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SIMULATED MINE LAND RECLAMATION IMPACT ON BIOMASS PARTITIONING AND NUTRIENT CONTENTS IN LOBLOLLY PINE

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By

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ABSTRACT

Forest productivity on reclaimed mine land is hindered by soil compaction. Different techniques have been used to alleviate the effect of compaction to various degrees of success. The Forestry Reclamation Approach (FRA) was developed in the Appalachians and has been used to improve forest productivity on reclaimed mines in this region. The FRA provides a step by step method designed to reduce compaction, control erosion, provide land stabilization and accelerate forest succession. This method had not been evaluated in the Gulf Coastal Plain, where the pan scraper reclamation method is commonly used. However, using pan scrapers increases mine soil compaction which reduces productivity. This study was carried out on an experimental site in Houston County, Texas managed by the Arthur Temple College of Forestry and Agriculture at Stephen F. Austin State University. The experiment was established as a randomized complete block design containing three treatments: pan scraper reclamation method traditionally used in this region, an FRA low compaction treatment, and an undisturbed control. Loblolly pine (*Pinus taeda* L.) seedlings of Texas provenance were hand-planted on each treatment.

Loblolly pine seedlings were measured, harvested and analyzed to determine dry biomass and nutrient (N, P, K, Ca, Mg) contents for the three treatments. Allometric equations relating dry weights of foliage, stem, branches and roots to diameter at groundline and height were developed to estimate tree biomass. Estimated biomass

accumulation improved with FRA treatment which produced a mean of 759 g foliage, 344 g branch, 440 g stem, 273 g root, 1579 g aboveground, and 1865 g total tree mass. On the pan scraper treatment, estimated biomass was: 159 g foliage, 67 g branch, 90 g stem, 77 g root, 334 g aboveground, 420 g total tree mass. On the control treatment, estimated mean biomass was: 244 g foliage, 111 g branch, 154 g stem, 102 g root, 537 g aboveground, 648 g total tree mass. All treatments allocated more biomass to foliage, however, biomass allocation to roots was relatively higher in the pan scraper treatment than FRA treatment.

Nutrient accumulation in tree biomass was highest in FRA treatment and it followed the pattern of biomass accumulation. The nutrient concentrations in different tree tissues decreased in the order foliage > stem > root, except for N and Mg in the pan scraper treatment. Foliage concentrations for all treatments were either at or exceeded the adapted critical concentrations except for N which was slightly lower. However, N was generally the most abundant nutrient in all treatments and was highest in foliage biomass. In summary, these results show that FRA can be an effective reclamation method to improve seedling growth and biomass production in the Gulf Coastal Plain.

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CHAPTER I: LITERATURE REVIEW

INTRODUCTION

Surface mining is defined by a broad range of mining activities that include removing existing portions or all of mountaintops to expose buried seams of coal. This process involves disposing of excess 'overburden' and 'interburden' in adjacent valleys. Overburden refers to the rock above the coal seam, and interburden is the rock between the coal seams. The overburden temporarily (and sometimes permanently) covers the surrounding valleys until they can be used to regrade the mining area. This process contributes to hydrologic changes and increases in erosion (Fox, 2009), loss of large areas of forested land, conversion of habitats and thus, displacement and loss of species. Surface mining of coal causes disturbance to land, resulting in soil compaction and disruption of existing site characteristics. From the above, it is imperative that the coal extraction process must ensure return of productivity to the affected land. Until recently, land mined for coal has been reclaimed to various post-mining land uses (e.g. hay and pasture, wildlife habitat, farmlands, biofuel crops, forestry, and infrastructure), but pre-mining productivity has not necessarily been reached. This could be attributed to i) a lack of forest productivity standard in the original Surface Mining Control and Reclamation Act (SMCRA) of 1977, (Rodrigue et al., 2002; Rodrigue and Burger, 2004) ii) compaction of soil caused by repeated movement of heavy equipment when grading land back to the approximate original contour (Torbert and Burger, 1996; Casselman et al.,

2006) and iii) the absence of a requirement to select appropriate topsoil materials well-suited to aid tree growth (Burger et al., 2007; Emerson et al., 2009; Skousen et al., 2011).

The Surface Mining Control and Reclamation Act (SMCRA) was enacted on August 3, 1977. It offered a federal-to-state oversight for active mines for reclamation, and provided financial resources for abandoned mine land reclamation programs (Skousen and Zipper, 2014). This act was intended to mitigate the environmental effects of surface mining, and enhance human safety, improve water quality, erosion control, and grading the land to approximate original contour (AOC). This approach was originally intended to control erosion and provide a sustainable land use for abandoned mine lands, however, compaction and thick ground cover have been found to be counter-productive in producing hardwood forests (Chaney et al., 1995; Torbert, 1995; Ashby, 1996; Rodrigue and Burger, 2004, Skousen, 2009). This difficulty led to the mine land reclamation to hay and pasture land (Ashby, 1991). Minesoils respond differently to grading. Rate of water absorption and percolation, and thus soil moisture and aeration required for root growth are significantly reduced on graded soils. However, grading improves soil stability on loose soils (Ashby, 1991). Despite its limited success under SMCRA, reclamation to forest plays a major role in environmental sustainability. Tree roots improve soil porosity, while leaves are sources of organic matter to the soil. SMCRA emphasizes reclamation of mined lands to sustainable post-mining use.

Compaction of the soil is caused by the large equipment used by mine operators during grading. Grading the soil surface is done to stabilize the soil and control erosion, however, Hatchell et al., (1970) showed that it reduces infiltration and increases erosion. Soil compaction obstructs root growth; thus, invasive species continue to exploit the native ones, preventing hardwood forests from being successfully established. Compaction alters the size, arrangement, and distribution of soil pores, which largely influences air, water, and gas movement in the soil, and thus, biological activity and root growth (Sutton, 1991). Soil compaction reduces soil productivity and environmental quality of reclaimed mine lands. These conditions have been shown to decrease water movement, restrict root growth, reduce plant yield, and increase surface runoff and erosion (Yao, 1994). Burger and Zipper (2011) identified soil compaction as the most influential physical factor hindering tree growth and survival on surface mined lands. Compaction inhibits infiltration and percolation, decreases soil porosity and aeration, and increases bulk density and soil strength, which together restrict loblolly pine root development (Unger and Cassel, 1991). Other effects of compaction on roots include reduced stem radial and elongation growth rates, shallow rooting, stunted whole tree form, root crushing and shearing-off. Effects of excessive soil compaction depend on the soil type, pH, groundwater level, climate, cation exchange capacity, organic matter content, and the level of initial compaction (Kozlowski, 1999; Ulrich et al., 2003; Blouin et al., 2008). Reclaimed soils are less erosion resistant than their pre-reclamation state, and more likely to produce runoff when compacted. Poorly aerated soils with low permeability (and therefore reduced plant available water) may cause decreased tree growth and survival (Rab, 1996; Grigal, 2000). Unfavorable soil conditions also impact the health and productivity of the forest (Kozlowski, 1999). The evaluation of the growth of forest tree seedlings on compacted soil is important due to cost incurred during site preparation for afforestation and also cost for replanting seedlings that do not survive. Ashby (1991) argued that the execution of the SMCRA provided little information on the types of soils essential to maximize tree growth. This resulted in the use of different soils and materials that were easily compacted and reduced forest productivity. Reestablishing forests on surface-mined land is particularly challenging. Ashby (1991) recommended a mixture of soils and coarse fragments for establishment of trees. Coarse fragments in soils creates an interface that supports water entry, movement, and encourages root growth.

The quality of an appropriate growth medium and its placement is essential for effective reforestation on surface mines. Soil is a combination of weathered materials, organic matter, water, food, and living creatures (Skousen et al., 2011). Its properties provide the structural support and other resources necessary for plant and animal survival in the forest, therefore, its composition and density directly affect the future stability of the restored vegetative community. Weathering describes the breaking down or dissolving of rocks and minerals on the surface of the Earth. Surface mining often leaves residues of unweathered rocks at the surface, which undergo rapid changes to its physical and chemical properties in a short period of time (Haering et al., 1993). This later forms a growth medium for vegetation; however, they are generally not suitable for restoring pre-mining forest capability. Depending on the climate and parent material, weathered rocks are rich in nutrient, supply air and water to plants, and are generally preferable to unweathered rocks. However, weathered rocks are not suitable as a growth medium if they are extremely acidic or pyritic (Isabell and Skousen, 2001). Skousen et al., (2011) identified properties of spoil materials that make them unsuitable for reclamation to forestry. They include large coarse fragments (typically > 2 mm), high pH or pyritic minerals that produce extremely low pH, and carbonaceous rocks (e.g black shales). Several studies on surface mines have reported good growth of forest trees on soils and weathered spoils exhibiting properties such as low soluble salts and slightly acidic pH (Torbert et al., 1988; Jones et al., 2005; Showalter et al., 2007).

Another hindrance to successful tree establishment is the competition from herbaceous vegetation (Torbert and Burger, 2000). Using appropriate ground cover effectively controls runoff by competing with native grasses and trees which further prolong natural succession (Ashby, 1987). According to SMCRA, operators are required to establish a diverse, effective and permanent vegetative cover of the same seasonal variety native to the area of land to be affected. The selected cover must equally be capable of stabilizing the soil from erosion (Section 816.111 of SMCRA). To comply with these standards, operators usually establish a quick growing dense ground cover composed of perennial grasses and other species, some of which are non-native, very dense and competitive with tree seedlings. Research suggested that competition from some of these aggressive grasses have hindered site reclamation (Torbert, 1990; Torbert and Burger, 2000). Torbert and Burger (2000) observed less-competitive species to be a better alternative when seeding ground cover. Redtop (*Agrostis gigantea* R.), birdsfoot trefoil (*Lotus corniculatus* L.), as well as other annual grasses, perennial grasses, and legumes have been found to control erosion effectively for the first year, while at the same time allowing for better establishment of native tree species (Holl, 2002). Other problems which have arisen from the competition of grasses are that they can grow taller than young tree seedlings in the early stages and hinder seedling growth. In addition, a heavy groundcover provides refuge for small rodents which can feed on the bark and other parts of tree seedlings (Torbert and Burger, 2000). More recently, reclamation has become more restricted to prevent soil compaction. Also, less-competitive species that are native in origin and seeded at lower rates is preferred to previously used herbaceous species (Burger and Graves, 2005). Weeds have also been a problem since the inception of the SMCRA. Topsoil and soil amendments used in reclamation often contain weed seeds, which in conjunction with planted ground cover can compete with trees for nutrients and sunlight. Weeds can be controlled by cultivation or application of herbicides, however, these practices are short-lived and expensive (Ashby, 1991). Planting trees to increase density is a natural and more beneficial means of controlling weeds and ground cover.

Amendments can be beneficial to tree growth on reclaimed mine sites. Mulches have been used in the reclamation process to retain soil moisture, improve soil fertility, reduce weed growth and maintain soil temperature (Wilson-Kokes et al., 2013). Examples of mulches include: organic (woodchips, shredded bark, straw), and inorganic (plastic sheets, stones). The major difference between these two types of mulching is decomposition. Organic mulches decompose and may deliver some nutrients to the soil. In a study, biomass production was found to improve on mulched plots than non-mulched plots (Ringe et al., 1990). Darby and Jason (2016) studied the effect of amendments on soil physical properties and tree growth. Addition of compost reduced bulk density to below root elongation limiting levels, resulting in improved tree growth. The use of wood chips as mulch has been used to great effect in reclamation (McConkey et al. 2012), however, Vinge and Pyper (2012) suggested that woody debris causes insulation to the ground, thus, their use should be carefully controlled and limited to specific objectives. Also, Arnold et al. (2005) suggested that mulch should be applied in thin layers to control weed development on the site.

Surface Mining and Reclamation in the Western Gulf Coastal Plain Region

The West Gulf Coastal Plain characterized by flat or gently undulating topography is a region where strip mining for lignite coal is a common practice. A cross pit spreader or other heavy equipment is used to excavate a pit 30 m wide and about 100 m deep through the overburden to expose the seams of lignite coal. Once this is done, overburden from the new pit is placed in previously excavated pits which has already had the coal removed. Overburden includes topsoil, clay, and a variety of rocks lying above the coal seam. Surface mining disrupts the soil profile and creates a mixture of soil and materials from the overburden. This is commonly referred to as mine soil. The process of coal extraction and leveling of the spoil takes place concurrently, and it involves the use of heavy equipment such as dozers and blades.

Reclamation can be used to contain the environmental effects of surface mining by rehabilitating disturbed areas. Reclamation is the process by which depleted or highly degraded lands are returned to productivity, and by which biotic function and productivity is restored. The primary objective of reclamation in surface mining is to reestablish adequate vegetative cover, soil stability, and water conditions. However, the techniques used in setting up a suitable plant growth medium, or mine soil, can impact soil properties and revegetation achievement (Zipper et al., 2013). Reclamation involves replacing the overburden, grading it to AOC, and spreading appropriate topsoil. It requires careful selection, handling, and replacement of mine soil in a manner that supports revegetation and limits erosion. Topsoil or selected overburden replacement requires careful selection. Topsoil can either be removed and stored or carried by trucks or scrapers to a spoil area that has been prepared for topsoil replacement. Soil or overburden materials considered most suitable for plant growth, spanning several meters, is stripped off with heavy scrapers and stockpiled adjacent to the open cut. After completion of mining, mine pits are backfilled with overburden materials and graded approximately to the pre-mine contour. No less than 1.2 m of appropriate materials are put over the graded overburden as the foundation for herbaceous and tree seedling establishment (R-C-T, 1982).

Overburden physical and chemical properties vary widely with depth within a mine and across different regions (Doll et al., 1984), thus it should carefully be evaluated prior to mining. Studies in this region concluded that mixed overburden materials can successfully support a range of vegetation types and increase productivity compared to adjacent undisturbed land when used as a substitute (Angel, 1973; Troups, 1986; DeLong et al., 2012). This can be attributed to the chemical and physical properties of the mixed overburden which provides a favorable rooting medium, containing little or no rocks, desirable concentrations of necessary plant nutrients, low sulfur content, soil texture suitable for plant growth, and adequate water retention ability (Angel, 1973).

