Economic Viability of Woody Bioenergy Cropping for Surface Mine Reclamation

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ABSTRACT

Planting woody biomass for energy production can be used as a mine reclamation procedure to satisfy the Surface Mining Control and Reclamation Act of 1977 (SMCRA) and provide renewable energy for the United States. This study examines the economic viability of bioenergy production on previously mined lands using multiple hardwood species and treatments. Five species were planted at two densities; one-half of the trees were fertilized in year two. Height and diameter of the trees were measured annually for five years; the first three years by cooperating researchers at Virginia Tech, the last two years specifically for this report. Current and predicted mass of the species, effects of planting density and fertilizer application, and the land expectation value (LEV) of each treatment were summarized. A sensitivity analysis was conducted to determine how changes in production costs, stumpage price, rotation length, and interest rate affect the economic feasibility of bioenergy production. Renewable energy and mine reclamation policies were investigated and it was determined that woody bioenergy can be planted as a mine reclamation procedure and may receive financial incentives. Production cost appears to have the largest impact on LEV and is often the difference between positive and negative returns for the landowner. The extra cost of fertilization and high density planting do not increase LEV; the unfertilized, low density treatments have the best LEV in all examined scenarios. In general, bioenergy was found to be economically viable as a mine reclamation procedure only in limited circumstances. In low cost, high price scenarios, bioenergy crops could have the potential to reforest both active and abandoned mine lands throughout southern Appalachia.

"Men and nature must work hand in hand. The throwing out of balance of the resources of nature throws out of balance also the lives of men."

- Franklin D. Roosevelt (Roosevelt, 1935)

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Chapter 1: Introduction and Objectives

1.1 Overview

Each year, thousands of acres of Appalachian forest are surface mined for the coal that lies beneath them. Subsequently, the land is reclaimed according to federal and state regulations. The Surface Mining Control and Reclamation Act (SMCRA) of 1977 requires these surface-mined lands to be restored at a minimum to a condition capable of supporting the uses which it was capable of supporting prior to any mining, or higher or better uses of which there is reasonable likelihood (30U.S.C., 1977). Growing biomass crops on these lands may be an economical approach for returning the land to a more natural state.

When applying for a permit to extract coal from a parcel of land, mine operators are required to submit a plan for how they intend to follow regulations for restoring the land to a usable state. From the passage of the SMCRA in 1977, thorough the early 2000s, hayland/pasture was the dominant land use for mine land reclamation (Ford, 2004; Isabell, 2004). Mine operators are also required to secure performance bonds for the duration of their operations and reclamation for an amount that would cover the completion of the reclamation plan outlined if the work had to be performed by a regulatory authority in the event of default (30U.S.C., 1977). Reclamation bonds are released once the land has reached standards of revegetation and productivity established by the appropriate regulating authority. The quicker mine operators are able to prove revegetation has occurred, the quicker they are able to retrieve their money tied up in performance bonds, following an applicable timeline. Mine operators are often allowed to choose the post mining land use and thus their motivations for permitting and reclamation may differ from the regulatory agency and landowner (Sullivan and Amacher, 2010). Therefore, incentives may be required to align the goals of the mine operators with those of the landowners.

The SMCRA states that during development of reclamation plans, consideration must be given to landowner preferences (30U.S.C., 1977). Ultimately, it is the mine operator who takes on the cost of reclamation and the decision of how it should be conducted is theirs, within the confines of applicable regulations. Mine operators frequently plant what will allow them to achieve bond release the quickest, in order to recoup their bond payment, which is often hayland/pasture (Ford, 2004; Isabell, 2004). Once final bond release is achieved, the mine operators are no longer held responsible for the health or productivity of the land. Because the mine operators do not usually own the land, decisions are likely made without full consideration of land benefits in the future (Sullivan and Amacher, 2009) and can lead to land use decisions that are not socially optimal. The ownership and decision-making structure can also lead to lands being left unproductive after reclamation, resulting in a dearth of economic returns for the landowner.

The growth of bioenergy crops is an emerging issue in discussions of the United States' energy future. One alternative use of mined land would be to plant trees for bioenergy production. Restoring previously mined lands using woody bioenergy crops may provide economic returns and ecosystem services such as erosion control, water quality protection, and enhanced carbon storage and wildlife habitat. These benefits would not be provided at the same levels if lands were reclaimed to hayland/pasture or other non-forested uses. Biomass growth studies have focused on finding the best tree species to use and optimal management practices to follow to encourage trees to grow into usable energy generation products, typically on existing agricultural lands. However, there are few studies on how these bioenergy trees grow on reclaimed surface mines or on the economics of energy plantations on these lands.

1.2 Biomass and Coal

Renewable Energy Portfolio Standards (RPS) in over half of the US states and federal incentives for investments in renewable energies, are both evidence of a transition away from using fossil fuels for electricity and toward renewable energies (Energy, 2009). Woody biomass is a renewable resource that has been used to create energy for hundreds of years and could be a main source of power generation in the future. Woody crops can be burned in designated biomass-only power plants or cofired in small percentages (5-20%) in existing power plants alongside coal with minimal (if any) plant upgrades and negligible efficiency losses. Capital costs of bioenergy upgrades have been estimated to be between $50-$300/kW, which is much less than the cost of increasing a burner's coal capacity (Baxter, 2011; Mann, 2001). Studies have found efficiency losses of burning 15% biofuel (85% coal) to be in the range of 0.9%-1.5% when compared to burning only coal (Gold and Tillman, 1996; Mann, 2001). These efficiency levels have the potential to increase as more research on growing trees specifically for energy generation is completed and improvements are made in generation technologies.

According to the Energy Information Administration (EIA), 50% of electricity in the US is generated by coal (Energy, 2011). A small percentage of this coal could be replaced with biomass, utilizing existing infrastructure and potentially decreasing overall energy costs. To provide a portion of the required amount of biomass to meet growing energy demands, trees could be grown on reclaimed mine lands. By using previously mined lands to produce biomass, agricultural lands are not displaced and otherwise unproductive land becomes productive.

1.3 Benefits of Woody Bioenergy

Woody bioenergy cropping as a mine reclamation procedure offers both environmental and economic benefits. Cofiring woody biomass with coal can be less expensive than alternative renewable energies, serve a customer base when people would prefer to purchase green power over fossil fuels, and utilize a waste that would otherwise incur a disposal cost when scrap wood materials are used (Hughes, 2000). Biomass has an advantage over other renewable energy technologies in that it is domestically produced, creating local jobs in multiple industries. Furthermore, the transportation system from mine to coal plant is already established. Often coal plants are in close proximity to mine sites; by cutting down on transportation costs, the cost of utilizing biomass for energy generation may be reduced.

Replacing fossil fuels with renewable technologies can be good for the environment as well as the economy. A majority of biomass fuels pollute less than burning coal in power plants that have not been upgraded with the most effective pollution control technologies, greatly decreasing the amount of sulfur, nitrogen, and ash emitted into the atmosphere (Hughes, 2000). The majority of the world's carbon emissions come from coal-generated electricity. One ton of CO_2 emissions (net) are avoided for every ton of biomass cofired. For every ton of biomass burned that would otherwise be deposited in a landfill without methane collection, reductions of CO_2-equivalent global warming potentials are equivalent to three tons (Tillman, 2000).

Other environmental benefits of growing woody biomass on previously mined lands include decreased runoff and erosion, nutrient retention, and increased carbon sequestration (Brinks et al., 2011). Reforesting mine sites provides benefits to the ecosystem that the likely alternative reclamation, hayland/pasture, does not. In addition to hydrologic and soil benefits, forested areas (including woody biomass crops) can provide habitat for native plants and animals (Zipper et al., 2011a).

As the market share for biomass energy increases and influences agriculture planting decisions, plant technology could progress to the point where faster-growing plants are continually replanted, resulting in decreased total emissions. In this case, carbon would be captured faster than it is emitted during biomass burning. Munsell et al. (2011) argue that demand for woody biomass to support renewable energy production could change sector dynamics by providing an additional revenue source, engendering new technology, fostering alternative harvesting and procurement strategies, and improving job security.

Planting woody bioenergy crops on lands previously mined for coal has the potential to keep energy revenue coming from the land following coal extraction, thereby providing renewable energy and employment for Appalachian communities while restoring ecosystem services. This research aims to determine if short rotation woody bioenergy crop production is an alternative land use option that will provide positive economic benefits in a relatively short period of time to landowners while decreasing consumption of fossil fuels for electricity generation in Appalachia by replacing it with bioenergy. An additional goal for this research is to explore existing incentives to reclaim abandoned mine lands through bioenergy production while also determining if policy changes and financial incentives are necessary to encourage growth of bioenergy crops on mined lands.

1.4 Study Objectives

The primary objectives of this study are to:

1. Investigate production potential of biomass on mine sites
2. Use growth, yield, and cost information to determine the economic viability of wood-based bioenergy as a potential post mine land use
3. Identify policy barriers and incentives embodied in surface mine regulations as well as specific policies for bioenergy that may influence economic viability of growing woody bioenergy crops as a post mining land use
    a. At federal and state levels
    b. For reclaiming permitted mine sites and abandoned mine lands

Production potential is determined by analyzing annual measurements of tree growth on three experimental sites in southwest Virginia. These sites were established in 2008 on previously reclaimed mine lands to test woody bioenergy growth. Each site was planted with species that have recently shown promise as woody bioenergy crops: hybrid poplar, black locust, sycamore, red oak and cottonwood. Trees were planted at two densities and some of the plots received fertilizer, testing a variety of management practices. At the time of this report, the trees were established and measured for five growing seasons.

Determining economic viability begins with regression analysis conducted on collected data to estimate equations to predict tree growth and volume. Then, utilizing current stumpage values, production costs, and tree volume, the net present value (NPV) of an investment in woody bioenergy is calculated. Sensitivity analyses are conducted to determine which conditions must exist for an investment in woody bioenergy to be positive. Analysis is conducted from a policy maker's standpoint, with the goal of making the land as valuable as possible for the landowner. Optimal rotation lengths are determined using land expectation value (LEV) calculations under alternative economic scenarios to simulate landowners' decisions in various situations.

Regulations originating from the Surface Mining Control and Reclamation Act of 1977 place restrictions on the resources land must be capable of supporting once mining is completed. Differences in regulations between states are investigated to determine if laws make bioenergy more or less viable in particular states. Federal and state policies are also investigated to see if financial incentives might exist to encourage landowners to request woody bioenergy plantations as post mine land use.

Currently, there exist approximately one million acres of abandoned mine lands in Appalachia (EPA, 2012). The SMCRA set up an abandoned mine reclamation fund to restore some of these lands to less destructive conditions than they were left after mining occurred. This study identifies incentives available for reclamation of abandoned mined lands with bioenergy plantations.

Chapter 2: Literature Review

2.1 Overview

In the past thirty years an abundance of research has focused on growing woody crops for bioenergy. The literature describes ideal species and management practices for high growth yields. Many of these studies are conducted in the US plains region on lands previously devoted to agriculture, and therefore do not exhibit the same characteristics found in the Appalachian coal region. Economic studies of mine reclamation have focused on bonding procedures, external costs of mining, and the wedge between mine operators and landowners when making reclamation decisions.

2.2 Tree Species Characteristics

The experimental sites in Wise County, Virginia used in this study were planted with tree species that recently have shown promise for use as bioenergy. Characteristics of hybrid poplar, black locust, and American sycamore which make them ripe for bioenergy are thus described. Investigations of management practices to achieve the most biomass in the quickest amount of time are also discussed.

2.2A Hybrid Poplar

The U.S. Department of Energy commissioned a study to estimate the amount of potential biomass available for energy production in the contiguous United States in 2005. The study was refined and repeated in 2011 and titled the *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*. This refined study examined growing four different woody biomass crops for energy generation. These crops included hybrid poplar, willow, pine, and eucalyptus. Hybrid poplar trees were found to be one of the most promising species groups for woody crops development nationally (Perlack and Stokes, 2011) due to their high rates of biomass productivity, ability to coppice and ease of genetic modification. Hybrid poplar trees were estimated to produce roughly five dry tons biomass per acre per year by age seven, with limited investment and management needed. Total biomass production from woody crops across the US was estimated to be 67 and 126 million dry tons per year by 2030 with the price of biomass at $50 and $60 per dry ton respectively. If production costs were to decrease over time due to improvements in planting and harvesting methods as well as species selection, yields were expected to increase 2% or 4% to 145 and 212 million dry ton per year, respectively, by 2022 and 207 and 315 million dry tons per year by 2030. These increases in availability may cause increases in crop prices and therefore food prices due to land being allocated to energy crop production instead of food products, but overall returns to agriculture would increase as a result (Perlack and Stokes, 2011). If these trees could instead be grown on unutilized mine lands, crop displacement could be avoided.

Additional studies have found hybrid poplar to have good growth potential on mine lands in Appalachia. Hybrid poplar is considered the top choice for woody biomass feedstock due to rapid growth, ease of manipulation, and adaptability to many ecosystems (Yuan et al., 2008). Biomass production remained high in hybrid poplar plantations even after 25 years of harvesting (Makeschin, 1999) and often are good up to 40 years of coppicing (Mitchell, 1995). Hybrid poplar has also been found to respond positively to fertilizer treatments; a study in Sweden found hybrids treated with fertilizer increased weight by 25%-30% in four years relative to unfertilized trees (Christersson, 2006).

Casselman et al. (2006) conducted a study across three states on post-mining land testing silviculture treatments on hybrid poplars, white pines, and native mixed hardwoods. The treatments included a weed control only treatment, a weed control plus tillage, and a weed control, tillage, plus fertilization treatment. The study concluded that hybrid poplars had greater volume and height growth than all other species tested. The high survival and rapid growth decreased the amount of weed control necessary to establish adequate ground cover. Similar to the study in Sweden, these hybrid poplars responded to silviculture treatments better than any of the other species (Casselman et al., 2006). Their study investigated production differences associated with varying treatments but did not incorporate costs associated with these differences; this study will incorporate those costs to see how recommendations may change under different scenarios.

Many studies have been conducted on short rotation coppice with poplar varieties in the United Kingdom over the past thirty years. Mitchell (1999) compiled information on best practices of poplar plantations for energy production. Mitchell (1995) observed that poplar varieties perform best when planted on well-drained, mildly acidic (pH between 6.0 and 7.0, while another study found a broader range of 5.0-7.5 pH to be acceptable) soils (peats and heavy clays are the worst) and where soils remain moist during the entire growing season. Tending to the trees by weeding in the early months is especially important for poplar species because of their low competitive ability, but is unnecessary in subsequent coppice cycles (Mitchell, 1995).

There is discrepancy among studies as to the appropriate planting density and rotation length for poplar bioenergy production. A compilation of studies found that planting was most often successful between 5,000 and 20,000 trees/ha (2,000 and 8,000 trees/acre, respectively) and harvests should occur every three-to-five years (Mitchell, 1999). One study states that poplar rotations for optimal biomass production were found to be no longer than four years, planted at 7,000 trees/ha (2,800 trees/acres) (Mitchell, 1995). Another study found that when planted at a density of 2,100 trees/ha (850 trees/acre) the optimal rotation is every six years (Turhollow, 1994). None of these studies were conducted on reclaimed mine lands and therefore rotation length for this experiment may be different. The current study aims to find the optimal rotation length for hybrid poplar and other species on reclaimed mine lands in southwestern Virginia.

2.2B Black Locust

Black locust has also emerged as having great potential for woody energy production, due to its high energy content and ability to coppice and flourish on marginal lands (Carpenter and Eigel, 1979; Perlack and Geyer, 1987; Stringer and Carpenter, 1986). Black locust grows quickly in poor site conditions and is a nitrogen-fixer which cuts fertilization costs on planted lands. Additionally, there is very little weed control necessary for black locust once they have coppiced at least once (Perlack and Geyer, 1987). Zimmerman and Carpenter (1980) conducted a study on previously mined lands in Kentucky and found coppice production of black locust to produce twice as much as the study control species. They also discovered biomass from the coppice had similar heat content to first rotation black locust and that the larger the tree stump, the faster new sprouts would appear. Larger stumps produced more sprouts than small stumps, which could indicate that each time the trees are harvested they coppice with more biomass.

A study on the effects of fertilization and irrigation on growth, survival, and biomass accumulation of black locust and American sycamore on reclaimed mines in Appalachia was conducted over a two year period beginning in 2008 (Brinks et al., 2011). Experimental plots underwent one of three different treatments: fertilization, irrigation, or fertilization and irrigation. The study had some distorted results due to heavy elk grazing on black locust and poor drainage for the irrigation system. Elk grazed more than 76% of the black locust seedlings yet attacked less than 3% of the American sycamore. This difference has been accredited to the higher nitrogen concentrations in black locusts attributed to nitrogen fixation. This observation may have important implications on the types of trees planted after mining due to increasing populations of elk in the Appalachian coal region. The study concluded that a fertilization-only treatment is best for growing trees for energy production, especially given the high installation and maintenance costs of irrigation systems. Fertilization treatment increased biomass production, and by increasing growth was expected to result in earlier canopy closure, thereby accelerating the economic and ecological benefits from planting on these sites (Brinks et al., 2011).

2.2C Sycamore

A report by Kszos et al. (2000) called American sycamore one of the five model species for wood bioenergy in the United States. Other model species included cottonwoods/poplar, sweetgum, silver maple and black locust. The report states sycamore bioenergy plantations are good habitat for a diverse collection of bird species and that these plantations are comparable to naturally regenerated mixed hardwood stands of the same age. In addition to being good bird habitat, Mercker (2010) found that sycamore stands provide important ecological and economic benefits by feeding a variety of insects. American sycamore trees are tolerant of wet conditions and have high survival rates even when soils have poor drainage, as long as the lands do not flood for weeks at a time (Mercker, 2010).

Multiple studies have been conducted on management techniques for growing American sycamores for bioenergy production. A compilation of growth studies throughout the southeastern United States showed that sycamore trees yield an average of 2.55 tons per acre per year when planted at a density of 3016 trees/acre and grown for 3.8 years (Table 1) (Coyle and Coleman, 2005).

Table 1: Reported production for sycamore energy crops in the southeastern US. Replicated from Coyle and Coleman (2005) and converted from Mg/ha to tons/acre using the following conversion rates: 2.47105 acres in a hectare; 1.10231131 short tons in a Mg

a) Fresh biomass was multiplied by 0.5 to account for water content
b) Grown with irrigation

State	Fertilization (kgN/acre/yr)	Production (tons/acre/yr)	Stocking (trees/acre)	Stand age (yrs)	Reference
Arkansas	0	1.12	357	5	Francis (1984)
Kentucky	23	1.83	14988	3	Wood et al. (1977)
Kentucky	68	1.52[a]	2419	5	Wittwer et al (1978)
Kentucky	68	2.90	2448	5	Wittwer et al (1978)
Georgia	9	4.10 [a]	10885	4	Steinbeck et al. (1972)
Georgia	9	2.59	1361	4	Steinbeck et al. (1972)
Georgia	49	2.05[b]	1405	4	Dickmann et al. (1985)
Mississippi	0	1.92	486	5	Tuskan and de la Cruz (1982)
Mississippi	22	3.03	911	3	Tang and Land (1996)
Mississippi	0	1.07	435	5	Krinard and Kennedy (1981)
South Carolina	32	2.81[b]	539	3	Coyle (2005)
Tennessee	182	1.78	1619	1	Tschaplinski et al. (1991)
Tennessee	61	6.47	1349	3	Van Miegroet et al. (1994)

Fertilizer has been found to increase growth in sycamore trees during the first few years of growth, helping stands reach canopy closure around the fourth year (Brinks et al., 2011; Coyle and Coleman, 2005; Davis, 2006). Canopy closure provides ecological benefits to the land early on and helps with weed control. Effects of fertilization appear to decrease as the trees age. Davis (2006) found that diameter growth slowed in the fifth year while height increment was still increasing in the seventh growing season.

Tree spacing has also been found to play an important role in sycamore growth. Saucier et al. (1972) found sycamores spaced further apart (1,800-10,900 trees/acre) produced more of their total biomass in stems and branches than in the trunk. Lower density plots increased individual tree diameters and did not impact tree height. Overall biomass yield was larger in the higher density than the lower density plots.

Hybrid poplar, black locust and sycamore species all have characteristics that may make them good candidates for short rotation bioenergy production. These characteristics might make one species grow better in fertilized soils, while another does better in unfertilized soil planted at high densities. Many of the studies on bioenergy production have occurred on lands that have never been mined; reclaimed mine lands have properties that may influence tree growth patterns and management practices. This study aims to find which management practices allow hybrid poplar, black locust, and sycamore species to flourish as short rotation woody bioenergy crops on reclaimed mine lands.

2.3 Harvesting Woody Bioenergy

There have been many studies devoted to finding the most efficient method of harvesting biomass for energy production. Harvesting, chipping, and transportation costs have been calculated to comprise up to 70% of the total cost of short rotation coppice crops provided to the mill (Mitchell, 1995). Other studies have found harvesting costs to be less of the total cost of production, at anywhere between 35%-50% (Betters et al., 1991; Turhollow, 1994). Because it is a major component in the cost of biomass for bioenergy growth, continued evaluation of harvesting methods is necessary to determine the economic feasibility of growing biomass for energy on reclaimed mine lands. To maximize the efficiency of machine harvesting, plots should be planted so that side slopes are not higher than 6% (Makeschin, 1999) with in-row slopes of up to 10% (Mitchell, 1999).

