly 2009; 14(4): 4.

[27] U.S. Census 2010 - New privately owned housing units in the United States by purpose and design. Washington D.C.: United States Census Bureau; 2010. [cited 2010 July 1] Available from:

http://www.census.gov/const/www/quarterly_starts_completions.pdf

[28] Joint Center for Housing Studies. LIRA historical data. Cambridge (MA): Harvard University; [cited 2010 July 1]. Available from: http://www.jchs.harvard.edu/media/lira/lira_historical_data.xls

[29] Taylor R. Softwood lumber forecast 2010 to 2014. Timber Mart-South Market News Quarterly 2009; 14(4): 23.

[30] Spelter H, McKeever D, Toth D. Profile 2009: Softwood sawmills in the United States and Canada. Madison (WI): U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory; 2009. Res. Pap.: FPL-RP-659

[31] APA Engineered Wood Association. Structural panels and engineered wood – quarterly production [slide show]. 2008 [cited 2010 July 1]. Available from: http://www.apawood.org/pdfs/unmanaged/marketstats/2008-Quarterly-EngWoodStats.pdf

[32] RISI. North American panel risk study [prospectus]. 2007 [cited 2010 July 1]. Available from: http://www.risiinfo.com/risi-store/do/product/detail/north-american-structural-panel-risk-study.html

[33] Lang AH, Mendell B, Freemem S, Sydor T. Projected annual wood demand, 2020. Wood Bioenergy South 2010; 2(1): 1.

[34] Annual Energy Outlook 2009. Washington D.C.: U.S. Energy Information Administration, Department of Energy; 2009. [cited 1 July 2010] Available from: http://www.eia.doe.gov/oiaf/archive/aeo09/index.html

[34] Gan J, Smith CT. A comparative analysis of woody biomass and coal for electricity generation under various C/o2 emissions reductions and taxes. Biomass and Bioenergy 2006; 30(4): 296–303

[35] Biorefinery locations [map]. Washington D.C.: Renewable Fuels Association 2010 Apr 27 [cited 2010 July 1] Available from: http://www.ethanolrfa.org/bio-refinery-locations/

[36] Schmer MR, Vogel KP, Mitchell RB, and Perrin RK. Net energy of cellulosic ethanol from switchgrass. Proc. of the Natl. Academy of Sciences 2008; 105: 464, vol. 105, 2008, p. 464-9.

[37] Carroll A, Somerville C. Cellulosic biofuels. Annual Rev. of Plant Biology 2009; 60: 165-82.

[38] Smith WB, Miles PD, Perry CH, Pugh SA. Forest resources of the United States, 2007. Washington D.C.: U.S. Department of Agriculture, Forest Service; 2009. Gen. Technical Rep.: WO-78..

[39] Landers JL, Van Lear DH, Boyer WD. The longleaf pine forests of the southeast: requiem or renaissance. J. of Forestry 1995; 93: 39-44

[40] Hickman, C. TIMOs and REITs. U.S. Department of Agriculture, Forest Service [unpublished paper]. 2007 March [cite 2010 July 1]; Available from: http://www.fs.fed.us/spf/coop/library/timo_reit.pdf.

[41] Fiacco B. The forest industry of the future: what will it look like? Timber Mart-South Market News Quarterly 2009; 14: 11-2.

[42] Haynes RW, Adams DM, Alig RJ, Ince PJ, Mills JR, Zhou X. The 2005 RPA timber assessment update. Portland (OR): U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; 2007. Gen. Technical Rep.: PNW-GTR-699.

[43] Alig RJ, Plantinga AJ. Future forestland area: Impacts from population growth and other factors that affect land values. J. of Forestry 2004; 102: 19-24.

[44] Kline JD, Azuma DL, Alig RJ. Population growth, urban expansion, and private forestry in western Oregon. For. Science 2004; 50: 33-43.

[45] Newell G, Eves C. The role of US timberland in real estate portfolios. J. of Real Estate Portfolio Management 2009; 15: 95-106.

[46] Timber Mart-South Market News Quarterly. 2009 Yearly Summary. 2009; 3-5

[47] Christensen LR, Caves RE. Cheap talk and investment rivalry in the pulp and paper industry. The J. of Industrial Economics 2003; 45(1): 47-73.

[48] Bergman MA, Johansson P, Bergman MA. Large investments in the pulp and paper industry: a count data regression. J. of For. Economics 2002; 8(1): 29-52.

[49] Benjamin J, Liliholm, RJ, Damery, D. Challenges and opportunites for the northeastern forest bioindustry. J. of Forestry 2009; 107: 125-131.

[50] Bolkesjø, TF, Trømborg, E, Solberg, B. Bio energy from the forest sector: Economic potential and interactions with timber and forest product markets in Norway. Scandinavian J of For. Res. 2006; 21: 175-185.

[51] Haynes RW. Forest management in the 21st century: changing numbers, changing context. J. of Forestry 2002; 100(2): 38-43.

[52] Röhnqvist M. Optimization in forestry. Mathematical Prog. 2003; 97: 267-84.

