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TWO YEAR RESPONSE OF A WOODY BIOFUEL PLANTATION TO INTENSIVE MANAGEMENT ON A RECLAIMED SURFACE MINE IN EASTERN KENTUCKY

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ABSTRACT OF THESIS

TWO YEAR RESPONSE OF A WOODY BIOFUEL PLANTATION TO INTENSIVE MANAGEMENT ON A RECLAIMED SURFACE MINE IN EASTERN KENTUCKY

The establishment of intensively managed woody energy crops on reclaimed surface mine lands provides an opportunity to diversify domestic biomass sources, while increasing the productivity and economic value of underutilized land. Our objective is to test the effect of fertilization and irrigation on the growth, survival, biomass accumulation, biomass allocation, leaf area, and nutrient dynamics of American sycamore (*Platanus occidentalis* L.) and black locust (*Robinia pseudoacacia* L.) planted on a reclaimed surface mine. In 2008, replicated plantings of sycamore and black locust were established on the Big Elk mine in eastern Kentucky. Treatments tested include annual granular fertilizer applications of 37 kg N, 30 kg P, and 16 kg K ha⁻¹, irrigation, irrigation + fertilization, and control. Following two growing seasons, American sycamore exhibited significantly (p < 0.05) greater height, diameter, leaf area, and stem biomass in fertilizer treatment compared to all other species and treatment combinations. Treatments had no affect on survival, but American sycamore exhibited significantly higher survival than black locust. Poor locust survival and growth were likely attributed to excessive ungulate browsing. Our findings indicate that fertilizer applications at young plantations on reclaimed mines in Appalachia increases tree height, diameter, and biomass accumulation.

KEYWORDS: Short rotation plantations, intensive silviculture, biofuels, surface mines, mine reforestation

Joshua Scott Brinks

April 28, 2010
TWO YEAR RESPONSE OF A WOODY BIOFUEL PLANTATION TO INTENSIVE MANAGEMENT ON A RECLAIMED SURFACE MINE IN EASTERN KENTUCKY

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THESIS

Joshua Scott Brinks

The Graduate School
University of Kentucky
2010
TWO YEAR RESPONSE OF A WOODY BIOFUEL PLANTATION TO INTENSIVE MANAGEMENT ON A RECLAIMED SURFACE MINE IN EASTERN KENTUCKY

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the College of Agriculture at the University of Kentucky

By

Joshua Scott Brinks

Director: Dr. John Lhotka, Assistant Professor of Silviculture

Lexington, Kentucky

2010

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Chapter 1: Literature Review

Introduction

As global reserves of finite fossil fuels are depleted, alternative energy sources must be identified. Renewable woody biofuels grown on reclaimed surface mines are a promising solution and benefit the current energy infrastructure in four primary ways: 1) they are a renewable source of energy; 2) they represent a cleaner energy (decreased SO\textsubscript{x} emissions); 3) they offset their own CO\textsubscript{2} emissions through carbon sequestration in subsequent growing seasons; 4) biofuels cultivated on reclaimed land do not impact agricultural production as opposed to corn-derived ethanol.

The reforestation of surface mines and other degraded lands will also play an important role in mitigating the effects of climate change. Forest management can increase carbon sequestration allowing reforested surface mines to serve as a carbon sink. In addition to increasing on site carbon sequestration, forest cover can further mitigate climate change by lowering surface temperatures in certain geographic regions and increasing water vapor. The reforestation of surface mines also provides numerous ecological benefits. Forests improve water quality and leaf litter improves soil conditions by increasing organic matter levels and nutrient levels. The use of native species also improves wildlife habitat and biodiversity.

This project examined effects of water and nutrient regime manipulations on biomass accumulation, allocation, nutrient concentrations, leaf morphology, and carbon and nitrogen uptake in American sycamore (*Platanus occidentalis*) and black locust (*Robinia pseudoacacia*) planted on a reclaimed surface mine. The study will also evaluate the influence of nutrient and water amendments on carbon sequestration potential of
reclaimed Appalachian coal mines. Finally, an examination of shifts in allocation will permit managers to maximize production of merchantable products in response to treatment and time.

**Biomass Basics**

Biomass is gaining popularity in the United States as an alternative fuel source due to public concern over shrinking fossil fuel sources and global climate change. In addition, bioenergy markets are being propelled by federal initiatives to increase production. Despite increases in production, great debate persists over net carbon budgets and effective species selection in biomass operations.

**Biomass Capacity in the United States**

Biomass is the largest source of renewable energy in the United States; recently surpassing hydro power and representing 3% of total energy consumption (Perlack et al. 2005). The United States Department of Agriculture estimates biomass can replace 30% of petroleum consumption by 2030, by means of increasing biomass feedstock to 1 billion dry tons per year (Perlack et al. 2005). While seemingly ambitious, USDA reports approximate 368 million dry tons can safely be produced from current accessible forestlands, 147 million dry tons of wood from processing residues, 47 million dry tons of construction and demolition debris, 64 million dry tons of logging residues, and 64 million dry tons of biomass from forest fuel reduction treatments to reduce fire potential (Perlack et al. 2005).

In spite of the USDA’s optimistic approach to biomass possibilities, several studies examining US and global potential present widely different scenarios (Berndes et al.
2003). This is a function of the theoretical nature of current research modeling feedstock supply, and the inclusion or exclusion of several factors such as types of energy crops and potential yields, types and amounts of residues, current agricultural land conversion rates, and available arable land.

Net Positive vs. Negative Carbon Sink


Sperow (2006) suggests carbon sequestration rates are highest in re-forested landscapes in comparison to cropland and grasslands. Furthermore, several studies find net carbon budgets are greater in forested landscapes, because harvest-related carbon inputs are limited to once per 5-10 years, high energy content, and fertilizer, herbicide, and pesticide inputs are relatively small (Vogt 1991, Johnson et al. 2007, Woodbury et al.
Conversely, annual crops such as corn require yearly harvest, intense fertilizer inputs, suffer from poor conversion rates, and low energy yield.

**Biomass Crops**

Identifying suitable biomass crops depends on environmental conditions (soil, moisture, light), end usage (ethanol, gasification, combustion, or pyrolysis), and biomass properties (moisture content, caloric value, ash/residue content, and cellulose to lignin ratio).

Bigtooth aspen (*Populus grandidentata*), eastern cottonwood (*Populus deltoides*), black locust, American sycamore, and willows (*Salix spp.*) are common woody feedstock species. Switch grass (*Panicum virgatum*), corn (*Zea mays*), soybean (*Glycine max*), rapeseed (*Brassica napus*), and miscanthus (*Miscanthus spp.*) are common herbaceous feedstock species. Woody species possess higher lignin content and tightly packed cellulose and hemi-cellulose, which favors combustion processes. Most herbaceous species lack lignin and tightly packed fibers making them easier to ferment and convert to ethanol (McKendry 2002a).

**Regional Impacts**

Although global and national interests in biomass production and utilization are growing, eastern Kentucky and the greater Appalachian region have a unique position in developing biomass markets. Millions of acres of marginal land exist throughout the Midwest and Appalachian regions. In Kentucky, the majority of these lands exist as reclaimed surface mines. Reclamation and reforestation of coal mines and stimulating stagnant mountain rural economies benefit the region, while contributing to global and national advancements in biomass research.
Reclaimed Mines in the Biomass Equation

Surface mines reclaimed with hardwood plantations can contribute to overall production of biomass feedstock, and return the landscape to a more natural state. Plantations were recognized for their value in mine reclamation as early as the 1930’s (Ashby and Baker 1968), but not as a biomass feedstock until the energy crisis of the 1970’s (Carpenter and Eigel 1979, Rowell and Carpenter 1980, Rowell and Carpenter 1982, Rowell and Carpenter 1983). Research interest waned by the 1990’s, but recent concerns over air pollution, finite fossil fuels, global climate change, and instability of foreign energy markets reinvigorated interest for biofuels at the turn of the century (Cook and Beyea 2000).

Coal mining disturbed 1.8 million acres (5% of Kentucky) of land between 1978 and 1999 in Kentucky, and averaged 260,000 acres of disturbed land per year (Cole et al. 2001). Ninety-eight % of Kentucky’s surface mining acreage is located in eastern Kentucky (Cole et al. 2001). This amounts to a large number of acres subject to reclamation efforts, potential biomass feedstock, and presents an opportunity for Kentucky to become a leader in woody biofuel production. In addition to extensive acreage available for biomass operations, Eastern Kentucky's widespread network of mining roads and coal firing plants that currently support the coal industry provide an outstanding existing infrastructure to support biomass production in the state. Furthermore, current coal firing plants can be modified to accommodate woody biomass (Patzek 2005, Johnson et al. 2007). This would provide Kentucky with an advantage over other states looking to increase biomass production.
Kentucky’s Rural Economy and Improvement of Degraded Lands

Biofuel plantations present an opportunity to boost eastern Kentucky’s impoverished economy. Ninety-eight percent of Kentucky’s 1.8 million acres permitted for surface mining are in eastern Kentucky. The majority of counties in eastern Kentucky suffer from poverty rates between 25-50% of the total population (Bureau 2005). Influx of jobs from reclamation projects via planting, harvesting, maintenance, administration, and additional feedstock plantations may promote regional creation of industrial processing centers. Subsequently, municipalities may benefit from property taxes, corporate taxes, and cash flow from residents and employees.

In addition to facilitating alternative fuels, biofuel plantations on reclaimed mines promote wildlife habitat, improve hydrology, and restore land to its natural cover type. Nearly all of eastern Kentucky was naturally forested before European settlement, but only 5% of mines are reclaimed as forest land (Sperow 2006). Although they do not create natural forest structure and diversity, biofuel plantations still provide several habitat and hydrologic benefits compared to traditional crops and standard post mining cover types (Sage and Robertson 1996). Furthermore, they present an opportunity to bring eastern Kentucky’s lands closer to their natural state (Paine et al. 1996, Sage and Robertson 1996, Sperow 2006).

Species Selection

Selecting appropriate species for plantation operations is vital to success. Several species have come in to favor with plantation managers over the years, but black locust (Robinia
*pseudocacia* L.) and American sycamore (*Platanus occidentalis* L.) have shown excellent growth response to plantation conditions on disturbed and undisturbed sites.