Decisions on when to harvest must be weighed based on cost, availability, and potential environmental damage. When focused on minimizing nutrient removal while also timing for sprouts to occur in the spring, harvesting is best completed in the dormant season when there is no foliage (Andersson et al., 2002). Winter harvesting on frozen soil limits the amount of compaction from harvesting machines (Makeschin, 1999), while winter harvesting when soil is soft and not frozen can actually increase compaction (Mitchell, 1999). Cost-based decisions might be more concerned with minimizing transportation costs and therefore harvesting should occur when moisture content in trees is lowest.

Moisture content is highest in hardwoods in spring just before bud break and lowest in summer (Andersson et al., 2002). Moisture content can be as high as 50%-60% when felled and freshly chipped; therefore drying is recommended to avoid decomposition (Makeschin, 1999; Mitchell, 1999). When left wet without ventilation, up to 3% loss of dry matter per month can decompose. Decomposition can be reduced simply by covering the wood chip pile (Mitchell, 1995). To avoid rapid decomposition, on-site chipping is often recommended only when fuel is to be used within a few days of harvest, while keeping whole stems is more appropriate when the storage period is expected to be longer (Mitchell, 1999). Piles left onsite throughout the dry summer months can reduce the moisture content to less than 30% (Mitchell, 1995) while reducing the concentration of nitrogen that becomes NO_x when burned at a plant (van den Broek et al., 2001).

Regardless of how the fuel is managed at the time of harvesting, it needs to be chipped prior to being burned for energy generation. This process is often more expensive when conducted as a second stage versus at the time of harvest and these costs can outweigh any gain from keeping stems solid (Mitchell, 1999). Bulk density of small trees is low and therefore increases transportation costs; bulk density can be increased by compaction or chipping. Yet wet chips are only recommended for transportation if they are to be consumed a short while after transport due to their susceptibility to degradation from microbiological (fungi and bacteria), physical, and chemical activities (Andersson et al., 2002). Chipping increases surfaces where microbes can become active while also releasing soluble content from plant cells, providing more food to the microbes. Therefore it is often most cost-effective to chip at the time of harvest when fuel is to be used a short time after harvest. If the fuel is going to be stored for a period of time prior to being burned, the amount of biomass loss due to degradation needs to be weighed against the increase in transportation costs of not chipping on site.

2.4 Reclamation Economics

There have been relatively few studies on the economics of mine reclamation. Of the studies available, most examine the economics and effectiveness of performance bonds. Brooks (1966) identified the existence of a market failure in mining, the divergence between social and private costs associated with mining. He identified, yet did not quantify, the main external costs of mining as air and water pollution, land erosion, and aesthetic and cultural land values. At the time of the article's publication, the SMCRA had not yet been introduced. The article outlines reasoning for adoption of a national public policy for mine reclamation. Three goals that can be accomplished with the help of public policy are (Brooks, 1966):

1. National productivity: Government intervention is necessary to maximize the net output that is put into production while minimizing the total costs associated with the optimal level of mining.

2. Environmental quality: When a cost is associated with cultural and aesthetic values the costs may outweigh the benefits of mining.
3. Redistribution of income: Mining can benefit local communities by adding employment, better roads, and education.

The SMCRA attempts to accomplish these goals, but falls short by many accounts. Gerard (2000) argued that mining performance bonds are not necessarily efficient, yet they encourage regulatory compliance and can effectively provide companies with justified reputations. Gerard (2000) also claims that bonds are effective when the following assumptions of the Coase Theorem are satisfied: 1) When there are clear rules, 2) When there are few contracting parties, and 3) When transaction costs are low. Harder to manage ecosystem services do not follow the Coase Theorem and are not fully bonded by reclamation bonds. Management of ecosystem services is one area where bonding fails to achieve efficient outcomes.

Sullivan and Amacher (2009) quantified some of the social costs associated with mining and make recommendations for reducing these inherent costs through new policy measures. They are consistent with Brook's opinion that reclamation efforts by mine operators do not match the socially optimal level and therefore result in high social costs. In order to capture some of these costs, Sullivan and Amacher (2009) suggested changing the format for the required performance bond to reflect specific site characteristics or change the bond process to a more comprehensive command and control-based regulation.

While quantifying social costs of mining is necessary to internalize external costs, they can be impractical to calculate in practice. Using the rational economic man theory that people and companies make decisions based on which options can provide the most benefit with designated resources, two approaches to calculating performance bond levels were compared – an ecosystem service value approach and a reclamation cost based approach (Cheng and Hu, 2009). It was found that calculating performance bonds based on ecosystem services will often result in a much larger bond than a mine operator would be willing and able to pay and that calculating bonds as the sum of overhead, engineering, and biological reclamation costs provides a more manageable and realistic estimation (Cheng and Hu, 2009).

Economic and policy influences on landowner decisions to reforest previously mined lands were examined in several studies. Sullivan et al. (2005) considered financial viability of mixed hardwood and pine plantations on already reclaimed surface mines from a landowner perspective, examining who pays the cost of conversion and the influence of carbon payments on the decision to reforest. Sullivan and Amacher (2013) studied optimal planting density of mixed hardwoods on mine lands from the mine operator's perspective and look at potential outcomes caused by policies and incentives. Correlations were drawn between the optimal planting level, top-soil type and tree stocking requirements for bond release. They found that regulations (stocking requirements) influence cost of reforestation and may impact the mine operator's reclamation decision and the resulting reforestation efforts.

Further implications and unintentional consequences from reclamation policies were outlined by Sullivan and Amacher (2010). Authors considered the private and social costs of reclamation performance standards, examining ground cover and survival requirements. They found that a strict ground cover requirement can result in unnecessary private and social costs of more than $700/ha and tree survival requirements can add an additional private cost of $200/ha and a social cost of up to $208/ha. They found that policies meant to help reforest surface mines are written in a way that provides unnecessary costs to the mine operator and landowner and furthermore have the potential to discourage reforestation.

Literature on mine reclamation economics has not investigated implications of planting woody bioenergy crops. Literature exists on the economics of woody bioenergy plantations and on forestry versus hayland/pasture as mine reclamation procedures, but not on the marriage of the two. This research aims to bridge that gap.

2.5 Biomass Production Economics

It is not appropriate to compare financial results from individual studies on bioenergy economics because they all include different inputs and assumptions, yet there are commonly used inputs, equations, and overall conclusions that tend to be the same and are thus discussed. Most studies searching for economic feasibility of woody bioenergy crops calculated the net present value (NPV) of a plantation over its bioenergy production lifetime (El Kasmioui and Ceulemans, 2012; Manzone et al., 2009; Perlack and Geyer, 1987). When a bioenergy investment is compared to an alternative investment (typically an agricultural crop harvested annually), NPV is utilized with an annuity factor and the gross margin, or equivalent annual value (EAV), is calculated (Dimitriou and Rosenqvist, 2011; Ericsson, 2006; Faasch and Patenaude, 2012; Rosenqvist and Dawson, 2005). The EAV equation is:

$$EAV = \frac{r}{(1-(1+r)^{-n})}\sum_{t=0}^{T}(1+r)^{-t} \times A_t$$

Where:

t = rotation length (years)

T = time period where payments are made or received

A = value of payment

r = discount rate

n = plantation lifetime, number of tree rotations

Sensitivity analyses encompassed planting density, management practices such as the addition of fertilizer and irrigation, energy market prices, discount rate, rotation length and production yield. Faasch and Patenaude (2012) described the following five elements as the most important factors in determining economic feasibility of short rotation forestry crops for bioenergy: 1) Yield level, 2) Woodchip market price (driven by oil price, climate change legislation, and increases in yield levels), 3) Subsidies, 4) Cost levels, and 5) Opportunity costs (most often measured against alternative agricultural crops). Cost levels are any costs associated with producing the crops including planting, fertilization, and harvesting. Opportunity costs are what the land owner is giving up by choosing to plant energy crops, most often the opportunity costs considered are planting agricultural crops.

The most common discount rates used in calculations are 5% and 6%, with higher discount rates requiring longer rotation lengths for positive financial returns. However, bioenergy economic analysis is not sensitive to changes in discount rate (Perlack and Geyer, 1987). Harvest rotation length generally varies from three to eight years, and most studies assume coppice management practices. Analyses consistently revealed the most influential factors in the bioenergy equation are yield, market price of wood chips, and harvesting costs (when harvesting costs are included in modeling) (Betters et al., 1991; Perlack and Geyer, 1987; Rosenqvist and Dawson, 2005). Ericsson (2006) found that bioenergy market price was more influential in an annual gross margin equation than yield. This is intuitive because an increase in yield increases the cost of harvest and transportation whereas an increase in market price is purely a benefit captured by the producer.

Bioenergy plantation management requires balancing costs and benefits of alternative practices. Each study examined different management techniques for improving the NPV of bioenergy investment. In one experiment, fertilization improved hybrid poplar biomass yield by 24% over non-fertilized plots, yet the benefits of additional yield did not outweigh the added cost of fertilizer (Strauss et al., 1988). In a different scenario, additional costs of planting at a higher density were offset by increased production (Perlack and Geyer, 1987). When woody bioenergy growth is compared to traditional agriculture products, bioenergy did better on average soils because agriculture crops grow better on sites with the best soils (Ericsson, 2006).

Economies of scale are often present in bioenergy crop plantations. Rosenqvist and Dawson (2005) found economies of scale started to take place on willow energy plantations in Northern Ireland over 1000 ha (2471 acres), mostly due to decreased harvesting costs. Production costs decreased with increasing the size of a planation and number of energy plantations in the area. An area with many energy plantations increased the availability of the newest planting and harvesting technologies, as well as the likelihood of an existing local energy market (Rosenqvist and Dawson, 2005).

Table 2: Biomass production cost for different countries, including dry mass yield values, rotation length and calculation period; source: El Kasmioui and Ceulemans (2012).

Stage	Country	Yield (Mg/ha/yr)	Production Cost ($/GJ)	Species	Rotation length (yrs)	Calculation period (yrs)	Included costs
Farm gate	Belgium	12	5.12	Willow	3	26	fixed, variable, land rent
Farm gate	Chile	15.0-25	4.77	Willow	5	15	variable, land rent
Farm gate	Chile	10.0-12	5.48	Poplar	8	15	variable, land rent
Farm gate	Ireland	8.8	2.77	Willow	3	23	variable
Farm gate	Italy	18	4.22	Poplar	5	10	variable, land rent
Farm gate	Spain	13.5	1.06	Poplar	5	16	fixed, variable, land rent
Farm gate	USA	11.23	4.22	Willow	3	22	fixed, variable, land rent
Farm gate	USA, NY	14.8	1.93	Willow	3	22	variable, land rent
Plant gate	Czech Republic	10	4.26	Poplar	3	21	fixed, variable, land rent
Plant gate	EU	9	5.16	Willow	3	22	fixed, variable, land rent
Plant gate	Poland	9	1.81	Willow	3	22	variable
Plant gate	Ireland	12	3.61	Willow	3	22	variable
Plant gate	Ireland	9	4.38	Willow	4	25	variable
Plant gate	Italy	10	5.80	Poplar	2	8	variable, land rent
Plant gate	USA	16	2.97	Poplar	6	12	variable, land rent

El Kasmioui and Ceulemans (2012) summarized biomass production costs covering North America, South America, and Europe. A majority of the collected studies used data found in literature as opposed to experimental plots, further expanding the data pool and providing a varied base for comparison. Each of these studies focused on the economics of woody crop to energy conversion and/or the production of woody crops for energy. A variety of techniques were used to calculate production costs with some studies showing costs from planting to the time of harvested transportation (farm gate) while others included transportation to the energy generating facility (plant gate). All of the included studies used a discounted cash flow approach to reflect the prolonged nature of an investment in woody bioenergy crops with discount rates between 3.5% y^{-1} and 7% y^{-1} for 80% of the studies (El Kasmioui and Ceulemans, 2012). The median farm gate production cost was found to be \$4.22/GJ and only slightly higher for plant gate production at \$4.26/GJ (Table 2) (El Kasmioui and Ceulemans, 2012).

Experiments with bioenergy plantations have been conducted over the past few decades across the globe. Many of these experimental trials took place in Western Europe, Brazil, Scandinavia, and the central plains of the United States, mostly on land previously used for growing agricultural crops. The literature has a dearth of bioenergy growth experiments on lands previously mined for coal. Differences in site characteristics may cause variations in tree growth among these locations and could be the difference between positive and negative economic returns. Additionally, alternative land use options for agricultural lands compared to mined lands may have a significant effect on a landowner’s management decision.

Short rotation woody bioenergy crops were found to be not competitive, marginally competitive, and competitive with traditional agricultural crops and energy sources depending on inputs and assumptions used in calculations. While the NPV may not be positive in all scenarios, bioenergy investment was often close to a breakeven point. Many studies expressed optimism for bioenergy, especially with technology improvements in harvesting and transportation or genetic improvements in crops geared at increasing yield. If improvements in these sectors are made, bioenergy crops may become competitive, but adoption may not occur without a change in public perception of energy plantations and the addition of government subsidies for the production and consumption of bioenergy.

2.6 Summary

There has been research on growing woody biomass for energy production (Perlack and Stokes, 2011) and on the economics of various reclamation procedures for mine lands (Baker, 2008; Sullivan and Amacher, 2009). Studies regarding the biological feasibility of using woody biomass as a reclamation procedure for active mine sites or as a viable option for reclamation of abandoned mine sites are limited (Brinks et al., 2011; Brunner, 2009; Zipper et al., 2011b). The economic viability of mine reclamation with woody biomass for energy production has also not been examined. This study of woody bioenergy growth patterns and economic analysis aims to fill those gaps.

Chapter 3: Policy

3.1 Overview

Environmental degradation caused by traditional sources of energy is a global issue and is being attacked by governments in many different forms. A variety of government policies are being implemented and each type of policy affects change in a unique way. Even with government support, biomass is struggling to compete with coal for energy generation and with other forest goods for production. Few policies currently exist that could encourage previously mined lands to be reclaimed using bioenergy.

Most states in the Appalachian coal region have established their own set of guidelines to comply with the SMCRA. Each of these states has the same general land use categories for mine reclamation, although their standards for successful completion of reclamation vary. While these differences in completion standards do not rule out the possibility of planting woody bioenergy crops, some states make it more difficult than others. The US federal government also has policies in place to encourage the restoration of abandoned mine lands which could encourage establishments of woody bioenergy plantations.

3.2 Renewable Energy Policy

Countries around the world are supporting renewable energy industries to combat the growing problem of climate change from increased carbon emissions. The United Kingdom government implemented the non-fossil fuel obligation (NFFO) in 1990 and the renewables obligation (RO) in 2002 as an attempt to mitigate these issues. The NFFO guaranteed electricity purchases from renewable resources at prices encouraging their development while the RO requires all utilities to purchase a portion of their electricity from renewable sources (Thornley, 2006). Both programs encourage use of biomass as an electricity input, although the UK, like the US, is in need of new programs to further develop a biomass energy market. Increasing the amount of renewable energy produced in the US would also decrease importation of fossil fuels and strengthen energy security. The US currently consumes more energy than it produces; net energy imports in 2010 accounted for approximately 22% of all energy consumed (EIA, 2011), the vast majority of imported energy, both gross and net, is petroleum. Of renewable energies currently available, biomass has the advantage of being 100% domestically produced, creating local jobs in a variety of industries. Although there are many benefits to utilizing woody biomass for electricity, numerous barriers exist that impede mainstream adoption.

Kangas et al. (2009) described benefits of utilizing renewable energy as public goods (e.g., cleaner air and water, climate stability); when considered in this light it is clear why these goods will naturally be under-provided if markets are unregulated. The negative externalities associated with fossil fuels (e.g., polluted air and water, climate change) will lead to market failures as well. Governments are able to introduce regulations to correct these externalities. Recognizing that a change to renewable energy will provide environmental and potentially economic benefits, and will not happen if markets are left alone, the US federal and state governments have implemented a number of programs to increase both the production of biomass materials and the generation of electricity using those materials.

In 1980 President Jimmy Carter signed the Energy Security Act into law. The Act states that a national program for increased production and use of biomass energy that does not impair the Nation's ability to produce food and fiber on a sustainable basis for domestic and export use must be formulated and implemented within a multiple-use framework. The Act defines biomass as any organic matter which is available on a renewable basis, including agricultural wastes and residues, wood and wood wastes and residues, animal wastes, municipal wastes, and aquatic plants (Perlack and Stokes, 2011). This was the beginning of the long, uncompleted road to creating a market for biomass energy in the US.

The federal Energy Policy Act of 1992 created the Renewable Energy Production Incentive (REPI), providing financial incentives to generate power from renewable energy sources. The REPI gives approximately 1.5¢ / kWh (1993 dollars, adjusted for inflation) produced from an eligible renewable energy source for the first ten years of the generating facility's operation (DOE, 2007). Although this credit can only be taken by 100% renewable fuel sourced facilities and not facilities cofiring biomass, there is currently an effort to expand the credit to include facilities where only a portion of production is from renewable sources.

New energy subsidies would likely be required for utilities to choose biomass over coal as the most financially viable option for energy production. Pfund and Healy (2011) identify six categories of energy subsidies:

1. Tax policy: Special exemptions, allowances, deductions, credits, etc., related to the federal tax code
2. Regulation: Federal mandates and government-funded oversight of, or controls on, business employing a specified energy type
3. Research and development
4. Market activity: Direct participation of government in the marketplace
5. Government services: Services provided by the federal government without a direct charge (e.g., oil and coal industry use of free ports and waterways for shipments)
6. Disbursements: Direct financial subsidies such as grants

All of these subsidies have been used in the past for bringing energy production inputs into the market and making them competitive with established technologies. Different types of subsides are currently being tried in the biomass industry to find the best ways to make biomass competitive. Becker et al. (2011) identified 370 policies in the United States that either directly or indirectly affect utilization of forest biomass. They found that tax incentives are the most common form, followed by technical assistance programs and procurement policies. Policies are directed toward all aspects of the supply chain for biomass including harvesting, transportation, manufacturing, and the consumer market. Some of these policies have been shown to work better than others, with most policies affecting the processing/generation sector and few incentives for transportation. The lack of incentives in the transportation sector is important because in general, the closer the source of biomass is to the generation facility, the lower the production costs. Incentives that focus on transportation could potentially support a larger facility than would otherwise be successful by allowing biomass material to be transported from a greater distance. These large facilities may not be sustainable in the long run once incentives have diminished.

The six previously outlined types of incentives described by Pfund and Healy (2011) have the following potential effects on a producer's decision: 1) A tax credit given to firms that produce a portion of their electricity with biomass would increase the amount of biomass burned to the point where the tax credit is exhausted. Tax credits can encourage biomass growth but may place a burden on the rest of the economy through reduced emissions, while the removal of tax credits can encourage technological progress (Gehlar, Somwaru, Dixon, Rimmer, and Winston 2010); 2) A regulation (e.g., a cap on carbon emitted), would use purely coal to begin with and then utilize biomass with coal for the reminder of the cap; 3) Money put into research and development of biomass will likely lead to faster-growing trees being utilized as well as technology that captures more energy from burning biomass, thereby making the use of biomass more efficient. Investment in research and development could lead to increased amounts of biomass being cofired as well as greater percentages of biomass to coal being utilized. Diverting funds into research and development could also look at the whole picture of utilizing biomass, from planting to generating electricity, and investigate the most efficient ways of establishing a biomass market; 4) Direct governmental participation in the marketplace could lead to increased use of biomass in government-owned utilities, but would do little for increasing overall biomass cofiring in the wider market in the short run. After a while, government interaction could lead to new technologies and greater efficiencies being discovered, but it would take longer than an incentive with direct involvement in competitive firms' decision making; 5) Services that could be provided by the government in the biomass energy market would be free or reduced cost of woody biomass harvested on public lands. This program would be challenging to implement but would greatly reduce the cost of biomass in comparison to coal and therefore make it more attractive to producers and replace a greater portion of the coal being burned; and 6) Federal disbursements could be made to subsidize capital costs as well as any additional maintenance costs associated with switching to biomass. These would decrease costs of biomass compared to coal in the short run for the utility and if maintenance costs are subsidized as well could lower overall costs in the long run.

Woody biomass will only become a mainstream source of energy when it is cost-competitive with alternative sources. Kangas et al. (2009) described a scenario where a profit-maximizing firm is choosing between two fuel inputs, biomass and coal. They assumed that the market for fuels and power are competitive so the firm's decision does not affect the market price of the inputs. Additionally, since they ran their model only for a short run scenario, capital costs are considered fixed. The plant operator chose the optimal output level while input use is constrained by MW power generation. The study analyzed the effects different policy instruments (e.g., feed-in tariffs-FIT, feed-in premiums-FIP, and emission trading) have on determining the optimal allocation of inputs. Two types of coal-burning power plants were evaluated. It was found that when a FIT or a FIP is implemented along with emission trading, the amount of biomass cofired was less than when only one of the policies was enacted. An FIP increased the use of biomass at both plants; at one plant cofiring was profitable without any incentives while the other was in need of policy assistance to economically cofire biomass. Additional profits gained from cofiring biomass are low enough that they did not affect plant operators' decisions on keeping their plants open or shutting down.