[53] Thek G. Obernberger, I. Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. Biomass and Bioenergy 2004; 27: 671-93.

[54] Dwivedi, P, Bush TG, Marinescu, M. Quantifying greenhouse gas emissions of wood pellet production from forest biomass in Florida and its subsequent utilization for electricity production in the Netherlands. BioEnergy Research. Forthcoming 2010.

[55] Prestemon JP, Wear DN. Linking harvest choices to timber supply. For. Science 2000; 46: 377-89.

[56] McKeever. Taking inventory of woody residuals. BioCycle 2003; 44:31-35.

[57] Gan J, Smith CT. Availability of logging residues and potential for electricity production and carbon displacement in the USA. Biomass and Bioenergy 2006; 30: 1011-1020.

[58] Eisenbies M, Vance E, Aust W, Seiler J, Intensive utilization of harvest residues in southern pine plantations: quantities available and implications for nutrient budgets and sustainable site productivity. BioEnergy Research 2009; 2: 90-8.

[59] Howard, J. U.S. timber production, trade, consumption, and price statistics 1965-2005. Madison (WI): U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 2007. Res. Pap.: FPL-RP-637.

[60] Carras JN, Young BC. Self-heating of coal and related materials: models, application and test methods. Progress in Energy and Combustion Science 1994; 20: 1-15.

[61] Wang H, Dlugogorski BZ, Kennedy EM. Coal oxidation at low temperatures: oxygen consumption, oxidation products, reaction mechanism and kinetic modeling. Progress in Energy and Combustion Science 2003; 29: 487-513.

[62] Jirjis R, Theander O. The effect of seasonal storage on the chemical composition of forest residue chips. Scandinavian Journal of Forest Research 1990; 5: 437-48.

[63] Svedberg UR, Hogberg HW, Hogberg J, Galle B. Emission of hexanal and carbon monoxide from storage of wood pellets, a potential occupational and domestic health hazard. Annals of Occupational Hygiene 2004; 48: 339-49.

[64] Arshadi M, Gref R. Emission of volatile organic compounds from softwood pellets during storage. Forest Products Journal 2005; 55: 132-5.

[65] Tumuluru JS, Xingya K, Sokhansanj S, Jim LC, Bi T, Melin S. Effect of storage temperature on off-gassing and physical properties of wood pellets. Proceedings of

2008 ASABE Annual International Meeting; 2008 June 29 – July 2; Providence, Rhode Island.

[66] Kuang X, Shankar TJ, Bi XT, Sokhansanj S, Jim CJ, Melin S. Characterization and kinetics study of off-gas emissions from stored wood pellets. Annals of Occupational Hygiene 2008; 562: 675-83.

[67] Kuang X, Shankar TJ, Bi XT, Lim CJ, Sokhansanj S, Melin S. Rate and peak concentrations of off-gas emissions in stored wood pellets–sensitivities to temperature, relative humidity, and headspace volume. Annals of Occupational Hygiene 2009; 53: 789-96.

[68] Svedberg U, Samuelsson J, Melin S. Hazardous off-gassing of carbon monoxide and oxygen depletion during ocean transportation of wood pellets. Annals of Occupational Hygiene 2008; 52: 259-66.

[69] Arshadi M, Gref R, Geladi P, Dahlqvist SA, Lestander T. The influence of raw material characteristics on the industrial pelletizing process and pellet quality. Fuel Processing Technology 2008; 89:1442-7.

[70] Arshadi M, Geladi P, Gref R, Fjallstrom P. Emission of volatile aldehydes and ketones from wood pellets under controlled conditions. Annals of Occupational Hygiene 2009; 53: 797-805.

[71] Lawson CJ, Hanson, RJ. Solving least squares problems. Philadelphia: Society for Industrial and Applied Mathematics; 1995.

[72] Sall J, Creighton L, Lehman A. JMP start statistics: a guide to statistics and data analysis using JMP and JMP IN software. Third Edition. Cary, NC: SAS Institute, 2005.

[73] O'brien R. A caution regarding rules of thumb for variance inflation factors. Quality and Quantity 2007; 41: 673-90.

[74] Gross domestic product: Implicit price deflator, vintage 2010-02-26, Index=100, Quarterly, Seasonally adjusted. St.Louis: Archival Federal Reserve Data – [cited 2010 May 1]. Available from: http://alfred.stlouisfed.org/.

BIOGRAPHICAL SKETCH

Todd Glenn Bush received his Bachelor of Arts from the University of Texas at Austin in 2007 with a major in geography (environmental resource management) and a minor in economics. During this time, he worked for Austin Energy performing economic research into renewable energy development. Subsequently he worked with Student Conservation Association (SCA) and the United States Navy performing natural resource management, including prescribed fire, mapping, and endangered species protection, on Navy lands in the Florida panhandle. Concurrent with his work for SCA he performed research into the wood pellet industry with Dr. Marian Marinescu at the University of Florida West Florida Research and Education Center (UF-WFREC). During his coursework for his Master of Science he continued to work closely with wood pellet producers in Florida.