**Black Locust as a Reclamation and Feedstock Species**

Black locust is a member of the *Faboideae* subfamily of the *Fabaceae* or pea family. It is characterized as being an early successional and intolerant species that typically lives to 70-80 years of age. Black locust is of moderate girth and height, reaching average diameters of approximately 30-45cm and heights of 30 meters. Its bark is ashy gray with deep furrows, and the leaves are large and odd-pinnately compound.

It is seeded and planted more than any other species on reclaimed mines, and numerous studies illustrate its superior performance compared to other species on reclaimed mines (Boring and Swank 1984, Ashby 1985). Black locust successfully establishes itself through manual broadcast or manual plantings, exhibits rapid juvenile growth, is a prolific sprouter, fixes soil nitrogen, has very high energy yield when burned (Stringer and Carpenter 1986), and displays increased survival rates compared to other species on reclaimed mines (Carpenter 1980, Gruenewald et al. 2007).

In addition to the aforementioned, black locust was traditionally thought to increase growth rates of interplanted species via soil nitrogen fixing, but studies have shown black locust out competes neighboring species for soil nitrogen in addition to their nitrogen fixing capacity. Therefore, pure stands are recommended (Carpenter 1980, Steinbeck 1999). Ashby (1985) found specimens could reach heights of 8 meters in 3 years, Carpenter (1980) saw growth up to 0.67 meters in one season, and Gruenewald et al. (2007) over 3 meters in 4 growing seasons.
American Sycamore as a Feedstock Species

American sycamore is a member of the Platanacea, an ancient family consisting of only one genera. Sycamore's are early successional and can be found in a variety of habitats from riparian zones to old fields. It is a fast growing species that is long lived and can reach immense sizes. Specimens can grow upwards of 35 meters in height and 2 meters in diameter. The bark is distinctive in its appearance with a reddish brown giving way to very light grey and smooth surface. The leaves are non descript; large, palmately veined and lobed with coarsely toothed to entire margins.

American sycamore has a long history as a plantation species, and was recognized for superior growth and ease of establishment as early as 1857 (Briscoe 1969). Numerous studies demonstrate sycamore’s extraordinary yield capacity, ease of establishment, and positive response to nutrient and water treatments (Steinbeck et al. 1972, Wood et al. 1976, Belanger and Pepper 1978, Wittwer et al. 1978, Witter 1980, Dickmann et al. 1985, Tang and Land 1996, Davis and Trettin 2006, Dickmann 2006). However, characteristics of sycamore plantations on disturbed mine soil has not been thoroughly examined.

Intensive Silviculture and Biomass Plantations

Understanding impacts of silvicultural techniques on plantation species is of primary concern to managers. Plantation managers must meet the demands of various buyers. Consequently, understanding the impacts of silvicultural techniques on biomass accumulation and allocation allows managers to meet the demands of differing buyers and increase the efficiency of their operations.
Fertilizer Treatments and Biomass Accumulation

Effects of intensive silviculture on height, diameter, and biomass accumulation have been extensively studied. Wood et al. (1976) reported biomass gains with fertilizer applications up to 3.5 times that of unfertilized plots, and near doubling of height and diameter for sycamore plantations on upland terraces in western Kentucky. Less dramatic growth increases in American sycamore, up to 23%, were reported on minesoils in southeastern Ohio (Kost et al. 1998). Similar results were reported in several additional studies (Wood et al. 1977, Wittwer et al. 1978, Laing et al. 1985, Mark D. Coleman 1998, Tuskan 1998, Samuelson et al. 2001, van den Driessche et al. 2003, Coyle and Coleman 2005, Cobb et al. 2008). Despite these studies, the role of fertilization in young plantation development is still in question. Nitrogen burn and proliferation of weedy competition are primary concerns. Furthermore, few assessments of the impacts of fertilization on plantation growth have taken place on reclaimed surface mines or other severely disturbed landscaped.

Irrigation Treatments and Biomass Accumulation

Upland and minesoil plantations receiving irrigation treatments respond with significant increases in height, diameter, and biomass accumulation (Casselman et al. 2006). American sycamore receiving irrigation treatments on upland coastal plains of Georgia exhibited 300-400% increases in height, diameter, and biomass (Allen et al. 2005b). Cobb et al. 2008 witnessed 132% biomass accumulation in American sycamore plantations on sandy sites, and Coyle and Coleman (2005) recorded twice as much biomass accumulation in irrigated sycamore plantations compared to non irrigated counterparts. Moreover, several studies had comparable findings on upland sites.

**Irrigation, Fertilization, and Biomass Allocation**

Quantifying effects of fertilizer and irrigation treatments on biomass allocation is a recent trend in silvicultural research. Identifying the impacts of intensive management as accelerated development or shifts in allocation is a key to understanding plant strategies. It was previously thought that fertilizer and irrigation treatments increase shoot production at the expense of roots, but recent studies suggest that nutrient and moisture amendments only accelerate natural shifts in development, as opposed to altering resource allocation. This is especially of concern for biomass managers targeting desirable organs i.e., stems and branches as opposed to roots and leaves. Spruce and pine stands in Sweden exhibited allocation shifts in branch and root tissue following irrigation and fertilizer treatments. Branch wood allocation increased after fertilizer and irrigation treatments, and root mass decreased following irrigation treatments, but increased after fertilizer treatments (Axelsson and Axelsson 1986), although these studies did not account for ontogeny.

Contrarily, eastern cottonwood plantations (*Populus deltoides*) in Wisconsin displayed decreases in coarse root, and increases to stem carbon allocation when subject to fertilizer
treatments (Coleman et al. 2004b). Coyle and Coleman (2005) evaluated the causes of biomass allocation shifts in two eastern cottonwood clones and American sycamore following nutrient and water amendments. The study found allocation shifts away from roots as nutrient and water treatments increased, but attributed those shifts to natural development. Coyle and Coleman (2005) also determined that only a shift from coarse root to fine root production was a function of resource amendments and not natural ontogeny. At this time, more research is needed, including additional species, sites, and regions, to fully understand the effects of nutrient and moisture amendments on plant allocation strategies.

**Impact of Silvicultural Treatment on Leaf Morphology**

Sigurdsson et al. (2001) observed an increase in leaf area following fertilizer treatments. Peterson et al. (2008) reported increases in leaf area index following intensive weed control, but no effect on specific leaf area. Similar increases leaf area were reported for fertilized and irrigated plantations in Georgia (Coleman et al. 2004a), poplar plantations in Minnesota (Coleman et al. 2006) and Canada (van den Driessche et al. 2003). Other studies witnessed no significant changes in leaf area following intensive management, despite increases in height and diameter (McConnaughay and Coleman 1999, Samuelson et al. 2008). McConnaughay and Coleman (1999) also noted the importance of accounting for morphological differences across varying age classes for the same species. Plantations directly planted with seedlings of the same age eliminate variance associated with varying age classes. DeBell and Clendenen (1996) reported increased leaf area in association with increased spacing of planted seedlings in plantations.
Finally, foliage macro nutrient concentrations may be affected by management practices. Fertilization and irrigation + fertilization treatments increased leaf nitrogen concentrations in a Canadian poplar plantation (van den Driessche et al. 2003). The same study reported elevated total phosphorus in foliage under irrigation treatments. Cobb et al. (2008) reported significant increases of foliar nitrogen in loblolly pine, sweet gum, and sycamore trees at a plantation in Georgia. Conversely, fertilization decreased leaf phosphorous concentrations in loblolly pine and sweet gum plantations in the southeastern United States (Samuelson et al. 2001).

Understanding the impacts of silvicultural treatments on leaf area and morphology are important to stand managers. Measurements of leaf area and leaf area index have implications for site production of woody tissue. Specific leaf area (leaf area divided by dry weight) evaluates leaf thickness and is an indirect measurement of leaf level photosynthetic activity at the leaf level, because thicker leaves typically have more palisade parenchyma, chlorophyll, and are more photosynthetically active. Maximizing leaf area and specific leaf area will increase site productivity and efficiency. Several studies examined impacts of silvicultural impacts on leaf area, but few, if any, have taken place on reclaimed mines or other disturbed sites. Few studies have quantified the impacts of fertilizer and irrigation treatments on specific leaf area. As a metric of leaf thickness, it indirectly measures leaf level photosynthetic capacity. Examining changes in specific leaf area in response to irrigation and fertilizer can reveal limiting factors of leaf level photosynthetic activity when in full sunlight environments (Evans and Poorter 2001). This will allow managers to maximize photosynthetic capacity in relation to intensive management strategies.
Conclusion

Despite extensive research on short rotation woody plantations, several gaps are present in the current research. Biomass accumulation studies on reclaimed agricultural fields and reclaimed bottom lands are pervasive throughout the literature, but an examination of short rotation woody plantation studies on reclaimed coal mines throughout Appalachia and other highly disturbed landscapes in the eastern United States. Furthermore, more experiments examining shifts in allocation in response to intensive silviculture are need across all landscapes. Lastly, there are no studies examining the effect of irrigation and fertilization on specific leaf area. This study will contribute to our understanding of biomass accumulation, allocation, and specific leaf in response to intensive management. Additionally, this study will lay the groundwork for diversification of Kentucky's energy industry and the promotion of surface mine reforestation as opposed to recent techniques.
Chapter 2: Biomass accumulation and allocation of a American sycamore and black locust plantation on a reclaimed surface mine in Eastern Kentucky

Introduction

Woody biomass is the leading renewable energy supply in the United States and the United States Department of Energy forecasts the potential need for a billion ton annual biomass supply by 2050 (English and Ewing 2002). Increased biomass demand will be met through fuel reduction treatments of natural stands, utilization of industrial waste residues, and reforestation projects (Perlack et al. 2005). Woody biofuel plantations provide an excellent opportunity to diversify and increase domestic energy feedstocks (Johnson et al. 2007). Non woody biomass such as switchgrass, miscanthus, and corn provide annual stocks, but woody crops can reduce erosion, runoff, and nutrient loss with longer rotations (Nyakatawa et al. 2006). Advancements in the processing of woody cellulosic tissue continue to increase its viability as source of ethanol manufacturing (McKendry 2002a, McKendry 2002b, Patzek 2005). Woody crops intended for co-firing with coal for electricity generation will prolong coal supplies, reduce NOx and SOx emissions, and contribute to national woody feedstock supplies (Boylan 1996). Kentucky permits mining on 1.8 million acres; a majority of which are located in the Eastern half of the commonwealth (Cole et al. 2001). Implementing short rotation woody plantations on reclaimed surface mines presents an excellent opportunity to increase wood production without diverting current agricultural or naturally forested lands to plantations (Casselman et al. 2006).