Tharakan et al. (2005) investigated the effects of policy changes on a biomass supplier, aggregator, and power producer. In this case the supplier was a plantation owner of fast-growing willow shrubs. Realizing a commercial market may not be created for biomass without the price of biomass comparable to that of an alternative (coal), the study focused on the internal rate of return (IRR) to all parties on their respective investments. They pointed out that current energy markets ignore social and environmental costs associated with fossil fuel use, resulting in a lower cost of production and hence, an overprovision of fossil fuel-based energy, relative to socially efficient levels (Tharakan et al., 2005). Authors suggested measures for correcting inefficiencies in the current energy market while indirectly promoting biomass, including new tariffs on coal that account for some of the social costs of using coal as an energy source and imposing taxes and tradable permits for SO_2 and NO_x. As an alternative, biomass could be directly affected by setting up a suitable production payment or tax credit for using biomass.

Internal rate of return (IRR) was then used to determine profitability of investment in biomass using different policy incentives (Tharakan et al., 2005). Each economic agent in their model was considered to be a profit-maximizing entity with a goal of a minimum IRR set at ~15% for the plant operator, ~10% for the aggregator, and ~6% for the farmer. The different policies modeled alone and then together were a green premium price, a tax credit, and cash payments from a Conservation Reserve Program (CRP). The CRP provides annual rent payments to farmers for providing resource conserving covers on their land. Growing woody biomass is accepted by the US Department of Agriculture as a way of qualifying for the CRP when executed in a way that is beneficial for wildlife and the environment (USDA, 2011). The study found conditions at the time of publishing made biomass too expensive to be recognized as an acceptable substitute for energy generation (Tharakan et al., 2005). If financial incentives were placed at a level that reflected the environmental benefits of switching to biomass, using biomass for electricity generation could be financially viable on a large scale. One reason biomass was not considered viable in the study is because the cost of growing willow shrubs was assumed to be substantial.

Tharakan et al. (2005) discovered that combining a tax credit with either a green premium price or a producer enrolled in the Conservation Reserve Program provides the best returns for all parties involved and is therefore probably the most viable option for the market place. They also found that mixing willow shrub biomass with woody residues is cheaper than using all willow biomass up to a certain point but there is a threshold after which adding woody debris ends up being less beneficial because current tax credits could be applied to woody residues. Their study did not place value on the environmental benefits of woody biomass over traditional biomass such as improved soil and water quality.

Merging woody biomass into the current energy market is proving a difficult task. Creating financial incentives in order to encourage widespread adoption of production as well as consumption is challenging because no two producers or consumers of woody biomass are the same. All of the policy incentives discussed above would encourage adoption of biomass cofiring by decreasing cost and making it more competitive with coal. These subsidies will move woody biomass towards being a complete substitute for coal. Therefore, when the price of coal increases, it may become natural that woody biomass is cofired to the percentage allowed in the particular power plant.

Even when utilization of biomass appears to make economic sense, not all firms will chose to adopt woody bioenergy techniques. Dwivedi and Alavalapati (2009) found that government, industry, academia, and non-governmental organizations were all in favor of promoting forest biomass-based bioenergy development in the southern US while Munsell et al. (2011) observed some firm owners were reluctant to adopt biomass for energy production. Profitability is the number one driver for farmers adopting new crops, although the farmer's personal values, and beliefs also help make these decisions (Rossi and Hinrichs, 2011). Many farmers are hesitant to invest in short rotation coppice crops due to a perception that financial returns are unstable. Other farmers have shown skepticism toward the benefits of bioenergy. Many landowners believe woody crops will not be any less profitable than traditional agriculture, but also will not be any more profitable and therefore there is not strong enough reasoning to make the switch (Rossi and Hinrichs, 2011). Perhaps people will become more accepting given more time and increased financial incentive, allowing for a strong biomass market to emerge.

Most states in the US have Renewable Portfolio Standards (RPS) which require a minimum level of electricity to be generated from renewable resources. Of the seven states involved in the Appalachian Regional Reforestation Initiative (ARRI), only Kentucky and Virginia do not have an RPS. The ARRI state RPS goals vary from providing 12.5%-25% of the states' electricity from renewable resources by 2020-2025 (Council, 2012). Virginia does not have an RPS, but it does have volunteer utility companies striving to achieve a goal of providing renewable energy equivalent to 15% of 2007 electricity sales by 2025. Electricity from woody biomass qualifies as a renewable energy and could be used to help meet these various goals.

In addition to goals for sourcing renewable electricity, utilities as well as federal and state governments currently have financial incentives in place to promote the adoption of renewable energy sources. A majority of these incentives are for facilities providing electricity from renewable sources; this type of incentive could indirectly spur demand for woody biomass. The federal government offers tax credits and grants for investment in alternative energy facilities, and individual states have similar financial incentives based on kWhs produced. Kentucky's Office of Agriculture Policy has set upestablished the County Agriculture Investment Program (CAIP), offering grants for farms upgrading to energy efficiency equipment or growing bioenergy crops. This program is directly encouraging planting woody bioenergy by paying for production costs including seeds, rootstock, limestone, equipment, labor, or structure for producing, harvesting and transporting energy crops (Council, 2012).

3.3 Mine Reclamation Policy

With approval of the federal Office of Surface Mining Reclamation and Enforcement (OSMRE), states are allowed to register their own rules and guidelines to follow under the SMCRA. However, state regulations must be consistent with, but no less strict than, federal regulations. Therefore, reclamation practices vary across states and it is up to the individual states to decide what is acceptable for achieving bond release. This study investigates whether differences in regulation cause bioenergy to be a more or less viable option for post mine land use in the seven states involved in the Appalachian Regional Reforestation Initiative (ARRI). These seven states include six states that have their own regulations under the SMCRA, known as primacy states: Virginia, Kentucky, Maryland, Ohio, Pennsylvania, and West Virginia. Each of these states has proven to the OSMRE that their regulations are at least as strict as the federal guidelines for reclamation and therefore the state holds primary responsibility for regulation of coal mining and reclamation. The last state, Tennessee, is a non-primacy state and is strictly under the federal program with the OSMRE holding authority over practices within the state.

The US federal government defines land use as specific uses or management-related activities, rather than the vegetation or cover of the land (30 CFR 701.5). Land uses may be identified in combination when joint or seasonal uses occur, and may include land used for support facilities that are an integral part of the use. Changes of land use from one of the following categories to another shall be considered as a change to an alternative land use which is subject to approval by the regulatory authority. Two of the uses defined by the federal regulations are cropland and forestry:

1) *Cropland.* Land used for the production of adapted crops for harvest, alone or in rotation with grasses and legumes, that include row crops, small grain crops, hay crops, nursery crops, orchard crops, and other similar crops.
2) *Forestry.* Land used or managed for the long-term production of wood, wood fiber, or wood-derived products.

Growing woody bioenergy may fall somewhere between these two categories. When forestry is the chosen reclamation procedure, federal regulations state that land must be used for long term production of wood products which is not the same as stating that the harvest rotations need to be "long", only that the land must be used for wood production in the long term (at least until bond release).

In order for mine operators to achieve bond release after reclamation, certain performance standards must be met. Successful revegetation is measured according to reference areas approved by the regulatory authority similar to that of the approved post mining land use. While federal requirements state that at least 80% of trees and shrubs on the site need to have been in place for two or more growing seasons at the time of bond release (CFR 816.116) (30U.S.C., 1977), individual states have their own, often more strict, standards.

3.3A Virginia Post Mining Land Use

The Virginia Legislative Information System (LIS) Administrative Code defines the Coal Surface Mining Reclamation Regulations in Chapter 130. As part of the permitting process, mine operators are required to designate the intended land use after reclamation. Ten distinct land uses are defined and include cropland, pastureland, grazing land, forestry, residential, industrial/commercial, recreation, fish and wildlife habitat, developed water resources, and undeveloped land or no current land use management (4VAC25-130-700.5). Virginia shares the definitions for cropland and forestry with those presented in the federal regulations. Any reclamation plan that describes a land use different than the current use needs approval by the Division and the landowner (4VAC25-130-816.133). Alternative post-mining uses must be approved as higher or better use of the land and meet the following criteria:

1. There is reasonable likelihood for achievement of the use.
2. The use does not cause actual or probable hazard to public health or safety, or threat of water diminution or pollution.
3. The use will not –
    a. Be impractical or unreasonable;
    b. Be inconsistent with applicable land use policies or plans;
    c. Involve unreasonable delay in implementation; or
    d. Cause or contribute to violation of Federal, State, or local law.

3.3B General Requirements of Revegetation

As part of Virginia reclamation procedure land must be covered in vegetation approved in the permit and plan that meets the following criteria:

1. Vegetation is diverse, effective and permanent;
2. Comprised of species native to the area, or if introduced species where desirable and necessary to achieve the approved post mining land use and approved by the division;
3. At least equal in extent of cover to the natural vegetation of the area; and
4. Capable of stabilizing the soil surface from erosion.

Commercial forestry in Virginia is required to meet a minimum stocking of 400 trees per acre and vegetative ground cover may not be less than that required to control erosion (4VACode, 2009). For final bond release, at least 80% of the trees and shrubs used to verify the stocking level must have been in place for at least three years (4VACode, 2009).

Other Appalachian coal mining states have similar regulations placing restrictions on the density of trees planted and their required age at bond release (Table 3). Minimum stocking requirements range from 300-450 trees per acre and all states require the trees to be at least two years old, with some states requiring a minimum of three growing seasons prior to bond release. Kentucky, Ohio, and Pennsylvania require that 75% of trees on the site to be commercial grade trees when commercial forestry is the designated land use (025PaCode, 1993; 405KyCode, 2013; 1501OhioCode, 2009). Maryland and Pennsylvania law require a more stringent stocking density of 600 trees per acre on steep slopes (slopes greater than 12% and 20%, respectfully), while the rest of the states require a minimum stocking density regardless of site slope (025PaCode, 1993; 26MdCode, 1998).

West Virginia regulations are stricter for a commercial forestry application than other states in the region. West Virginia law enforces specific diversity requirements. Commercial forests must be planted with at least six of the following species: white oak, chestnut oak, northern red oak, black oak, white ash, yellow-poplar, basswood, cucumber magnolia, black walnut, sugar maple, black cherry, or native hickories 7.4./b.1.H.1 (38WVCode, 2011). For this reason, planting bioenergy crops would not be designated as a commercial forestry practice as it is in other eastern mining states.

West Virginia has designated a new post mine land use category as Bio-oil Crop Land (38WVCode, 2011). The federal Office of Surface Mining has approved a Bio-oil Crop Land designation; a name change to Bio *fuel* is pending. Lands designated to biofuel crops must have their reclamation plan approved by an agronomist employed by the West Virginia Department of Agriculture prior to any reclamation. The landowner must also find a market that biofuel crops can be sold into and enter into a contract of at least two years with that entity in order for the reclamation permit to be accepted.

Table 3: Successful stocking standards for land designated as commercial forestry in Appalachian coal states.

State	Minimum trees/acre[1]	Minimum yrs of tree growth[2]	Other restrictions
Kentucky	300	2	75% of trees need to have good-excellent commercial value
Maryland	400	3	70% herbaceous cover ≥2 years old
Ohio	450	3	75% commercial species
Pennsylvania	450	2	75% commercial species
Virginia	400	3	Ground cover enough to control erosion
West Virginia	450	2	No monocultures, specific hardwood species required
Tennessee	n/a	80% of trees must be in place for 60% of the liability period (usually 5 yrs)	

[1]Minimum stocking level requirement set by the state for bond release
[2]State requirement for bond release

Differences in policy requirements can lead to varying costs of mine reclamation across Appalachia. Sullivan and Amacher (2010) examined how policy can inhibit forest reclamation and lead to unnecessary private and social costs. Two areas of regulation were identified in their study: percentage ground cover and stand density at bond release. Both of these performance standards were found to cause external private and social costs which could be eliminated with changes in policy (Sullivan and Amacher, 2010). Additional regulations may exist which result in incentives to reclaim mine lands to less than optimal uses.

3.4 Abandoned Mine Lands

In addition to reclaiming active mines with wood bioenergy crops, abandoned mine lands could be reclaimed as well, thereby increasing total acreage available for energy production. Each year the Office of Surface Mining Reclamation and Enforcement (OSMRE) provides grants to restore abandoned mine lands and treat water quality issues associated with mining operations that occurred before the passage of the SMCRA in 1977. Some of the issues associated with these abandoned mine lands include surface and ground water pollution, entrances to open mines, water-filled pits, unreclaimed or inadequately reclaimed refuse piles and mine sites (including some with dangerous high-walls), sediment-clogged streams, damage from landslides, and fumes and surface instability resulting from mine fires and burning coal refuse (OSMRE, 2011). The grants are funded by fees on each ton of coal mined, collected from active miners, within each state during the previous fiscal year. States apply for funding on an annual basis with top priority given to projects that protect public health, safety, and property against the extreme dangers of mining operations (McElfish et al., 1990). The use of these funds coupled with potential profit from bioenergy could create incentives to reclaim abandoned mine lands with biomass for energy.

Allegheny Energy, TXU Energy (in Texas), DOE Office of Fossil Energy, OSM, and the Tennessee Valley Authority (TVA) are a few agencies/companies involved in using the potential of a high paying carbon market to reforest abandoned mine lands. If utility companies were given incentives for carbon sequestration or if sequestration were required as part of a carbon reduction program, and bioenergy plantations could qualify for the program, utilities would be motivated to reclaim abandoned mine lands to meet these goals (Myers, 2003). As an alternative or concurrent method, utilities might be able to set up biomass plantations on AMLs to sequester carbon while simultaneously creating a fuel to be used in the generation of electricity.

In 2008, the Environmental Protection Agency (EPA) and the DOE's National Renewable Energy Laboratory (NREL) started the RE-Powering America's Land Initiative to develop renewable energy projects on Superfund, brownfields, and abandoned mine sites. The EPA solicits applications for feasibility studies to develop AMLs with solar photovoltaics, concentrated solar power, wind, wood or crop waste biopower or biorefinery, or geothermal stations. Planting woody bioenergy crops would not qualify for this program, but if a wood-based generating facility were established through this program in a region rife with AMLs, it becomes more economically feasible for nearby AMLs to be restored with woody bioenergy crops. The establishment of this program demonstrates the government is concerned with environmental and social issues associated with AMLs and is trying to address these issues by restoring the land while providing jobs and energy generation for local communities.

Chapter 4: Methods

4.1 Overview

To determine the economic feasibility of bioenergy as a mine reclamation procedure, trial sites were re-measured for two growing seasons in southwest Virginia with the intent of estimating growth of woody crops on reclaimed surface mines. Measurements of trees on these experimental sites were conducted for the first five years of establishment. Data collected were analyzed using regression equations for per tree and per acre biomass. Per-acre biomass equations were used in combination with production costs and hardwood stumpage prices to find the net present value and land expectation value for a variety of conditions. Sensitivity analyses were conducted to determine which economic situations would need to be in place to provide positive returns (where LEV>0) to a landowner on an investment in bioenergy for mine reclamation. A comparison of the short rotation bioenergy plantation with an option for managing longer rotation products, such as pulp and sawtimber, is also made.

4.2 Field Data

In spring of 2008, three experimental plots were established in the coal fields of Wise County, Virginia for the purpose of testing different tree species and treatments for growing biomass on reclaimed mine lands. The trial sites were named Red River, Across the Road and Bean Gap. After mining, all three sites had been reclaimed with grasses and woody shrubs. Two sites were previously planted with trees that experienced poor survival, Bean Gap and Red River. The mine operators responsible for the sites had achieved bond release, although the lands were left without potential to return to forest or another useable state without additional investment.

To prepare the experimental sites for planting, the land was ripped, creating furrows spaced approximately 2.5 meters apart. Five tree species were planted, including: hybrid poplar

(*Populus trichocarpa* L. (Torr. And Gray ex Hook) x *Populus deltoids* (Bartr. Ex Marsh.) hybrid 52-225), American sycamore (*Platanus occidentalis)*, black locust (*Robinia pseudoacacia)*, and northern red oak (*Quercus rubra*) coupled with eastern cottonwood (*Populus deltoides*), along with a group of mixed hardwoods (black cherry (*Prunus serotina*), oaks (*Quercus* sp.), sugar maple (*Acer saccharum)*, American sycamore (*Platanus occidentalis)*, black locust (*Robinia pseudoacacia)*, ash species (*Fraxinus* sp.), and dogwoods (*Cornus* sp.)). Each of the primary species (hybrid poplar, black locust and American sycamore) was planted on each of the three sites at two different planting densities – high (3400 trees ha^{-1} or 1376 trees $acre^{-1}$) and low (860 trees ha^{-1} or 348 trees $acre^{-1}$). Red oak was planted at low density, and it was also planted in combination with eastern cottonwood with the combined planting at high density spacing. The group of mixed hardwoods was planted only at low density, which is a typical planting density when reclaiming mines to forest. The plots were further split so that each species at both densities received one of two treatments, either fertilization or no fertilization (no fertilizer was applied to the mixed hardwood control group) (Zipper et al., 2011b).

The site locations in southwestern Virginia receive approximately 120 cm of mean annual precipitation, have a mean annual temperature of 12°C, and all have <15% slope. The Red River site is located at 806 m elevation and was originally reclaimed in the early 2000's. At the time of experimental setup, the Red River site was mostly grasses with approximately 10% covered with pines. Across the Road, at 686 m elevation, was reclaimed with grasses in the mid-1980s and hosted a mixture of early successional volunteer species. The Bean Gap site, 616 m in elevation, was reclaimed in the late 1990s with a mixture of native hardwoods and eastern white pine, although few trees survived and therefore the vegetation prior to biomass establishment was mostly grasses (Evans, 2011).

Black locust and American sycamore seedlings and hybrid poplar cuttings were planted specifically to track biomass growth for bioenergy utilization. Eastern cottonwoods were similarly planted for bioenergy, yet also to train slower-growing northern red oaks planted amongst them to grow straight in order to increase their timber value. Each site was also planted with two control plots – one low density red oak plot to compare stem straightness and timber production to that of the red oak/cottonwood plot, and one mixed hardwood site to compare against the bioenergy species (Figures 1-4).

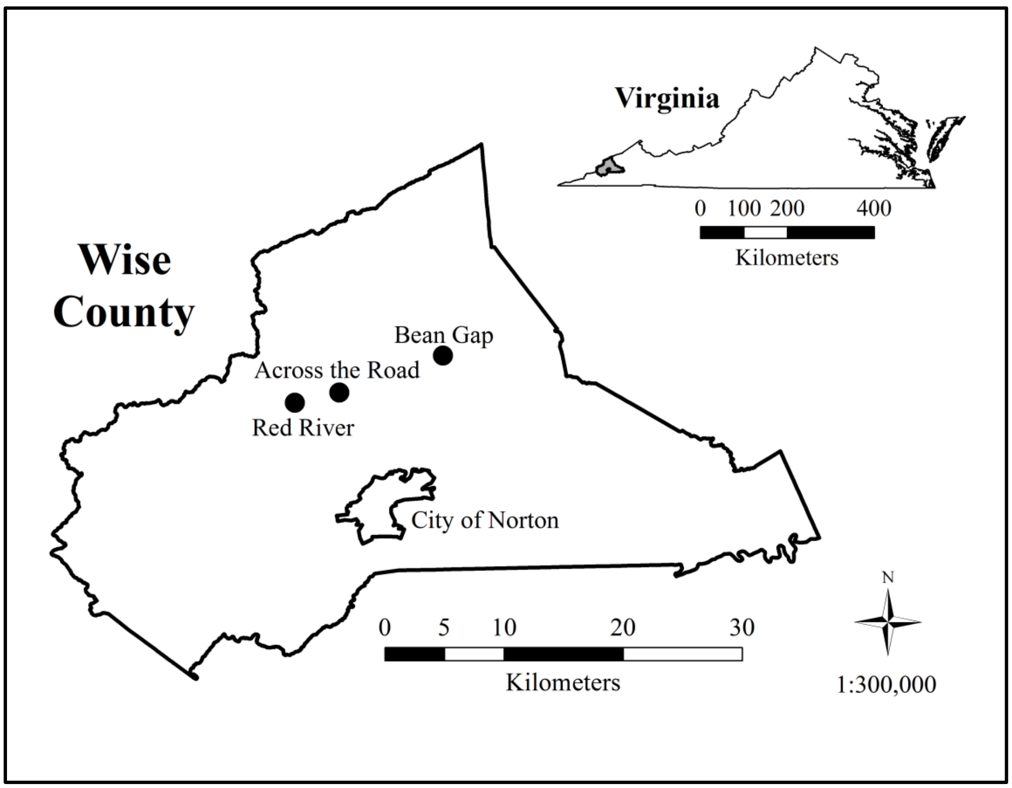

Figure 1: Biomass plots located in Wise County and context within Virginia.