The scraper pan method is the most commonly used reclamation technique in this region. It includes one or two multi-wheeled pans attached to a farm tractor. Scraper pans can either be self-loaded by their moveable bowl or loaded by a hydraulic excavator track hoe. Pan scrapers can load topsoil down to a specific depth and from multiple areas in a single cycle, and can unload stockpiles directly on graded spoils at a specified depth. This method has recorded success in the region and has proven to be a cost-effective method of reclamation, however, the equipment used has compacted the soil to varying degree (Yao, 1994). The scraper placed mine soil results in poorer soil physical properties and lower yield responses compared to other reclamation methods (Hooks et al., 1992; Dunker and Darmody, 2005)

Luminant Mining Company, LLC (Luminant) has been using improved reclamation techniques to successfully reclaim over 40,000 ha of its mined lands to forests, wildlife habitat and pastures with high productivity comparable to that of unmined land (Angel, 2017). Several studies have been carried out on sites managed by Luminant. Angel (1973) revealed that the choice of overburden can also provide a better medium for growth than native soils. By using a mix of selected overburden, soil pH and texture at reclaimed sites has shown remarkable improvement. In a study, Hons (1978) found that fertilization with nitrogen and phosphorus improved yields of grasses and legumes at a mine site in Big Brown. Similar results were found at the Martin Lake mine in east Texas, where height and diameter of two-year old seedlings increased upon addition of nitrogen and phosphorus fertilizers (Shupe, 1986).

Reclamation of lignite strip-mines in Texas must meet the Railroad Commission of Texas (RCT) standards. It requires that mine operators reclaim lands to an approximate contour similar or greater than the pre-mine land use (R.C.T, 1982). The majority of reclaimed mined land in this region is restored to forest plantations which includes commercial pine timber and mixed hardwood stands. Several species of trees have been used in reclamation, and varying degrees of success have been recorded depending on the site and region. Black walnut (*Juglans nigra* L.), black cherry (*Prunus serotina* E.), loblolly pine (*Pinus taeda*, L.), yellow-poplar (*Liriodendron tulipifera* L.), and white ash (*Fraxinus americana* L.) have been found to grow well on reclaimed surface mines (Torbert et al., 1985; Gorman and Skousen, 2003). Reforestation efforts in this region focuses largely on loblolly pine plantations due to the species' high survivability, growth rates and low seedling costs (Troups, 1986).

Loblolly Pine

Loblolly pine is commonly found in the southeastern United States, though also widely grown on plantations. It is an extremely versatile pine capable of growing among various annual and perennial plants; considered in the group of southern yellow pines, and shares characteristics with other species in the group such as longleaf pine (*Pinus palustris* M.), shortleaf pine (*Pinus echinata* M.), and slash pine (*Pinus elliottii* E.). They are generally hard, dense, and possess excellent strength-to-weight ratio. Loblolly pine is the most dominant timber specie in the United States occupying over 13.4 million ha of forest land (Schultz, 1997). Loblolly pine is shallow rooted with majority of its lateral roots found in the top 15-46 cm of the soil (Burns and Honkala, 1990). However, the nature and length of the taproot and lateral roots is influenced by age, soil physical properties and soil biological activities. It typical grows well in acidic, loamy, moist, sandy, well-drained and clay soils. However, this pine specie has high tolerance for flooding and moderate drought. Categorized as a fast-growing specie which produces quality litter, it is often used for soil stabilization and reclamation (Baker and Langdon, 1990). It is the most important commercial tree species in East Texas, and is commonly used in forestry post-mining land use (Priest et al., 2015). This is because of its low cost, rapid growth rates, high commercial value, ability to tolerate extreme weather and nutrient conditions (Troups, 1986). Several studies have been completed concerning the growth and establishment of loblolly pine on reclaimed mined soil. Wood (1985) documented seedling survival and growth of loblolly pine in lignite coal mine overburden under various treatments. Bryson (1973) recorded better survival and first-year growth rates of loblolly pine than shortleaf pine on Texas Utilities' mine at Fairfield, Texas. When comparing survival and height growth of two to ten year old loblolly pine plantations on mine soils with same species on adjacent undisturbed land, Bilan (1980) found that mine soils were equally conducive for the production of loblolly pine as on adjacent soils. Priest et al., (2015) observed a variation in loblolly pine allometry on reclaimed mine land compared with unmined land from different studies. In the same study, the total aboveground biomass was greater on mined sites than unmined sites among trees with similar size. These studies prove that loblolly pine can survive and grow on mine soils, particularly in east Texas. Wood (1985) identified the following economic advantages of using disturbed areas for loblolly pine plantations: i) minimal site clearing, ii) reduced competing vegetation, iii) well-maintained, accessible road networks; and iv) feasibility of machine planting.

The Appalachian Regional Reforestation Initiative (ARRI) and Forest Reclamation Approach (FRA)

The Appalachian Regional Reforestation Initiative (ARRI) which started in 2004 is a cooperative effort between states within the Appalachian Region and the Office of Surface Mining, Reclamation and Enforcement (OSMRE) to facilitate restoration of quality forests on reclaimed mines in the region (Angel et al., 2005). The goals of ARRI are to plant higher quality value hardwoods on reclaimed mine lands, increase their survival rates, and create high quality forests through the utilization of the Forest Reclamation Approach (FRA). Angel et al. (2005) summarized the FRA in five steps:

1. Create a suitable rooting medium for good tree growth that is no less than 1.2 m deep and comprised of topsoil, weathered sandstone and/or the best available material. The nature of the material used as a growth medium for plants determines its growth and survival. Therefore, it is important to carefully select soil materials that support growth and provide adequate nutrients to the plant. Soils with pH of about 5.0 to 7.0, sandy loam textured, well drained and aerated are highly recommended. These soils are formed from weathered brown stones and/or unweathered ‘gray’ materials found in lower depths. Other soil types such as a mix of weathered non-pyritic sandstone and siltstone have been shown to provide the right medium for growth (Burger et al., 2007). These unweathered

stones tend to develop chemical properties similar to those of native soil materials over time (Showalter et al., 2010). In a study, Emerson et al. (2009) highlighted that brown sandstone is a better top soil due to observed growth and survival of planted hardwood species. Studies comparing weathered and unweathered soil types in Appalachia show that hardwoods growing on weathered rock materials had superior growth and survival rates (Torbert, 1990; Angel et al., 2008).

2. Loosely grade the topsoil or topsoil substitutes placed on the surface to create a non-compacted growth medium. This involves the use of end dumping to place soil piles in mine pits. In the past, soils were compacted to reconstruct the topography followed by seeding with grasses to stabilize the slopes. Unfortunately, these reclamation methods do not support establishment of native species. Instead it created compact soils with high bulk densities. Studies revealed that tree growth and survival reduced at high soil densities (Davidson et al., 1984; Torbert, 1990; Ashby, 1991, 1997). Effects of high soil density include reduced soil water holding capacity, reduced soil pores which hinders oxygen supply and growth of tree roots. Thus, reducing compact soils is important to the success of reforestation of mine soils. Forest soils are naturally loose and support establishment of deep-rooted woody species, thus operations that compact the soil and hinder tree growth should be avoided. To achieve this, the top soil (about 1.2 m) should only be graded lightly with few passes, using small equipment for grading preferably during dry conditions (Sweigard et al., 2007). Angel et al.

(2006) concluded that loose grading of the soil enhanced growth and survival of seedlings. In the same study, survival and growth of some species were hindered on soils that experienced small amounts of machine traffic. Also, loose soil surfaces reduce erosion by allowing water infiltration (Fields-Johnson et al., 2010).

3. Use native and non-competitive ground covers that are compatible with growing trees. It is important to use herbaceous ground cover during forestry reclamation to prevent erosion, and provide adequate cover to the soil and planted seedlings. This step involves establishing appropriate ground cover that effectively controls erosion without disrupting planted trees. While choosing the appropriate ground cover, fast growing and competitive grasses should be avoided because they aggressively compete for soil nutrients and inhibit growth of the planted seedlings. Using less-competitive species with lower seeding rates is desired. Utilizing ground cover with tree compatible species minimizes competition with planted seedlings and increases their survival. Loose grading the soil (step 2) allows water infiltration, however, using these less competitive ground covers reduces erosion. If fertilization is necessary, fertilizers low in nitrogen and sufficient in phosphorus and potassium should be applied to avoid excessive ground cover and support tree growth (Burger et al., 2005). Studies on mine sites revealed that herbaceous ground covers support tree growth and establishment

(Chaney et al., 1995; Ashby, 1997; Torbert and Burger, 2000), and controls erosion (Jeldes et al., 2010).

4. Plant two types of trees – early successional species for wildlife and soil stability, and commercially valuable crop trees. Species which are native to the area and are adapted to existing conditions are suited for this step. Early successional trees improve soil nutrients, attract wildlife that propagate seeds and act as 'nurse trees' on the reclaimed area. Crop trees of economic value and native to the region should be planted alongside early successional trees.
5. Use proper tree planting techniques. To maximize survival, planted seedlings must be properly taken care of from nursery to planting. Seedlings should be stored in a cool place away from direct sunlight and excessive temperatures. Planting should be carried out in the right season, preferably in late winter to early spring. In Appalachia, experienced personnel are often employed for tree planting to ensure that trees are planted at the correct depth to accommodate the root system (Burger et al., 2005).

In summary, the purpose of FRA is to create a forest community with an ecological balance to maximize all the multiple uses of the reclaimed land. The compacted soil layer is replaced with non-compacted soil or soil substitute, and then FRA is implemented with the tree-compatible herbaceous cover to provide opportunity for establishment of native species from surrounding forest to reinhabit the site (Zipper et al., 2013). The FRA is being used effectively in the Appalachians, about 438 ha of mined land was reclaimed using FRA in Tennessee from 2007 to 2009. Similar success was recorded in Virginia and West Virginia, where 2743 ha and 8049 ha were reclaimed respectively (Zipper et al., 2011). When properly implemented, the FRA can be a cost effective and regulatory compliant reclamation method for coal mining operators, create valuable forests, and provide protection for watershed and wildlife habitat. Although, its success in recreating a forest ecosystem is yet to be proven because ecosystems require many years to be successfully established, however, the FRA has successfully established forests on reclaimed mines in the Appalachia.

CHAPTER II: EFFECTS OF FRA AND PAN SCRAPER RECLAMATION ON VEGETATION

INTRODUCTION

The Surface Mining Control and Reclamation Act (SMCRA) of 1977 requires that coal mining operations are conducted in an environmentally responsible manner and that land is adequately reclaimed to an equal or greater land use capacity than its pre-mining state (Public Law 95-87, 1977). To achieve this, reclamation efforts must address soil structure, soil fertility, microbial populations, top soil conservation and nutrient cycling in order to restore the land to the approximate original contour (AOC) and continue to a self-sustaining ecosystem. Dunker et al. (1991) identified poor soil physical conditions as the most severe and challenging factors in the reclamation of soils. Some of these factors including soil texture, soil aggregation, soil moisture, bulk density (BD), and slope are known to hinder vegetative growth on reclaimed land (Slick and Curtis, 1985; Sutton, 1991; Dunker et al., 1995; Kozlowski, 1999b). Reestablishing forests on surface-mined land is particularly challenging; however, a series of reforestation research by Virginia Tech's Powell River Project since 1980 shows that restored forests can be equally or more productive than the native forests removed by mining (Burger and Zipper, 2011). A comparison of young loblolly pine seedlings on reclaimed mine land and unmined land, Priest et al. (2015) found that biomass and volume productivity were similar in both cases. Casselman et al. (2006) also reported improved survival of hardwoods on reforested mines the Appalachians.

Soil tillage techniques have been used to improve soil physical properties. Salem et al. (2015) found tillage to be effective in reducing bulk density, increasing filtration and moisture retention, which also improved plant yield, however, this effect was only short-term. In addition, tillage has often been used to improve soil-water interaction, soil-temperature interaction, soil aeration, seed-soil contact, nutrient accessibility, porosity, pore size distribution, and microbial activities. Disk harrowing, bedding, chisel plowing, and subsoiling were identified as the four general types of tillage practices (Miller et al., 2004). The same study also recommended a combination of these techniques as an option for tillage. The success of tillage in reducing compaction in soils is dependent on the type of equipment and the soil physical properties (Unger and Cassel, 1991). A series of studies revealing the effect of tillage on compacted soils have been conducted. Foil and Ralston (1967) concluded that loosening the soil reduced soil bulk density to varying levels (clay>loam>loamy sand) and consequently improved pine growth and survival. Angel et al. (2018b) found cross ripping to be more effective in reducing bulk density and increasing the above and belowground biomass of loblolly pine seedlings than ripping or agricultural disking alone.

Despite the documented success of tillage, some negative effects exist if not properly carried out under the right conditions. McVay et al. (2006) concluded that excessive surface disking reduced soil organic carbon. Other studies reported little or no vegetative response to tillage methods. Evans et al. (2013) found that while deep ripping may have reduced soil density, it was not responsible for growth of planted seedlings. Other site and soil factors proved responsible for growth performance. Dunker (1995) showed that all the experimented tillage treatments significantly reduced soil strength and increased plant yield, however, the best tillage treatments were those that reached depths of about 120 cm. Undisturbed land plant yields were reached or exceeded with deeper tilled treatments.

Compaction alters the size, structure and distribution of soil pores that affects the movement of air, water, and gas within the soil pores and therefore biological activity and root growth (Sutton, 1991). Compacted soils reduce seedling establishment and growth rate by over 50 %, depending on the amount of root growth restriction and the average BD increment (Schultz, 1997). It is important to minimize the negative effects of soil compaction on plant growth by implementing proper management strategies for a particular land use. When properly utilized, FRA has shown to eliminate compaction and all the problems associated with reclaiming mined lands and enhances results in the restoration of productive forests to mine lands (Burger et al., 2005; Zipper et al., 2011). Barton et al., 2017 indicated that loose-dumped spoils generated 10 times more stems per acre than the conventionally graded spoil. Sena et al., (2014) recorded 86 percent seedling survival rate on FRA plots planted with native hardwood species on brown weathered sandstone, and observed that vegetation totally covered the ground. Similar success was recorded by Skousen et al., (2013) with American chestnut (*Castanea dentata* B) showing excellent survival on mined lands reclaimed using FRA.