Intensive management of forest plantations can greatly increase biomass production (Coyle and Coleman 2005, Cobb et al. 2008, Coyle et al. 2008). Fertilization can enhance nutrient availability on highly degraded sites and irrigation can mitigate the
impacts of severe drought (Coleman et al. 2004a, Casselman et al. 2006). Mechanical
and chemical control of weedy competition can increase productivity of target species
(Petersen et al. 2008). However, early fertilization of tree plantations may exacerbate
herbaceous competition and lower biomass production (Ramsey et al. 2003).

Garnering a greater understanding of the impacts intensive management on plant
strategies will allow land managers to refine their silvicultural practices with the goal of
increasing efficiency and profitability of biomass operations. Traditionally, resource
amendments were thought to divert allocation from roots to stem and foliage, but recent
studies have suggested this is an artifact of ontogeny (Coleman et al. 2004a, Coyle and
Coleman 2005, Coleman et al. 2006), i.e. fertilizer and irrigation applications only
accelerate natural shifts in allocation, as opposed to altering plant strategies.

American sycamore (Platanus occidentalis L.) and black locust (Robinia pseudocacia L.)
have long histories as plantation species (Wittwer et al. 1978, Witter 1980, Dickmann et
al. 1985). American sycamore is characterized by fast growth and their propensity for
bottomland sites makes them an ideal candidate for the anaerobic conditions of heavily
compacted sites. Several studies have established the value of black locust as a
reclamation species in the greater Appalachian region (Zimerman and Carpenter 1980,
Rowell and Carpenter 1983, Boring and Swank 1984, Ashby 1985, Stringer and
Carpenter 1986). It enhances soil conditions by fixing nitrogen and performs well on cast
overburden of reclaimed mines. Numerous studies have quantified the impact of nutrient
applications on plantation growth (Coleman et al. 2004a, Coyle and Coleman 2005);
however, more research is needed to better understand the effects of fertilizer treatments
on reclaimed surface mines. Past studies questioned the impacts of increased resource
availability on relationships between diameter, height, and biomass, but recent findings suggest nutrient amendments only accelerate ontogenetical stages and do not alter allometric relationships (Coyle and Coleman 2005, Coleman et al. 2006, Coyle et al. 2008). This study may further our understanding of these relationships.

Despite an extensive body research on short rotation woody plantations, very few studies have examined the effects of intensive management on height, diameter, predicted biomass, and survival of trees on reclaimed surface mines. Additionally, no studies have attempted to quantify resource partitioning and shifts in allocation of woody plantations on reclaimed mines. The objectives of this study are to test the effects of granular fertilizer, irrigation, and irrigation + liquid fertilization applications on growth, biomass accumulation, and biomass allocation on a black locust and American sycamore plantation established on a reclaimed surface mine in Eastern Kentucky. This paper presents data following two growing seasons.

Methods

Study Site

The study is located on a reclaimed surface mine within the Cumberland Plateau physiographic region near Hazard, Kentucky (Knott County). The region is characterized by warm humid summers and cool winters. Yearly rainfall average is 127 cm year\(^{-1}\). The average July high temperature is 30\(^{\circ}\) C and the average January low is -5\(^{\circ}\) C. Upland oak-hickory hardwood forests dominated the site prior to being cleared for mining. The soil profile is undeveloped, compacted, derived from shale and sandstone, and large rocks pervade the soil matrix (Conrad 2002).
The study site was previously reclaimed using smooth grading. Large equipment used to reclaim mines creates high levels of soil compaction, which can negatively affect tree growth by inhibiting root growth and reducing soil drainage and aeration (Unger and Cassel 1991). The site was ripped with a D-11 dozer in February of 2008 to alleviate compaction and reduce weedy competition. Twelve 0.209 ha plots, three replicates of each treatment, were established following ripping. In March 2008, half of each plot was planted with American sycamore, while the other half was planted with black locust. 1-0 bare root seedlings were used. Large boulders and rough topography prevented uniform seedling plantings. Mean seedling density across all plots was 1842 stems ha\(^{-1}\).

Following surface ripping and planting, the vegetation community was populated by early successional and other disturbance dependant plants reported at other reclaimed surface mines in the region (Bell and Ungar 1981, Holl and Cairns 1994, Holl 2002). Dominant genera include: *Rubus, Lespedeza, Ailanthus, Ambrosia, Oxalis, Cirsium, Veronia, Leucanthemum, Rudbeckia, Festuca*, and *Coronilla*.

*Field Methodology*

For each species, seedling height and basal diameter were tracked a centrally located 0.019 ha measurement sub plot (Figure 2.1). All seedlings in the 0.019 measurement subplots were tagged to facilitate re-measurement. Each species plot half also contained two 0.008 ha destructive sampling sub plots (Figure 2.1). At least two treated border rows were present around all measurement and destructive harvest sub plots. Control (C), fertilization (F), irrigation (I), and irrigation + fertilizer (IF) treatments were replicated three times and randomly assigned to the experimental plots. All fertilized plots received 36 kg ha\(^{-1}\) of granular nitrogen, phosphorous, and potassium during June of
2008 and 2009. 3.4 million liters of water ha\(^{-1}\) were applied to I and IF treatments throughout the 2008 and 2009 growing seasons with a drip irrigation system. 36 kg ha\(^{-1}\) of liquid nitrogen, phosphorous, and potassium was applied to IF plots during the 2008 and 2009 growing seasons. To control competing vegetation, glyphosate was administered to all plots at a rate of 0.871 liters ha\(^{-1}\) with backpack sprayers during June of 2008 and 2009.

Field and Laboratory Measurements

Initial seedling basal diameters and heights were recorded in measurement sub plots after planting in May 2008. Basal diameter was taken to the nearest tenth of an mm with digital calipers at two locations, 90° apart from one another, and then averaged. Measurements taken following the first growing season were recorded in January of 2009 and following the second growing season in December of 2009. To evaluate the effect of ungulate browse on the responses of the planted seedlings, browse was categorically assessed across four levels using methods adapted from Keigly and Frisina (1998). Where level 1 indicates an uninterrupted growth type, 2 equates a released type, 3 indicates an arrested growth pattern, and 4 represents retrogressed growth architecture.

Destructive harvests were used to develop allometric equations, analyze partition fractions, and test for shifts in allocation. For each species, 1 seedling was excavated from a destructive sampling subplot within each replicate plot. Destructive sampling occurred across 14 days during September and October of 2009 and a total of 24 specimens were excavated (3 per species and treatment combination). Destructive methods were adapted from Coyle and Coleman (2005) who excavated 1-2 trees per replicate plot and Davis and Trettin (2006) who excavated 13 total trees, 6-8 from each
species, for above and below ground analysis. Harvested trees were defoliated in September prior to excavation. All roots were excavated from a 60 x 60 cm square centered on the tree to a 30 cm depth. This method was derived from similar studies (Albaugh et al. 1998, King et al. 1999, Pregitzer et al. 2002, Coyle and Coleman 2005, Coyle et al. 2008) and adapted to accommodate soil conditions at our site. Trees were partitioned into roots, stems, and leaves. Diameters and heights were recorded before partitions were oven-dried for 48 hours at 60°C, and then weighed to the nearest hundredth of a gram.

Statistical Analysis

Destructively sampled trees were used to develop a regression equation for predicting above ground leafless biomass (SAS 9.1; SAS Institute Inc., Cary, NC). Per stem biomass was predicted using a linearized version of a power function that included species, seedling height, and basal diameter as independent variables. Equations were then used to predict above ground leafless biomass of each tree located in the 0.019 ha measurement subplots. Analysis of variance (ANOVA) was used to test for differences (α = 0.05; n=3) in plot mean height, basal diameter, and per stem biomass among the two species and four treatments following two growing seasons. Pre treatment analysis revealed no significant differences for basal diameter, but American sycamore heights were significantly lower in fertilized plots compared to irrigation and irrigation+fertilizer plots. For analysis of biomass accumulation, we used average per stem plot mean biomass (n=3) as a dependant variable because area based calculations would have differed due to varying plot densities, not disparate growth patterns. A generalized linear model was used for the ANOVA (n=3) that tested for differences in seedling survival
among treatment and species. The generalized linear model utilized a binomial distribution and a logit link function to account for the binomial nature of survival data (Littell et al. 2002).

Following the methodology outlined in Coyle and Coleman (2005), shifts in resource allocation were tested by calculating K coefficients when regressing one tissue partition against another or total mass using the model:

\[ \ln y = a + K \ln x \]

where x and y are tissue components or total biomass being compared

Utilizing tissue components or total biomass as independent variables adjusts for shifts in allocation due to ontogeny and not nutrient or moisture amendments (Causton and Venus 1981; Hunt 1991; Coyle and Coleman 2005). Log transformed data was used in an analysis of covariance to test for different slopes (K) in each treatment.

**Results**

**Survival and Growth**

Granular fertilizer treatments increased American sycamore basal diameter (Figure 2.1) and height (Table 2.1). Mean sycamore height was 168.54cm in fertilized plots compared to 79.50cm in irrigation plots and 100.41cm in controls. Basal diameter in fertilized plots was nearly double (31.6mm) that of other treatments.

Average seedling basal diameter and height of black locust did not differ among the treatments following two growing seasons. Average basal diameter was between 17.8mm (fertilization) and 12.9mm (irrigation + fertilization). Mean height of black
locust was 121.79cm in fertilizer, 89.52cm in irrigation, 89.29cm in irrigation + fertilizer, and 83.85cm in control treatments.