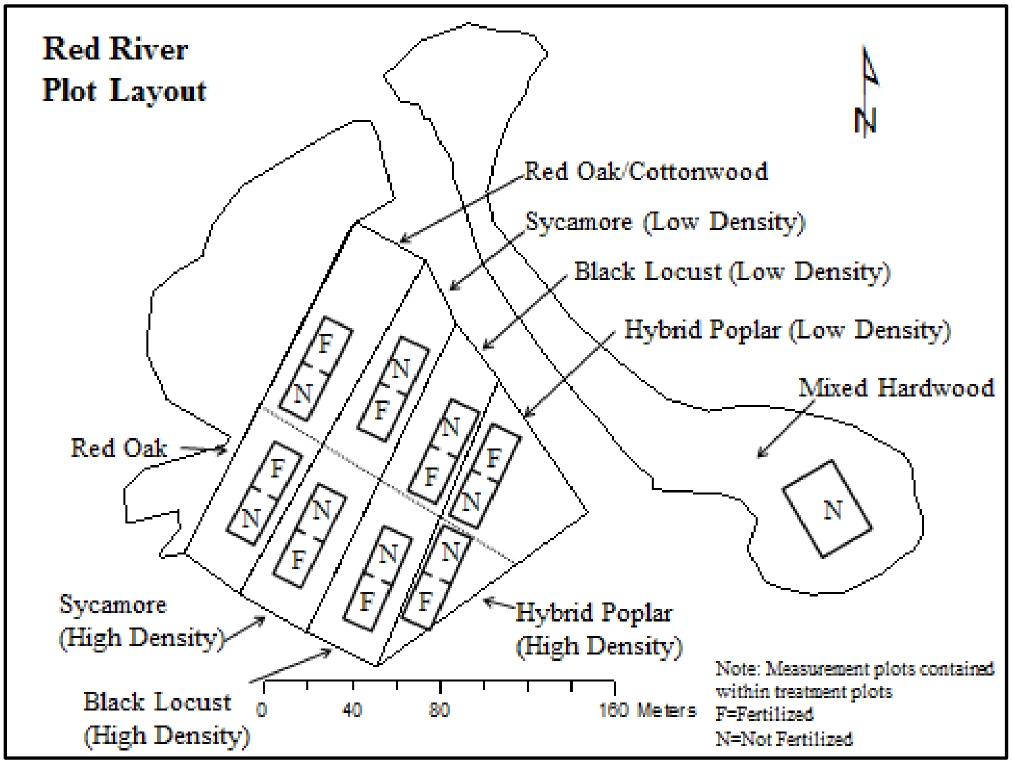

Figure 2: Red River plot layout, Wise County, VA. Figure excerpted from Evans (2011).

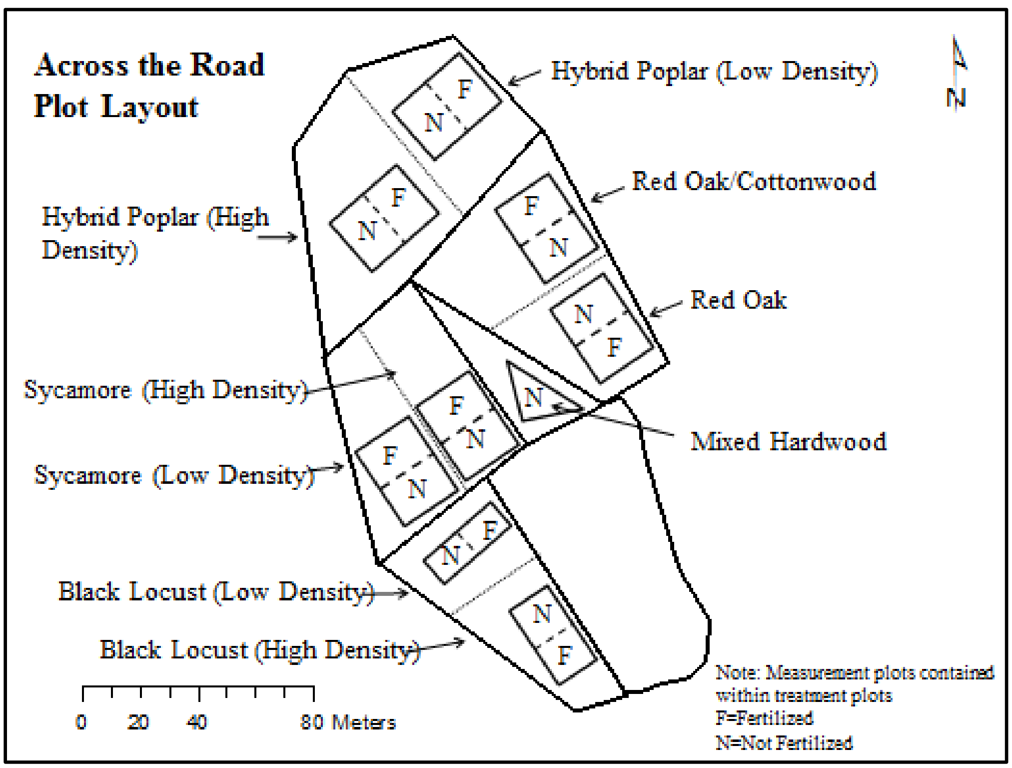

Figure 3: Across the Road plot layout, Wise County, VA. Excerpted from Evans (2011).

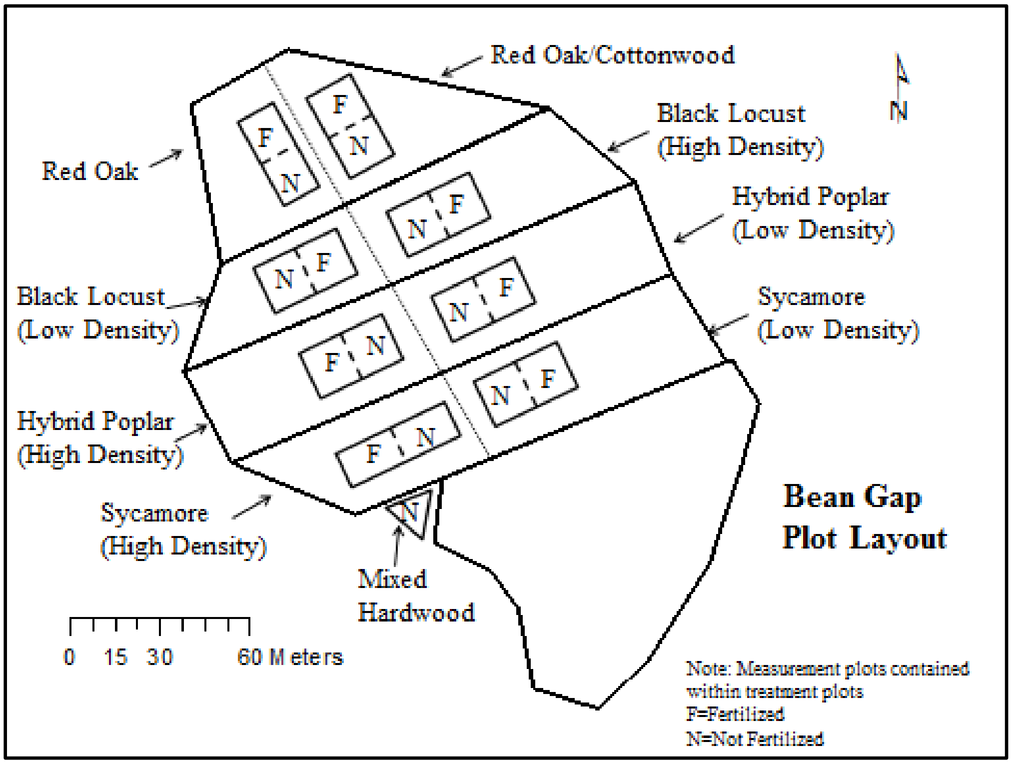

Figure 4: Bean Gap plot layout, Wise County, VA. Figure excerpted from Evans (2011).

There was very little rain in the summer of 2008, and as a result red oak and cottonwood survival was poor. Red oak and cottonwood species were replanted the following winter to bring density back up to original planting levels. In December of 2009, 118 milliliters of granular 19:19:19 fertilizer was applied in a 0.5 m diameter circle around each of the trees in all plots designated to receive fertilizer.

Tree height and diameter for each species has been measured at either the beginning or end of every growing season since the sites were established. Data for the 2008-2010 growing seasons were measured through previous work conducted through Powell River Project at Virginia Tech (Evans et al., 2010; Evans, 2011; Evans et al., 2009). Data were gathered for 2011 collaboratively by the Powell River Project (through efforts by Mr. Daniel Evans) and by Forest

Resources and Environmental Conservation personnel. Data were obtained for 2012 using resources available for the current study in the Forest Resources and Environmental Conservation department at Virginia Tech.

Height to the highest live bud and ground-line diameter were measured using a metric Philly rod and calipers, respectively. Measurements were recorded for each tree within measurement plots, totaling roughly 700-800 stems of each species (eastern cottonwood and northern red oak counted toward one sample of 700-800). Oven-dry wood density was estimated for each species using the Global Wood Density Database (Zanne et al., 2009) for comparing species. The measured data were used to calculate a biomass index for each tree, providing an estimate of dry woody biomass. The biomass index was then used to compare differences in the effects of fertilization and planting density on each species.

$$BI = d^2 \times h \times w$$

Where:

BI *= biomass index (g/tree)*

d *= ground line diameter (cm)*

h *= height (cm)*

w *= oven dry wood density (g/cm^3) for the particular species* (Table 4)

Table 4: Oven dry wood density (g/cm^3) for each species in trial as depicted by the Global Wood Density Database; source: Zanne et al. (2009).

Species	Oven dry wood density (g/cm^3)
Black locust	0.60
Hybrid poplar	0.34
American sycamore	0.46
Red oak	0.56
Cottonwood	0.47
Hardwood species (other)	0.47

4.3 Treatment Influence on Biomass Growth

Utilizing data collected during annual re-measurements, estimates were made on how different treatments affect tree growth and overall biomass accumulation. The independent variables in the constructed models are: species (hybrid poplar **HP**, black locust **BL**, American sycamore **SY**, northern red oak **RO**, eastern cottonwood **CW**, mixed hardwood **HW**), site (Red River **RR**, Bean Gap **BG**, Across the Road **ATR**), planting density (**Low** and **High**; 348 and 1376 trees/acre respectively), fertilizer (no fertilizer **NoFert** vs. fertilizer **Fert**), and age (continuous variable). The dependent variable for the equation is biomass index (g/tree; as calculated previously).

An Ordinary Least Squares (OLS) regression model, with 11124 observations is created with dummy variables, as described previously. Hybrid poplar, planted at low density on the Red River site which did not receive fertilizer, is the dummy variable reference group for the equations. All dummy variables have a value of zero and therefore do not appear in the written equations, although are included in the regression and results. The first regression equation is used to determine differences between the species, sites and management treatments (Equation 1). Fertilization and density independent variables are multiplied by each species to measure whether the impact fertilization and planting density has on biomass differs across species.

Equation 1:

$$\mathbf{BI} = B_0 + B_1\mathbf{ATR} + B_2\mathbf{BG} + B_3\mathbf{High} + B_4\mathbf{Fert} + B_5\mathbf{Age} + B_6\mathbf{BL} + B_7\mathbf{SY} + B_8\mathbf{BLFert} + B_9\mathbf{SYFert} + B_{10}\mathbf{BLHigh} + B_{11}\mathbf{SYHigh}$$

4.4 Predicting Biomass per Acre

A landowner-focused economic analysis of bioenergy planting requires prediction of biomass production per acre. Using field-measured tree diameters, per acre biomass is estimated by adapting the Clark III and Schroeder (1985) biomass equation, as follows:

$$biomass\ tons = a \times (ground\ line\ diameter^2)^b \times {}^{lbs}/_{ton} \times {}^{trees}/_{acre}$$

Coefficients *a* and *b* are determined by tree species (Table 5), adapted from Clark III and Schroeder (1985). These equations were derived from measurements of trees in larger size classes than the trees being considered here, and those species did not include hybrid poplar. These equations were selected after surveying the literature and finding them to be the best available for the purpose of this research.

Table 5: Parameters used for predicting total biomass, adapted from Clark III and Schroeder (1985).

Species	**Coefficient *a***	**Coefficient *b***
Black locust	6.12062	1.08931
Red oak	5.08421	1.23759
All other species	3.29754	1.29311

Regression equations for biomass production per acre are estimated utilizing the same independent variables described for the per tree equations in Section 4.3. The growth and yield model for short term bioenergy growth is then estimated using the following linear form (Equation 2):

$$Q = B_0 + B_1 D + B_2 F + B_3 A + e$$

Where:

Q = total stand biomass (tons/acre)

D = dummy for high density (1 if high density, 0 if low density)

F = dummy for fertilization present (1if fertilized, 0 if not fertilized)

A= stand age (years)

e = sample error

Using Equation 2, total biomass tons per acre are calculated for all species together as well as each species separately. Through trial and error, a linear model is found to best fit the data. A linear form is chosen because tree growth over the first five years has exhibited a linear characteristic. Ideally, overall tree growth would be expected to follow a sigmoidal pattern, tapering once canopy closure has occurred.

4.5 Economic Analysis of Woody Bioenergy Planting

4.5A Management Regime Considered

Coppicing as a management practice has the potential to make certain species of woody crops economically viable as bioenergy sources. Black locust, hybrid poplar and sycamore all have a strong ability to coppice and therefore will reduce production costs by not having to be replanted after each harvest. There is discrepancy about regrowth rates of coppiced trees; some studies find coppiced trees grow back quicker and have higher yields than the original planted rotation, while others say subsequent rotations yield lower amounts of biomass (Rédei et al., 2011; Ribeiro and Betters, 1995). The optimal number of harvest rotations from a single planting is still being researched; Ribeiro and Betters (1995) state three or four rotations are average before a replant. The optimal number of harvest rotations from a single planting varies by species and may also vary with soil and site properties, but there is not all the information available to determine optimal harvest rotations for the primary species on these sites. In order to be conservative in the economic analysis, the assumed management plan for this analysis is a planted rotation followed by two coppice rotations. All rotations are considered to be the same length and yield is assumed the same for each rotation.

4.5B Production Costs

Production cost estimates are used to predict the total cost of an investment in woody bioenergy as a mine reclamation procedure. Production cost estimates used to mimic the varied costs of planting and management of woody biomass are adapted from short rotation intensive culture studies for producing energy from wood (El Kasmioui and Ceulemans, 2012; Perlack and Geyer, 1987; Strauss and Wright, 1990), and from Sullivan et al. (2005) estimated costs of mine land reforestation. These studies included the cost of the trees, fertilization, and planting. All costs are broken down to a per-tree basis and then calculated according to planting density per acre of the trial sites. A range of production costs are thus calculated and used in financial sensitivity analyses for this report, representing high, medium, and low costs of establishing forest cover on reclaimed surface mines (Table 6).

Table 6: Production cost estimates ($/acre) for trees, planting and fertilization.

	Low	**Medium**	**High**
Low density			
No Fertilizer	$25	$ 85	$290
Fertilizer	$45	$145	$370
High density			
No Fertilizer	$65	$225	$770
Fertilizer	$85	$285	$850

4.5C Biomass Market Prices

The cost of production can be used with estimated growth and stumpage values to estimate a net present value (NPV) for an investment in woody bioenergy crops on a reclaimed surface mine. Stumpage value is the value of standing trees calculated as the difference between the value of products that can be made from the trees and the processing costs, along with some margin of profit. It is assumed that the landowner is a price taker and will accept the stumpage value for the bioenergy product.

Stumpage prices collected by Timber Mart-South are used in the sensitivity analysis. Stumpage prices are separated by state into highs and lows and each group is averaged to supply a range of regional prices (TimberMart-South, 2012). Prices are recorded in dollars per short ton (~2,000 lbs.). For the biomass growth analysis (Equation 2), the hardwood pulpwood stumpage price for west of the Blue Ridge Mountains in Virginia is used. Pulpwood is defined here as having at least a 6" diameter at breast height (DBH) (TimberMart-South, 2012). Stumpage values are averaged over every quarter the past six years (2007-2012) for the analysis. The maximum high and low stumpage values during the six year time period are also used for comparing extreme market conditions (Table 7).

Table 7: Stumpage values for hardwood pulpwood from 2007-2012 for west of the Blue Ridge Mountains in Virginia.

Metric	**Value ($/ton)**	**Quarter**	**Year**
Low	1.97	1	2008
Medium (average)	3.80	1-4	2007-2012
High	6.88	4	2012

4.5D Net Present Value

The growth and yield predictions are used in an economic analysis to determine net present value of biomass for each species and treatment. Net present value (NPV) uses a rate of return from an alternative investment to discount the value of all revenues and costs to the starting time period, allowing for the opportunity costs of the money being tied up in the investment to be taken into consideration when making a decision. Net present value provides a direct comparison between opportunities as the difference between the present value of revenues and the present value of costs. A sensitivity analysis is conducted with a variety of discount rates to compare returns for alternative investments.

NPV = present value of revenues – present value of costs

NPV is calculated using the following general formula:

$$NPV = \sum_{t=0}^{T} P_t \times Q_t \,/(1+r)^t - \sum_{t=0}^{T} C_t \,/(1+r)^t$$

Where:

P_t = price at time t ($)

Q_t = volume at time t (tons/acre)

C_t = costs incurred at time t ($/acre)

r = rate of return

t = rotation length (years)

T = harvest age (years)

The general NPV equation is modified to include one planted and two coppice rotations for the analysis (Equation 3):

$$NPV = \left(P \times \frac{Q}{(1+r)^{3t}}\right) + \left(P \times \frac{Q}{(1+r)^{2t}}\right) + \left(P \times \frac{Q}{(1+r)^{t}}\right) - (\frac{C}{(1+r)^{t}})$$

P = stumpage price ($/acre)

Q = total biomass (tons/acre)

r = rate of return

C = production costs (incurred at planting)

t = rotation length (years)

4.5E Land Expectation Value

Net present value of a single rotation only considers the opportunity costs of money tied up in the trees until the end of the first harvesting cycle (or to the end of coppicing rotations from one planting). It is assumed that the landowner will keep the land in bioenergy production after the first harvest and capture future benefits. The land expectation value takes into consideration the land on which the trees are growing and therefore calculates the opportunity cost of subsequent rotations. LEV is calculated as the NPV of an infinite number of rotation cycles, as follows:

$$LEV = \frac{NPV\ (1+r)^T}{[(1+r)^T - 1]}$$

For this analysis, one planted and two coppice rotations are considered and the equation used is (Equation 4):

$$LEV = \frac{NPV(1+r)^{3t}}{[(1+r)^{3t} - 1]}$$

4.6 Long Rotation Analysis

Once planted, trees could be managed on a short rotation basis for bioenergy. However, the same trees potentially could be left to grow on a longer rotation, and then harvested for pulpwood or sawtimber. If the bioenergy market looks promising, trees could be cut within a few years of planting. In the case that the bioenergy market is experiencing low prices as a result of excessive supply, or returns are not going to be positive, the landowner has the option of keeping trees in the ground for a longer period of time and harvesting when the stand is ready to be used for some other timber product; this option is considered by comparing short rotation economics with those of longer rotations. To predict volume for these other timber products, a formula specific to a longer harvest rotation is necessary. The linear form, presented previously, may be a good representation for short term tree growth, but certainly trees will not grow linearly forever, at some point the growth rate slows down. Hence, for the long rotation analysis, a model is employed that follows a non-linear curve, such as that utilized for mixed hardwood species by Aggett (2003) (Equation 5):

$$\ln(Q) = B_0 + B_1S + B_2N + \frac{B_3}{A} + e$$

Where:

Q = total stand biomass (tons/acre)

S = site index

N = stand density at harvest (stems/acre)

A = stand age (years)

e = sample error

When bioenergy sites are reclaimed, trees will be planted at chosen densities, but survival of these trees is variable based on how old they are at the time of harvest. Therefore a survival equation for trees on reclaimed mined lands based on original planting density and stand age at time of harvest is used (Aggett, 2003) to find stand density at harvest (Equation 6):

$$N = P \times \frac{-8.6884 \times \ln(A) + 84.472}{100}$$

Where:

N = stand density at harvest (stems/acre)

P = stand density at planting (stems/acre)

A = stand age (years)

For the long term growth analysis (Equation 5), it is assumed that all biomass will be selected for pulpwood if the harvest rotation is less than 20 years; therefore the same stumpage prices used in the bioenergy rotation scenario (Equation 2) are used. If the rotation is longer than 20 years, it is assumed that 33% of total biomass would be utilized for sawtimber and 67% for pulpwood. Sawtimber is defined here as trees with at least a 12" DBH (TimberMart-South, 2012). Therefore a range of mixed hardwood sawtimber prices compiled by Timber Mart-South for west of the Blue Ridge Mountains in Virginia are used in the analysis (Table 8). Stumpage values are averaged over every quarter the past six years (2007-2012) for the analysis. The maximum high and low stumpage values during the six year time period are also used for comparing extreme market conditions (Table 8).

Table 8: Stumpage values for mixed hardwood sawtimber from 2007-2012 for west of the Blue Ridge Mountains in Virginia.