Other research efforts have also recorded reforestation success of native hardwood species using the FRA (Angel et al., 2008; Burger et al., 2008; Emerson et al., 2009; Fields-Johnson et al., 2010). Diverse, fast-growing stands of native trees mixed with native herbs and grasses were observed during field surveys (Angel et al., 2008). Angel et al. (2006) showed that by minimizing compaction through decreased grading, the height and survival of white oak (*Quercus alba*, L.), eastern white pine (*Pinus strobus*, L.), northern red oak (*Quercus rubra*, L.), black walnut (*Juglans nigra*, L.), and yellow poplar (*Liriodendron tulipifera*, L.) were significantly greater compared with those grown in compacted mine soils. Other related studies confirmed the efficiency of FRA. When spoils were end-dumped and graded with one or two passes, hardwood species recorded over 80 percent survival rates in southern West Virginia (Emerson et al., 2009).

Prior to this study, the FRA had not been tested in the Gulf Coastal Plain, and due to its success in the Appalachians, it has become a subject of interest to determine how similar processes can improve forest productivity in other regions. This study was created to evaluate the performance of loblolly pine seedlings on reclaimed mined lands using FRA and to investigate the effect of FRA and a traditional reclamation approach (pan scraper) on early seedling biomass production and allocation.

MATERIALS AND METHODS

Study Area

In January 2016, a 1-hectare experimental site was established in Houston County, Texas (31° 12' 25.8804" N, 95° 23' 40.5204" W) on a previously non-forested land. Mean annual precipitation and 24 hour temperature for the region are 1148 mm and temperature of 19 ^{o}C respectively (N.O.A.A., 2018). Loblolly pine is one of the dominant species found in this region. Prior to establishment, the site was an unmanaged pasture land consisting a wide variety of vegetation including grasses, shrubs and other herbaceous vegetation. The soils at the site were classified as very fine, smectic, thermic Vertic Hapludalf. The surrounding native area consisted of fully grown loblolly pine plantations.

Experimental Design

To simulate reclaimed mine land, two reclamation treatments and a control treatment were installed. Both reclamation treatments were dug to approximately 1.3 m with a CAT excavator. No special control method was used to prevent competition from herbaceous vegetation and no fertilizers were applied. Treatment plots were arranged in randomized complete block designs with three treatments and three replicates making a total of 9 plots. Loblolly pine seedlings of Texas provenance were hand planted on separate 0.08 ha treatment plots within a block at a 2.4 x 2.7 m spacing. The measurement plot consisted of approximately 120 seedlings per plot, the outer two rows on each treatment were considered buffer rows, yielding a measurement plot of 48 seedlings. By the end of February 2016, every reclamation treatment was completed and well-planted. The treatments were:

1. Control: designed to mimic site conditions on non-reclaimed sites, the only mechanical movement on the control plot was one or two passes of the dozer during clearing of vegetation. No other disking, ripping or other soil treatments were conducted on the control plots.
2. FRA: with expertise from OSM personnel, the FRA plots were designed similar to the Appalachian practices with little adjustments where necessary to meet the condition of the site. The FRA treatment plots were dug to a depth of 1.3 m using a CAT excavator. The soil was stockpiled by a rubber-tired loader and end-dumped using smaller buckets. These buckets were dumped in piles of adjacent pits overlapping the preceding pile. No further grading was required on these plots.
3. Pan scraper: designed to represent the common practice in this region, the pan scraper sites were dug up to 1.3 m depth with an excavator. The soil was stockpiled by a rubber-tired loader, which trafficked as much as possible to compact the stockpile. A CAT dozer was used to deliver the soil in thin piles into the 1.3 m pit, simulating the process of the conventional scraper method. Frequent

trafficking by the loader created soil compaction, much like the conditions observed on mine soils reclaimed with the pan scrapers.

Sample Collection

Soil bulk density data used as reference in this study was taken from Phillips et al. (2019). BD was measured in June 2017 using the slide hammer method (Blake and Hartge, 1986). Soil cores were sampled using 5.08 cm x 2.54 cm aluminum liners (AMS Inc., American Falls, ID, USA). Soil cores were oven dried at 105 °C until constant weight was achieved. The BD of the soil was then determined by dividing the mass of soil by its volume.

In June 2018, height of buffer zone seedlings (root collar to base of needles) was measured. Based on height data, seedlings were stratified (i.e. 0.5-1.0 m, 1.1 – 1.3 m…2.0-2.5 m) and an attempt was made to select at least one seedling from each stratum to adequately represent the total sample area. A total of 27 seedlings were randomly selected within their stratification categories. Groundline diameter (GLD) was measured using calipers for all 27 selected seedlings prior to harvesting. Volume index (VI) was calculated using the following equation (1):

$$VI = GLD^2 * H \quad (1)$$

GLD = seedling diameter at ground line

H = seedling height

Destructive Sampling

Destructive biomass harvests were conducted between June and July, 2018 to develop prediction equations that are site-specific. Three seedlings per plot (a total of nine seedlings per treatment), which adequately represented the range of tree sizes were felled at the ground line using a hand saw or loppers. Large black bags were laid out on the ground prior to felling to avoid loss of any seedling component. Samples were immediately taken to Arthur Temple College of Forestry and Agriculture Research lab in black bags and stored in a cooler at 4 ^{o}C. Each seedling was separated into foliage, branches, and stem. Soil pits were excavated by using a mattock and a shovel. The pits (30 cm radius) were dug adjacent to pre-selected seedlings. The root component of each sampled seedling was extracted and transported to the Arthur Temple College of Forestry and Agriculture research lab in black bags and stored in a cooler at 4 ^{o}C. Root samples were washed on a mesh (0.25 mm) to remove soil particles and prevent loss of small diameter roots.

All seedling components were dried at 65 ^{o}C and weighed. For each sampled seedling, aboveground and belowground components were added and used to determine the total biomass.

Statistical Analyses

Analysis of Variance (ANOVA) and Tukey's post hoc test was used to test treatment effects on tree height, GLD, foliar mass, branch mass, stem mass, root mass (0 – 10 cm and 11 – 20 cm), total above- and belowground biomass, and volume index. Using an ANOVA statement, honesty significant difference (HSD) tests were performed to test for differences in mean bulk density values on each treatment.

All analyses were performed in SAS 9.4 (SAS Institute, Cary, NC, USA). Probability of significant differences was tested at $\alpha = 0.05$. Assumptions of normality and homogeneity of variance were verified using PROC UNIVARIATE and PROC GLM respectively. Response variables did not require transformation.

Nonlinear regressions were used to create allometric relationships from the harvested seedlings to estimate the various biomass components of all planted seedlings on the site. Treatment plots were considered as separate experimental units for statistical modeling and comparison. Coefficients were estimated from the non-linear model form in equation (2) below using PROC NLIN. This model had similarly been used in previous loblolly pine allometric analyses (Priest et al., 2015; Angel et al., 2018). Height and GLD were used as independent variables. Dependent variables included foliar mass, branch mass, stem mass, root mass (0 – 10 cm and 11 – 20 cm), total above- and belowground biomass components. The model to be fit is shown in the equation (2) below:

$$Y = \beta_0 * (GLD^{\beta 1}) * (H^{\beta 2}) \quad (2)$$

Where,

Y = Dry weight biomass component (g)

GLD = Ground-line diameter (mm)

H = Seedling height (m)

$\beta_0, \beta_1, \beta_2$ = Regression parameters

Allometric analyses were carried out using the estimates of above- and belowground biomass. The non-linear model parameters were then tested for significance among various treatments. Regression models parameterized from the 27 randomly selected seedlings were then used to estimate the biomass of individual trees and allocation responses across all trees in the study.

RESULTS

Bulk density

The experimental installation resulted in noticeable treatment effects on bulk density ($p < 0.05$) (Table 1). Bulk density was significantly greater in the control than in the FRA treatment.

Table 1. Mean bulk density followed by standard errors in parentheses for the three treatments.

Treatment	Bulk density (mg m^{-3})
Control	1.38[a] (0.04)
FRA	1.15[b] (0.05)
Pan Scraper	1.27[ab] (0.08)
Pr>F	0.0404

Means followed by the same letter are not significantly different ($\alpha = 0.05$).

Growth Response

The 27 sampled loblolly seedlings exhibited some contrast between the treatments. Seedlings on the FRA treatment outgrew seedlings on the other treatments in height and GLD, while seedlings on the pan scraper treatment were shorter in height and thinner in GLD (Table 2). Treatment effects were observed in height, GLD and volume index ($p < 0.05$). There was significant difference between the mean height and GLD of seedlings on FRA and pan scraper. A similar trend was observed in seedling volume. The FRA seedlings had significantly higher volumes than pan scraper seedlings.

Table 2. Mean Height, GLD and Volume Index response to treatment of 27 sampled seedlings.

Treatment	Height (m)	GLD (mm)	VI (cm^3)
Control	1.4^{ab} (0.1)	25.8^{ab} (3.0)	1156.6^{ab} (330.3)
FRA	1.7^{a} (0.2)	35.4^{a} (4.1)	2751.3^{a} (839.2)
Pan Scraper	1.1^{b} (0.1)	23.8^{b} (2.7)	815.6^{b} (251.2)
Pr>F	0.0297	0.0453	0.0411

Means followed by the same letter are not significantly different among treatments ($\alpha = 0.05$). Standard errors are given in parentheses

Loblolly Pine Biomass

The pattern in loblolly pine seedling height and GLD was similar for above and belowground biomass between treatments. Treatment effects were evident on foliage, branch, stem, root (0 -10 cm), belowground, aboveground and total seedling biomass of the 27 sampled seedlings ($p < 0.05$) (Table 3). There was no treatment effect on biomass of roots in 11 – 20 cm depth ($p > 0.05$). Twenty-five of the sampled seedlings had roots growing up to 20 cm. The two shallow rooted seedlings having all their root mass within 10 cm were in the pan scraper treatment.

Table 3. Mean seedling above- and belowground biomass of 27 sampled seedlings during the third growing season.

Treatment	Control (g)	FRA (g)	Pan Scraper (g)	Pr>F
Foliage	191.9^{ab} (35.2)	417.4^{a} (101.5)	178.8^{b} (35.2)	0.0269
Branch	87.8^{ab} (15.7)	187.4^{a} (46.2)	77.2^{b} (16.6)	0.0275
Stem	123.1^{ab} (29.1)	245.2^{a} (60.7)	96.0^{b} (23.4)	0.0386
Root 0-10 cm	61.7^{b} (13.7)	144.4^{a} (32.4)	69.1^{ab} (12.7)	0.0219
Root 11-20 cm	21.5^{a} (2.8)	24.0^{a} (4.1)	13.1^{a} (3.1)	0.0737
Belowground	83.2^{b} (16.1)	168.4^{a} (34.0)	82.1^{b} (14.2)	0.0214
Aboveground	402.8^{ab} (77.7)	850.0^{a} (207.3)	352.0^{b} (73.3)	0.0284
Total tree	486.0^{ab} (93.1)	1018.4^{a} (240.5)	434.1^{b} (86.7)	0.0265

Means followed by the same letter are not significantly different among treatments ($\alpha = 0.05$). Standard errors are given in parentheses.

FRA had more foliage, branch, stem, belowground, aboveground and total seedling biomass compared to other treatments. Pan scraper seedling biomass was lowest in all tissues except roots <10 cm where it was intermediate. Control produced the lowest biomass for roots >10 cm. There was a significant difference between FRA and pan scraper in foliage, branch, stem, aboveground and total seedling biomass. There was no significant difference in roots 11-20 cm biomass between all treatments. No differences existed in belowground biomass between control and pan scraper. FRA root <10 cm biomass was significantly different from control.

Table 4. Percentage composition of foliage, branch, stem, belowground and aboveground biomass from the destructive harvest of 27 seedlings across the three treatments

Treatment	Foliage %	Branch %	Stem %	Belowground %	Aboveground %
Control	39.6[a] (1.4)	18.1[a] (1.1)	23.9[a] (1.5)	18.3[a] (1.6)	81.7[a] (1.6)
FRA	41.1[a] (1.4)	18.1[a] (1.2)	23.5[a] (1.3)	17.3[a] (0.9)	82.7[a] (0.9)
Pan Scraper	41.9[a] (1.6)	16.9[a] (1.1)	21.5[a] (1.2)	19.7[a] (1.1)	80.3[a] (1.1)
Pr>F	0.5548	0.6923	0.4035	0.4008	0.4008

Means followed by the same letter are not significantly different among treatments ($\alpha = 0.05$). Standard errors are given in parentheses

The percentage foliage, branch, and stem, belowground and aboveground biomass of the total biomass was not affected by tillage treatment ($p > 0.05$) (Table 4). There was no significant difference between treatments in the percentages of all sampled tissues. Seedlings in FRA had the highest root weight, but lower percentage when compared with total plant biomass (Table 3, 4). Despite the obvious larger size of the FRA seedlings, percentage biomass allocation was still similar to other treatments for all sampled 27 seedlings. There was no significant difference in the root:shoot ratio between all treatments. Ratios were 0.30, 0.21, and 0.17 for FRA, pan scraper and control treatments respectively.

The model shown in equation (2) was used to predict mass of foliage, branch, stem, roots (< 10 cm and 11-20 cm), total belowground, total aboveground and total seedling biomass. Equation (2) was previously used for similar studies (Priest et al., 2015) which was found to be adequate for predicting biomass and volume of young trees. The regression coefficients were significant for all biomass components in each treatment ($p < 0.05$) (Table 5).