Sycamore survival was unaffected by treatment and ranged from 83.3% in the irrigation + fertilization treatment to 76.5% in plots receiving irrigation. Despite no intra-species differences in survival, sycamore survival was significantly higher than black locust across all treatments, which was less than 60% in all treatments.

Ungulate browsing was higher on black locust compared to American sycamore (Table 2.1). Eighty-five percent of all black locusts exhibited browse level of 2 or greater, while only 1 percent of American sycamores displayed a similar browse pattern.

**Biomass Accumulation**

Per stem biomass was predicted from species, seedling diameter and height using a linearized version of a power function (n = 24). Model coefficient of determination ($r^2$) was 0.97 and residual analysis indicated that assumptions of normality and homogeneity of variance were met. No significant interactions among treatment or species were present. Regression equations were as follows:

Black Locust: $\ln(\text{Weight}) = -5.85 + 2.10*\ln(\text{Height}) + 1.78*\ln(\text{Diameter})$

Sycamore: $\ln(\text{Weight}) = -6.13 + 2.10*\ln(\text{Height}) + 1.78*\ln(\text{Diameter})$

where weight is listed in grams stem$^{-1}$, height in centimeters, and basal diameter in millimeters

Mean per stem predicted above ground leafless biomass was greatest in American sycamore (Table 2.1). Sycamore mean per stem mass in fertilized plots (373.18g) was
nearly four times greater than the next highest treatment (97.95g I; 85.46g IF; 48.70g I). Mean black locust per stem mass was 113.03g in fertilized plots and 53.44g in control treatments.

**Biomass Allocation**

Sycamore root mass, shoot mass, leaf mass, and total mass were significantly higher under fertilizer treatments (Table 2.2). Irrigation treatments resulted in the lowest sycamore root mass, shoot mass and total mass, but control plots produced the lowest leaf mass (Figure 2.2). All black locust partition and total masses were lowest in control treatments. Although fertilizer treatments reduced root fractions for black locust and American sycamore resource, the effect was not statistically significant and there was no relationship between root fraction (Table 2.4) and total mass. No significant treatment effects were detected for either shoot or leaf fractions in either species. K coefficient analysis utilized to test for shifts in allocation irrespective of developmental stages did not identify any significant effects of treatment on resource allocation for either species (Table 2.3).

**Discussion**

**Growth Measurements and Survival**

American sycamore height and diameter were significantly greater in granular fertilizer treatments than in the other treatments following two growing seasons. Fertilized sycamore heights were 68 % greater compared to controls and more than doubled the heights of irrigation treatments. American sycamore under controlled drainage on a former agricultural field in South Carolina reported greater height and diameters than at
our site (Davis and Trettin 2006). While irrigation has been used to increase growth in short rotation plantations (Cobb et al. 2008, Samuelson et al. 2008), this treatment did not increase growth or biomass accumulation for American sycamore or locust. In fact, apparent trends in height and basal diameter data suggest that irrigation may have negatively impacted the growth of sycamore. Other studies reported that American sycamore may be nutrient, not moisture, limited in the relatively humid and wet southeastern United States (Coleman et al. 2004a, Coyle and Coleman 2005, Davis and Trettin 2006). However, no studies have indicated a negative impact of irrigation on sycamore growth metrics. Although our study site was ripped to alleviate compaction, which has been shown to increase growth (Casselman et al. 2006, Shrestha et al. 2009), bulk density may still be high compared to undisturbed sites (Conrad 2002). The combined effects of irrigation treatments and high compaction levels may have produced sustained anaerobic conditions that resulted in reduced height and diameter for sycamore despite its affinity for moist conditions.

American sycamore survival at our site was similar to a mixed hardwood planting, and outperformed hybrid poplars and white pine on similar substrates on a West Virginia reclaimed surface mine (Casselman et al. 2006). Casselman et al. (2006) reported 80 % and 72 % survival for mixed hardwoods and hybrid poplars, respectively, under chemical weed and fertilizer treatments following one growing season, while sycamore at our site exhibited a mean survival of 80 % across all treatments. Although survival at our site was comparable to other plantations established on surface mines in the region, plantations founded on abandoned agricultural fields and drained bottomlands witnessed higher rates of survival. American sycamore in South Carolina had a survival of 90 % under
controlled drainage and 79% under uncontrolled drainage after two growing seasons (Davis and Trettin 2006).

There was no statistical effect of any treatment on black locust height and diameter. Analogous to American sycamore, granular fertilizer resulted in elevated mean heights and diameters, but there was no negative effect of irrigation on mean height or diameter that was found for American sycamore. Black locust was significantly outperformed by American sycamore in all growth metrics and treatments. This trend may be attributed to differential ungulate browsing seen between black locust and American sycamore.

Starfire Mine, since renamed Big Elk Mine, is home to the highest densities of elk in the eastern Kentucky reintroduction zone (Dahl 2008). More than 80% of all black locusts, irrespective of treatment, exhibited browse and subsequently growth of many trees was completely arrested due to browse of every apical meristem. Numerous specimens were scraped up or completely uprooted. Prior studies of black locust on reclaimed coal mines in Eastern Kentucky (Carpenter and Eigel 1979, Carpenter 1980) reported higher growth metrics than at our site, but it appears that ungulate browsing severely mitigated black locust growth in our study and likely confounded the effects of nutrient and moisture treatments in our study. Dahl (2008) estimated the elk population at approximately 7,000, and without a natural predator in the region they may approach 14,000 in the near future. This could have serious implication for forest succession and the success of reforestation plantings throughout the entire Appalachian region as elk migrate out of eastern Kentucky and into neighboring states with surface mine lands that serve as excellent habitat.
Nutrient and moisture amendments had no significant impact on survival for either species. Despite no treatment effect, American sycamore had significantly higher survival compared to black locust. Lower survival of black locust is likely attributed to excessive ungulate browsing. Additionally, weedy competition at the site was intense. Competition may also have promoted rapid height growth in fertilized plots. Typically, this would come at the expense of girth, but fertilizer applications may have allowed for rapid height growth in response to weeds while maintaining an appropriate diameter.

**Biomass Accumulation**

Granular fertilizer applications led to large gains in total mass and per stem above ground leafless biomass in American sycamore. Fertilizer treatments increased total mass by 287 % over irrigation + fertilization treatments and 608 % compared to control plots. Per stem above ground leafless biomass nearly quadrupled in fertilizer treatments (373.18g) compared to controls (97.95g) and nearly eight times greater than irrigation treatments (48.7g). Stocking densities were not consistent across all plots, but using a mean stocking rate of 1849 stems ha\(^{-1}\) mean annual biomass production was 0.36 Mt yr\(^{-1}\) after two growing seasons. This is significantly lower than other studies (Table 2.4). Fertilized direct seeded black locusts on a reclaimed mine in Eastern Kentucky produced 3.3 Mt yr\(^{-1}\) following two growing seasons (Carpenter and Eigel 1979), but their study had much higher stocking rates. Even greater gains were witnessed for American sycamore in Western Kentucky (Wood et al. 1977), the Savanna River Site in South Carolina (Coyle and Coleman 2005), and on former agricultural land in South Carolina (Davis and Trettin 2006). Irrigation appeared to negatively affect sycamore height, diameter, above ground leafless biomass, and total mass, but had a positive effect on total leaf mass. Although
negative effects on a variety of growth metrics is not supported by other studies, an increase in leaf mass following irrigation is in congruence with other studies (Coleman et al. 2004a, Coyle and Coleman 2005).

*Biomass Allocation*

There was no statistical significance of any treatment on root, stem, or leaf fractions for any treatment or species at our site. Although there was no statistical significance, trends of declining root fraction with fertilizer applications for both species at our site support other findings (Coyle and Coleman 2005). Coyle and Coleman (2005) reported similar shifts in partition fractions, but our study only included two growing seasons. Therefore, it is possible the statistical significance of their findings was a function of a longer examination period. Furthermore, harsh site conditions associated with reclaimed surface mines, such as in our study, may have delayed allocation shifts due to ontogeny present in other studies with higher site quality and a longer duration.

Analysis of K coefficients indicated no effect of treatments on biomass allocation for either sycamore or black locust. Coyle and Coleman (2005) reported similar results for sycamore at the Savannah River Site in South Carolina. They contributed slight shifts in fine root allocation to intensive management. The pervasiveness of large boulders throughout the soil matrix at our study prevented an accurate analysis of fine vs. coarse root production, thus we were unable to test for allocation shifts of fine roots. It is possible that characteristics of the soil matrix (cast mining overburden) affected tree response to resource amendments at our site. Their analysis was also done following three growing seasons; it is possible that shifts in allocation are only possible once trees
reach a particular developmental stage that has not happened at our site due lower site quality and fewer growing seasons.

Conclusion

Granular fertilizer applications can significantly increase American sycamore height, diameter, and predicted stem on ripped reclaimed surface mines. These results suggest that reclaimed mine sites can serve as viable biomass production sites with management. Our study indicates that early fertilizer applications can accelerate young stand development, but long term benefits remain to be seen. This accelerated growth may have both ecological and economic benefits; plantations can serve as a nurse crop that improves soil porosity, nutrients, and organic matter and mining companies can receive bond release earlier because of a rapidly closing canopy. Despite significant gains in height, diameter, and stem mass, our results showed no shift in allocation in response to treatments following two growing seasons on a reclaimed surface mine. Irrigation treatments at highly compacted sites may create sustained anaerobic conditions that are detrimental to growth; even for species with an affinity for wet sites. Further examination is needed, but drip irrigation systems include excessive costs when compared to manual broadcast of granular fertilizer. Despite the long history of black locust as a reclamation species and the benefit of its high caloric content for biofuel operations, the establishment of black locust may need to be reconsidered due to potential browse impact by the large reintroduced elk herds present on surface mines in the region.
Chapter 2 Tables

Table 2.1: Predicted mean per stem mass, basal diameter, height, survival, and browse following two growing season. Lower case letters indicate significance (p<0.05; n=3) across species and treatments. Control [C], irrigation [I], fertilizer [F], and irrigation + fertilizer [IF].