Metric	Value ($/ton)	Quarter	Year
Low	10.19	4	2009
Medium (average)	18.49	1-4	2007-2012
High	36.16	1	2007

4.7 Summary

Utilizing current prices for woody biomass, along with costs of growing biomass on mined lands and growth projections, the potential viability of growing biomass for energy generation on reclaimed mine lands can be estimated. The land expectation values generated from the long term (Equation 5) and short term (Equation 2) growth equations are compared to find which scenarios make it best to invest in bioenergy vs. longer rotation timber products. A sensitivity analysis is conducted to test the different species at varying prices, rotation age, discount rates and costs. Utilizing this cost information highlights regulation changes which would be necessary across states to adopt planting trees for bioenergy as a common reclamation procedure.

Chapter 5: Results

5.1 Overview

The five years of measured data are utilized to create a growth model which is then used in an economic analysis to determine the viability of bioenergy growth on previously mined lands in Appalachia. Biomass accumulation for each species and treatment is reviewed and compared. Tree survival rates over the five years are examined with three of the species having survival rates above 80%. Regression equations (using Equation 2) are created to predict future years of tree growth for each species as well as a combined mixed hardwood equation. Using stumpage prices from the past six years, production costs derived from similar studies, and total biomass generated from the growth equations, net present values and land expectation values are calculated. The land expectation values are then used to find optimal harvest rotations for the different management practices and compared with returns for an investment in a longer rotation forest product. This analysis is meant to display the economic viability of an investment in a short rotation woody crop plantation and compare it to other options facing the landowner.

5.2 Field Results

Tree growth rate over the first five years varied by species, fertilization, and planting density, with each species responding to fertilizer and planting density in different manners. The unfertilized hybrid poplar and sycamore trees increased their growth rates more in the fifth growing season than any previous year (Figure 5). Unfertilized black locust hit its peak growth rate by the fourth year and for the trees planted at high density, growth rate declined in the fifth year. Growth rate for fertilized trees increased rapidly early on (in the third year) and both high and low density black locust treatments hit their peak growth rate in the fourth year, with the growth rate declining in the fifth growing season. Black locusts are nitrogen-fixing trees;

perhaps by the fifth growing season the trees have reached a nitrogen threshold after which additional nitrogen inhibits instead of increases growth (Figures 5 and 6). It is also possible that physiological effects cause by locust leaf miner (*Odontota dorsalis)*, an insect pest that infests black locust throughout the region and which has been observed to occur in these plantings, may have interfered with black locust growth. Low density hybrid poplar growth rate is also slowing but its growth rate had not begun to decline by the fifth year.

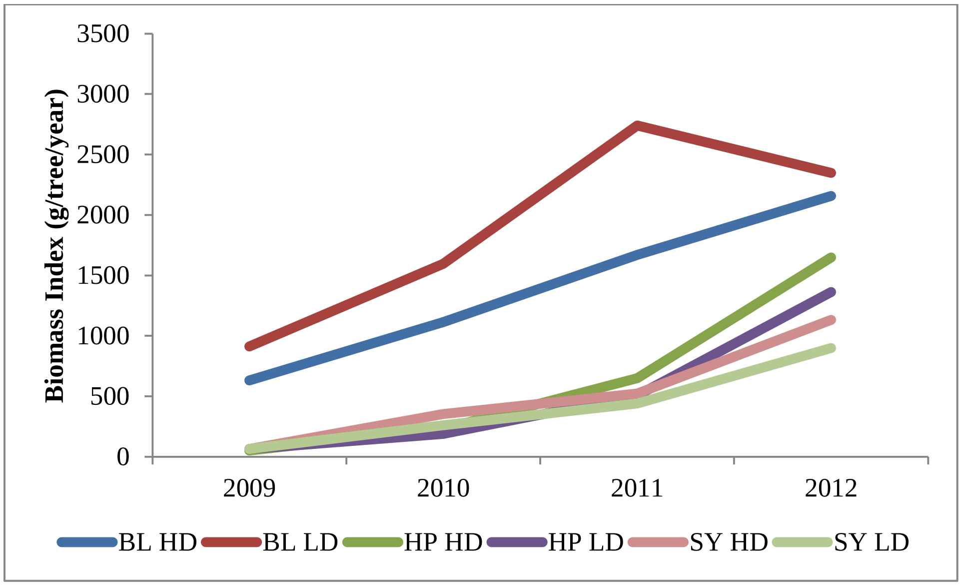

Figure 5: Annual growth increment (g/tree/year) for non-fertilized black locust (BL), hybrid poplar (HP) and sycamore (SY) trees planted at high density (HD) and low density (LD).

Most of the trees planted survived through the fifth growing season. Red oaks and cottonwoods did not survive as well as the other species, with 73% and 58% survival, respectively, after five years (the next lowest survival is hybrid poplar at 83%) (Figure 7). Additionally, the red oak and cottonwood trees that did survive have much lower biomass accumulation compared to the other species. Red oak and cottonwoods do not appear to be viable species for bioenergy crops on surface mines due to high mortality and have thus been excluded from further analysis.

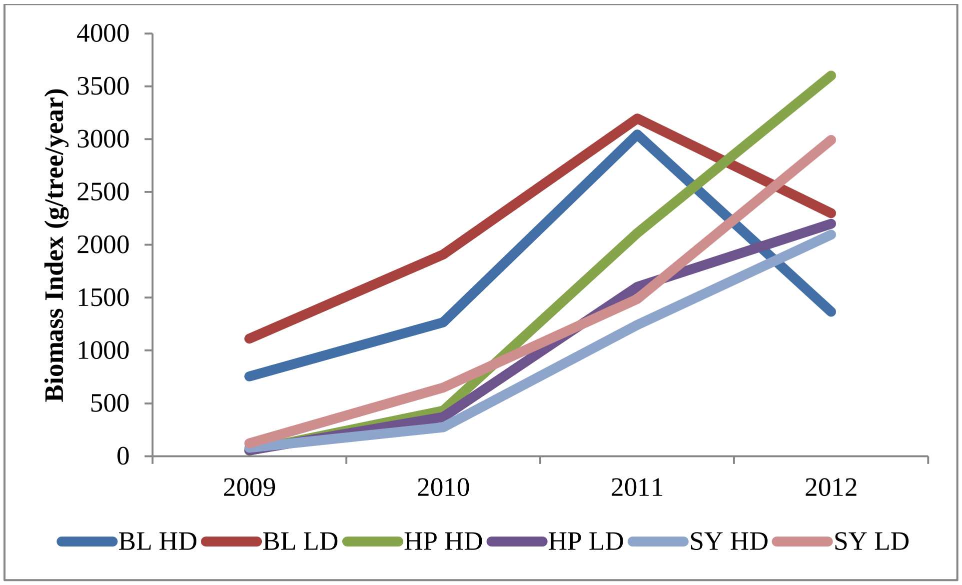

Figure 6: Annual growth increment (g/tree/year) for fertilized black locust (BL), hybrid poplar (HP) and sycamore (SY) trees planted at high density (HD) and low density (LD).

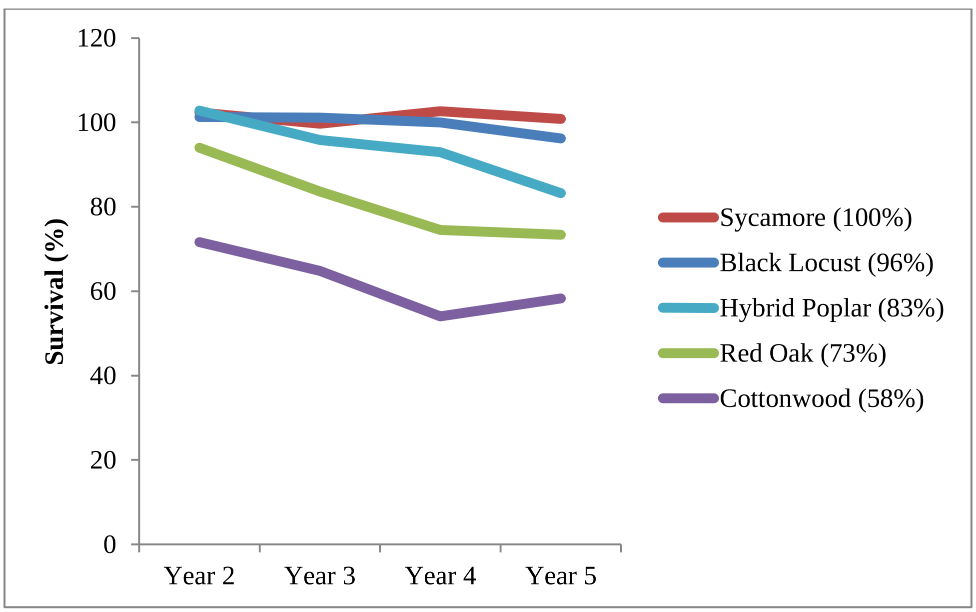

Figure 7: Individual species survival year by year for five years across all three sites, end of season survival reported.

The biomass indices for each species and treatment are compared. After five years of growth, black locust out-produces all other species in the trial, regardless of planting density or application of fertilizer. On average on a per-tree basis, black locust (biomass index= 7671 g/tree unfertilized and 8383 g/tree fertilized) and fertilized sycamore (4799 g/tree) have a higher biomass index after five years when planted at low density than at the high density. High density hybrid poplar produces the most biomass after black locust (5137 g/tree when fertilized and 2273 g/tree unfertilized). When fertilizer is applied, low density sycamore (4799 g/tree) follows hybrid poplar and black locust, but when fertilizer is not applied, high density sycamore precedes (2259 g/tree) the hybrid poplar.

Overall, when considered on a per-tree basis, tree planting density has as a greater effect on biomass index than fertilizer does, with low density trees out-producing trees planted at high density. However, fertilization increases overall biomass index for all species and planting densities, in some cases by a substantial margin (greater than twice as much). Compared on a tons per acre basis, the high density treatments out-produce low density treatments and fertilized treatments out produce unfertilized treatments, except in the case of black locust (Table 9 and Figure 8).

Table 9: Mean biomass (tons/acre) by year, species, planting density, and fertilization; black locust (BL), hybrid poplar (HP), and American sycamore (SY).

NO FERT	**2008**	**2009**	**2010**	**2011**	**2012**
BL high density	0.87	4.11	7.64	10.96	14.53
BL low density	0.42	1.95	4.00	6.94	7.38
HP high density	0.10	0.37	1.09	2.76	6.39
HP low density	0.06	0.16	0.37	0.96	2.42
SY high density	0.09	0.43	1.74	3.47	6.78
SY low density	0.04	0.13	0.46	0.76	1.52
FERT					
BL high density	0.87	4.82	8.07	12.25	14.43
BL low density	0.42	3.07	4.46	6.87	8.46
HP high density	0.10	0.31	1.42	6.44	12.53
HP low density	0.06	0.19	0.66	2.82	4.85
SY high density	0.07	0.41	1.28	4.56	9.09
SY low density	0.09	0.23	0.87	2.11	4.88

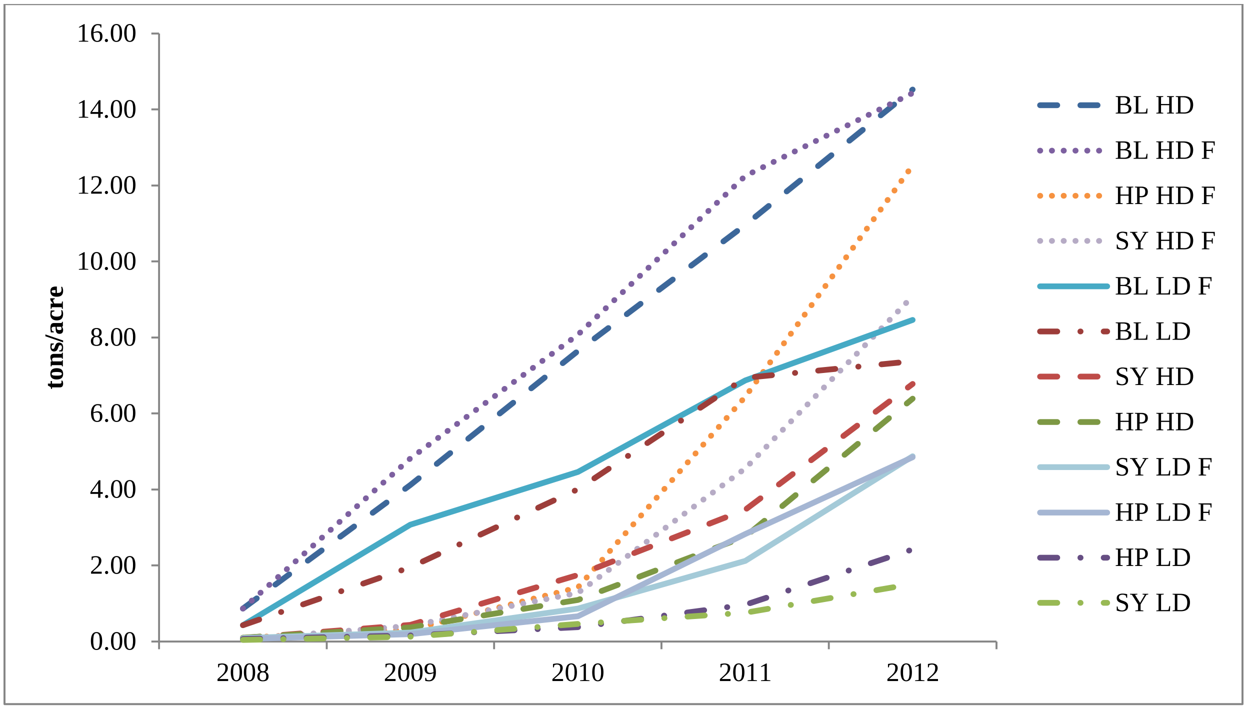

Figure 8: Average biomass (tons/acre) by year, species, and treatment. Black locust (BL), hybrid poplar (HP), sycamore (SY), high density (HD), low density (LD), fertilized (F).

5.3 Treatment Influence on Biomass Growth

To maintain consistency with earlier models of growth impacts on the Powell River Project sites, regression models are first estimated to predict biomass index of individual trees, using age, site, fertilization, and planting density as predictor variables. To examine the relationship each species has with fertilizer and planting density, the fertilization and density independent variables are multiplied by each of the species variables in a regression model (Equation 1 and Table 10). All variables except fertilized black locust are statistically significant at the 1% level (fertilized black locust is significant at the 10% level). Fertilization is found to have a significant positive effect on hybrid poplar (the presence of fertilizer increases biomass index on average by 416.95 g/tree), black locust (653.56 g/tree) and sycamore trees (113.40 g/tree). Fertilizer's positive effect seems reasonable due to the nature of fertilization.

Hybrid poplar does better when planted at high density while black locust and sycamore trees planted at high density have lower biomass indices than those planted at low density. This result is expected; trees need space to grow and therefore when trees are planted too closely together they do not grow as large as they would if given more space. Because these regression equations use dummy predictor variables, one dummy variable for each group needs to be excluded from the model (hybrid poplar, Red River, low density planting, no fertilizer).

Equation 1:

BI = -1911.631 – 1325.393**ATR** – 579.4374**BG** + 322.7397**High** + 416.9531**Fert** + 1070**Age** + 2462.935**BL** + 386.1704**SY** + 236.6086**BLFert** – 303.5562**SYFert** – 1413.538**BLHigh** – 445.3333**SYHigh**

Table 10: Regression results for effect of fertilization and planting density on biomass index (g/tree). N= 15236

Variable[2]	Coefficient	Standard Error	P-value
Across the Road[1]	-1325.393	64.270	0.000
Bean Gap[1]	-579.437	59.630	0.000
Planted at High Density[1]	322.740	97.190	0.001
Fertilization[1]	416.953	92.816	0.000
Age (years)	1070	18.653	0.000
Black Locust[1] (BL)	2462.935	126.934	0.000
Sycamore[1] (Sy)	386.170	128.4	0.003
Fertilized Black Locust[1]	236.6096	125.863	0.060
Fertilized Sycamore[1]	-303.556	128.66	0.018
Black locust planted at High Density[1]	-1413.538	136.345	0.000
Sycamore planted at High Density[1]	-445.333	137.841	0.001
Constant	-1911.631	107.517	0.000

[1]Dummy variable, where 1=yes, 0=no
[2]A regression of the residuals on suspected endogenous variables was highly insignificant and had an F-statistic of 0.00 and an adjusted R^2 of -0.0010.

5.4 Predicting Biomass per Acre

Measured data are utilized in regression models for predicting future years of biomass growth on previously mined sites in Appalachia. Separate models are also developed to predict total woody biomass on a per-acre basis for each species as well as one equation for predicting overall hardwood growth, again on a tons per acre basis. Linear models are chosen to predict total biomass because they best fit the data; the trees exhibit a linear pattern for beginning stages of their growth. Individual growth and yield models are developed for black locust, hybrid poplar and American sycamore species.

In order to allow for economic analysis of biomass production, models for predicting total biomass tons per acre are estimated for all species together as well as each species separately, with age, fertilization and planting density as independent variables (Table 11). Variables significant at the 5% level across all models include planting density and age. Fertilization is significant at the 5% confidence level in the combined species model as well as the hybrid poplar and sycamore models. For the range of biomass growth predictions in the literature, these models fall on the conservative end, under predicting biomass on a tons per acre basis.

Fertilization is not statistically significant at the 10% level for black locust trees; trees that did not receive fertilizer grew roughly the same as those that were fertilized. Black locust trees planted at high density yield more tons per acre than those planted at low density. Therefore, recommended management techniques for growing black locust with the goal of achieving the greatest volume on a per acre basis are to plant at high density and let them grow without applying fertilizer.

There is a larger difference between hybrid poplars that received fertilizer and those that did not than with the black locust trees. For hybrid poplar, high density fertilized areas yield the most biomass, followed by high density non-fertilized and low density fertilized, which both yield approximately the same tonnage per acre. The differences in treatments is even more spread out with the sycamore species; the high density fertilized trees yield the most, followed by high density non-fertilized, low density fertilized, and low density non-fertilized (Table 11 and Figures 9-13). For both hybrid poplar and sycamore, it appears important to fertilize and plant at high density to produce the greatest amount of biomass.

Across all species, age has the largest impact on predicting total biomass; it is the most significant predictor variable. This means that a per-unit increase in age (one additional year of growth) has more effect on per-acre biomass than applying fertilizer or changing planting density. Therefore if increasing biomass tonnage is the only thing a land owner is interested in and the management choice is between applying fertilizer or increasing planting density and waiting one more year to harvest the bioenergy, it is usually best to wait an additional year. An overall recommendation for maximizing biomass on a tons per acre basis, when tonnage is the only concern, is to plant at high density and leave the trees in the ground for a 15 year rotation (the maximum rotation length investigated with this model), as each additional year of growth increases biomass.

Table 11: Regression results (Equation 2) for predicting biomass (tons/acre) of all species, effects of planting density and fertilization.

Variable	**Coefficient (standard error)**			
	All Species	**Black Locust**	**Hybrid Poplar**	**Sycamore**
High Density Planting (D)	2.425* (0.136)	3.807* (0.234)	2.027* (0.248)	1.351* (0.154)
Fertilization (F)	0.702* (0.129)	0.167 (0.221)	1.514* (0.244)	0.465* (0.141)
Age (A)	2.319* (0.045)	3.190* (0.076)	2.085* (0.085)	1.578* (0.048)
Constant	-4.764* (0.173)	-5.397* (0.298)	-5.227* (0.319)	-3.588* (0.194)

*significant at $\alpha=0.01$

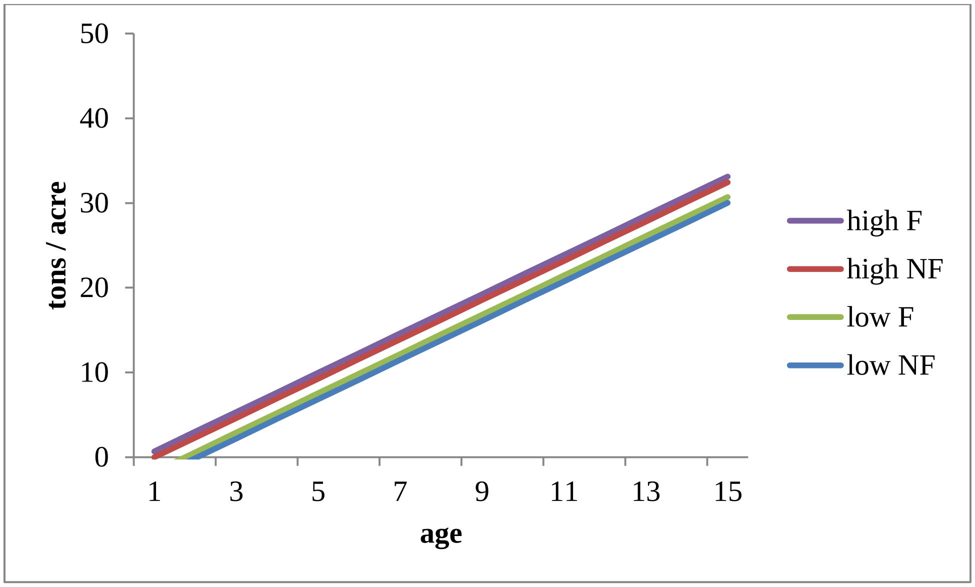

Figure 9: Predicted biomass growth (tons/acre) for combined species (hybrid poplar, black locust and American sycamore) woody bioenergy on previously mined lands in southern Appalachia using four management treatments: planting at high and low density, with and without the application of fertilizer.