Table 5. Regression coefficients for seedling biomass components for all treatments based on equation 2

	β_0	β_1	β_2	Pr > F
Foliage				
Control	1.2899	1.5119	0.1405	<.0001
FRA	0.1163	2.2751	-0.1206	<.0001
Pan Scraper	0.1706	2.2075	-0.7266	<.0001
Branch				
	β_0	β_1	β_2	Pr > F
Control	0.6104	1.5428	-0.2066	0.0001
FRA	0.025	2.5452	-0.523	<.0001
Pan Scraper	0.011	2.8471	-1.6495	<.0001
Stem				
	β_0	β_1	β_2	Pr > F
Control	1.4346	1.2199	1.1494	<.0001
FRA	0.758	1.4271	1.0117	<.0001
Pan Scraper	0.2048	1.888	0.3515	<.0001
Root (0-10 cm)				
	β_0	β_1	β_2	Pr > F
Con	0.7021	1.2765	0.7624	0.0002
FRA	0.1821	1.8266	0.1362	<.0001
Pan Scraper	0.1731	1.9176	-0.7547	<.0001
Root (11-20 cm)				
	β_0	β_1	β_2	Pr > F
Control	1.3657	0.8029	0.4087	<.0001
FRA	0.7742	1.0494	-0.5618	0.0071
Pan Scraper	491.7	-1.3232	3.6019	0.0006
Total Belowground				
	β_0	β_1	β_2	Pr > F
Control	1.4163	1.166	0.6803	<.0001
FRA	0.2934	1.7799	-0.0969	<.0001
Pan Scraper	1.0211	1.3824	-0.0388	<.0001
Total Aboveground				
	β_0	β_1	β_2	Pr > F
Control	4.0386	1.3839	0.3528	<.0001
FRA	0.4547	2.0765	0.0725	<.0001
Pan Scraper	0.3629	2.1964	-0.6235	<.0001
Total Tree				
	β_0	β_1	β_2	Pr > F
Control	5.6703	1.3338	0.4075	<.0001
FRA	0.6853	2.0257	0.0226	<.0001
Pan Scraper	0.8196	2.0067	-0.4935	<.0001

Regression coefficients were used to estimate the biomass of each seedling tissue on the experimental site using height and GLD of the seedling. Regression coefficients for each biomass tissue were all significant ($p < 0.05$) (Table 5). A total of 336 seedlings (control = 101, FRA = 122, pan scraper = 113) previously measured and reported in Phillips et al. (2019) were used for this study. H, GLD and VI were significant for all treatments ($p < 0.05$) (Table 6). FRA seedlings outgrew the control and more compacted pan scraper treatments in height, GLD and seedling volume index two years after planting (Table 6).

Table 6. Mean seedling H, GLD, and volume index of 336 seedlings on all treatments.

Treatment	H (m)	GLD (mm)	VI (cm^3)
Control	1.5^{b} (0.0)	30.3^{b} (0.8)	1557.6^{b} (108.0)
FRA	2.1^{a} (0.2)	46.9^{a} (1.3)	5658.4^{a} (367.9)
Pan Scraper	1.1^{c} (0.0)	22.4^{c} (0.8)	800.0^{c} (75.1)
Pr>F	<.0001	<.0001	<.0001

Means followed by the same letter are not significantly different ($\alpha = 0.05$). Standard errors are given in parentheses

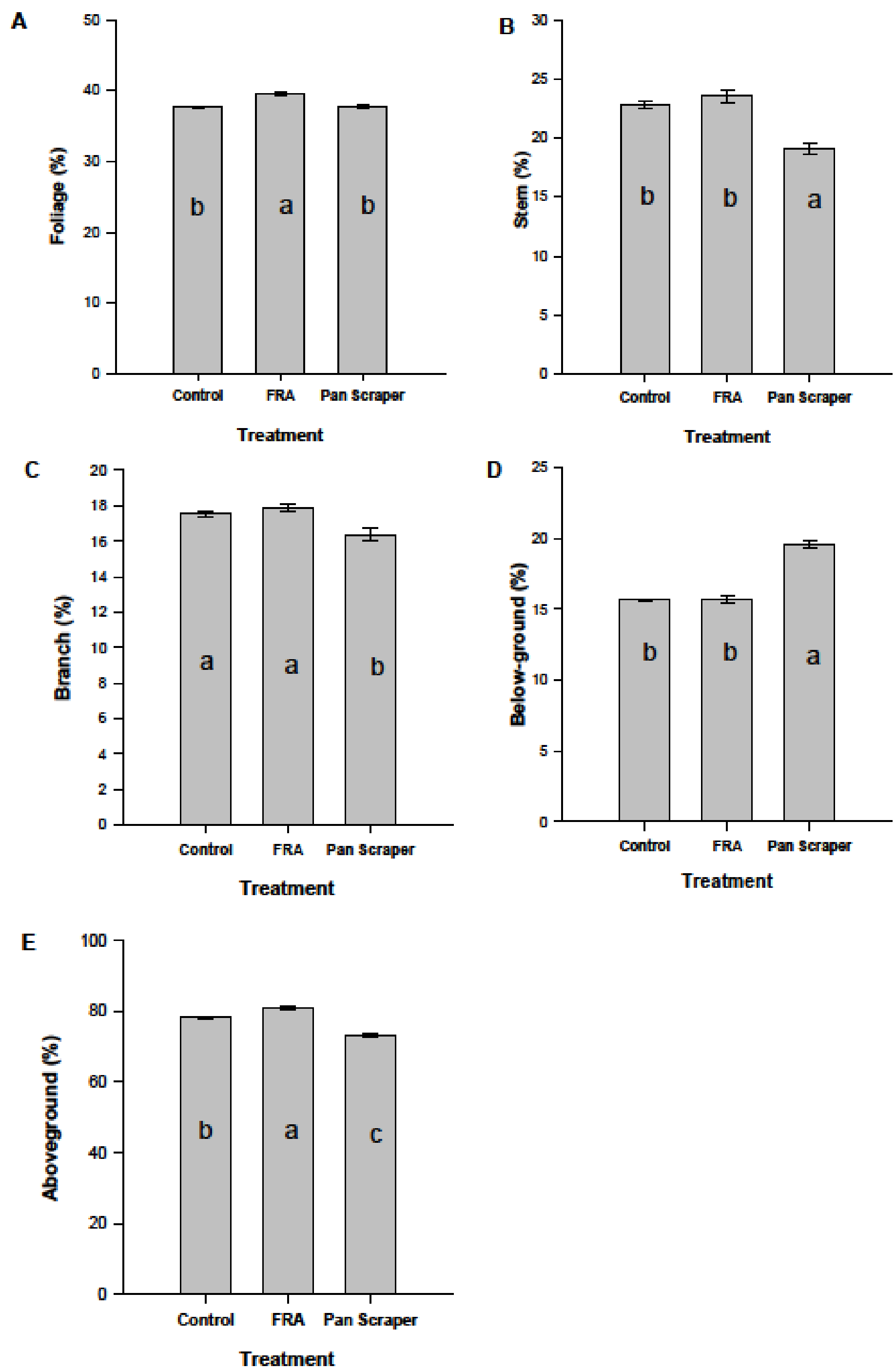
Predicted above and belowground biomass of loblolly pine seedlings exhibited similar patterns to height and GLD. P-values in Table 7 suggests that all tissue biomass was affected by treatment ($p < 0.0001$). FRA produced significantly more foliage, branch, stem, root, aboveground and total tree biomass, while pan scraper produced the lowest mean biomass for all tissues. No difference existed in root (< 10 cm) biomass between control and pan scraper seedlings. In this table, the importance of the stratification and selection method was further displayed because representative seedlings were selected from each treatment. For example, control and pan scraper plots had more border row seedlings between 0.8-1.0m height classes while FRA had a greater frequency of taller trees. However, stratified sampling ensured that small, medium and large size seedlings were sampled in all treatments.

Table 7. Predicted mean aboveground and belowground biomass of 336 seedlings with standard errors in parentheses.

Treatment	Control (g)	FRA (g)	Pan Scraper (g)	Pr>F
Foliage	244.0[b] (10.3)	759.1[a] (44.1)	159.0[c] (8.5)	<.0001
Branch	110.9[b] (4.2)	344.3[a] (21.8)	67.1[c] (3.5)	<.0001
Stem	153.9[b] (7.8)	440.0[a] (23.3)	90.0[c] (6.5)	<.0001
Root 0-10 cm	76.9[b] (3.5)	246.9[a] (12.2)	62.9[b] (2.8)	<.0001
Root 11-20 cm	24.8[b] (0.7)	28.7[a] (0.7)	15.9[c] (1.2)	<.0001
Belowground	101.8[b] (4.2)	273.1[a] (12.4)	77.2[c] (3.6)	<.0001
Aboveground	536.5[b] (22.5)	1579.3[a] (86.7)	334.4[c] (18.5)	<.0001
Total tree	648.0[b] (26.9)	1865.4[a] (99.0)	420.4[c] (22.3)	<.0001

Means followed by the same letter are not significantly different ($\alpha = 0.05$).

Biomass allocation was equally responsive to treatments similar to biomass production. Treatment variability affected percent distribution of biomass on each seedling ($p < 0.005$). When total biomass was separated into individual component parts, the distribution of each aboveground and belowground biomass by seedling component were variable by treatment. Foliage accounted for largest proportion of total seedling biomass (38.3% on average), followed by stem (21.8%), branches (17.2%), roots (16.9%) (Figure 1A, B, C). Among the three treatments, FRA had the highest biomass allocation in foliage while control had the lowest. The biomass allocation to branches, stem and roots was similar in control and FRA treatments were statistically different from pan scraper treatment. The largest stem allocation was in FRA and smallest in pan scraper. The biomass allocation to roots ranged from 15.7% - 19.5% and was higher in pan scraper than the other two treatments (Figure 1D, E). Biomass accumulation was highest in FRA for all tissues. Total tree biomass in FRA (948.25 kg ha^{-1}) was about 5-fold higher compared to pan scraper stand.


A
Foliage (%)
50
40
30
20
10
0
b
a
b
Control
FRA
Pan Scraper
Treatment
B
Stem (%)
30
25
20
15
10
5
0
b
b
a
Control
FRA
Pan Scraper
Treatment
C
Branch (%)
20
18
16
14
12
10
8
6
4
2
0
a
a
b
Control
FRA
Pan Scraper
Treatment
D
Below-ground (%)
25
20
15
10
5
0
b
b
a
Control
FRA
Pan Scraper
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E
Aboveground (%)
100
80
60
40
20
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FRA
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Treatment

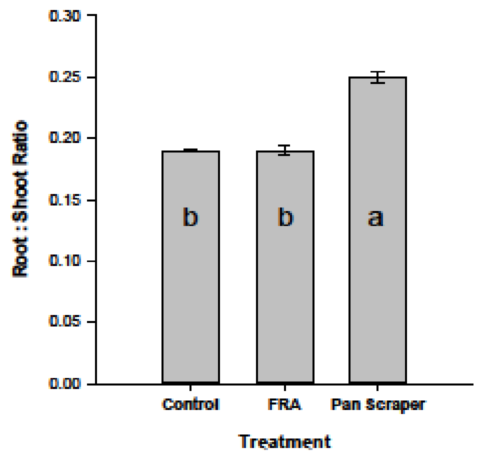


Figure 1. Percent foliage (A), stem (B), branch (C), belowground (D), aboveground (E), Root: Shoot ratio (F) with standard error bars. Same letters in a graph are not different ($\alpha = 0.05$).

Root:shoot ratio was significantly different by treatment (Figure 1). The increase in the absolute root biomass allocation in the pan scraper seedlings changed the root:shoot ratio so much that it was higher than other two treatments and thus, significantly different. The disparity in this ratio was largely driven by the increased root biomass and was noted without a subsequent increase in shoot biomass. It should be noted that there is a significant variation in the root/shoot ratio of pan scraper and FRA (0.25 – 0.19), nonetheless, the ratio is inversely related to the size of the seedling. FRA and control seedlings with larger size and biomass had the same root:shoot ratio, and that was lower than in pan scraper with smaller seedling size and biomass. Also, there was a significant linear relationship between aboveground biomass and belowground biomass for individual treatments ($p < 0.05$). The coefficients of determination exceeded 0.97 for all treatments (Table 8).

Table 8. Coefficients of linear equation Y = a + bX for all treatments about predicted above- and below- ground biomass.

Treatment	a	b	R^2	Pr>F
Control	1.79363 (1.4)	0.18634 (0.0)	0.9831	<.0001
FRA	47.37449 (2.2)	0.14289 (0.0)	0.9915	<.0001
Pan Scraper	13.0147 (1.1)	0.19183 (0.0)	0.9768	<.0001

*standard errors are given in parenthesis

DISCUSSION

Bulk Density

The understanding of how environmental factors impact growth and productivity of forest ecosystems has been a focus of scientific interest for decades (Jokela, 2004). The purpose of tillage in site preparation was to improve existing soil physical properties and encourage seedling establishment and development. Bulk density is the most common measure of soil compaction and it has been shown to affect growth and production of seedlings (Dollhopf and Postle, 1988). Problem with bulk density measurements on vertic soils is associated with its swelling and shrinking nature. The soil typically has a high bulk density when dry and low density when swollen. The treatments implemented in this study created differing levels of compaction as evidenced by the bulk densities (Table 1). The FRA treatment, as expected, had the lowest bulk density suggesting a lower compaction level while control had the highest density. The lower compaction level in the FRA treatment (i.e. bulk density) corresponds to similar studies in Appalachia (Angel et al., 2006). During site preparation, compaction is often a problem and can have negative impacts on survival and growth of seedlings. Previous studies showed that tillage was used to reduce compaction on pan scraper reclaimed sites (Angel et al., 2018), while many others reported that tillage was responsible for reducing soil BD, thus increasing tree rooting ability and resulting in greater growth (Campell, 1973; Dewitt and Terry, 1983; Zhou et al., 1998). Root growth was found to be limited when average BD was between 1.40-1.45 mg m^{-3} and 1.55-1.70 mg m^{-3} for clay soils and sandy clay loams respectively (Daddow and Warrington, 1983). However, in this study, the bulk density of all treatments (i.e. 1.15 to 1.38 mg m^{-3}, Table 1) was generally below the accepted level at which root growth can be severely impeded and thus reduce overall plant yield. These minimum levels are approximately 1.40 mg m^{-3} for clayey soils, 1.70 mg m^{-3} for loamy soils and 1.75 mg m^{-3} for sandy loam soils (U.S.D.A-NRCS, 1996). Our experimental site did not provide extreme growth limiting bulk density levels; therefore, other factors not included in this study may be of greater importance in evaluating the development of seedlings on the site.