<table>
<thead>
<tr>
<th>Species</th>
<th>Treatments</th>
<th>Stem Mass g</th>
<th>Diameter (mm)</th>
<th>Height (cm)</th>
<th>Survival %</th>
<th>Browse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sycamore</td>
<td>C</td>
<td>97.95±33.4a</td>
<td>18.8±2.8a</td>
<td>100.4±15.5b</td>
<td>80.0a</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>48.7±16.3a</td>
<td>14.1±1.9a</td>
<td>79.5±9.4b</td>
<td>76.5a</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>373.2±37.1b</td>
<td>31.6±1.4b</td>
<td>168.5±3.7a</td>
<td>80.1a</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>IF</td>
<td>85.5±19.6a</td>
<td>16.5±0.9a</td>
<td>114.8±18.9ab</td>
<td>83.3a</td>
<td>0.0</td>
</tr>
<tr>
<td>Black Locust</td>
<td>C</td>
<td>52.4±3.8a</td>
<td>13.1±0.3a</td>
<td>83.9±8.1b</td>
<td>53.7b</td>
<td>78.4</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>65.4±17.2a</td>
<td>14.5±1.6a</td>
<td>89.5±7.9b</td>
<td>58.5b</td>
<td>88.3</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>113.0±13.0a</td>
<td>17.8±0.1a</td>
<td>121.7±13.4ab</td>
<td>58.5b</td>
<td>93.1</td>
</tr>
<tr>
<td></td>
<td>IF</td>
<td>56.9±22.8a</td>
<td>12.8±1.9a</td>
<td>89.3±13.1b</td>
<td>49.9b</td>
<td>84.7</td>
</tr>
</tbody>
</table>
Table 2.2: Mean root (RF; RM), shoot (SF; SM), and foliage (LF; LM) fractions and mass of destructive harvests following two growing seasons. Lower case letters indicate significance (p<0.05; n=3) across species and treatments. Control [C], irrigation [I], fertilizer [F], and irrigation + fertilizer [IF].

<table>
<thead>
<tr>
<th></th>
<th>RF</th>
<th>SF</th>
<th>LF</th>
<th>RM</th>
<th>SM</th>
<th>LM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sycamore</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.43±0.01a</td>
<td>0.39±0.02b</td>
<td>0.15±0.02c</td>
<td>93.0±0.6a</td>
<td>85.9±4.1a</td>
<td>33.8±4.9ab</td>
</tr>
<tr>
<td>I</td>
<td>0.43±0.04a</td>
<td>0.41±0.04b</td>
<td>0.12±0.04c</td>
<td>45.4±21.9a</td>
<td>43.9±19.4a</td>
<td>17.1±12.5a</td>
</tr>
<tr>
<td>F</td>
<td>0.33±0.08ab</td>
<td>0.49±0.02ab</td>
<td>0.17±0.04c</td>
<td>509.6±120.0b</td>
<td>763.2±78.5b</td>
<td>263.0±61.4b</td>
</tr>
<tr>
<td>IF</td>
<td>0.34±0.01ab</td>
<td>0.48±0.03ab</td>
<td>0.16±0.03c</td>
<td>133.8±35.5a</td>
<td>188.9±47.5a</td>
<td>70.7±33.3ab</td>
</tr>
<tr>
<td><strong>Black Locust</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.32±0.02ab</td>
<td>0.46±0.04ab</td>
<td>0.19±0.04c</td>
<td>36.9±11.5a</td>
<td>56.2±20.0a</td>
<td>21.3±18.5ab</td>
</tr>
<tr>
<td>I</td>
<td>0.34±0.13ab</td>
<td>0.52±0.07ab</td>
<td>0.110.04a</td>
<td>62.9±55.0a</td>
<td>168.0±158.5</td>
<td>31.5±29.3a</td>
</tr>
<tr>
<td>F</td>
<td>0.21±0.05b</td>
<td>0.62±0.06a</td>
<td>0.16±0.03c</td>
<td>31.8±11.6a</td>
<td>97.5±44.7a</td>
<td>27.1±11.7ab</td>
</tr>
<tr>
<td>IF</td>
<td>0.31±0.04ab</td>
<td>0.56±0.04ab</td>
<td>0.12±0.02c</td>
<td>60.4±14.5a</td>
<td>114.0±33.5a</td>
<td>21.3±3.5ab</td>
</tr>
</tbody>
</table>
Table 2.3: Analysis of allometric K coefficient for varying partition and total mass comparisons (n=3). Control [C], irrigation [I], fertilizer [F], and irrigation + fertilizer [IF]

<table>
<thead>
<tr>
<th></th>
<th>Sycamore</th>
<th>Black Locust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root F vs. total mass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.025</td>
<td>-0.026</td>
</tr>
<tr>
<td>I</td>
<td>-0.080</td>
<td>-0.131</td>
</tr>
<tr>
<td>F</td>
<td>0.055</td>
<td>0.004</td>
</tr>
<tr>
<td>IF</td>
<td>-0.163</td>
<td>-0.214</td>
</tr>
<tr>
<td>Shoot F vs. total mass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.129</td>
<td>0.150</td>
</tr>
<tr>
<td>I</td>
<td>0.067</td>
<td>0.088</td>
</tr>
<tr>
<td>F</td>
<td>-0.010</td>
<td>0.011</td>
</tr>
<tr>
<td>IF</td>
<td>0.076</td>
<td>0.097</td>
</tr>
<tr>
<td>Root F vs. leaf F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>-0.054</td>
<td>-0.097</td>
</tr>
<tr>
<td>I</td>
<td>-0.238</td>
<td>-0.282</td>
</tr>
<tr>
<td>F</td>
<td>-0.136</td>
<td>-0.180</td>
</tr>
<tr>
<td>IF</td>
<td>-0.156</td>
<td>-0.200</td>
</tr>
<tr>
<td>Shoot F vs. leaf F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>-0.343</td>
<td>-0.279</td>
</tr>
<tr>
<td>I</td>
<td>-0.046</td>
<td>0.017</td>
</tr>
<tr>
<td>F</td>
<td>-0.211</td>
<td>-0.148</td>
</tr>
<tr>
<td>IF</td>
<td>-0.208</td>
<td>-0.144</td>
</tr>
<tr>
<td>Shoot F vs. root F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>-0.075</td>
<td>-0.174</td>
</tr>
<tr>
<td>I</td>
<td>-0.434</td>
<td>-0.533</td>
</tr>
<tr>
<td>F</td>
<td>-0.218</td>
<td>-0.317</td>
</tr>
<tr>
<td>IF</td>
<td>-0.374</td>
<td>-0.473</td>
</tr>
<tr>
<td>Root F vs. shoot F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>-0.135</td>
<td>-0.433</td>
</tr>
<tr>
<td>I</td>
<td>-0.731</td>
<td>-1.030</td>
</tr>
<tr>
<td>F</td>
<td>-0.983</td>
<td>-1.279</td>
</tr>
<tr>
<td>IF</td>
<td>0.089</td>
<td>-0.209</td>
</tr>
</tbody>
</table>
Table 2.4: Summarization of mean annual production of other intensively managed plantations throughout the southeastern United States

<table>
<thead>
<tr>
<th>State</th>
<th>Fertilization (kg N ha(^{-1}) yr(^{-1}))</th>
<th>Production (Mg ha(^{-1}) yr(^{-1}))</th>
<th>Stocking (trees ha(^{-1}))</th>
<th>Age (yr)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Georgia</td>
<td>22</td>
<td>9.2</td>
<td>26898</td>
<td>4</td>
<td>Steinbeck et al. (1972)</td>
</tr>
<tr>
<td>Georgia</td>
<td>22</td>
<td>5.8</td>
<td>3363</td>
<td>4</td>
<td>Steinbeck et al. (1999)</td>
</tr>
<tr>
<td>Georgia</td>
<td>121</td>
<td>4.6</td>
<td>3472</td>
<td>4</td>
<td>Dickmann et al. (1985)</td>
</tr>
<tr>
<td>Kentucky</td>
<td>56</td>
<td>4.1</td>
<td>37037</td>
<td>3</td>
<td>Wood et al. (1977)</td>
</tr>
<tr>
<td>Kentucky</td>
<td>168</td>
<td>3.4</td>
<td>5978</td>
<td>5</td>
<td>Wittwer et al. (1978)</td>
</tr>
<tr>
<td>Kentucky</td>
<td>169</td>
<td>6.5</td>
<td>6050</td>
<td>5</td>
<td>Wittwer et al. (1980)</td>
</tr>
<tr>
<td>Kentucky</td>
<td>36</td>
<td>0.4</td>
<td>1849</td>
<td>2</td>
<td>This study</td>
</tr>
<tr>
<td>Mississippi</td>
<td>55</td>
<td>6.8</td>
<td>2252</td>
<td>3</td>
<td>Tang and Land (1996)</td>
</tr>
<tr>
<td>South Carolina</td>
<td>80</td>
<td>6.3</td>
<td>1333</td>
<td>3</td>
<td>Coyle and Coleman (2005)</td>
</tr>
<tr>
<td>Tennessee</td>
<td>450</td>
<td>4.0</td>
<td>4000</td>
<td>1</td>
<td>Tschaplinski et al. (1991)</td>
</tr>
</tbody>
</table>
Chapter 2 Figures

Figure 2.1: Layout of individual half acre experimental unit. Dashed line represents species divide. Light gray areas are measurement sub plots for tagged and tracked trees. Black areas are destructive harvest sub plots.
Figure 2.2: Basal diameter of American sycamore and black locust under varying treatments following two growing seasons. Letters indicate significant differences (p<0.05) across treatments and species.
Figure 2.3: Mean destructive harvest partition fractions, expressed as a fraction of total tree mass, for American sycamore and black locust following two growing seasons.
Figure 2.4: Destructive harvest mean root fraction in American sycamore and black locust following two growing seasons. Letters indicate significant differences (p<0.05) across treatments and species.
Chapter 3: Carbon and nitrogen dynamics of a American sycamore and black locust plantation on a reclaimed surface mine in Eastern Kentucky

Introduction
Increasing levels of atmospheric CO\textsubscript{2} is a growing concern for both scientists and politicians. The 2004 Intergovernmental Panel on Climate Change (IPCC) reported that CO\textsubscript{2} emissions have increased 80 percent from 1970-2004. As a result of this, atmospheric CO\textsubscript{2} levels have risen from 228 ppm during pre industrial times, to a current level of 379 ppm (IPCC 2007). This was primarily attributed to energy use and manufacturing, transportation, and industrial production of goods.