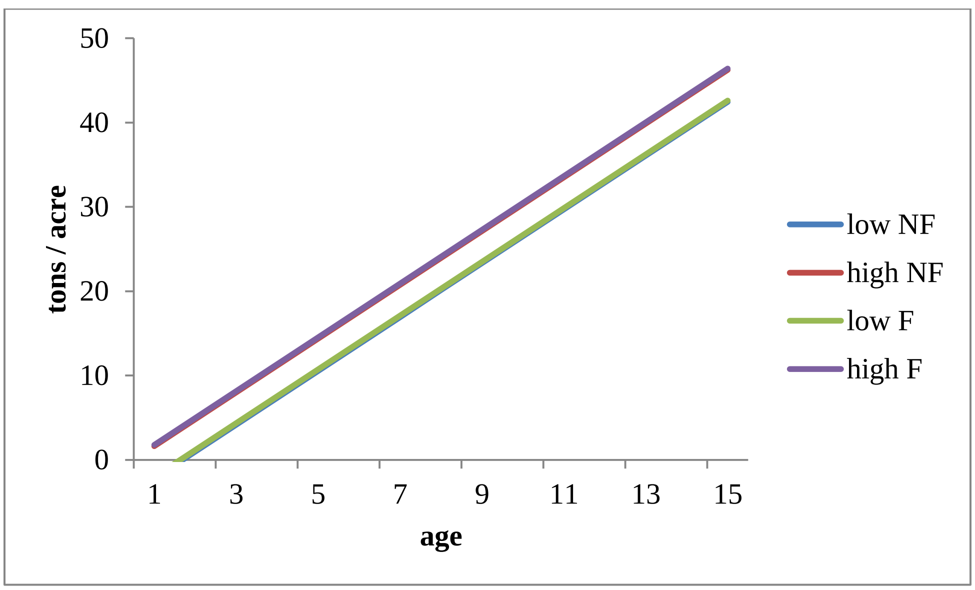

Figure 10: Black locust biomass predicted growth (tons/acre) under four management treatments: planting at high and low density with and without the application of fertilizer.

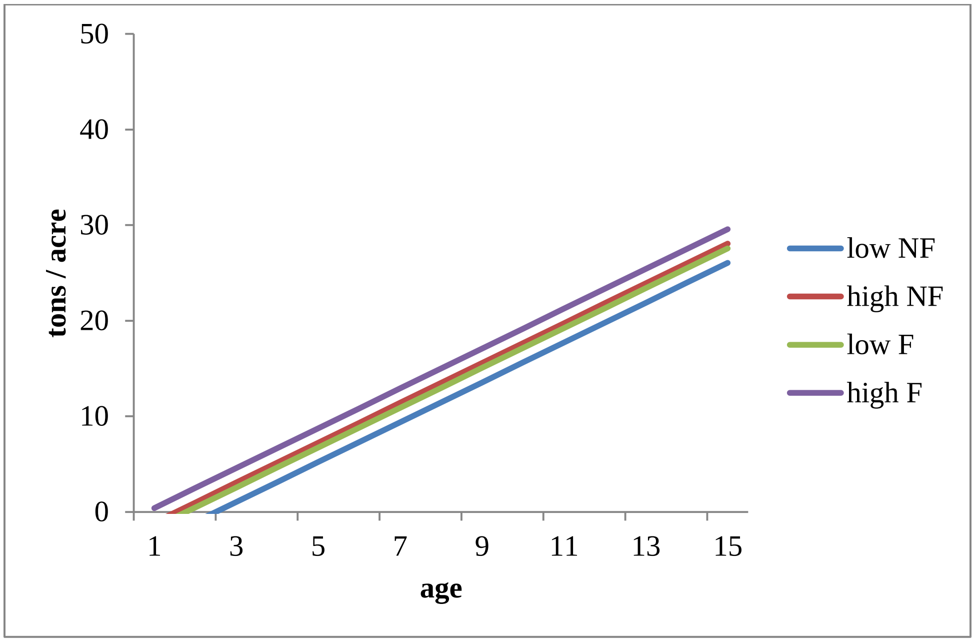

Figure 11: Hybrid poplar biomass predicted growth (tons/acre) under four management treatments: planting at high and low density with and without the application of fertilizer.

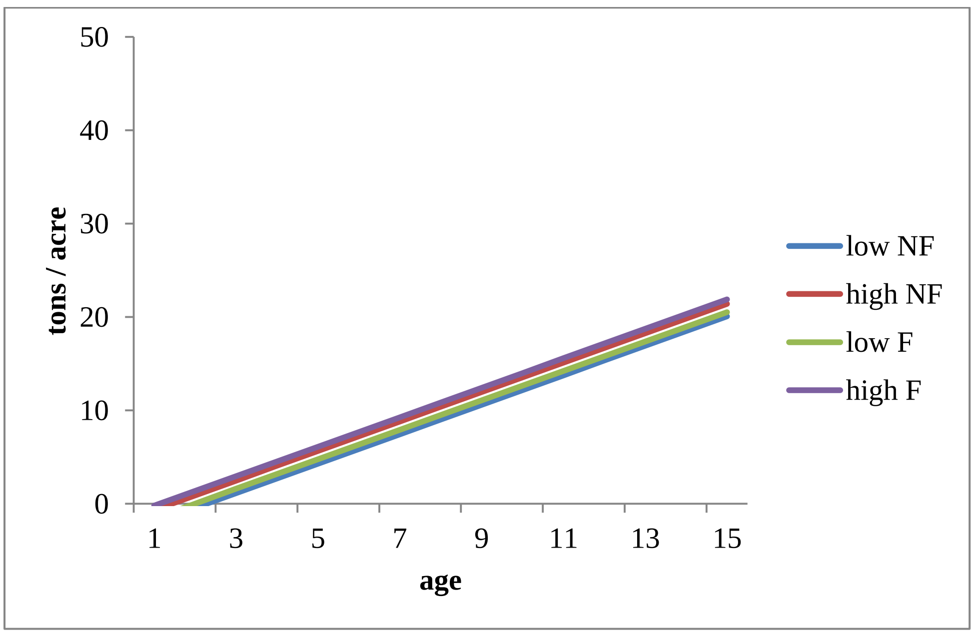

Figure 12: American sycamore biomass predicted growth (tons/acre) under four management treatments: planting at high and low density with and without the application of fertilizer.

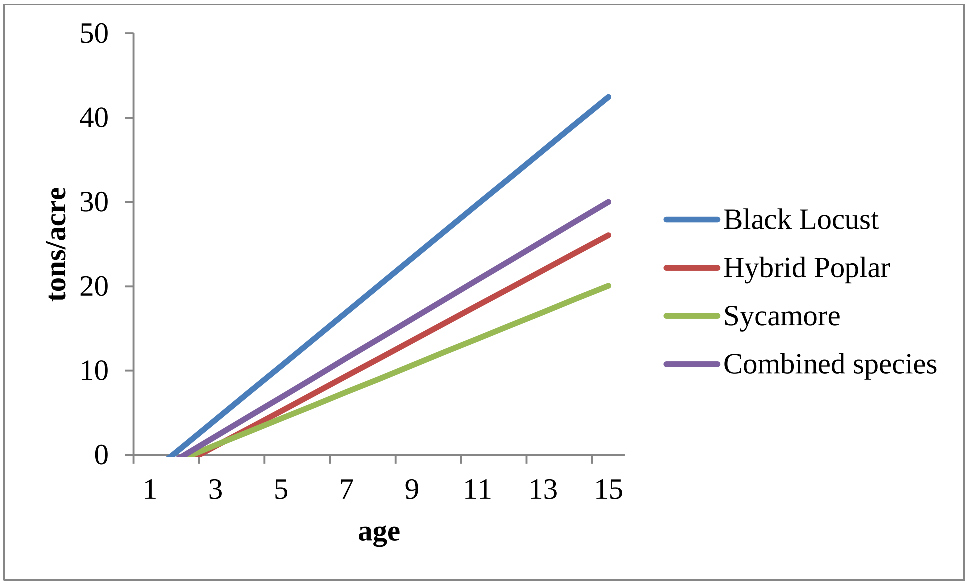

Figure 13: Comparison of predicted biomass growth (tons/acre) for each species and a combined species predicted growth equation; all planted at low density and receiving no fertilizer.

5.5 Economic Analysis of Woody Bioenergy Planting

The bioenergy rotation growth and yield equations (Equation 1 and Table 12) are used along with production costs and stumpage values, to calculate LEV which is used to judge financial viability and to determine an optimal rotation length for each species and treatment. Analysis is conducted with the goal of making the land as valuable as possible for the landowner. The optimal rotation length is the number of years the trees should be kept in the ground for each rotation to achieve the largest land expectation value. The analysis considers rotation lengths between 1-15 years; after 15 years it is assumed growth will no longer follow the linear pattern described by the equation and therefore a different equation must be utilized. A range of production costs and stumpage prices were chosen to examine how changes in price and cost affect the optimal rotation length for each species and treatment. Repeated cycles of single planting with two coppice rotations are used for the LEV calculations. Assuming a 5% discount rate, land expectation values ranged from -$916.48 per acre for planting sycamores at high cost and receiving a low stumpage price, to $257.39 per acre for black locust trees in a low cost, high price scenario. Rotation lengths for positive land expectation values varied between 9 and 15 years.

Table 12: Linear growth and yield regression equations for each species as well as a mixed hardwood growth and yield equation. Q= total biomass (tons/acre) D= dummy variable for planted at high density; F= dummy variable for fertilized; A= tree age (years).

Species	**Yield Equation**
All Species Combined – mixed hardwood	$Q = -4.764 + 2.425D + 0.702F + 2.319A$
Black Locust	$Q = -5.397 + 3.807D + 0.167F + 3.190A$
Hybrid Poplar	$Q = -5.227 + 2.027D + 1.514F + 2.085A$
Sycamore	$Q = -3.588 + 1.351D + 0.465F + 1.578A$

Low density, non-fertilized management yields the highest LEV in every scenario, across all species. Additional costs associated with fertilization and planting at higher density outweigh the benefit of the resulting increased biomass on a per acre basis. For almost all scenarios, planting at high density results in lower economic returns than both low density planting and treatments with fertilizer. The high density planting treatments are the last to become profitable in most scenarios – they require the lowest discount rate, the longest rotations, lowest production costs, and highest stumpage prices in order to achieve a positive LEV.

Black locust is a bit of an aberration from the rest of the species. Under the low production cost, high stumpage price scenario, black locust actually achieves better returns when planted at high density than when fertilizer is applied to the low density treatment. As before, the fertilizer coefficient in the black locust growth equation is not significant; fertilized black locusts have a slower growth rate than their unfertilized equals in the later years which may be reflected in the LEV under the low cost, high stumpage price scenario.

Across all species, land expectation value is most sensitive to changes in production cost. Short rotation bioenergy crops are never profitable under the high production cost scenario. Overall, the discount rate does not have a large effect on LEV although it does affect profitability of shorter rotations more than longer rotations. Higher discount rates make shorter rotations unprofitable for all treatment scenarios. Consistent with forestry economics, as the discount rate increases, the optimal rotation length decreases and an investment in bioenergy becomes less profitable (Tables 13-15).

Table 13: Optimal rotation and LEV for combined species (hybrid poplar, black locust and American sycamore) using a 3% discount rate. Den= density, NP= no peak where no optimal rotation is found in the 15-year rotation analysis, LEV for year 15 is reported.

	Low Production Cost				Medium Production Cost				High Production Cost			
Optimal rotation (years)												
	No Fertilizer		Fertilizer		No Fertilizer		Fertilizer		No Fertilizer		Fertilizer	
Stumpage Price	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den
Low	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Medium	15	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
High	14	13	14	13	NP	NP	NP	NP	NP	NP	NP	NP
Land Expectation Value ($/acre)												
	No Fertilizer		Fertilizer		No Fertilizer		Fertilizer		No Fertilizer		Fertilizer	
Stumpage Price	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den
Low	72.00	26.18	47.28	1.46	(9.58)	(191.34)	(88.67)	(270.44)	(288.27)	(932.27)	(394.56)	(1038.6)
Medium	170.63	132.77	148.22	110.37	89.06	(84.75)	12.27	(161.53)	(189.64)	(825.68)	(293.62)	(929.65)
High	336.62	131.30	317.91	294.38	254.57	94.15	181.66	21.23	(24.12)	(646.79)	(124.23)	(746.89)

Table 14: Optimal rotation and LEV for combined species (hybrid poplar, black locust and American sycamore) using a 5% discount rate. Den= density, NP= no peak where no optimal rotation is found in the 15-year rotation analysis, LEV for year 15 is reported.

	Low Production Cost				**Medium Production Cost**				**High Production Cost**			
Optimal rotation (years)												
	No Fertilizer		Fertilizer		No Fertilizer		Fertilizer		No Fertilizer		Fertilizer	
Stumpage Price	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den
Low	13	15	15	NP	NP	NP	NP	NP	NP	NP	NP	NP
Medium	12	12	12	13	15	NP	NP	NP	NP	NP	NP	NP
High	11	10	11	10	13	15	14	NP	NP	NP	NP	NP
Land Expectation Value ($/acre)												
	No Fertilizer		Fertilizer		No Fertilizer		Fertilizer		No Fertilizer		Fertilizer	
Stumpage Price	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den
Low	27.07	(13.90)	5.46	(35.13)	(40.84)	(193.94)	(107.07)	(260.17)	(271.51)	(807.19)	(360.25)	(895.93)
Medium	79.99	43.23	59.17	22.52	10.17	(138.81)	(54.87)	(203.85)	(220.50)	(752.07)	(308.05)	(839.61)
High	169.66	143.52	151.46	125.18	97.26	(46.30)	32.96	(109.34)	(134.90)	(659.55)	(220.45)	(745.10)

Table 15: Optimal rotation and LEV for combined species (hybrid poplar, black locust and American sycamore) using a 7% discount rate. Den= density, NP= no peak where no optimal rotation is found in the 15-year rotation analysis, LEV for year 15 is reported.

	Low Production Cost				**Medium Production Cost**				**High Production Cost**			
Optimal rotation (years)												
	No Fertilizer		Fertilizer		No Fertilizer		Fertilizer		No Fertilizer		Fertilizer	
Stumpage Price	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den
Low	11	12	12	13	NP	NP	NP	NP	NP	NP	NP	NP
Medium	10	10	11	11	13	15	14	NP	NP	NP	NP	NP
High	9	9	9	9	11	12	12	13	15	NP	15	NP
Land Expectation Value ($/acre)												
	No Fertilizer		Fertilizer		No Fertilizer		Fertilizer		No Fertilizer		Fertilizer	
Stumpage Price	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den
Low	8.98	(31.14)	(11.93)	(51.71)	(55.63)	(199.91)	(117.85)	(262.13)	(270.88)	(772.16)	(354.09)	(855.37)
Medium	43.67	7.16	23.42	(13.04)	(23.07)	(166.10)	(85.55)	(227.58)	(239.59)	(738.35)	(322.08)	(820.83)
High	102.36	74.58	84.28	56.51	33.96	(106.55)	(28.35)	(167.82)	(187.09)	(681.60)	(268.35)	(762.86)

The sensitivity analysis findings are consistent with what would be expected from economic theory. In general, as the cost of production increases or the stumpage price decreases, the optimal rotation length will increase. This is because as the cost of production goes up, the opportunity cost of keeping the current rotation in the ground decreases. Likewise, as stumpage price decreases, the opportunity cost of keeping the current rotation growing decreases as well, therefore lengthening the optimal harvest rotation.

The optimal rotation lengths found in this study are longer than those reported in the literature for short rotation woody crops. Rotation lengths in the literature range from 1-13 years, with an average rotation of 6.5 years (Bowersox and Ward, 1976; Bungart et al., 2000; Carpenter and Eigel, 1979; Hansen, 1991; Makeschin, 1999; Mitchell, 1999; Ribeiro and Betters, 1995). Coppice rotations are generally even shorter than traditional bioenergy rotations, averaging about 3.5 years per rotation (Geyer, 1981; Rédei et al., 2011; Saucier et al., 1972; Stringer and Carpenter, 1986). There could be many reasons rotation lengths are shorter in the literature than in this study; most notably that this study is conducted on previously mined lands where soils may not be as productive as other soils where woody crops are grown.

Another reason longer rotations may have been found in this study than in previous studies is because this study includes the cost of production and wood sale price; previous studies determined rotation lengths in a variety of ways, although most studies do not report how rotation length was determined. Many studies are focused on yield potentials for short rotation woody crops and therefore determined rotation length based on when yield was the highest, with no consideration to management costs, or simply did not report how they chose rotation length (Dawson et al., 2006; Rédei et al., 2011; Ribeiro and Betters, 1995).

Table 16: Optimal rotation and LEV for black locust at a 5% discount rate. Den= density, NP= no peak where no optimal rotation was found within the 15-year rotation analysis, the LEV for year 15 is reported.

	Low Production Cost				**Medium Production Cost**				**High Production Cost**			
Optimal rotation (years)												
	No Fertilizer		Fertilizer		No Fertilizer		Fertilizer		No Fertilizer		Fertilizer	
Stumpage Price	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den
Low	12	13	13	14	NP	NP	NP	NP	NP	NP	NP	NP
Medium	10	10	11	11	13	NP	NP	NP	NP	NP	NP	NP
High	10	10	10	9	12	13	13	14	NP	NP	NP	NP
Land Expectation Value ($/acre)												
	No Fertilizer		Fertilizer		No Fertilizer		Fertilizer		No Fertilizer		Fertilizer	
Stumpage Price	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den
Low	51.17	12.31	27.72	(10.65)	(18.14)	(168.72)	(85.34)	(235.93)	(248.81)	(781.97)	(338.52)	(871.68)
Medium	127.74	98.72	103.63	74.02	55.00	(90.12)	(12.93)	(157.04)	(176.68)	(703.37)	(266.11)	(792.80)
High	257.39	247.00	233.20	224.40	181.51	45.34	111.09	(23.61)	(55.63)	(571.46)	(144.58)	(660.42)

Table 17: Optimal rotation and LEV for hybrid poplar at a 5% discount rate. Den= density, NP= no peak where no optimal rotation was found within the 15-year rotation analysis, the LEV for year 15 is reported.

	Low Production Cost				**Medium Production Cost**				**High Production Cost**			
Optimal rotation (years)												
	No Fertilizer		Fertilizer		No Fertilizer		Fertilizer		No Fertilizer		Fertilizer	
Stumpage Price	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den
Low	14	NP	15	NP	NP	NP	NP	NP	NP	NP	NP	NP
Medium	13	13	13	13	NP	NP	NP	NP	NP	NP	NP	NP
High	12	12	11	11	14	NP	15	NP	NP	NP	NP	NP
Land Expectation Value ($/acre)												
	No Fertilizer		Fertilizer		No Fertilizer		Fertilizer		No Fertilizer		Fertilizer	
Stumpage Price	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den
Low	19.48	(21.88)	(0.31)	(41.62)	(48.08)	(201.92)	(112.83)	(266.67)	(278.76)	(815.17)	(366.01)	(902.42)
Medium	64.57	26.26	47.57	9.26	(3.82)	(154.21)	(66.00)	(216.39)	(234.50)	(767.46)	(319.18)	(852.15)
High	140.89	110.06	129.94	99.57	70.67	(74.15)	12.60	(132.01)	(160.22)	(687.41)	(240.58)	(767.77)

Table 18: Optimal rotation and LEV for American sycamore at a 5% discount rate. Den= density, NP= no peak where no optimal rotation was found within the 15-year rotation analysis; the LEV for year 15 is reported.

	Low Production Cost				**Medium Production Cost**				**High Production Cost**			
Optimal rotation (years)												
	No Fertilizer		Fertilizer		No Fertilizer		Fertilizer		No Fertilizer		Fertilizer	
Stumpage Price	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den
Low	15	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Medium	13	14	14	15	NP	NP	NP	NP	NP	NP	NP	NP
High	12	12	12	13	15	NP	NP	NP	NP	NP	NP	NP
Land Expectation Value ($/acre)												
	No Fertilizer		Fertilizer		No Fertilizer		Fertilizer		No Fertilizer		Fertilizer	
Stumpage Price	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den	Low Den	High Den
Low	8.52	(34.02)	(13.13)	(55.68)	(58.99)	(214.06)	(125.66)	(280.72)	(289.66)	(827.31)	(378.83)	(916.48)
Medium	43.28	2.42	21.94	(18.48)	(24.88)	(177.65)	(90.76)	(243.53)	(255.55)	(790.90)	(343.93)	(879.28)
High	102.41	65.74	82.25	45.64	32.36	(116.55)	(32.19)	(181.10)	(198.31)	(729.81)	(285.37)	(816.86)

5.6 Long Rotation Analysis

An important aspect of growing trees is that they are not completely reliant on the spot market for sale prices. The same trees planted for short rotation bioenergy can be left to grow for a longer rotation and then harvested for pulp or another forest product, if bioenergy sale price at the time of a short rotation harvest is not high enough for the landowner. A comparison between the different products produced from a longer rotation and that of the short rotation option facing the landowner is therefore made here. The analysis is again conducted with a goal of making the land as valuable as possible for the landowner. A growth and yield formula to predict biomass volume for rotations between 10 and 60 years was derived from the Aggett (2003) equation (Equation 5):

$$\ln(Q) = 4.8621 + 0.0145S + 0.0002N + \frac{11.2291}{A} + e$$

This equation does not take into account the effect of a fertilization management strategy, and therefore does not allow a direct comparison to each of the treatments in the short rotation model. Contrary to the short rotation estimations, the long term stands planted at low density achieve a greater total amount of biomass on a tons per acre basis than the stands planted at high density (Figure 14). This is likely because the short term equation is derived from only five years of tree growth, and at this point most of the trees have not achieved crown closure and therefore high density planting has greater overall biomass. This growth equation takes into consideration trees which have achieved crown closure and therefore the trees planted at lower density are allowed to grow to their individual maximum size.