Seedling Growth

Height and Volume Growth

Loblolly pine seedling height, diameter and volume index varied between treatments. In this study, sampled seedlings and total seedlings showed similar results in terms of height, diameter and volume productivity between FRA and pan scraper treatment. In both cases, FRA treatment produced significantly different results from the pan scraper. Pan scraper seedlings, despite not having the lowest bulk density, showed least growth in height and diameter. Previous studies found seedling height to be lower when bulk density exceeded 1.3 mg m^{-3} and 1.4 mg m^{-3} on different soil types (Kozlowski, 1999). As a result of the site conditions created by compaction, the growth of loblolly pine seedlings was lower in the pan scraper and control treatment seedlings with the higher density soils. In a greenhouse study, Hatchell et al. (1970) reported lower development of loblolly pine seedlings on compacted soils. Studies on other tree species under similar conditions reported similar responses (Tworoski et al., 1983; Corns, 1988). In a study on oak species, Jordan and Hubbard (2003), reported that compaction reduced germination, establishment and growth. Similarly, field studies have reported similar results. Angel et al. (2006) concluded that small traffic (i.e. one or two passes) can result in enough compaction to significantly hinder the survival and growth of some species. Compared to conventional reclamation methods, loosening the soil (FRA) allows seedlings to achieve faster growth (Zipper et al., 2011), hence, better height (Torbert and Burger, 1994). FRA improved height, GLD and volume index of loblolly pine seedlings on the experimental site. This was most likely an indication of improved soil physical conditions that allowed roots to capture and utilize soil resources more effectively (Will et al., 2002b). The findings in this study are supported by similar research on reclaimed mined lands (Angel et al., 2008; McCarthy et al., 2008, 2010; Miller et al., 2015). Notably, soil tillage was found to improve height of various tree species on reclaimed mined lands in various studies (Casselman et al., 2006). Angel et al. (2018b) found improved seedling growth rates on a surface mine in east Texas when cross-ripping and disking was implemented. Based on functional tillage treatments, Furtado et al. (2016) found positive responses in tree seedling size. Other studies on non-mined land report that tillage increased seedling height one growing season (Lincoln et al., 2006). Nonetheless, studies of tree growth on mine soils prepared using non-FRA techniques, including conventional grading methods, show productivity below pre-mining reference points, even when soil compaction has been mitigated by ripping the soil (Burger and

Fannon, 2009; Burger and Evans, 2010). Tree growth will reach and probably surpass that of unmined lands with the proper implementation of the FRA reclamation technique.

Biomass

Aboveground Biomass

The prediction equation estimated the biomass of the individual seedling tissues which were vital for the determination of the biomass and volume at a stand level, due to the intensive labor required to destructively harvest trees. The predicted biomass quantity was in the order foliage>stem>branch>belowground in all treatments. Foliage biomass increases rapidly at the initial grow stages until it reaches a stage of no subsequent increment. The results from this study correlates with research on young pine stands where foliage biomass was higher than other biomass components (Wang et al., 1995). Both sampled and predicted biomass produced similar results for FRA treatment and pan scraper treatment. The biomass accumulation differences found between treatments is a reflection of the effects of the different approach to site preparation and tillage. Increased compaction can reduce overall quantity of the plant (i.e. total weight, shoot weight, and branch weight) (Jordan and Hubbard, 2003). In this study, seedlings planted on the FRA treatment produced higher aboveground biomass than other treatments. Low trafficking and loose soil piles in FRA resulted in a BD of 1.15 mg m^{-3} and therefore significantly improved biomass after two years compared to other treatments. In another study, shoot biomass reduced when BD exceeded 1.3 mg m^{-3} (Kozlowski, 1999). Other studies showed that tillage intensity improves biomass production on reclaimed mine lands.

Angel et al. (2018) concluded that increasing tillage intensity improved biomass production in stem, root, aboveground, and total tree components compared to the other treatments. Similar results were found on unmined lands. Lincoln et al. (2006) found that loblolly pine seedling planted on tilled soils showed significant increases in seedling height and biomass production as compared to untilled soils. On reclaimed soils, the biomass of hybrid poplar increased as tillage intensity increased. However, the same study also attributed biomass increase to site conditions and tree species. Overall, the pan scraper treatment was significantly lower in all examined tissue biomass components. Research has shown that scraper positioned mine soil contributes to poorer physical soil properties and lower yield responses relative to other methods of reclamation (Mcsweeney and Jansen, 1984; Hooks et al., 1992; Dunker and Darmody, 2005). The greater total aboveground biomass observed in the FRA treatment may additionally have resulted from the ability of loblolly seedlings to respond faster to increased availability of resources, consequently partitioning similar belowground biomass as a result. The findings also show that aboveground biomass was less responsive to compaction than belowground biomass. Ludovici (2008) and Scott & Burger (2014) reached similar conclusions when examining loblolly pine on compacted and uncompacted soils.

Belowground Biomass

Belowground biomass of seedlings was evaluated to provide an indication of the ability of treatments to adequately support plant growth. Generally, a reclamation technique which supports actively growing roots of pines is deemed sufficient for pine yields and can be used as a measure of reclamation success. This is because pine root biomass accounts for 20%-30% of the total mass of large trees (Ludovici, 2008) leaving significant amounts of nutrients in the soil after harvest. In addition to increasing soil nutrient availability, decomposing stumps also improve aeration, root penetration, cation exchange efficiency, and reduce soil bulk density (Sucre and Fox, 2009); they also supply fertile microsites and moisture which are beneficial to growth of neighboring trees and therefore improve forest productivity (Van Lear et al., 2000). As a result, forest management practices that reduce the allocation of biomass to pine roots would decrease the soil's nutrient pools (Ludovici, 2008). Since tree root systems persist for decades after harvesting, roots are a major component of forest carbon budgets, and declines in root biomass may have long-term effects on site quality (Ludovici, 2008). Soil compaction has generally been observed to restrict rooting area, hinder root penetration, and decrease root biomass (Materechera et al., 1991; Sutton, 1991; Hakl et al., 2007). In Ludovici (2008), biomass of taproots and lateral roots decreased with compaction. The control and pan scraper treatment had higher bulk density (i.e. 1.38 mg m^{-3} and 1.27 mg m^{-3} respectively) and therefore lower belowground biomass than FRA. This result is similar to report from Kozlowski (1999a) where root biomass was found to reduce when compacted soil bulk density exceeded 1.3 mg m^{-3}. The pan scraper treatment recorded two seedling roots that did not grow beyond the 10 cm depth. This is probably a result of the compact layers caused by mechanical trafficking. Bennie (1996) further points out that increases in soil strength caused by mechanical impedance reduces the rate of root elongation and extension, and alters root diameters which limits the available soil volume for water and nutrients. The belowground biomass trends were similar to aboveground trend, with more belowground biomass on the more tilled FRA treatments. Studies evaluating the effect of soil tillage are somewhat limited due to difficulties associated with destructively sampling roots, which can easily be under or overestimated (Schilling et al., 2004). However, appropriate tillage can reduce compaction, loosen the soil and create space for plant roots to elongate and develop properly. Nambiar and Sands (1992) proposed that loosening the soil improved root penetration and exploration of radiata pine (*Pinus radiata* D.Don) into deeper parts of the soil and significantly improved plant growth. Additionally, yellow-poplar (*Liriodendron tulipifera* L.) seedlings recorded higher seedling development and biomass production in dozer ripped and fertilized soils (Casselman et al., 2006). This study predicted that belowground biomass in the FRA treatment was significantly higher than other two treatments, thus, tree seedlings may have exploited soil resources more rapidly prompting increased growth and survival (Will et al., 2002; Coyle et al., 2008). Studies showed a negative correlation between loblolly pine root growth and associated bulk density. Lower bulk density was associated with higher root length and biomass of loblolly pine seedlings (Foil and Ralston, 1967). It is unclear as to why seedlings on the control treatment (with higher BD) had more root biomass than pan scraper seedlings. However, Sinnett et al. (2008) suggested that roots tend to develop vertically to avoid compact areas and stones without any significant effect on net productivity. Inferences from the belowground data in this study is somewhat limited since different root classes were not measured and roots may have been under sampled in control and pan scraper treatments as a result of higher bulk densities.

Biomass Allocation

Improved resource availability resulted in significant growth increases and, therefore accelerated development, but had little effect on percent belowground allocation that was concurrent with development. The order of biomass allocation to seedling components in the FRA was foliage > stem > branch > roots, while pan scraper seedlings allocated biomass in the order foliage > roots > stem > branch. Generally, all treatments partitioned a greater amount of biomass to foliage. This is typical of trees of this size and supported by studies on allocation patterns of young loblolly pine and slash pine (Chmura et al., 2007). Aboveground biomass allocation was the same in all treatments (i.e. foliage > stem > branch). The biomass pattern identified in FRA seedlings underline the dynamic nature of growth during the early stages of stand development. Smith's (1971) study points out that biomass production in young loblolly pine tissues was highest in foliar mass. Loblolly pine was found to exhibit rapid growth during the first two years during which significant foliage and branch production occurs (Chung and Barnes, 1977; Adegbidi et al., 2005). Biomass partitioning between roots and shoots is a reflection of the equilibrium between carbon and resource acquisition (King et al. 1999).

Thus, biomass allocates to the organ responsible for uptake of the particular deficient nutrient. The frequent trafficking on the pan scraper plot may have reduced the seedlings access to nutrients, hence allocating more biomass to its roots as it searches for available nutrients. Decreased biomass allocation to roots in response to enriched nutrient availability has been previously observed for numerous species exhibiting a wide range of growth patterns (Mcconnaughay and Coleman, 1999). The same study also reported that biomass allocation among different plant species remained the same in response to a particular environmental stressor, however, these observed differences were only observed at a particular age. Other studies concluded that seedlings initially respond to abnormal rooting conditions by partitioning more below ground, but gradually as the soil conditions improve, balanced changes in allocation patterns are observed (Priest et al., 2015). This uneven allocation pattern could be a response to initial environmental stress. King et al. (1996, 1999) reported small shifts in biomass allocation in loblolly pine in response to sensitivity to environmental conditions that altered resource availability. Burkes et al. (2003) also highlighted differences in biomass allocation in young pine stands attributed to stand density. However, changes in biomass allocation may only be short-term. For example, Stovall et al. (2012) identified changes in biomass partitioning of smaller trees in response to treatment, however, these changes were only short-term. This could also be experienced on reclaimed mine lands where adverse conditions persist. Although not assessed in this study, other studies have found loblolly pine biomass production and allocation to be affected by various factors such as plant origin, genetics, fertilization, irrigation and stand density (Van Lear et al., 1986; Coyle et al., 2008; Stovall et al., 2012; Aspinwall et al., 2013; Schuler et al., 2017).

A strong relationship exists between roots and shoot of loblolly pines, and any modification to the structure of one affects the other (Schultz, 1997). In young loblolly pine, the ratio of root weight:shoot weight is between 0.20-0.25 (Schultz, 1997), and may be as much as 0.83 for younger pines of approximately 1.0 m tall (Monk, 1966). From this study, the root:shoot ratio ranged from 0.19-0.25 (FRA-pan scraper) with average height of 1.14-2.12 m (pan scraper-FRA). The higher ratio in pan scraper could be associated with its smaller aboveground tissues and higher root biomass allocation. Gedroc et al. (1996) reported that low-nutrient availability resulted in an increase in the root:shoot ratio of two separate tree species, however, this was only early on in development. Similarly, the FRA and pan scraper seedlings followed similar trends with regards to presumed nutrient access. Ludovici (2008), Scott and Burger (2014) established that aboveground growth is less affected than belowground growth in compacted soils, hence, a shift in root:shoot biomass ratio. However, this shift in ratio may only be existent during the early stages of growth and affected by other factors. It is also possible that the pan scraper seedlings with the higher root/shoot ratio encountered greater compaction and hence allocated more biomass to the roots while trying to establish a solid stand.

CONCLUSION

Successful surface-mined land reclamation by reforestation involves the selection of sites with suitable soil characteristics for sustainable tree growth and establishment. By using appropriate reclamation treatments, soil conditions can be altered to reduce conditions that hinder the establishment and growth of seedlings on these lands. The effect of reclamation can be evaluated by site productivity. Site productivity is a complex measure, however, most long-term studies on forestation rely on tree survival, height, diameter, volume index, and biomass weight as relevant measures of productivity (Miller et al., 2004). Generally, tillage has been found to improve vegetative growth of seedlings on mined lands (Ashby, 1996; Burger and Evans, 2010; Angel et al., 2018). From this study, reclamation procedures using FRA reduced compaction caused by using heavy equipment during site grading. These results also show the effect of silvicultural treatments on growth and biomass production of tree seedlings on reclaimed mine lands. Seedlings planted on the low compacted soil FRA treatments (i.e. lower bulk density) resulted in better total height, diameter and seedling volume after two growing seasons. FRA treatments produced the highest aboveground and belowground biomass while growth and biomass production of seedlings was lowest in the pan scraper treatment. This showed the efficiency of the FRA method over the traditional pan scraper method. The lower height, diameter and biomass production of pan scraper seedlings also indicate that pan scraper treatment may be effective in reducing bulk density, but it does not provide equal or better growth than unmined sites. Additionally, while results from this study showed no overall negative impact of soil compaction, reclamation activities should be directed at minimizing the level of soil compaction and productivity.