Scientists have begun to quantify the impacts of elevated levels of atmospheric CO\textsubscript{2} and other greenhouse gas emissions over the past two decades. The IPCC states that increasing temperatures, rising sea levels, and decreasing polar ice are likely to be a function of amplified anthropogenic CO\textsubscript{2} emissions. Rates of temperature and sea level rises have both doubled over the past 50 and 15 years, respectively (IPCC 2007). Moreover, elevated atmospheric greenhouse gases have likely increased the frequency of extreme weather events such as heat waves, heavy rains, high seas, fires and cyclones (Westerling et al. 2006, Bowman et al. 2009).

International concern over the anthropogenic contributions to rising levels of atmospheric greenhouse gasses continues to grow. The Kyoto Protocol, a protocol to the United Nations Framework Convention on Climate Change (UNFCCC), was established to achieve "stabilization of greenhouse gas concentration in the atmosphere at a level that would minimize dangerous anthropogenic interference with the climate system."

Although The United States did not ratify the treaty, legislative measures are being
proposed that put forward possible cap and trade systems. Additionally, further
development of Joint Implementations, Clean Development Mechanisms, and other
international carbon credit markets will increase the profitability of carbon sequestration
operations in developed countries.

Forests will play an important role in climate change mitigation. Rates of forest carbon
sequestration are well established, but the overall effects of forest cover on radiative
forcing are poorly understood (Jackson et al. 2008). Although forests typically act as
long term sinks, their impacts on stand biophysical properties may exacerbate climate
change by increasing sunlight absorption and by altering local hydrology (Jackson et al.
2008, Reyer et al. 2009). Studies suggest that the impacts of forests on climate change
are largely regional (Canadell and Raupach 2008). Forests in the southeastern United
States may cool surface temperatures by up to 4 degrees C, but boreal afforestation and
reforestation can have a negative impact by absorbing more sunlight compared to snow
cover (Randerson et al. 2006).

Intensive management of forests via fertilization and irrigation may enhance the carbon
sequestration capacity by increasing carbon concentrations or total biomass
accumulation. The conversion of agricultural land and naturally forested stands to
intensively managed plantations may maximize carbon sequestration, but would decrease
food production and continue to lower an already shrinking number of naturally forested
stands. The establishment of woody plantations on abandoned or degraded lands presents
an excellent opportunity to sequester atmospheric carbon. Instituting sequestration
projects on these lands facilitates the mitigation of anthropogenic greenhouse gas
emissions without reducing agricultural production and natural forested stands (Niu and
Duiker 2006). In the Appalachian region, the establishment of woody energy crops on the vast acreage of reclaimed surface mine lands represents an opportunity to transform an underutilized land base into a sustainable source of bioenergy feedstock. Extensive road networks present on surface mines provide an outstanding existing infrastructure to support biomass production. Intensive management of woody plantations on reclaimed mines, i.e. fertilization, irrigation, and weed control, can accelerate stand development and subsequently increase carbon sequestration potential (Casselman et al. 2006).

Recent studies have been implemented to identify the carbon sequestration potential of certain species (Jacobs et al. 2009), but few studies have examined carbon dynamics on severely degraded lands and the effects of moisture and nutrient amendments on carbon sequestration. Despite the benefits of fertilizer applications for biomass accumulation and carbon sequestration, excessive fertilization can negatively affect site carbon budgets. Excess granular fertilizer can release nitrous oxides that are damaging global warming gasses (Crutzen et al. 2007). Inefficient use of fertilizer also leads to unnecessary mining, manufacturing, and distribution of fertilizer which negatively impacts site carbon budgets and contributes to atmospheric CO$_2$ deposition. Additionally, some studies question the effectiveness of fertilization on early plantation development at rich sites (van den Driessche et al. 2003, Coleman et al. 2004a, Coyle and Coleman 2005). Other research has examined the effectiveness of progressively scaled nutrient amendments for young plantations, but few studies were implemented on severely disturbed sites (Coyle and Coleman 2005, Casselman et al. 2006). Our objectives are to evaluate the effect of nutrient and water amendments on the carbon sequestration potential and nitrogen use efficiency of intensively managed American sycamore and black locusts plantations on
reclaimed surface mines. Examination of nitrogen use efficiency will aid in the formulation of fertilization regimes that minimize costs and enhance carbon budgets of intensively managed plantations.

**Methods**

**Study Site**

The study is located on a reclaimed surface mine in the Cumberland Plateau at Big Elk Mine near Hazard, Kentucky in Knott County. Southeastern Kentucky is characterized by warm humid summers and cool winters. Prior to being mined, the site was dominated by oak-hickory forests common to the region. The soil profiles are undefined and heavily compacted with a shale and sandstone substrate and large boulders are pervasive throughout the soil matrix (Conrad 2002).

The study site was previously reclaimed using smooth grading and was ripped with a D-11 dozer in February of 2008 to alleviate compaction and reduce weedy competition. In March 2008 twelve 0.209 ha plots were established and planted with 1-0 bare root seedlings of American sycamore (*Platanus occidentalis* L.) and black locust (*Robinia pseudocacia* L.). Mean seedling density was 1842 stems ha\(^{-1}\) across all plots, because large boulders and rough topography prevented uniform seedling plantings. Following site preparation and planting, *rubus, lespedeza, ailanthus, ambrosia, oxalis, cirsium, veronia, leucanthemum, rudbeckia, festuca,* and *coronilla* and other early successional genera populated the site. Similar disturbance dependant species were reported at other reclaimed surface mines in the region (Bell and Ungar 1981, Holl and Cairns 1994, Holl 2002).
Field Methodology

For each species, height and basal diameter were tracked in a centrally located 0.019 ha sub plot containing tagged seedlings (999 total; Figure 3.1). One destructive sample (n = 3) was excavated from each replicate plot within one of two 0.008 ha destructive zones of each plot (Figure 2.1). At least two treated border rows were present around all measurement and destructive harvest sub plots. Control (C), fertilization (F), irrigation (I), and irrigation + fertilizer (IF) treatments were replicated three times and randomly assigned to the experimental plots. All fertilized plots received 36 kg ha\(^{-1}\) of granular nitrogen, phosphorous, and potassium during June of 2008 and 2009. 3.4 million liters ha\(^{-1}\) of water was applied to I and IF treatments throughout the 2008 and 2009 growing seasons with a drip irrigation system. 36 kg ha\(^{-1}\) of liquid nitrogen, phosphorous, and potassium was applied to IF plots during the 2008 and 2009 growing seasons. To control competing vegetation, glyphosate was administered to all plots at a rate of 0.871 liters ha\(^{-1}\) with backpack sprayers during June of 2008 and 2009.

Field and Laboratory Measurements

Basal diameter was taken to the nearest tenth of a mm with digital calipers at two locations, 90° apart from one another, and then averaged. Basal diameters and heights were recorded for tagged trees in measurement sub plots directly after planting in April 2008. First growing season heights and basal diameters were recorded in January of 2009 and following the second growing season during December of 2009.

One tree from each replicate plot (n=3) was excavated across 14 days during September and October of 2009 for a total of 24 specimens. Destructive harvests were used to develop allometric equations to predict root mass, stem mass, and foliage mass of tagged
trees in measurement subplots using height and diameter as independent variables. Destructively harvested trees were defoliated and sub sampled for leaf area in September. All roots were excavated from a 60 x 60 cm square centered on the tree to a 30 cm depth. This method was derived from similar studies (Albaugh et al. 1998, King et al. 1999, Pregitzer et al. 2002, Coyle and Coleman 2005, Coyle et al. 2008) and adapted to accommodate soil conditions at our site. Diameters and heights of destructive harvests were recorded before they were partitioned into roots, stems, and leaves, oven-dried for 48 hours at 60°C, and then weighed to the nearest hundredth of a gram.

Leaf, Soil and Tissue Analysis

Excavated partitions were sub sampled (n=3) for tissue nutrient analysis. Subsamples were pulverized with a Spex SamplePrep 800M Electric Mixer/Mill. Total carbon and nitrogen concentrations were determined by dry combustion using a LECO CHN 2000 analyzer (Leco Corp. – St. Joseph, MI). The resulting gases were equilibrated in a ballast chamber followed by infra-red detection for CO₂ and H₂O. N₂ was determined by a thermal conductivity detector after reduction of N oxides and removal of CO₂ and H₂O. Soil samples were taken to a 15 cm depth from each species and treatment combination (n=3). They were pulverized in an electric mill and processed for chemical analysis. Soil samples were analyzed at the UK College of Agriculture Regulatory Services Laboratory for pH, nitrogen, calcium, potassium, phosphorus, exchangeable bases, and cation exchange capacity. Six leaves from each excavated tree were sub sampled from varying cardinal directions and crown depth for leaf area calculations. Leaf area was calculated to the nearest hundredth of a cm² with a Li-Cor LI-3100 Area Meter. Subsamples were
dried at 60 C and weighed to the nearest hundredth of a gram with an Ohaus Adventurer-Pro digital scale to calculate specific leaf area (SLA).

Statistical Analysis

Excavated trees were used to develop regression equations for predicting stem, root, and foliage biomass (SAS 9.1; SAS Institute Inc., Cary, NC). Root, stem, and foliage partitions were predicted using a linearized version of a power function that included species, seedling height, and basal diameter as independent variables; significant independent variables were identified via backward elimination, stepwise selection. Equations were then used to predict biomass partitions of trees being tracked in measurement subplots. Soil samples and tissue samples from destructive harvests (n=3) were used in an ANOVA with LSMEANS to detect significant treatment and species differences for carbon and nitrogen concentrations, soil chemistry, leaf area, and specific leaf area.