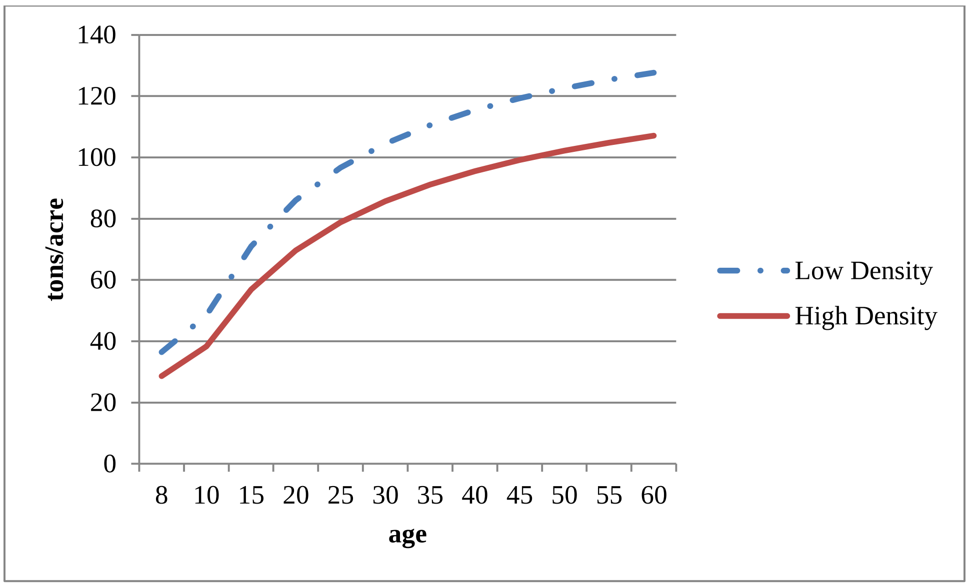

Figure 14: Total tree growth (tons/acre) using the long rotation formula (Equation 5), high and low density planting.

Reforestation cost estimates along with stumpage values and estimated growth using the long term growth model (Equation 5) are used to estimate harvest cycles that receive the highest land expectation value of a long term rotation for given discount rates. Production costs used in the long term scenarios are the same as those used in the short term analysis, because the only difference in management is the trees are left in the ground longer. Stumpage price from two products is considered in the analysis, sawtimber and pulpwood.

Low density planting results in the best returns on investment in all long term growth scenarios. This is likely because the low density trees grow larger than the high density trees and therefore have a higher stumpage value. As expected, higher discount rates result in lower land expectation values, and shorten the optimal rotation, but only for the high production cost scenarios. This is because the opportunity cost of current and future rotations increases with higher discount rates. As production costs increase, either as a whole or by planting more trees per acre, the optimal rotation length increases and the land expectation value of the investment decreases. Discount rate and production cost do not have as much influence as product differentiation does on the optimal rotation length, as evidenced by the lack of flexibility in rotation length under the different scenarios.

When the trees reach 20 years of age, it is assumed that product differentiation occurs; 33% of the harvest can be sold as sawtimber, while the remaining 67% stays in pulpwood production (Figure 15). Under low and medium production cost scenarios, an optimal rotation length occurs exactly at 20 years when the product differentiation occurs. This is likely due to the sudden increase in stumpage value for the sawtimber as compared to the value of hardwood pulpwood. For situations when production costs are high and stumpage price is low, the optimal rotation length is at or above a 20 year cycle (Tables 19-21).

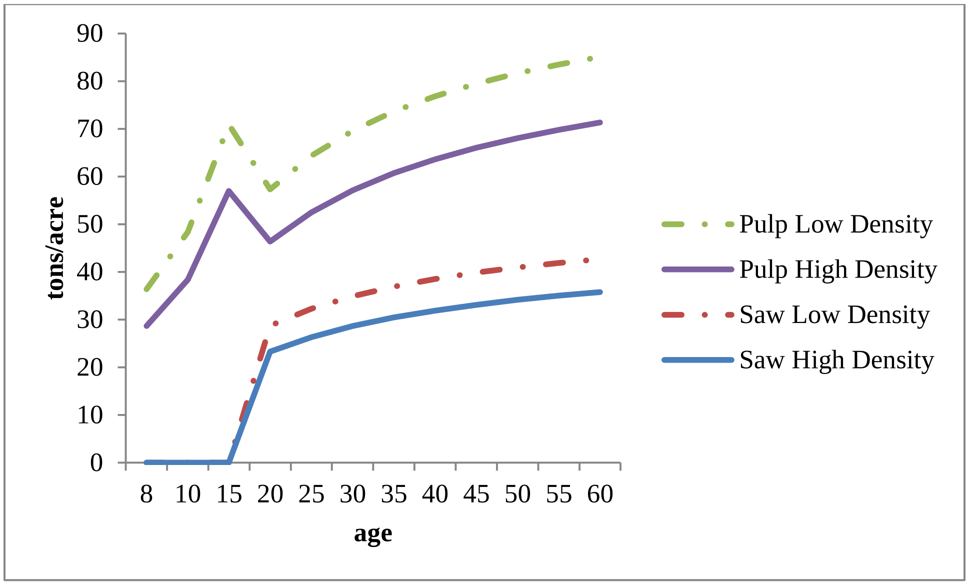

Figure 15: Tree growth using the long term formula (Equation 5), separated by end product.

In all scenarios, the LEV for the long rotation forestry is higher/less negative than for short rotation crops. This is interesting given the inclusion of coppice rotations in the short rotation situations. The stumpage prices used for the first 20 years of tree growth are the same; it is only at 20 years that product differentiation occurs, so the differences in optimal rotation length and LEV are likely caused by the rapid increase in product value.

Table 19: Optimal rotation lengths and land expectation values for mixed hardwoods using a 3% discount rate; NP= no peak where no optimal rotation found within a 60-year growth period, LEV for age 60 is reported.

Optimal Rotation at 3% discount rate						
	Low Production Cost		**Medium Production Cost**		**High Production Cost**	
	Low Density	High Density	Low Density	High Density	Low Density	High Density
Optimal Rotation (years)						
Stumpage						
Low	20	20	20	24	24	NP
Medium	20	20	20	20	20	50
High	20	20	20	20	20	23
Land Expectation Value ($/acre)						
Stumpage						
Low	450.27	268.65	310.80	(91.48)	(143.01)	(822.70)
Medium	876.31	613.75	736.84	247.23	273.79	(732.96)
High	1724.60	1300.88	1585.13	934.36	1122.08	(266.63)

Table 20: Optimal rotation lengths and land expectation values for mixed hardwoods using a 5% discount rate; NP= no peak where no optimal rotation found within a 60 year growth period, LEV for age 60 is reported.

Optimal Rotation at 5% discount rate						
	Low Production Cost		**Medium Production Cost**		**High Production Cost**	
	Low Density	High Density	Low Density	High Density	Low Density	High Density
Optimal Rotation (years)						
Stumpage						
Low	20	20	20	22	22	NP
Medium	20	20	20	20	20	45
High	20	20	20	20	20	21
Land Expectation Value ($/acre)						
Stumpage						
Low	207.46	99.23	107.56	(162.30)	(222.34)	(783.68)
Medium	415.19	267.45	315.29	4.96	(16.39)	(756.90)
High	828.79	602.52	728.89	339.98	397.22	(530.09)

Table 21: Optimal rotation lengths and land expectation values for mixed hardwoods using a 7% discount rate; NP= no peak where no optimal rotation found within a 60 year growth period, LEV for age 60 is reported.

Optimal Rotation at 7% discount rate						
	Low Production Cost		**Medium Production Cost**		**High Production Cost**	
	Low Density	High Density	Low Density	High Density	Low Density	High Density
Optimal Rotation (years)						
Stumpage						
Low	20	20	20	21	21	NP
Medium	20	20	20	20	20	45
High	20	20	20	20	20	20
Land Expectation Value ($/acre)						
Stumpage						
Low	109.53	30.90	25.59	(189.69)	(252.88)	(773.38)
Medium	229.21	127.84	145.26	(92.76)	(133.43)	(764.02)
High	476.49	320.86	383.55	100.26	104.86	(632.20)

Chapter 6: Conclusions

6.1 Overview

The purpose of this study was to determine if growing woody bioenergy crops is economically viable as a mine reclamation procedure. Another aim of the study was to identify any policies that may act as barriers to using bioenergy cropping as a mine reclamation procedure as well as incentives available for growing energy crops. In order to fulfill the SMCRA requirements, mine operators must reclaim the mined lands and they generally choose between designating land as hayland/pasture, traditional forestry production, or development (typically industrial or commercial).

This study explored a new option for reclamation which could potentially provide positive financial returns to the landowner shortly after reclamation is completed and for years into the future. Analysis was completed from a policy maker's prospective with a goal of achieving the highest value for the plot of land. Reclamation to bioenergy would help meet some of the growing energy demand in the United States with fewer negative environmental impacts than traditional energy sources. Most bioenergy crops grown in the US are grown on lands that would otherwise be used for growing agricultural crops. Planting woody bioenergy on previously mined lands does not interfere with the agricultural supply chain by taking up land that would otherwise be suitable for food crops.

Black locust trees are perhaps the best species to grow in a bioenergy plantation due to their high wood density (0.60 dry g/cm^3 compared to American sycamore at 0.46 dry g/cm^3 and hybrid poplar at 0.34 g/cm^3), and ability to grow quickly. Black locust trees are ideal for planting on mined lands because they are a nitrogen-fixing species; the addition of fertilizer (an extra cost) does not have a significant effect on overall growth. For every treatment in the experiment, black locust out-produced all other species with the same treatment thereby resulting in the highest (or least negative) land expectation values. When investing in black locust and using a 5% discount rate, LEV ranges from $-871.68 to $257.39 with coppice harvest rotations of greater than 15 years and 10 years, respectively, dependent on production costs and stumpage values.

Optimal rotation lengths for each species were found by optimizing the land expectation value for each combination of production costs and stumpage values based on given discount rates. Rotation lengths varied between 9 and 15 years for scenarios that received positive returns; for those scenarios with negative returns, an optimal rotation length was not found within 15 years of growth. Due to creating the short rotation growth equations with five years of actual growth data, they were not used to predict growth beyond 15 years. Consistent with traditional forestry economics, as the stumpage price or discount rate increases, the rotation length shortens due to the increased opportunity cost of keeping the current trees in the ground, and to allow for future rotations to happen sooner. Additionally, as the cost of production increases, the optimal rotation lengthens in order to extend the period of time between when those costs occur and harvest revenues.

Using a long rotation analysis, which allows for the sale of two products – pulpwood and sawtimber, optimal rotation lengths were found to be at the point of differentiation. Sawtimber prices, complied by Timber-Mart South, are roughly five times as much as pulpwood prices and therefore the point chosen for trees to be sold as sawtimber instead of pulpwood became the cutoff for the optimal rotation length. This threshold for product differentiation, chosen to be 20 years, is merely one of many possibilities as there is no clearly defined age at which trees are sold for sawtimber instead of pulpwood; this threshold could warrant further investigation.

There are no explicit policy barriers to reclaiming mined lands as bioenergy plantations, although there are restrictions. Six of the seven southeastern states involved in the Appalachian Regional Reforestation Initiative (ARRI) would likely classify reclamation to bioenergy as commercial forestry for permitting purposes. The seventh state, West Virginia, has a biofuel category; a permit for woody bioenergy reclamation would likely be held to the regulations associated with that classification. Standards for bond release under the commercial forestry designation require stocking levels of between 300-450 trees/acre which all need to be in place for 2-3 growing seasons, depending on which state they are in. A few of the states require 70%-75% of trees included in the stocking count to be considered commercial species and all states require between 70%-80% established ground cover for bond release. These ground cover requirements increase the cost of reclamation without increasing the value of the final bioenergy product and therefore make it more difficult to receive positive returns on an investment in bioenergy. Virginia also has a diversity requirement for planting, although it is not clearly defined, planting monoculture energy plantations may pose problems in the future.

West Virginia’s regulations are stricter than the other ARRI states for mine reclamation as commercial forestry. A bioenergy plantation monoculture would not be allowed in West Virginia under their commercial forestry classification, but it could be permitted as biofuel crop land and be held to those standards. Perhaps West Virginia’s biofuel crop land designation will receive a large number of applications and other states in the region will follow suit by creating a new land classification of their own designated to bioenergy production.

Most states currently have Renewable Portfolio Standards (RPS) requiring a minimum level of electricity to be generated from renewable resources. Woody bioenergy qualifies as a renewable source and can be used toward meeting these goals. Of the seven ARRI states, only Virginia and Kentucky do not have RPSs currently, although Virginia does have a volunteer RPS program. Financial incentives exist for building new facilities that generate electricity from renewable resources, as well as for updating existing facilities to support renewable fuels. These incentives indirectly encourage landowners to invest in bioenergy. The state of Kentucky directly impacts bioenergy expansion by providing grants to farmers who grow bioenergy crops. Incentives available are not extensive, yet they exist in a variety of formats.

Based on findings of the current research, growing bioenergy crops as a mine reclamation procedure is likely only profitable in limited scenarios. Black locust appears to be the best tree species to plant for woody bioenergy on previously mined lands; it grows quickly and does not require the addition of fertilizer, yet is still only profitable when production costs are low and sale prices are high. However with more silviculture research and additional policy incentives, growing bioenergy crops profitably on previously mined lands is not far out of reach.

6.2 Limitations and Future Research

This study measured five years of tree growth on previously mined lands to determine the growth potential of five species using different management practices. The growth and yield equations resulting from these data are thus limited by the short time period of measured growth. Additional years of growth are necessary to fine-tune these equations. The study modeled 15 years of growth by extrapolating linear growth from the first five years of measured data (see Appendix). Should biomass growth in future years follow a different form (such as the non-linear form of Equation 5), the economic analysis would change. There are not many studies on woody bioenergy growth on previously mined lands; continued growth measurements will be a valuable addition to reclamation and bioenergy research.

Research exists on coppice regrowth patterns, but few studies have been conducted on mine reclamation sites. The first rotation growth predictions were used when estimating coppice regrowth for this analysis. Past research has shown coppiced trees grow the same or better than the original planting in subsequent rotations. After the first harvest on the trial sites, regrowth should be measured to determine how well the different species and treatments coppice on the mined sites. If coppice rotations result in greater amounts of biomass, then financial returns could be better than shown in this analysis.

Costs of producing short rotation woody crops and reclaiming mined lands with hardwood species have been recorded, but not extensively. Even less researched are costs associated with producing woody crops on previously mined lands. This study utilized production cost information from previous studies depicting a wide variety of costs. The range of production costs used for this study is large – from $25 - $850 per acre – which results in a wide range of land expectation values. Recording current, more precise, costs of woody bioenergy production would be valuable to adjust findings from this report. Additionally, this study analyzed the costs and benefits of planting and fertilizing the bioenergy trees. If those costs were instead borne by the mine operator, with the landowner receiving all the benefits, the economics of the analysis would be different than what is reported here.

All reclamation policies are subject to change, however slowly those changes may happen. West Virginia's biofuel crop land designation is proof that at least some regulators are seeing bioenergy as a viable land use option. Policy evaluation should continue in case other states adopt new land use designations to better fit woody bioenergy production. As the price of fossil fuels increases and if policies change in a manner that discourages burning these fuels, more policy incentives, financial and otherwise, are likely to emerge to promote renewable resources. To take advantage of these incentives, government policies should continue to be measured.

This study differs from previous studies by combining growth models of different species and management practices with stumpage values and production costs to determine economic viability of short rotation woody bioenergy crops on previously mined lands. Past studies focus on one portion of this analysis, such as bioenergy growth or production costs. This study incorporates differences in growth that occur on mined lands likely due to soil and site characteristics that are not included in other experiments. Information on coppice regrowth is also limited in the literature; while this study does not measure a coppice rotation it does take coppice estimates into consideration for the economic analysis. Most studies on the economics of short rotation woody crops focus on calculating net present value of the investment. Including subsequent rotations in the analysis by determining the land expectation value is an important addition to the literature because when a landowner is faced with two options for reclamation, it is important to compare the value of multiple rotations to realize the entire value of the investment. Using the data collected in this study and measurements for future years of tree growth, along with updated production cost information, economic viability estimates of growing woody bioenergy crops as a mine reclamation procedure can be polished.

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Appendices

A. Average Biomass (g/tree)

NO FERTILIZER	2008	2009	2010	2011	2012
Black Locust (High Density)	652	2826	5393	7727	10478
Black Locust (Low Density)	848	3824	7573	12164	15918
Hybrid Poplar (High Density)	99	297	1022	2467	6035
Hybrid Poplar (Low Density)	136	368	945	2115	5141
Mixed Hardwood	70	275	473	965	2242
Red Oak	82	89	174	264	516
Red Oak/Cottonwood	104	124	224	385	574
Sycamore (High Density)	73	335	1281	2696	5459
Sycamore (Low Density)	99	351	1187	2210	4221
FERTILIZER	**2008**	**2009**	**2010**	**2011**	**2012**
Black Locust (High Density) F	652	3213	5940	9301	11903
Black Locust (Low Density) F	848	4529	8861	14670	16506
Hybrid Poplar (High Density) F	99	296	1713	5994	12891
Hybrid Poplar (Low Density) F	136	329	1431	4488	8417
Red Oak F	82	119	336	540	832
Red Oak/Cottonwood F	104	101	284	443	759
Sycamore (High Density) F	73	380	1105	4104	8105
Sycamore (Low Density) F	99	540	2347	5095	11415

B. Average Biomass Tons per Acre

NO FERT	2008	2009	2010	2011	2012
Black Locust (High Density)	0.87	4.11	7.64	10.96	14.53
Black Locust (Low Density)	0.42	1.95	4.00	6.94	7.38
Hybrid Poplar (High Density)	0.10	0.37	1.09	2.76	6.39
Hybrid Poplar (Low Density)	0.06	0.16	0.37	0.96	2.42
Mixed Hardwood	0.04	0.22	0.50	0.90	1.73
Red Oak	0.06	0.07	0.12	0.19	0.29
Red Oak/Cottonwood	0.07	0.07	0.26	0.22	0.42
Sycamore (High Density)	0.09	0.43	1.74	3.47	6.78
Sycamore (Low Density)	0.04	0.13	0.46	0.76	1.52
FERT	**2008**	**2009**	**2010**	**2011**	**2012**
Black Locust (High Density) F	0.87	4.82	8.07	12.25	14.43
Black Locust (Low Density) F	0.42	3.07	4.46	6.87	8.46
Hybrid Poplar (High Density) F	0.10	0.31	1.42	6.44	12.53
Hybrid Poplar (Low Density) F	0.06	0.19	0.66	2.82	4.85
Red Oak F	0.04	0.09	0.23	0.33	0.49
Red Oak/Cottonwood F	0.06	0.06	0.30	0.22	0.53
Sycamore (High Density) F	0.07	0.41	1.28	4.56	9.09
Sycamore (Low Density) F	0.09	0.23	0.87	2.11	4.88

C. Biomass Summary by Year

C1 2008

No Fertilizer	Biomass - ATR	Biomass - BG	Biomass - RR	Mean biomass (g)	ATR - t/acre	BG - t/acre	RR - t/acre	Mean t/acre	Biomass ton/acre ATR	Biomass ton/acre BG	Biomass ton/acre RR	Mean Biomass ton/acre
Black Locust (High Density)	684	558	714	652	1191	1214	1220	1208	0.90	0.75	0.96	0.87
Black Locust (Low Density)	642	990	912	848	479	488	401	456	0.34	0.53	0.40	0.42
Hybrid Poplar (High Density)	181	46	71	99	755	1255	1069	1026	0.15	0.06	0.08	0.10
Hybrid Poplar (Low Density)	160	37	213	136	273	505	482	420	0.05	0.02	0.11	0.06
Mixed Hardwood	41	92	75	70	116	1011	267	465	0.01	0.10	0.02	0.04
Red Oak	66	98	82	82	632	880	592	701	0.05	0.09	0.05	0.06
Red Oak/Cottonwood	68	72	172	104	621	668	529	606	0.05	0.05	0.10	0.07
Sycamore (High Density)	62	70	87	73	1417	948	894	1086	0.10	0.07	0.09	0.09
Sycamore (Low Density)	71	106	121	99	360	465	232	352	0.03	0.05	0.03	0.04