In summary, the simulated FRA treatment showed that forest productivity can be achieved as a result of the fast growing and high biomass performance of the planted loblolly pine seedlings. If the observed trends persist, FRA will improve site characteristics and enhance loblolly pine productivity on reclaimed mined lands. This allows mine operators to meet regulatory goals while also improving ecosystem quality. This study hypothesized that using the end dumping method of the FRA will likely prove to be the better treatment for the long-term growth and survival, as loblolly pine seedlings are able to grow and penetrate deeper into the soil.

CHAPTER III: EFFECTS OF FRA AND PAN SCRAPER RECLAMATION ON NUTRIENT ACCUMULATION OF VEGETATION

INTRODUCTION

Reclamation of surface mine sites to forests has grown over the years (Burger et al., 2007). This practice improves wildlife habitat, encourages soil and water conservation, improves wood value, and provides an economically beneficial use of land after mining (Burger and Fannon, 2009). The objective of forest reclamation is to restore land productivity and develop a long-term sustainable ecosystem native to the mined area (Macdonald et al., 2015). The use of native species that will adequately provide diversity of economic and ecological values is necessary to establish the desired forest ecosystem. Interest in selection of tree species and its adaptation to post-mining sites has increased in recent years (Baumann et al., 2006). Proper implementation of forestry reclamation approach (FRA) will increase the survival and growth rates of trees, increase overall productivity, and promote natural succession of plant and wildlife communities (Zipper et al., 2011).

There are 17 essential nutrients needed to support plant growth and survival. These plant nutrients can be further classified into four classes: primary- nitrogen (N), phosphorus (P), and potassium (K); secondary- sulphur (S), calcium (Ca), and magnesium (Mg); micronutrients- boron (B), chlorine (Cl), manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), molybdenum (Mo), and nickel (Ni); non-fertilizer elements carbon (C), hydrogen (H), and oxygen (O) (Li, 2016). The abundance of plant nutrients depends on the amount of soil nutrients, uptake modality, and soil properties (Barber, 1995). On the other hand, the availability of plant nutrients is influenced by the chemical and physical properties of soil such as inherent mineral content, organic matter, water permeability, water holding capacity, filtration, and bulk density (Fernandez and Hoeft, 2009). Tillage can influence plant nutrient availability by altering the physical and chemical properties of the soil. Tillage causes changes in soil hydraulic properties, organic matter, structure, and texture which can affect chemical movement and plant growth (McDowell and McGregor, 1984; Unger and Cassel, 1991; Strudley et al., 2008). However, Dick (1983) suggested that nutrient availability to plants may be affected by soil structure disturbance as a result of improper tillage. Many studies have reported soil disturbance from mining, as well as survival and growth on reclaimed mined lands which are highly variable due to unfavorable soil conditions such as poor drainage, restricted rooting depths, pH extremes, and soil compaction (Vogel, 1981; Torbert et al., 1988).

Plant tests are used to evaluate soil fertility and identify any nutrient deficiencies. Different methods have been developed to assess the nutritional status of pines in different ecosystems, including determination of the quality and relative abundance of macronutrients in foliage (Jokela et al., 1991; Brockley, 2001; Albaugh et al., 2010); assessment of tree tissue biomass (Priest et al., 2015; Angel et al., 2018b); and growth and survival of stands (Andrews et al., 1998; Angel et al., 2006). However, foliar analysis has been the most widely used method for assessing the nutrient content of forest stands (Adams and Allen, 1985; Jokela et al., 1991). It is a reliable and cost-effective method for evaluating the nutrient conditions of the site. However, the use of foliar tests to predict nutrient content has limitations including geographic region, seedling age, season of sampling, sampling position within the crown, and analytical procedures for determination (Wells et al., 1986; Jokela et al., 1991; Brockley, 2001).

Most studies on reclaimed mined lands have generally been engineered towards growth and survival (Zeleznik and Skousen, 1996; Angel et al., 2006; Emerson et al., 2009; Showalter et al., 2010), forest productivity (Gorman and Skousen, 2003; Sweigard et al., 2007) and ecosystem C sequestration (Shrestha and Lal, 2006; Amichev and Burger, 2008). However, fewer studies have been conducted on nutrient content of species on reclaimed mined lands. Angel et al., (2018a) found that C and macronutrient content in aboveground components of loblolly pines on reclaimed mine lands exceed or follow similar trends to that of unmined lands. Tilling the soil was found to improve nutrient concentrations in aboveground biomass components of hybrid poplar growing on reclaimed mines (Casselman et al., 2006). Many studies concentrated on nutrient content of species on non-mined lands. C and nutrient content in the aboveground tissues of intensively managed loblolly pine growing on non-mined lands has been reported several times in the literature (Adegbidi et al., 2005; Albaugh et al., 2012; Zhao et al., 2014). Zhao et al. (2014) suggested that differences in C and nutrient content were a result of changes in total tree biomass. Stand density was found to affect foliar nitrogen of mid-rotation loblolly pine plantations (Akers et al., 2013).

Interest in nutrient content of seedlings on reclaimed mine land has increased as the forest productivity potential of species becomes widely recognized. If succeeding ecosystems are to be effectively managed, better understanding of stand characteristics and ecosystem dynamics (e.g. biomass and distribution of nutrients) is essential. The measurement of C and nutrients in various components of seedling biomass is important for the design of effective reclamation and plantation management systems. Thus, it is important to monitor the nutrient content of loblolly pine components growing on reclaimed mined lands in order to provide context for the growth and sustainability of the restored ecosystem. This information will expand knowledge on the effectiveness of reclamation practices, and assist in identifying post-mining stands requiring fertilization. The experimental site provided a unique opportunity to add to the database of studies on nutrient concentration representative of loblolly pine plantations on reclaimed mined lands in the Gulf Coastal Plain. The specific objectives of this study were as follows:

1. To compare the foliar nutrient concentrations with baseline levels for loblolly pine found in the literature.
2. To compare nutrient concentrations across all treatments and examine the impact of FRA treatment on nutrient accumulation.

MATERIALS AND METHODS

Study Area

This study was conducted as a simulated mine reclamation on the Gail Creek property in Houston County, (31° 12' 25.8804" N, 95° 23' 40.5204" W) located in east Texas. The property is managed by the Arthur Temple College of Forestry and Agriculture at Stephen F. Austin State University. The climate in Houston County is characterized as sub-tropical humid, experiencing warm summers, receiving an average annual rainfall of 1148 mm and average temperature of 19 ^{o}C (N.O.A.A 2018). This area is known as the Pineywoods Ecoregion, and the vegetation comprised of a variety of trees, shrubs, woody vines, and herbaceous vegetation. As the name implies, pine forest ecosystems dominate much of the landscape, with shortleaf (*Pinus echinate* M.), longleaf (*Pinus palustris* M.), and loblolly pine (*Pinus taeda* L.) being the three southern yellow pine species native to this region.

The site was previously non-forested, and consisted of mainly grasses and shrubs. Prior to installation of the experimental mined land simulation, some post oaks (*Quercus stellate* W.), loblolly pine and other shrubs were also found on the site. The soil at the Gail Creek property consisted of Moswell series (fine, smectic, thermic Vertic

Hapludalfs) which typically has a high-water holding capacity because of the high clayey content.

Experimental Design

The experiment was established as a randomized complete block design (RCBD) on a one-hectare site. The experiment was replicated in three blocks, totaling nine experimental plots. Each plot measured approximately 27.4 m by 29.3 m (0.08 hectares). Two reclamation techniques and an unmined control were simulated on the site and randomly assigned to each plot. The pan scraper treatment was heavily compacted and designed to mimic the pan scraper reclamation method commonly used in this region. The FRA treatment simulated end-dumping with very little or no subsequent grading. The control treatment was undisturbed other than a single pass by the dozer to clear existing vegetation.

The two reclamation treatments were excavated to a depth of 1.3 m with a CAT excavator. For the pan scraper plots, soil was pushed back into the 1.3 m pits and spread in approximately 15 cm layers until the pits were filled using a CAT D6T dozer. The soil was then trafficked upon to simulate the pan scraper reclamation method. In the FRA treatment, buckets of soil were dropped into the 1.3 m deep pit. These full buckets were dumped adjacent to the previous pile, thus overlapping the pile until the pits were filled. Soil piles were left loose with no further trafficking. The control plots were cleared of all vegetation and experienced no further trafficking with heavy machinery. Installation of the different reclamation methods was completed in January and February of 2016.

Genetically improved, containerized loblolly pine seedlings of Western Gulf provenance were hand planted at a 2.4 x 2.7 m spacing on each plot with a buffer of atleast 5 m on February 23, 2016. About 50 seedlings were hand planted on each plot and the outer two rows were designated as buffer rows designed to minimize edge effects. There was no further disking or ripping, no cover crop was planted and no herbicides or fertilizers were applied.

Sample Collection

Sampling of loblolly pine seedlings occurred in June and July 2018 during the third growing season. Total heights of all buffer row seedlings were measured and stratified (i.e. 0.5-1.0 m, 1.1-1.3 m…2.0-2.5 m). At least one tree was randomly selected from each stratum for each plot, yielding 27 trees for destructive harvesting. Groundline diameter (GLD) was measured for each of the 27 seedlings prior to harvesting.

Destructive Sampling

The 27 selected seedlings were felled using a hand saw or loppers at the ground line. All harvested seedlings were transported promptly to Arthur Temple College of Forestry and Agriculture research laboratory in black plastic bags, where they were kept in cold storage at 4 ^{o}C. Each sampled seedling was later separated into three tissue types:

stem, branch, and foliage. After separation, they were stored in paper bags and oven-dried at 65 ^{o}C until constant dry weight was obtained.

In July 2018, each root system was excavated in 10 cm layers up to 20 cm deep. A mattock was used to loosen the soil surrounding the harvested seedling stump, and then a shovel was used to dig a pit around the stump to a 30 cm radius. Twenty-five of the seedlings had their entire root system within 20 cm depth, hence the decision to sample to this depth. Efforts were made to collect all or as much roots as possible in the excavated pit. Roots were then promptly transported to Arthur Temple College of Forestry and Agriculture research laboratory in black plastic bags and kept in cold storage at 4 ^{o}C. Each root system was separated from the adhering soil mass by light tapping, then washed thoroughly on a fine sieve (0.25 mm) to remove all soil particles and minimize root loss. They were then dried at 65 ^{o}C until a constant weight was obtained. No effort was made to categorize root systems.

Carbon (C) and Nutrient Concentrations

Approximately 6-10 g of dried samples of roots, needles, and stem were sent to Texas A&M Soil, Water and Forage Testing Laboratory, College Station, Texas for C and nutrient analysis. Total C was determined by combustion using an ELTRA Helios (ELTRA Elemental Analyzers, Haan, Germany), while N was determined by high temperature combustion process using Elementar Rapid N III (Elementar Americas, New

York City). Other elements were determined by an Optical Emission Inductively Coupled Plasma (ICP-OES) analyzing unit (Spectro Blue) after a nitric acid digestion.

Statistical Analyses

All statistical analyses were performed using SAS (SAS 9.4, SAS Institute, Cary, NC) with probability of significant differences was tested at $\alpha = 0.05$. Data were assessed for normality using PROC UNIVARIATE, and homogeneity of variance using PROC GLM. A nonlinear model form similar to that in Angel et al. (2018a) was adopted to provide a fit for C and element estimates. Coefficients were estimated from the non-linear model form in equation (3) using PROC NLIN. The original model contained age and site index parameters which were excluded in this study since all seedlings were of the same age and site index was not studied. The resulting model was used to predict elemental contents in loblolly pine seedlings in all treatments by using height and GLD.

$$E = \beta_0 + \beta_1(GLD) + \beta_2(H) \quad (3)$$

Where

E = elemental content (g)

GLD = groundline diameter (mm)

H = seedling height (m)

β_0, β_1, β_2 = estimated regression parameters.

Height and GLD data for all seedlings in the experiment (approximately 50 per plot, nine plots) were then fit in the equation to estimate elemental concentration for the entire study population. Analysis of Variance (ANOVA) and Tukey's test was subsequently employed to test treatment effects on C and macronutrients with honestly significant difference (HSD) tests performed for post-hoc tests of differences in treatment means.

RESULTS

Individual Seedling Tissue Nutrient Concentrations

Macronutrient concentrations for the harvested 27 seedlings were averaged by treatment for each tissue component (Table 9). Foliar C, N, P, Ca were not affected by treatment ($p > 0.05$), and there was no significant difference between all treatments. Foliar K was highest in control and there was no significant difference between other two treatments, while foliar Mg was lowest in control and exhibited no significant difference between other two treatments. Differences in concentration of nutrients across treatments was relatively small, with the largest difference being a 50% increase between the treatment with the least concentration and the treatment with the greatest concentration.

Table 9. Mean C and nutrient concentrations by tissue component for 27 sampled loblolly pine seedlings followed by standard errors in parentheses.