Results

Biomass Partition Equations

Per stem root, shoot, and foliage biomass were predicted from seedling diameter and or height using a linearized version of a power function and residual analysis indicated that assumptions of normality and homogeneity of variance were met (Table 3.1). No significant interactions existed between treatment and metrics of seedlings size in models for stem and foliage biomass. Species was a significant variable for predicting root, stem, and foliage mass. Basal diameter was the only significant independent variable when predicting American sycamore root and foliage mass while height was the only
significant variable for black locust foliage biomass. Height and basal diameter were
significant for stem mass of both species. A significant interaction between species and
basal diameter was present for root mass. Correction for logarithmic bias of transformed
models was completed using the Baskerville correction factor (Baskerville 1972).

Carbon and Nitrogen Concentrations

There were no significant effects of treatment or species on root carbon. No treatment
had significantly higher stem carbon content within species, but fertilized black locust
stems (46 %) had significantly lower carbon levels compared to sycamore stems under
treatment (48 %), fertilization (48 %), and irrigation + fertilization (48 %) treatments.
Foliation carbon concentrations peaked at 0.49 % for IF black locusts. This was
significantly higher than all other black locust treatments and sycamore treated with I and
IF.

Greater inter and intra species variation was present for nitrogen concentrations. Black
locust controls had the greatest root nitrogen concentrations at 2.98 percent. This was
significantly higher than irrigated locusts (2.09 %) and all sycamore treatments. All
locust treatments had significantly higher root nitrogen than sycamore treatments (Figure
3.2). Stem nitrogen levels revealed similar results; there were no intra species treatment
differences, but all locust treatments had significantly higher nitrogen levels compared to
every sycamore treatment. Black locust leaves possessed the highest nitrogen
concentrations for any tissue or species, but no intra species differences were detected.
Carbon Sequestration and Nitrogen Uptake

Predicted carbon sequestration was significantly greater for fertilized sycamore across all tissue components (Figure 3.3). Fertilized sycamores sequestered 255.67 kg ha\(^{-1}\), 329.21 kg ha\(^{-1}\), and 142.27 kg ha\(^{-1}\) of carbon in roots, stems, and leaves, respectively (Figure 3.4). This totaled 726.14 kg ha\(^{-1}\) following two growing seasons. The next highest treatment was sycamore controls with 214.16 kg ha\(^{-1}\). Root nitrogen was significantly higher in fertilized sycamores and locusts compared to all other treatments (Figure 3.4). Stem and foliage nitrogen exhibited similar results. Total nitrogen levels of fertilized sycamore was significantly higher than all other treatment and species combinations except fertilized black locust (9.11 kg ha\(^{-1}\)).

Leaf Area and Specific Leaf Area

Fertilized American sycamore had the highest leaf area at 343.42 cm\(^2\) (Table 3.4). This was significantly higher than all other treatments for either species. Irrigation resulted in the lowest sycamore (94.08 cm\(^2\)) and locust (53.39 cm\(^2\)) leaf area. There were no statistical differences among any locust treatment for leaf area. Specific leaf area varied from 115.48 (locust IF) to 219.12 (locust F), but there were no significant differences.

Soil Chemistry

Granular fertilizer applications resulted in significantly elevated levels of soil phosphorous and potassium (Table 3.3). Mean locust phosphorous was 70.33 lbs acre\(^{-1}\) in fertilized plots and 39.33 lbs acre\(^{-1}\) in fertilized sycamore more plots. The next highest readings were 9.33 lbs acre\(^{-1}\) and 9.00 lbs acre\(^{-1}\) in black locust IF and C treatments, respectively. No treatment or species effects were detected for other soil metrics. Mean
cation exchange capacity was 8.59 meq/100g, mean base saturation was 80.17 %, and mean organic matter content was 4.67 %.

**Discussion**

*Carbon Concentrations and Sequestration*

Stem carbon concentrations ranged from 46.1 % in fertilized black locust to 47.8 % in fertilized sycamores. There was no treatment or species effect on carbon concentrations. Fertilized American sycamore outperformed all other species treatment combinations in total carbon sequestered for roots, stems, and foliage at our site. Granular fertilizer applications significantly increased total carbon sequestration by 239 % over the next highest treatment combination (sycamore controls). This was primarily a function of increased biomass accumulation under fertilizer treatments, not disparate carbon concentrations.

Carbon concentrations at our site fall within ranges established for eight and twelve year old plantations of considerably larger American chestnut (*Castanea dentata*), black walnut (*Juglans nigra*), and red oak (*Quercus rubra*) in southwestern Wisconsin (Jacobs et al. 2009). Although carbon concentrations were similar, total stem carbon in our best performing treatment (fertilized American sycamore) was much lower at our site (.329 Mg ha⁻¹) compared to their worst performing species (red oak; 3.4 Mg ha⁻¹). This is likely attributed to planting densities and advanced age. Stocking density at their site was 3588 stems ha⁻¹ compared to 1849 stems ha⁻¹ at our site, and their study was conducted after eight growing seasons while ours was done following only two. Stem carbon concentrations at our site were also similar to values reported for trembling aspen (*P. tremuloides*; 47.09%) reported at a Wisconsin plantation (Ruark and Bockheim 1988).
Conversely, Gower et al. (1991) reported higher stem carbon concentrations for a red pine (*P. resinosa*; 53.28%) and eastern white pine (*P. strobus*; 49.74%) plantation. Given the success of eastern white pine in surface mine reclamation projects throughout the Midwest and Appalachia (Casselman et al. 2006), their elevated carbon concentrations compared to other common reclamation species in the region may warrant their selection for carbon sequestration endeavors.

**Nitrogen Concentrations and Uptake**

There was only one significant effect of nutrient and moisture amendments on intra species nitrogen concentrations. There was a trend of granular fertilizer applications increasing sycamore root and shoot nitrogen concentrations, while irrigation had a negative effect on foliar nitrogen levels. Similarly, irrigated black locusts had significantly lower root nitrogen concentrations compared to controls. Black locust also exhibited significantly greater levels of nitrogen across all treatments and partitions compared to American sycamore. Generally, locust nitrogen concentrations were two to four times greater for roots and more than double in stems and foliage. This was expected, because locusts are known for their ability to form symbiotic relationships with soil bacteria that fix nitrogen (Rice et al. 2004).

Nitrogen concentrations were higher in black locust tissue, but due to much greater biomass accumulation total nitrogen was significantly greater in fertilized sycamore plots compared to all other treatments except fertilized locusts. Thirty-seven kg of elemental nitrogen ha\(^{-1}\) were applied to fertilized plots. Mean nitrogen uptake in fertilized sycamores plots was 14.53 kg ha\(^{-1}\). Moreover, despite a difference of 59.47 kg ha\(^{-1}\) between applied and sequestered nitrogen following two growing seasons, there was no
significant residual nitrogen loading in fertilized soils. Total nitrogen uptake and percent uptake of applied nitrogen at our site was lower than similar studies. Total nitrogen uptake at an upland sycamore plantation in Tennessee was approximately 140 kg ha\(^{-1}\) following three growing seasons (van Miegroet et al. 1994). The amount of total nitrogen applied in fertilizer treatments sequestered by the target crop in their study was 31% compared to 24% at our site. Furthermore, American sycamore at an upland Western Kentucky plantation sequestered 86.2 kg ha\(^{-1}\) and 58.5 kg ha\(^{-1}\) of nitrogen following three growing seasons and applications of 167 kg N ha\(^{-1}\) and 112 kg N ha\(^{-1}\), respectively (Wood et al. 1977). This represented 52% of total nitrogen applied in both treatments. Greater comparative total nitrogen uptake and percent uptake of applied nitrogen at these sites compared to our study may be a function of extended study durations and reduced weedy competition. Our study encompassed two growing seasons and was established at a highly disturbed site with an intensive herbaceous cover.

Despite uniform herbicide applications across all treatments, weedy competition was severe; the most aggressive genera were *cirsium*, *ambrosia*, and *lespedeza*. Therefore, it is plausible that intense competition accounted for much of the remaining 23.47 kg ha\(^{-1}\) of nitrogen in fertilized sycamore plots. Nitrogen leaching or runoff may also explain the unaccounted nitrogen. Although soil nitrogen was unaffected by fertilizer applications, significantly elevated levels of phosphorous and potassium were present in fertilized soils. Nitrogen and phosphorus runoff are a primary concern for intensively managed plantations (Nyakatawa et al. 2006). More effective fertilizer regimes can increase profit margins while mitigating the negative effects of runoff.
Total nitrogen in fertilized black locust plots was 9.11 kg ha\(^{-1}\), but due to black locust's ability to form symbiotic relationships with nitrogen fixing bacteria, it is unclear what proportion of that is a result of fertilizer applications and what is a function of nitrogen fixing. Studies have yet to establish reliable rates of nitrogen fixing in black locust (Rice et al. 2004), but it is likely that elevated nitrogen concentrations and total sequestered nitrogen are a function of nitrogen fixing bacteria in spite of no detectable species effect on soil nitrogen levels.

Sycamore nitrogen concentrations at our site were in congruence with levels established at a plantation in Georgia under varying irrigation and fertilizer regimes (Cobb et al. 2008). They reported foliage sycamore nitrogen concentrations of 1.53 % under control treatments and 1.85 % - 2.03 % in fertilized plots. Despite similar nitrogen concentrations as in our study, Cobb et al. (2008) detected significantly elevated levels of foliar nitrogen concentrations under treatments of irrigation + 85 kg of nitrogen and irrigation + 114 kg of nitrogen. Although foliar nitrogen concentrations were similar to our study, mean stem nitrogen concentrations were greater at our site (0.46 % to 0.56 %) compared with 0.35 % to 0.16 % in sycamores under a control and fertilizer treatments in their study following six growing seasons. Increased nitrogen concentrations in response to fertilizer treatments were also reported for hybrid poplars at a Minnesota plantation (Coleman et al. 2006). Conversely, no significant effects of fertilizer applications on foliar nitrogen concentrations were indentified at a green ash (Fraxinus pennsylvanica) plantation established on a ripped mine in Ohio (Kost et al. 1998). However, they reported similar foliar nitrogen concentrations (1.50 %).
American sycamore and black locust nitrogen concentrations at our site were slightly lower than reported values for aspen plantations in Alberta, Canada. van den Driessche et al. (2003) reported foliar nitrogen concentrations from 3.42 % to 4.02 % for stands under control, fertilization, and weed control treatments. They detected significantly higher concentrations for seedlings under fertilized + weed control treatments compared to controls. Foliar nitrogen concentrations were nearly double in hybrid poplars on a reclaimed mine in West Virginia compared to sycamore at our site, and only slightly higher than black locusts at our site (Casselman et al. 2006).