C2 2009

No Fertilizer	Biomass - ATR	Biomass - BG	Biomass - RR	Mean biomass (g)	ATR - t/acre	BG - t/acre	RR - t/acre	Mean t/acre	Biomass ton/acre ATR	Biomass ton/acre BG	Biomass ton/acre RR	Mean Biomass ton/acre
Black Locust (High Density)	2089	2361	4028	2826	1220	1324	1371	1305	2.81	3.45	6.09	4.11
Black Locust (Low Density)	1910	4471	5090	3824	540	465	430	478	1.14	2.29	2.41	1.95
Hybrid Poplar (High Density)	389	269	234	297	976	1301	1150	1142	0.42	0.39	0.30	0.37
Hybrid Poplar (Low Density)	370	261	472	368	209	488	465	387	0.09	0.14	0.24	0.16
Mixed Hardwood	72	473	279	275	310	1045	314	556	0.02	0.55	0.10	0.22
Red Oak	78	77	112	89	653	836	639	710	0.06	0.07	0.08	0.07
Red Oak/Cottonwood	93	102	176	124	662	441	511	538	0.07	0.05	0.10	0.07
Sycamore (High Density)	266	343	396	335	1440	1227	953	1207	0.42	0.46	0.42	0.43
Sycamore (Low Density)	196	458	400	351	302	441	197	314	0.07	0.22	0.09	0.13
Fertilizer	Biomass - ATR	Biomass - BG	Biomass - RR	Mean biomass (g)	ATR - t/acre	BG - t/acre	RR - t/acre	Mean t/acre	Biomass ton/acre ATR	Biomass ton/acre BG	Biomass ton/acre RR	Mean Biomass ton/acre
Black Locust (High Density) F	2913	2902	3824	3213	1147	1452	1452	1350	3.68	4.65	6.12	4.82
Black Locust (Low Density) F	2688	5484	5414	4529	383	732	610	575	1.14	4.42	3.64	3.07
Hybrid Poplar (High Density) F	293	321	275	296	511	1162	1185	953	0.17	0.41	0.36	0.31
Hybrid Poplar (Low Density) F	199	280	508	329	337	523	616	492	0.07	0.16	0.34	0.19
Red Oak F	79	155	124	119	566	595	842	668	0.05	0.10	0.11	0.09
Red Oak/Cottonwood F	68	92	142	101	534	592	511	546	0.04	0.06	0.08	0.06
Sycamore (High Density) F	272	416	451	380	1313	720	1022	1018	0.39	0.33	0.51	0.41
Sycamore (Low Density) F	224	961	434	540	395	453	256	368	0.10	0.48	0.12	0.23

C3 2010

No Fertilizer	Biomass - ATR	Biomass - BG	Biomass - RR	Mean biomass (g)	ATR - t/acre	BG - t/acre	RR - t/acre	Mean t/acre	Biomass ton/acre ATR	Biomass ton/acre BG	Biomass ton/acre RR	Mean Biomass ton/acre
Black Locust (High Density)	3717	4790	7671	5393	1394	1176	1301	1290	5.71	6.21	11.00	7.64
Black Locust (Low Density)	4245	8389	10084	7573	430	523	465	472	2.01	4.83	5.17	4.00
Hybrid Poplar (High Density)	804	1777	485	1022	1057	848	1243	1049	0.94	1.66	0.67	1.09
Hybrid Poplar (Low Density)	643	1132	1060	945	441	197	476	372	0.31	0.25	0.56	0.37
Mixed Hardwood	111	967	343	473	418	558	2230	1069	0.05	0.59	0.84	0.50
Red Oak	140	127	256	174	476	682	627	595	0.07	0.10	0.18	0.12
Red Oak/Cottonwood	130	159	383	224	639	1104	1150	964	0.09	0.19	0.49	0.26
Sycamore (High Density)	672	1368	1802	1281	987	1371	1227	1195	0.73	2.07	2.44	1.74
Sycamore (Low Density)	486	1700	1376	1187	197	314	453	321	0.11	0.59	0.69	0.46
Fertilizer	Biomass - ATR	Biomass - BG	Biomass - RR	Mean biomass (g)	ATR - t/acre	BG - t/acre	RR - t/acre	Mean t/acre	Biomass ton/acre ATR	Biomass ton/acre BG	Biomass ton/acre RR	Mean Biomass ton/acre
Black Locust (High Density) F	5024	5412	7383	5940	1069	1467	1173	1236	5.92	8.75	9.55	8.07
Black Locust (Low Density) F	5611	9527	11445	8861	430	436	488	451	2.66	4.57	6.16	4.46
Hybrid Poplar (High Density) F	1183	2899	1056	1713	1104	476	1104	894	1.44	1.52	1.28	1.42
Hybrid Poplar (Low Density) F	515	1730	2048	1431	604	232	534	457	0.34	0.44	1.21	0.66
Red Oak F	255	355	397	336	499	523	819	614	0.14	0.20	0.36	0.23
Red Oak/Cottonwood F	192	172	489	284	558	697	1196	817	0.12	0.13	0.64	0.30
Sycamore (High Density) F	726	1497	1093	1105	999	1138	962	1033	0.80	1.88	1.16	1.28
Sycamore (Low Density) F	609	4223	2211	2347	256	279	465	333	0.17	1.30	1.13	0.87

C4 2011

No Fertilizer	Biomass - ATR	Biomass - BG	Biomass - RR	Mean biomass (g)	ATR - t/acre	BG - t/acre	RR - t/acre	Mean t/acre	Biomass ton/acre ATR	Biomass ton/acre BG	Biomass ton/acre RR	Mean Biomass ton/acre
Black Locust (High Density)	5628	5898	11656	7727	1147	1278	1359	1261	7.12	8.31	17.46	10.96
Black Locust (Low Density)	7774	10551	18165	12164	505	697	418	540	4.33	8.11	8.37	6.94
Hybrid Poplar (High Density)	1880	4106	1414	2467	697	1359	441	832	1.44	6.15	0.69	2.76
Hybrid Poplar (Low Density)	867	2210	3267	2115	174	465	441	360	0.17	1.13	1.59	0.96
Mixed Hardwood	224	1914	757	965	341	1150	215	569	0.08	2.43	0.18	0.90
Red Oak	196	183	413	264	1147	366	546	686	0.25	0.07	0.25	0.19
Red Oak/Cottonwood	355	202	597	385	465	534	546	515	0.18	0.12	0.36	0.22
Sycamore (High Density)	1101	3056	3931	2696	1417	1366	941	1241	1.72	4.60	4.08	3.47
Sycamore (Low Density)	766	3218	2648	2210	302	407	197	302	0.26	1.44	0.58	0.76
Fertilizer	Biomass - ATR	Biomass - BG	Biomass - RR	Mean biomass (g)	ATR - t/acre	BG - t/acre	RR - t/acre	Mean t/acre	Biomass ton/acre ATR	Biomass ton/acre BG	Biomass ton/acre RR	Mean Biomass ton/acre
Black Locust (High Density) F	7802	7428	12672	9301	1278	1104	1196	1193	10.99	9.04	16.71	12.25
Black Locust (Low Density) F	10046	11652	22312	14670	366	488	418	424	4.05	6.27	10.29	6.87
Hybrid Poplar (High Density) F	3243	9911	4829	5994	441	1115	1045	867	1.58	12.18	5.57	6.44
Hybrid Poplar (Low Density) F	808	4088	8569	4488	209	523	627	453	0.19	2.36	5.93	2.82
Red Oak F	375	492	752	540	581	610	523	571	0.24	0.33	0.43	0.33
Red Oak/Cottonwood F	263	238	828	443	569	348	430	449	0.16	0.09	0.39	0.22
Sycamore (High Density) F	1567	4316	6430	4104	1289	934	987	1070	2.23	4.44	7.00	4.56
Sycamore (Low Density) F	873	7695	6718	5095	325	488	256	356	0.31	4.14	1.89	2.11

C5 2012

No Fertilizer	Biomass - ATR	Biomass - BG	Biomass - RR	Mean biomass (g)	ATR - t/acre	BG - t/acre	RR - t/acre	Mean t/acre	Biomass ton/acre ATR	Biomass ton/acre BG	Biomass ton/acre RR	Mean Biomass ton/acre
Black Locust (High Density)	6901	8210	16323	10478	1118	1173	1359	1217	8.50	10.62	24.45	14.53
Black Locust (Low Density)	14352	12690	20710	15918	418	465	395	426	6.62	6.50	9.02	7.38
Hybrid Poplar (High Density)	3498	11421	3187	6035	395	1138	941	825	1.52	14.33	3.31	6.39
Hybrid Poplar (Low Density)	1398	4911	9114	5141	139	441	465	348	0.21	2.39	4.67	2.42
Mixed Hardwood	646	3407	2672	2242	341	1150	215	569	0.24	4.32	0.63	1.73
Red Oak	298	286	964	516	595	488	476	520	0.20	0.15	0.51	0.29
Red Oak/Cottonwood	342	333	1046	574	674	1080	523	759	0.25	0.40	0.60	0.42
Sycamore (High Density)	1552	4850	9976	5459	1313	1352	987	1217	2.25	7.23	10.86	6.78
Sycamore (Low Density)	1269	5953	5441	4221	279	453	197	310	0.39	2.97	1.18	1.52
Fertilizer	Biomass - ATR	Biomass - BG	Biomass - RR	Mean biomass (g)	ATR - t/acre	BG - t/acre	RR - t/acre	Mean t/acre	Biomass ton/acre ATR	Biomass ton/acre BG	Biomass ton/acre RR	Mean Biomass ton/acre
Black Locust (High Density) F	10917	9631	15162	11903	958	1127	1185	1090	11.53	11.96	19.80	14.43
Black Locust (Low Density) F	10431	16313	22775	16506	505	488	430	474	5.81	8.77	10.79	8.46
Hybrid Poplar (High Density) F	8075	23256	7343	12891	395	1069	825	763	3.52	27.40	6.68	12.53
Hybrid Poplar (Low Density) F	1701	6766	16784	8417	174	465	581	407	0.33	3.47	10.75	4.85
Red Oak F	546	493	1457	832	552	610	511	558	0.33	0.33	0.82	0.49
Red Oak/Cottonwood F	416	348	1512	759	697	1057	511	755	0.32	0.41	0.85	0.53
Sycamore (High Density) F	2159	5433	16722	8105	1115	962	1022	1033	2.65	5.76	18.84	9.09
Sycamore (Low Density) F	1366	18964	13916	11415	337	488	256	360	0.51	10.20	3.92	4.88

D. Height and Diameter Summary by Year

D1 2008

No Fertilizer	gld (cm) - ATR	gld (cm) - BG	gld (cm) - RR	Mean gld (cm)	ht (m) - ATR	ht (m) - BG	ht (m) - RR	Mean ht (m)	Mean Biomass Index (g/tree)
Black Locust (High Density)	1.27	1.12	1.31	1.23	0.81	0.78	0.90	0.83	97
Black Locust (Low Density)	1.23	1.51	1.44	1.39	0.77	1.11	1.05	0.98	144
Hybrid Poplar (High Density)	0.99	0.62	0.72	0.77	0.55	0.50	0.60	0.55	15
Hybrid Poplar (Low Density)	0.96	0.58	1.10	0.88	0.51	0.41	0.75	0.56	21
Mixed Hardwood	0.63	0.81	0.72	0.72	0.29	0.66	0.51	0.49	16
Red Oak	0.57	0.62	0.64	0.61	0.36	0.44	0.49	0.43	11
Red Oak/Cottonwood	0.50	0.53	0.53	0.52	0.41	0.43	0.43	0.42	9
Sycamore (High Density)	0.69	0.71	0.78	0.73	0.43	0.49	0.47	0.46	14
Sycamore (Low Density)	0.71	0.83	0.88	0.81	0.39	0.48	0.45	0.44	18

D2 2009

No Fertilizer	gld (cm) - ATR	gld (cm) - BG	gld (cm) - RR	Mean gld (cm)	ht (m) - ATR	ht (m) - BG	ht (m) - RR	Mean ht (m)	Mean Biomass Index (g/tree)
Black Locust (High Density)	2.10	2.14	1.95	2.06	1.35	1.45	1.95	1.58	727
Black Locust (Low Density)	2.01	2.97	2.01	2.33	1.27	2.00	2.01	1.76	1056
Hybrid Poplar (High Density)	1.39	1.22	0.93	1.18	1.04	0.95	0.93	0.97	67
Hybrid Poplar (Low Density)	1.20	1.22	1.22	1.21	0.80	0.93	1.22	0.98	84
Mixed Hardwood	0.73	1.48	0.65	0.96	0.37	0.91	0.65	0.64	72
Red Oak	0.60	0.62	0.52	0.58	0.42	0.43	0.52	0.46	13
Red Oak/Cottonwood	0.66	0.68	0.52	0.62	0.48	0.47	0.52	0.49	14
Sycamore (High Density)	1.20	1.34	0.85	1.13	0.59	0.91	0.85	0.78	79
Sycamore (Low Density)	1.06	1.50	0.79	1.11	0.53	1.23	0.79	0.85	83
Fertilizer	gld (cm) - ATR	gld (cm) - BG	gld (cm) - RR	Mean gld (cm)	ht (m) - ATR	ht (m) - BG	ht (m) - RR	Mean ht (m)	Mean Biomass Index (g/tree)
Black Locust (High Density)	2.45	2.42	2.80	2.56	1.57	1.74	1.83	1.71	850
Black Locust (Low Density)	2.34	3.35	3.29	2.99	1.45	2.09	2.04	1.86	1257
Hybrid Poplar (High Density)	1.26	1.29	1.19	1.25	0.89	1.05	1.04	0.99	67
Hybrid Poplar (Low Density)	1.06	1.26	1.51	1.27	0.71	0.91	1.26	0.96	78
Red Oak	0.60	0.69	0.72	0.67	0.40	0.43	0.51	0.45	14
Red Oak/Cottonwood	0.58	0.67	0.78	0.68	0.40	0.91	0.50	0.60	11
Sycamore (High Density)	1.19	1.48	1.48	1.38	0.63	0.91	0.92	0.82	93
Sycamore (Low Density)	1.06	2.04	1.46	1.52	0.50	1.23	0.81	0.85	140

D3 2010

No Fertilizer	gld (cm) - ATR	gld (cm) - BG	gld (cm) - RR	Mean gld (cm)	ht (m) - ATR	ht (m) - BG	ht (m) - RR	Mean ht (m)	Mean Biomass Index (g/tree)
Black Locust (High Density)	2.74	3.04	3.84	3.21	0.83	0.93	1.17	0.98	1840
Black Locust (Low Density)	2.90	4.00	4.37	3.76	0.88	1.22	1.33	1.15	2651
Hybrid Poplar (High Density)	1.84	2.46	1.44	1.91	0.56	0.75	0.44	0.58	298
Hybrid Poplar (Low Density)	1.61	2.12	2.07	1.93	0.49	0.64	0.63	0.59	272
Mixed Hardwood	0.87	2.03	1.31	1.40	0.26	0.62	0.40	0.43	141
Red Oak	0.75	0.75	0.97	0.82	0.23	0.23	0.29	0.25	28
Red Oak/Cottonwood	0.75	0.81	1.14	0.90	0.23	0.25	0.35	0.27	63
Sycamore (High Density)	1.73	2.37	2.55	2.21	0.53	0.72	0.78	0.68	432
Sycamore (Low Density)	1.49	2.57	2.31	2.12	0.45	0.78	0.70	0.65	342
Fertilizer	gld (cm) - ATR	gld (cm) - BG	gld (cm) - RR	Mean gld (cm)	ht (m) - ATR	ht (m) - BG	ht (m) - RR	Mean ht (m)	Mean Biomass Index (g/tree)
Black Locust (High Density)	3.15	3.26	3.81	3.41	0.96	0.99	1.16	1.04	2117
Black Locust (Low Density)	3.38	4.38	4.55	4.10	1.03	1.33	1.39	1.25	3165
Hybrid Poplar (High Density)	2.14	2.87	2.06	2.36	0.65	0.87	0.63	0.72	498
Hybrid Poplar (Low Density)	1.50	2.50	2.74	2.25	0.46	0.76	0.83	0.68	447
Red Oak	0.96	0.91	1.17	1.01	0.29	0.28	0.36	0.31	52
Red Oak/Cottonwood	0.86	0.85	1.26	0.99	0.26	0.26	0.39	0.30	54
Sycamore (High Density)	1.74	2.40	2.07	2.07	0.53	0.73	0.63	0.63	365
Sycamore (Low Density)	1.61	3.67	2.81	2.70	0.49	1.12	0.86	0.82	789

D4 2011

No Fertilizer	gld (cm) - ATR	gld (cm) - BG	gld (cm) - RR	Mean gld (cm)	ht (m) - ATR	ht (m) - BG	ht (m) - RR	Mean ht (m)	Mean Biomass Index (g/tree)
Black Locust (High Density)	3.32	3.43	4.66	3.80	2.57	3.03	3.50	3.03	3336
Black Locust (Low Density)	3.87	4.48	5.78	4.71	2.68	3.39	3.57	3.21	5251
Hybrid Poplar (High Density)	2.53	3.25	2.28	2.69	2.22	2.67	1.98	2.29	843
Hybrid Poplar (Low Density)	1.63	2.69	3.16	2.49	1.35	2.30	2.35	2.00	672
Mixed Hardwood	1.15	2.64	1.80	1.86	0.69	1.60	1.26	1.18	298
Red Oak	0.83	0.85	1.16	0.95	0.56	0.52	0.76	0.61	46
Red Oak/Cottonwood	1.09	0.92	1.38	1.13	0.70	0.57	0.83	0.70	57
Sycamore (High Density)	2.07	3.21	3.45	2.91	1.35	2.16	2.40	1.97	1044
Sycamore (Low Density)	1.75	3.28	3.00	2.68	1.04	2.13	1.74	1.64	745
Fertilizer	gld (cm) - ATR	gld (cm) - BG	gld (cm) - RR	Mean gld (cm)	ht (m) - ATR	ht (m) - BG	ht (m) - RR	Mean ht (m)	Mean Biomass Index (g/tree)
Black Locust (High Density)	3.92	3.82	4.84	4.20	3.01	3.37	3.75	3.38	4765
Black Locust (Low Density)	4.39	4.80	6.26	5.15	2.84	3.72	3.79	3.45	6626
Hybrid Poplar (High Density)	3.13	4.88	3.69	3.90	2.50	3.86	3.20	3.19	2279
Hybrid Poplar (Low Density)	1.78	3.35	4.70	3.28	1.63	2.52	3.67	2.61	1612
Red Oak	1.04	1.04	1.52	1.20	0.75	0.62	0.96	0.78	92
Red Oak/Cottonwood	0.95	0.95	1.57	1.16	0.69	0.68	1.01	0.79	72
Sycamore (High Density)	2.34	3.68	4.19	3.40	1.92	2.36	2.94	2.41	1708
Sycamore (Low Density)	1.79	4.51	4.28	3.52	1.23	3.15	2.46	2.28	2090

D5 2012

No Fertilizer	gld (cm) - ATR	gld (cm) - BG	gld (cm) - RR	Mean gld (cm)	ht (m) - ATR	ht (m) - BG	ht (m) - RR	Mean ht (m)	Mean Biomass Index (g/tree)
Black Locust (High Density)	3.67	3.94	5.47	4.36	3.08	3.29	4.29	3.55	5279
Black Locust (Low Density)	5.20	4.90	6.24	5.45	3.30	3.70	4.24	3.75	7671
Hybrid Poplar (High Density)	3.15	4.82	3.03	3.67	2.50	3.74	2.27	2.84	2273
Hybrid Poplar (Low Density)	2.09	3.50	4.43	3.34	1.60	2.47	3.34	2.47	1732
Mixed Hardwood	1.50	3.32	2.78	2.54	0.81	2.14	1.70	1.55	761
Red Oak	1.00	0.99	1.64	1.21	0.74	0.53	1.14	0.80	113
Red Oak/Cottonwood	1.07	0.99	1.73	1.27	0.76	0.69	1.08	0.84	103
Sycamore (High Density)	2.38	3.83	4.91	3.70	1.58	2.66	3.02	2.42	2259
Sycamore (Low Density)	2.20	4.18	4.03	3.47	1.34	2.69	2.26	2.10	1545

Fertilizer	gld (cm) - ATR	gld (cm) - BG	gld (cm) - RR	Mean gld (cm)	ht (m) - ATR	ht (m) - BG	ht (m) - RR	Mean ht (m)	Mean Biomass Index (g/tree)
Black Locust (High Density)	4.53	4.34	5.26	4.71	3.52	3.62	4.57	3.90	6334
Black Locust (Low Density)	4.45	5.58	6.43	5.49	3.13	3.96	4.53	3.87	8383
Hybrid Poplar (High Density)	4.28	6.71	4.38	5.12	2.99	5.00	3.44	3.81	5137
Hybrid Poplar (Low Density)	2.25	3.76	6.19	4.07	1.75	2.47	4.80	3.01	3236
Red Oak	1.22	1.23	1.95	1.47	1.12	0.71	1.32	1.05	207
Red Oak/Cottonwood	1.15	1.08	1.94	1.39	0.99	0.83	1.16	1.00	143
Sycamore (High Density)	2.68	3.96	6.10	4.24	2.10	2.82	3.93	2.95	3691
Sycamore (Low Density)	2.16	6.49	5.71	4.79	1.42	3.85	3.05	2.77	4799