Tissue	Treatment	C (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
Foliage	Control	48.4^{a}	0.94^{a}	0.10^{a}	0.59^{a}	0.33^{a}	0.10^{b}
		(0.75)	(0.25)	(0.01)	(0.06)	(0.05)	(0.01)
	FRA	48.3^{a}	0.83^{a}	0.10^{a}	0.49^{b}	0.40^{a}	0.12^{a}
		(0.83)	(0.18)	(0.01)	(0.09)	(0.09)	(0.01)
	Pan Scraper	48.1^{a}	0.80^{a}	0.09^{b}	0.48^{b}	0.37^{a}	0.12^{a}
		(0.42)	(0.17)	(0.01)	(0.07)	(0.06)	(0.01)
	Pr > F	0.6154	0.3287	0.0513	0.0097	0.0838	0.01
Stem	Control	47.9^{a}	0.21^{a}	0.04^{a}	0.19^{a}	0.20^{a}	0.07^{a}
		(0.64)	(0.08)	(0.01)	(0.03)	(0.03)	(0.01)
	FRA	48.1^{a}	0.16^{ab}	0.03^{b}	0.17^{a}	0.22^{a}	0.06^{a}
		(0.58)	(0.05)	(0.00)	(0.04)	(0.03)	(0.01)
	Pan Scraper	47.8^{a}	0.13^{b}	0.03^{b}	0.16^{a}	0.21^{a}	0.06^{a}
		(0.73)	(0.07)	(0.00)	(0.03)	(0.03)	(0.01)
	Pr > F	0.4602	0.044	0.0096	0.1109	0.386	0.3925
Root	Control	47.0^{a}	0.32^{a}	0.06^{a}	0.22^{a}	0.22^{a}	0.09^{a}
		(0.71)	(0.11)	(0.02)	(0.05)	(0.06)	(0.01)
	FRA	46.9^{a}	0.21^{b}	0.04^{b}	0.15^{b}	0.19^{a}	0.08^{a}
		(0.70)	(0.05)	(0.01)	(0.04)	(0.05)	(0.02)
	Pan Scraper	46.8^{a}	0.25^{ab}	0.04^{b}	0.16^{b}	0.24^{a}	0.08^{a}
		(0.78)	(0.07)	(0.01)	(0.04)	(0.09)	(0.02)
	Pr > F	0.7624	0.016	0.016	0.0036	0.2781	0.7387

Mean values within a column followed by the same letter are not significantly different from each other (α=0.05)

Stem C, K, Ca and Mg were not affected by treatments (P > 0.05, Table 9), and no significant difference occurred among treatment means. Stem N and P were affected by treatment effects (P < 0.05) and concentration was highest in the control treatment.

Root C, Ca and Mg were not affected by treatment and there was no significant difference among treatment means, while N, P and K concentrations were affected by treatments (Table 9). Root N, P, K concentrations was highest in control and was similar for FRA and pan scraper. C concentration followed the order foliage>stem>root. The order of N, P, K, Ca, Mg concentrations was as follows: foliage>root>stem.

Carbon and macronutrient concentrations in all biomass tissues were predicted using nonlinear regressions (Table 10). The coefficients were significant for all nutrients except C in control treatment ($p < 0.05$). Regression coefficients were used to estimate the nutrient content of each seedling tissue on the experimental site using height and GLD of the seedling. The height and GLD of a total of 336 seedlings (control = 101, FRA = 122, pan scraper = 113) previously measured and reported in Phillips et al. (2019) were used for this study estimate.

Table 10. Regression coefficients for seedling nutrient concentrations based on equation 3

Treatment		C	N	P	K	Ca	Mg
Control	β0	47.0338	0.5816	0.0859	0.5187	0.3231	0.1143
	β1	-0.087	-0.0224	0.000256	0.00027	0.000336	0.000481
	β2	2.5835	0.6672	0.0088	0.0427	-0.00365	-0.0174
	Pr > F	0.0114	0.1366	0.2185	0.7526	0.9943	0.6485
FRA	β0	46.8261	0.8025	0.0864	0.458	0.1803	0.1301
	β1	-0.00382	-0.0075	0.000302	-0.00267	-0.00207	0.00119
	β2	0.9192	0.1729	-0.00107	0.0749	0.175	-0.0296
	Pr > F	0.3739	0.8775	0.824	0.9089	0.1074	0.5693
Pan Scraper	β0	49.0901	0.5033	0.086	0.3777	0.3813	0.1261
	β1	0.0023	-0.00159	-0.00035	-0.00741	0.00348	-0.00024
	β2	-0.9331	0.2966	0.0114	0.2435	-0.0818	-0.00054
	Pr > F	0.2661	0.4881	0.9621	0.4557	0.8906	0.9349

Stand-level C and Nutrient Concentration

C and macronutrients concentration were predicted using regression coefficients from Table 10 and height and GLD measurement taken from Phillips et al. (2019). C and all macronutrient concentrations in all biomass components were significantly affected by treatment effect ($P < 0.05$). Tissue nutrient concentration was generally highest in foliage for all macronutrients (Table 11). When examining only foliage, FRA had higher C, P and Ca concentrations than pan scraper, N was higher in pan scraper, while K and Mg were the same for both treatments. Similarly, concentrations of C, N, and Mg were higher in FRA than pan scraper for stem tissue, K was higher in pan scraper, while P and Ca were the same for both treatments. For belowground components, N, K, Ca, and Mg concentrations were higher in pan scraper than FRA while P concentration was the same for both treatments. C:N ratio was highest in stem components and lowest in foliage. FRA C:N ratio was higher than pan scraper in foliar tissue, but lower in stem tissue. FRA and pan scraper belowground C:N ratio were not significantly different and the ratio was not affected by treatment.

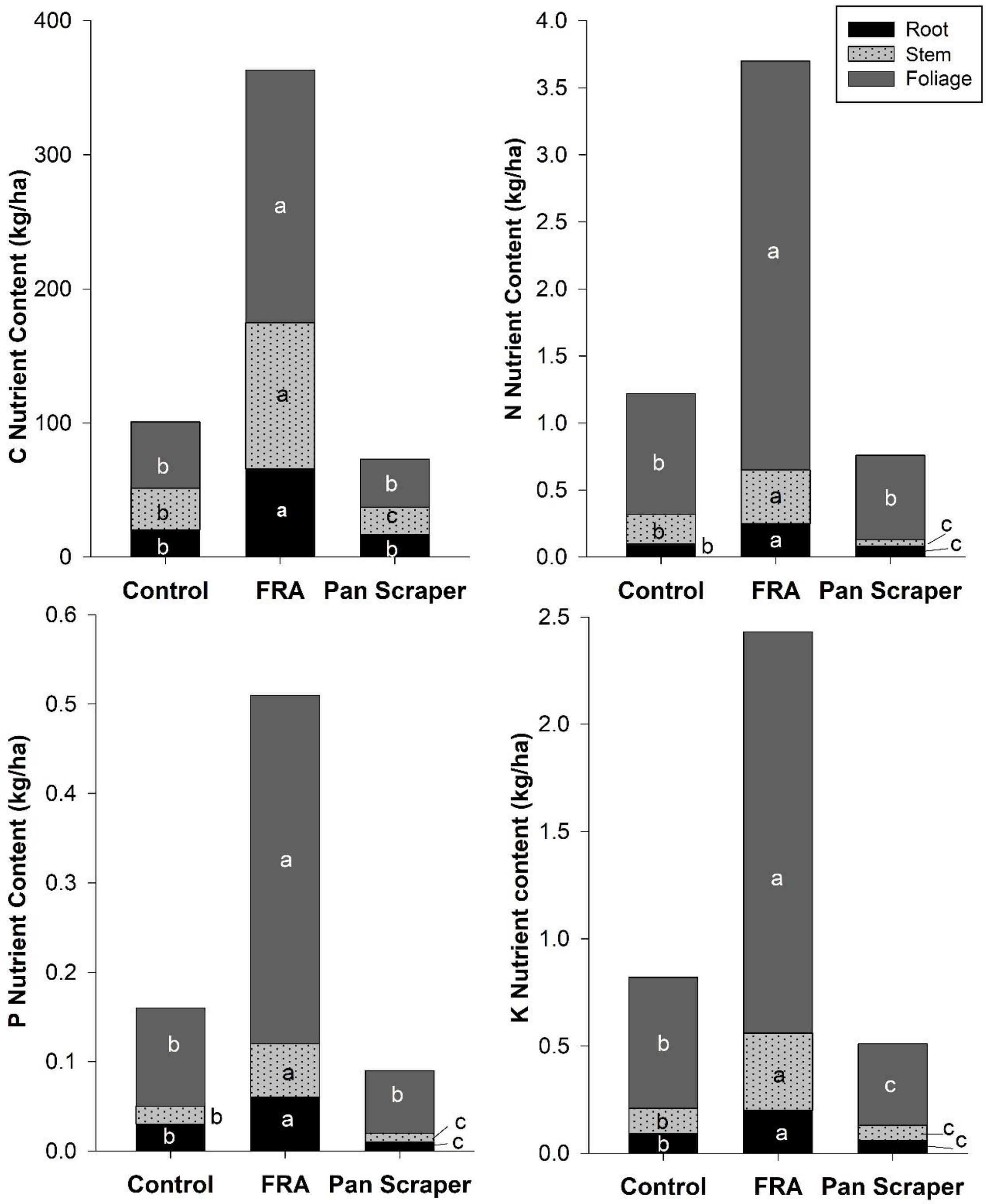
Table 11. Mean C and macronutrient concentrations by tissue component of 336 loblolly pine seedlings followed by standard errors in parentheses.

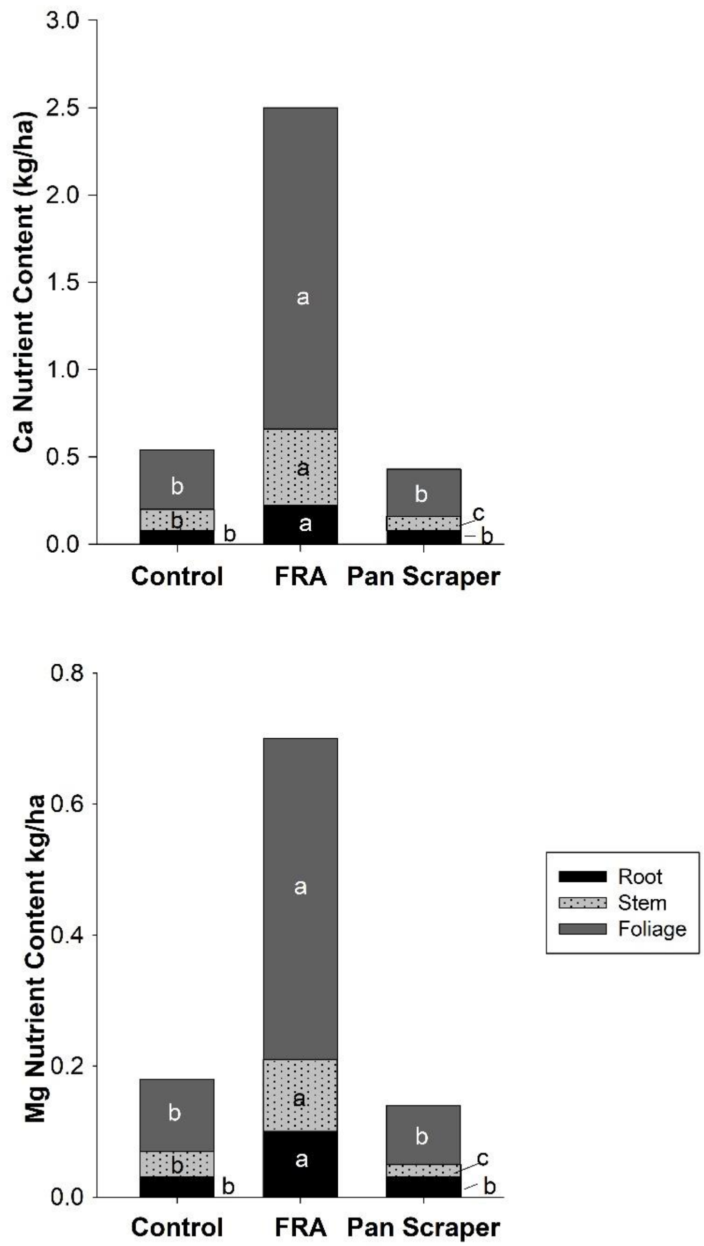
Tissue	Treatment	C (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	C:N
Foliage	Control	48.21[b] (0.06)	0.89[a] (0.01)	0.11[a] (0.00)	0.59[a] (0.00)	0.33[c] (0.00)	0.10[c] (0.00)	56.07[b] (1.10)
	FRA	48.59[a] (0.04)	0.82[c] (0.01)	0.10[b] (0.00)	0.49[b] (0.00)	0.45[a] (0.01)	0.12[a] (0.00)	60.04[a] (0.62)
	Pan Scraper	48.08[c] (0.03)	0.85[b] (0.00)	0.09[c] (0.00)	0.49[b] (0.00)	0.37[b] (0.00)	0.12[b] (0.00)	56.74[b] (0.04)
	Pr>F	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Stem	Control	48.07[b] (0.04)	0.34[a] (0.00)	0.03[a] (0.00)	0.19[a] (0.00)	0.20[b] (0.00)	0.06[a] (0.00)	152.54[c] (0.00)
	FRA	48.50[a] (0.05)	0.17[b] (0.00)	0.03[b] (0.00)	0.16[b] (0.00)	0.21[a] (0.00)	0.06[b] (0.00)	288.38[b] (2.85)
	Pan Scraper	47.62[c] (0.05)	0.12[c] (0.00)	0.03[b] (0.00)	0.17[b] (0.00)	0.21[a] (0.00)	0.05[c] (0.00)	394.09[a] (6.73)
	Pr>F	<.0001	<.0001	<.0001	<.0001	0.0003	<.0001	<.0001
Root	Control	47.12[b] (0.02)	0.27[a] (0.01)	0.06[a] (0.00)	0.22[a] (0.00)	0.20[b] (0.00)	0.08[a] (0.00)	187.49[a] (33.37)
	FRA	47.31[a] (0.05)	0.20[c] (0.00)	0.04[b] (0.00)	0.15[c] (0.00)	0.17[c] (0.00)	0.07[b] (0.00)	197.89[a] (41.10)
	Pan Scraper	46.64[c] (0.03)	0.25[b] (0.01)	0.04[b] (0.00)	0.16[b] (0.00)	0.26[a] (0.01)	0.08[a] (0.00)	198.01[a] (5.06)
	Pr>F	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.9654

Mean values within a column followed by the same letter are not significantly different from each other (α=0.05)

Nutrient Content

In this study, nutrient content increased with biomass accumulation (Figure 2), with the FRA stands accumulating the most concentration in C and other nutrients. The FRA treatment significantly increased C and other nutrient content in foliage, stem and root (Figure 2). The nutrient content of the FRA treatment was more than three times that of pan scraper treatment for all nutrients. Generally, nutrient content in FRA was stored in the order foliage>stem>root. There was no significant difference between control and pan scraper for C, N, P, Ca, or Mg content, or for the C:N ratio in foliage. Similarly, C, Ca, and Mg content in roots was not significantly different for control and pan scraper treatments. Pan scraper stem tissue nutrient content was lower than other treatments. Stand nutrient content across treatment variations were the result of changes in both mass and nutrient concentration of all elements.