Leaf Area and Specific Leaf Area

Mean leaf area was significantly higher under fertilized sycamore treatments. Fertilized sycamore had nearly double the leaf area of the next highest treatment (sycamore IF). The positive effects of fertilization on leaf area were also witnessed for hybrid poplars on a Minnesota plantation (Coleman et al. 2006). However, it was not of the same order of magnitude. Fertilization increased mean leaf area by 20 % in at their site whereas a 102 % increase was witnessed for sycamores and 46 % increase in locusts at our site compared to controls. Although sycamore plots receiving irrigation were not significantly lower, it perpetuated a trend of the negative effects of irrigation treatments on sycamores at our site. Irrigated sycamores exhibited lower mean height, diameter, total biomass, shoot nitrogen, foliage nitrogen, root carbon, and leaf area. We attributed this to the additive effects of high soil compaction and irrigation treatments creating sustained anaerobic conditions that limited nutrient uptake by lowering chemical and electrical gradients across root surfaces.
Even though we detected significant effects of treatments on leaf area, differences in specific leaf area were insignificant between species and treatments despite a lower mean SLA in sycamore in F and IF plots. SLA is a measure of leaf thickness and is an indirect measure of photosynthetic capacity (Evans and Poorter 2001). Our results suggest that fertilizer and nutrient amendments did not significantly increase photosynthetic capacity per unit leaf area; however, total woody biomass production was positively correlated with leaf area.

**Conclusion**

Although fertilizer applications do not significantly alter carbon concentrations, it is clear they can greatly accelerate biomass accumulation and subsequent total carbon sequestration on reclaimed surface mines. The benefits of nutrient amendments are apparent, but excessive fertilization can negatively affect site carbon budgets (Canadell and Raupach 2008). Therefore, adopting efficient fertilizer regimes will be paramount. Our results suggest that lower rates of fertilizer applications will increase plantation economic efficiency and carbon budgets on reclaimed surface mines with similar overburden. This would maximize growth of target species, and increase carbon sequestration while minimizing the negative radiative forcing effects of residual soil nitrogen. Soil analysis indicates that a fertilizer mix with reduced nitrogen, potassium, and phosphorus may be appropriate, but several studies suggest that growth may be phosphorous limited in the plantation growth (Misra et al. 1998, Miller et al. 2003). Our results indicate that nitrogen levels of 15 kg ha\(^{-1}\) would be sufficient for early plantation growth given our level of weed control. More intensive weed control may increase possible levels of nitrogen uptake. Maintaining the appropriate nutrient balance will be
necessary as to avoid mitigating the positive effects of nitrogen applications if phosphorus is lowered below a critical mass.
### Table 3.1: Best-fit regression equations used to predict the natural log of root, stem, and biomass partitions in grams using the natural log of basal diameter (bd; mm) and height (ht; cm).

<table>
<thead>
<tr>
<th></th>
<th>Black locust</th>
<th>American sycamore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation</td>
<td>r²</td>
<td>Equation</td>
</tr>
<tr>
<td>Root Biomass</td>
<td>-1.80 + 1.97bd</td>
<td>0.81</td>
</tr>
<tr>
<td>Stem Biomass</td>
<td>-5.89 + 1.10ht + 1.78bd</td>
<td>0.97</td>
</tr>
<tr>
<td>Foliage Biomass</td>
<td>-15.77 + 3.92ht</td>
<td>0.87</td>
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Table 3.2: Mean root and shoot nitrogen and carbon concentrations expressed as a percent of total partition mass following two growing seasons. Lower case letters indicate significance (p<0.05; n=3) across species and treatments. Control [C], irrigation [I], fertilizer [F], and irrigation + fertilizer [IF]

<table>
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<tr>
<th></th>
<th>Root N</th>
<th>Shoot N</th>
<th>Foliar N</th>
<th>Root C</th>
<th>Shoot C</th>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>C</td>
<td>0.5a</td>
<td>0.5a</td>
<td>2.2a</td>
<td>44.6a</td>
<td>47.6a</td>
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<tr>
<td>I</td>
<td>0.6a</td>
<td>0.5a</td>
<td>1.7a</td>
<td>43.1a</td>
<td>47.0ab</td>
</tr>
<tr>
<td>F</td>
<td>0.8a</td>
<td>0.6a</td>
<td>2.1a</td>
<td>44.3a</td>
<td>47.7a</td>
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<tr>
<td>IF</td>
<td>0.5a</td>
<td>0.5a</td>
<td>1.7a</td>
<td>42.7a</td>
<td>47.6a</td>
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<td><strong>Black Locust</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3.0b</td>
<td>1.7b</td>
<td>3.4b</td>
<td>42.1a</td>
<td>46.5ab</td>
</tr>
<tr>
<td>I</td>
<td>2.1c</td>
<td>1.4b</td>
<td>3.0b</td>
<td>43.4a</td>
<td>46.9ab</td>
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<tr>
<td>F</td>
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<td>3.6b</td>
<td>41.3a</td>
<td>46.1b</td>
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<tr>
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<td>3.3b</td>
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Table 3.3: ANOVA p value table (n=3) for soil organic matter (OM), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), total nitrogen (N%), soluble salts (SS), cation exchange capacity (CEC) and base saturation

<table>
<thead>
<tr>
<th></th>
<th>DF</th>
<th>OM</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
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<th>CEC</th>
<th>BSAT</th>
<th>Ex K</th>
<th>Ex Ca</th>
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<td><strong>0.001</strong></td>
<td>0.210</td>
<td>0.100</td>
<td>0.579</td>
<td>0.691</td>
<td>0.492</td>
<td>0.939</td>
<td>0.404</td>
<td><strong>0.044</strong></td>
<td>0.203</td>
<td>0.229</td>
<td>0.418</td>
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<tr>
<td>Species</td>
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<td>0.236</td>
<td><strong>0.036</strong></td>
<td>0.720</td>
<td>0.371</td>
<td>0.222</td>
<td>0.543</td>
<td>0.276</td>
<td>0.924</td>
<td>0.778</td>
<td>0.108</td>
<td>0.677</td>
<td>0.944</td>
<td>0.223</td>
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<td>0.400</td>
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<td>0.100</td>
<td>0.835</td>
<td>0.527</td>
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<td>0.762</td>
<td>0.695</td>
<td>0.445</td>
<td>0.129</td>
<td>0.463</td>
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Table 3.4: Mean foliage nitrogen, carbon, leaf area, and specific leaf area following two growing seasons. Carbon and nitrogen are expressed as a percent of total foliage mass. Lower case letters indicate significance (p<0.05; n=3) across species and

<table>
<thead>
<tr>
<th>Species</th>
<th>Nitrogen</th>
<th>Carbon</th>
<th>Leaf Area (cm²)</th>
<th>SLA</th>
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<tr>
<td>Sycamore</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>2.0a</td>
<td>48.1ab</td>
<td>170.4±24.8bc</td>
<td>160.1±1.6a</td>
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<tr>
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<td>47.6b</td>
<td>94.1±10.4cbsd</td>
<td>174.8±17.4a</td>
</tr>
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<td>343.4±44.4a</td>
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*a standard error lower than significant digits
Chapter 3 Figures

Figure 3.1: Layout of individual half acre experimental unit. Dashed line represents species divide. Light gray areas are measurement sub plots for tagged and tracked trees. Black areas are destructive harvest sub plots.
Figure 3.2: Mean nitrogen distribution by partition expressed as a percent of total plant nitrogen for American sycamore and black locust after two growing seasons.
Figure 3.3: Total predicted carbon sequestration for American sycamore and black locust following two growing seasons. Letters indicate significant differences (p<0.05) across treatments and species.
Figure 3.4: Mean predicted per stem nitrogen by partition for American sycamore and black locust following two growing seasons. Letters indicate significant differences (p<0.05) across treatments and species.
Figure 3.5: Total predicted nitrogen for American sycamore and black locust following two growing seasons under varying treatments. Letters indicate significant differences (p<0.05) across treatments and species.
Appendix A: Chapter 2 Residual Plots

Residuals of plot mean basal diameters:

Residuals of plot mean height:
Untransformed allometric model predicting stem weight by height and diameter:

Curvature and changing spread necessitated natural log transformations of all independent and dependent quantitative variables.

Log transformed allometric model of predicted stem weight:
Residual plots of "K" coefficient analysis

All K coefficient analysis is performed with log transformed independent and dependent variables.

Root fraction vs. total mass:

Shoot fraction vs. total mass:
Root fraction vs. leaf fraction:

Shoot fraction vs. leaf fraction:
Shoot fraction vs. root fraction:

Root fraction vs. shoot fraction:

Analysis of residuals and determination of appropriate transformations for remaining chapter one statistical analyses were performed with the same assessments of curvature, outliers, and changing spread displayed in the previous residual plots.
Appendix B: Chapter 3 Residual Plots

Untransformed allometric model predicting root mass using height and diameter as independent variables:

![Residual Plots](image1)

Curvature and change in spread required log transformation:

![Residual Plots](image2)
Untransformed allometric model predicting leaf mass using height and diameter as independent variables:

Curvature and change in spread required log transformation:
Residual plot of soil phosphorus by species and treatment:

Change in spread required natural log transformation:
Total soil nitrogen by species and treatment:

Soil potassium by species and treatment:
Root carbon by species and treatment:

 Shoot carbon by species and treatment:
Residuals of specific leaf area:

Curvature and change in spread required natural log transformation:

Analysis of residuals and determination of appropriate transformations for remaining chapter one statistical analyses were performed with the same assessments of curvature, outliers, and changing spread displayed in the previous residual plots.
Literature Cited


Vita

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