Root
Stem
Foliage
C Nutrient Content (kg/ha)
N Nutrient Content (kg/ha)
P Nutrient Content (kg/ha)
K Nutrient content (kg/ha)
Control
FRA
Pan Scraper


Ca Nutrient Content (kg/ha)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
a
a
a
b
b
b
b
c
b
Control
FRA
Pan Scraper
Mg Nutrient Content kg/ha
0.8
0.6
0.4
0.2
0.0
a
a
a
b
b
b
b
c
b
Control
FRA
Pan Scraper
Root
Stem
Foliage

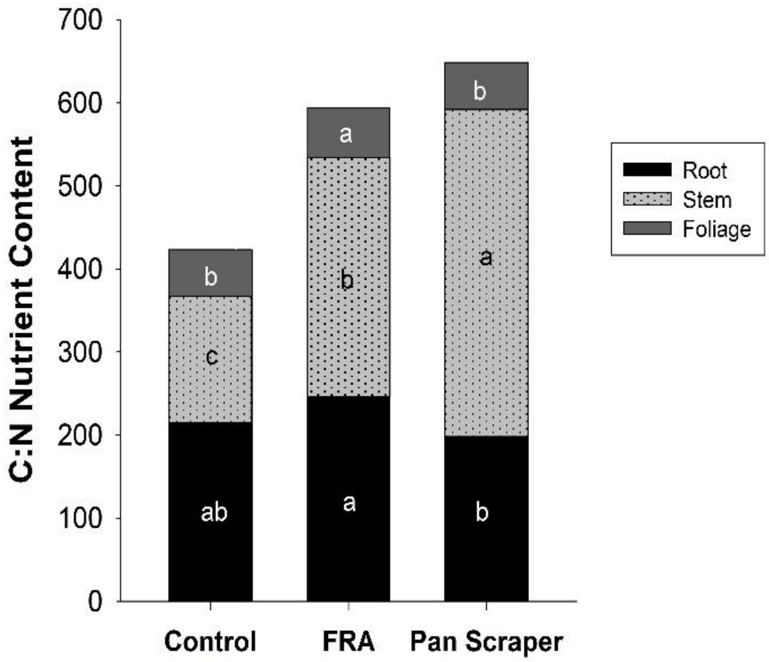


Figure 2 Carbon (C), nitrogen (N), potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg) content and C:N ratio for foliage, stem and root tissues of loblolly pine stands planted on three treatments

Among tissues, foliage stored most of the nutrient content in all treatments, while roots contained the least nutrient content in FRA for all nutrients. Foliage accounted for 52% of C content in FRA and 49% in control and pan scraper. Pan scraper stored the highest percentage of N and P in its foliage, while FRA stored the highest K, Ca, and Mg content in its foliage. Control stored the highest C, N, P, Ca, and Mg content in stems. Control stored more P in its roots than in stem. This trend was similar in pan scraper where more N and Mg was stored in the roots than stem. In summary, most of C and macronutrients were stored in aboveground tissues.

C:N ratio varied between tissues and treatment. Treatment affected stand-level foliar and stem C:N ratios ($P < 0.05$), while roots were not significantly influenced. FRA had higher C:N ratios in foliage and roots but lower C:N ratio in stem (Figure 2). Foliage, stem and roots accounted for 39.53%, 23.50%, and 15.69% of total seedling mass in FRA seedlings; and 37.74 %, 19.05%, 19.52% of total seedlings mass in pan scraper respectively. However, these three components contained varying amount of nutrient allocation. FRA seedling foliage allocated more C, K, Ca, and Mg; and less N and P compared to pan scraper. Higher amount of C, N, P, K, and Mg was allocated in FRA seedling stem; and less Ca compared to pan scraper. The more compact pan scraper allocated higher C, N, K, Mg; and less P and Ca compared to FRA.

DISCUSSION

Improving soil physical properties by FRA improved height, GLD (Phillips et al., 2019) and biomass of loblolly pine seedlings after two years, and subsequently resulted in higher total C and nutrient concentration in plant tissues. For the sampled seedlings, tillage had no significant effects on the concentration of foliar C, N, P, Ca; stem C, K, Ca, Mg; and root C, Ca, Mg. The lack of significant differences in concentration in response to these treatments may be due to the relatively young age of the pine seedlings or the small sample size. As described in the previous chapter, treatments altered growth rates, however, nutrient concentration of sampled seedlings of a given size were not altered.

Loblolly pine seedling C and nutrient concentrations for the whole study area were predicted using equation 3 and the treatment effect was significant for each tissue component (Table 10). Foliar analysis was used to quantify the amount of nutrients currently being taken up by the tree. This method is founded on the assumption that the tree is a more suitable measure of the availability of soil nutrients (Brockley, 2001). Jokela (2004) established critical concentrations for loblolly pine foliage N, P, K, Ca, and Mg as 1.2, 0.1, 0.4, 0.15 and 0.8% respectively, as baseline concentrations for estimating soil nutrient supply and deficiency. This critical level concept relies on the assumption that growth is not limited by other nutrients or environmental conditions. C and nutrient concentrations varied considerably among biomass components and were significantly influenced by the reclamation treatment in a given component. With the exception of N, all other foliar nutrients were either at or above these critical concentrations for each treatment when averaged across all seedlings. N concentration was between 0.82-0.89% which is lower than the determined critical concentration level. P concentration ranged between 0.09-0.11% across treatments, indicating that they did not play any significant role in hindering growth in these stands. Albaugh et al. (1998) reported foliar nutrient concentrations of N, P, K, Ca, and Mg as 0.95%, 0.10%, 0.42%, 0.14%, and 0.07% for nonfertilized plots and 1.29%, 0.11%, 0.56%, 0.11%, and 0.06% for fertilized plots of loblolly pine seedlings growing in North Carolina. K, Ca, and Mg concentrations for both reclamation treatments were higher than those obtained by Albaugh et al. (1998), while N and P were either at or below the observed concentrations in the same study. Despite this low N concentration, no visible symptoms of foliar deficiency were observed in all treatments.

Generally, concentrations of nutrients between various biomass components vary greatly, and concentrations of nutrients tend to be high in actively growing sections of the tree, such as the foliage (Smith et al., 1970; Iivonen et al., 2006). Studies on managed loblolly pine plantations suggests that aboveground components accumulate C and nutrients more rapidly than belowground components (Maier et al., 2004; Adegbidi et al., 2005). Nutrient concentrations in loblolly pine are lowest in stem wood and highest in needles (Schultz, 1997). Results from this study clearly show all macronutrients having higher concentrations in the foliage than the stem. When compared with stem component, roots in the FRA treatment in this study had higher N, P and Mg concentration, while roots in the pan scraper treatment had higher N, P, Ca, and Mg concentration. Helmisaari and Siltala (1989) report on nutrient concentrations of Scots pine (*Pinus sylvestris* L.) stems suggests that younger stands generally have higher nutrients concentrations due to a greater demand for nutrients in fast-growing trees. A close comparison of results from this study with Angel et al. (2018a) reporting on older trees on actual reclaimed mines shows that stem nutrients concentrations on this site were at similar or greater levels, except for N which was generally deficient on this site. However, since that study was carried out on an actual mine site with different soil properties, results could have been affected by soil or overburden physical and chemical properties which were not studied on the simulated site used for this study. The nature of the soil is also responsible for nutrient content differences. Ku and Burton (1973) found that P, K, and Na content in loblolly pine stands were higher in poorly drained coastal plain soils than in the well-drained coastal plain soil. Also, Emerson et al. (2009) attributed the growth and survival of seedlings to the nature of topsoil material. Selecting the appropriate top soil material or overburden suitable for reforestation is necessary for proper tree growth and survival. This is because the nature of the overburden is often responsible for the nutrients available for plant uptake. Torbert (1990) reported that pH levels in overburden affected nutrient availability, which affected the productivity of planted trees. The present study did not analyze soil for nutrients or chemical properties at the time of sampling, however, Wilson-Kokes and Skousen (2014) suggested that low nutrient availability in mine soils generally results in lower foliar nutrient concentrations in the trees growing on the soils.

In loblolly pines, N is the most abundant nutrient, followed by K, Ca, Mg, and P (Schultz, 1997). However, this hierarchical classification is dependent on the age of seedlings. Results from this study shows N as the most abundant nutrient in all treatments and perfectly follows with other nutrients and tissues as described by literature. Thus, reclamation methods discussed in this study have no impact on nutrient allocation to tissues. Seedlings growing on the FRA plots were taller and contained more biomass, therefore, nutrient content was also bigger. Generally, site preparation can impact available soil nutrients for atleast 15 years after treatment (Schultz, 1997), thus impacting the amount of nutrient available for plant uptake. Using the FRA to prepare the site improved nutrient accumulation in this study by facilitating seedling access to nutrients. Since allocation was not affected by treatment, it is clear to say that FRA increased the rate of nutrient accumulation but allocation to components remained the same among treatments. Therefore, nutrient allocation could be a result of other underlying site factors. Jokela et al. (1991) established that site preparation combined with weed control could influence stand response by reducing competing vegetation, redistributing soil nutrient reserves, expanding the quality and quantity of rooting area, and influencing the release of nutrients from the soil.

When compared with 2-5-year old loblolly pines on reclaimed surface mines in Angel et al. (2018a) and 7-year old loblolly pines on fertilized treatments, the mean foliar N, P, K, Mg concentrations in the FRA treatment were lower than results found in these studies, while mean C and Ca in this study were higher. Mean stem N content was lower than that of results from Zhao et al., (2014) on 12-year-old mid-rotation loblolly pine trees, and Angel et al., (2018a) on one rotation loblolly pine trees; it was however higher than Albaugh et al. (2008). Mean stem P, K, Ca, and Mg were higher than results from Albaugh et al., (2008); Zhao et al., (2014); and Angel et al., (2018a). The C concentration in dry stem and foliage in FRA seedlings were 48.5% and 48.6% respectively, which is about a 3% difference from mass-based C concentration found in literature. Houghton (1996) and Gower et al. (2001) reported mass-based C concentrations in dry wood and foliage as 50% and 45% respectively which is often used as a constant factor for conversion of biomass to carbon stocks. However, mean stem C was within the range 45-54% C dry weight found in literature for loblolly pines (Angel et al., 2018a). It is noteworthy that comparisons between this study and other highlighted studies were based on mean values which may not be adequate and does not take into consideration differences in study design. However, Angel et al. (2018a) suggested that concentrations in aboveground parts of loblolly pine on reclaimed mine lands can exceed similar stands found on unmined sites. Thus, based on the previous study on biomass productivity on this simulated mine site which showed that the FRA treatments seedlings were producing biomass at very high rates comparable to unmined sites, we can infer that loblolly pines seedlings in this study are accumulating macronutrients at comparable rates to those found on unmined sites. For seedlings on the FRA treatment, the C:N ratio in stem was lower than pan scraper treatment but higher in foliage and belowground. This suggests that FRA had little influence on nutrient use efficiency. On older trees, Zhao et al. (2014) found cultural density and planting density to be responsible for observed C:N ratio in aboveground biomass components.

Long term evaluation of C and nutrient content in trees is necessary for ecosystem recovery, and useful for selection and improvement of forestry management techniques (Maier et al., 2004; Adegbidi et al., 2005). Aboveground biomass components contained 77-82% C and more than 78% of other macronutrients in this study. With a high C content in the aboveground biomass, it is expected that pine seedlings in this study can contribute to the overall ecosystem C storage on the long-term. Proper reclamation techniques should contribute largely to the overall ecosystem C. Ecosystem C storage was generally a result of increased accumulation of C in loblolly pine woody and foliar biomass (Maier et al., 2004).

Based on the stand-level estimates, the total weight of the elements in the seedlings increased in bigger seedlings. The FRA treatment had larger seedlings and thus recorded higher nutrient content at the stand scale. Studies have showed that similar trends exist between elemental content and biomass accumulation. Wang et al. (1995) concluded that nutrient accumulation increased with stand age and tree size. The same study recorded higher concentrations in leaves than in stem of trees. Both reclamation treatments in this study reported similar trends.

CONCLUSION

Prior to establishment of forest plantations, mechanical site preparations are common practices, particularly for severely trafficked reclaimed mines (Furtado et al., 2016; Angel et al., 2018). These activities are carried out in order to reclaim the topography and restore vegetative productivity on reclaimed mine lands. Unfortunately, there is limited information on the growth and nutrient accumulation of fast-growing loblolly pine stands on reclaimed mine lands. To ensure the sustainability of biomass production, understanding C allocation, critical nutrient levels and overall nutrient content of seedlings is necessary. This study has demonstrated that while improved tillage using FRA increased biomass, it also increased C and nutrient content in loblolly pine seedlings. Foliar nutrient concentrations were affected by treatments, and higher concentrations of most nutrients were found in aboveground tissues associated with FRA treatments. Despite no fertilizer application, results suggest that loblolly pine seedlings accrued sufficient C and other macronutrients within the first two years of planting. Also, a large proportion (about 52%) of total carbon content is stored in the foliage while aboveground C content of the FRA was about 82% of the total seedling C. Furthermore, foliar nutrient concentrations of seedlings on the FRA treatment were at or above the accepted critical concentrations, thus suggesting that using FRA to reclaim mine land can produce seedlings that match those reported in literature for unmined land plantations and reclaimed mine lands (with or without the addition of fertilizer).

Overall, this study has shown that proper reclamation using FRA method had a significant effect on the concentration but more so on the content of C and other macronutrients in seedlings on a simulated reclaimed mine site. A careful combination of results from this study with other similar studies on different soil types and site conditions will assist forest managers in assessing the effects of reclamation techniques.

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