EVALUATING MINE SOIL PREPARED BY SCRAPER PANS FOR HERBACEOUS PLANTS AND PINE SEEDLINGS AT AN EAST TEXAS LIGNITE SURFACE MINE

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By

HANNAH ZOE ANGEL, Bachelor of Science in Forestry

Presented to the Faculty of the Graduate School of Stephen F. Austin State University

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EVALUATING MINE SOIL PREPARED BY SCRAPER PANS FOR
HERBACEOUS PLANTS AND PINE SEEDLINGS AT AN EAST TEXAS
LIGNITE SURFACE MINE

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ABSTRACT

Since 1974, Luminant Mining Company, LLC (Luminant) has planted over 38.7 million trees on its reclaimed lignite surface mine operations in Texas. For decades, the use of improved reclamation techniques on Luminant’s mined lands have resulted in over 31,160 ha reclaimed to forests, wildlife habitat, and pastures with productivity levels similar to those found on unmined lands. The development of new reclamation methodologies offers opportunities to further improve productivity of planted trees at Luminant’s Martin Lake Oak Hill Mine in east Texas. The conventional haulback or ‘truck shovel' reclamation method uses haul trucks for the selective transport and placement of oxidized overburden to serve as the reforestation growth medium. Transport and placement of overburden can also be accomplished using scraper pans. Operating scraper pans is more cost effective than the truck shovel method; thus, there is a desire to institute scraper pans as the primary method of reclamation. However, given a lack of information, there are concerns of the effects of scraper pans on mine soil compaction and vegetative establishment.

To address the potential compacting effects of scraper pans, four soil tillage treatments replicated five times were implemented at the Oak Hill Mine in August 2015 using a randomized complete block design: 1) No Tillage (control); 2) Disking (30-35 cm depth); 3) Single-Ripping (90 cm depth)/Disking (30-35 cm...
depth); and, 4) Cross-Ripping (90 cm depth)/Disking (30-35 cm depth). Soil physical and chemical properties were investigated at 0-30, 30-60, and 60-90 cm depth intervals. After one growing season, vegetative response was measured for an herbaceous winter cover crop in May 2016 and for loblolly pine (*Pinus taeda* L.) tree seedlings in October 2016.

Aboveground biomass production of the winter cover crop was highest on the ripped treatments. The untilled control resulted in the lowest herbaceous establishment and growth. Loblolly pine tree seedling survival across all treatments exceeded the standard for mined lands in this region. Highest survival occurred on the tilled plots (> 90%) compared to the control (85%) (*p* < 0.10). Cross-ripping was superior in terms of lowering soil bulk density (1.36 Mg m⁻³) and soil strength (2,220 kPa), and increasing tree seedling relative volume index growth (32 cm³) (*p* < 0.10). Above and belowground biomass of loblolly pine seedlings showed significant treatment effects (*p* < 0.10) and followed similar trends to seedling volume growth. In summary, disking alone improved herbaceous cover and pine seedling survival, while cross-ripping coupled with disking provided the most favorable responses in mine soil physical properties and vegetative growth.
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CHAPTER I: LITERATURE REVIEW

INTRODUCTION

The federal Surface Mining Control and Reclamation Act (SMCRA) of 1977 requires surface mine operations to reclaim lands to an equal or greater land use capability than that which preceded mining (Public Law, 95-87). Often times it is challenging to predict the health and quality of mine soil after final grading and reclamation methodologies occur. Additionally, the long-term soil capacity for vegetation may be affected if unfavorable soil replacement and grading procedures are used, especially during wet soil conditions (Slick and Curtis, 1985). Operating heavy machinery under such conditions may lead to severe soil compaction, which may be difficult to reverse (Kozlowski, 1999).

When the federal law was first implemented, inspectors focused on mine stability which was accomplished by smoothly leveling the mine soils used in reclamation procedures (Sweigard et al., 2007a). Reforestation under SMCRA in the eastern coalfields was difficult for numerous reasons, primarily because of the effects that heavy reclamation equipment had on mine soil compaction (Skousen et al., 2009). As a result, grassland reclamation became the preferred way of stabilizing mine sites. On the other hand, mined land reforestation has been successfully practiced pre-and post SMCRA’s implementation in the Gulf Coastal Plain.
Region through decades of improved reclamation procedures involving site preparation, tree selection, and planting techniques.

Research dealing with the chemical and biological soil properties affecting reclamation success has been extensive on mine sites in the Gulf Coastal Plain Region (Angel, 1973; Bearden, 1984; Doolittle, 1986; Doolittle, 1991; Hons, 1978; Johns, 2000; McCallister, 1981; Ng, 2012; Peach, 2001; Willett, 1978). These studies also report on soil physical properties, though only as small components to broader studies. Fewer studies have focused solely on the degree and magnitude of soil compaction at surface and subsurface zones (Yao, 1994; Yao and Wilding, 1994). The negative consequences of compaction on plant growth and site productivity may be ongoing for decades if not mitigated (Ludovici, 2008; Miller et al., 2004). However, alleviating mine soil compaction prior to reforestation increases the soil resources available to trees compared to what would be available in a firm, dense soil growth medium (Torbert et al., 1988). Previous studies conducted on reclaimed mined lands have shown improved tree performance by loosening compacted mine soil through the use of subsurface tillage (Burger and Evans 2010; Casselman et al., 2006).

The purpose of this research was to provide researchers and mine personnel with information on how reclamation techniques influenced revegetation efforts on mined lands in east Texas. As such, this study
investigated surface and subsurface soil tillage techniques to ameliorate mine soil compaction. Specific study objectives included: 1) investigating physical and chemical properties of mine soil prepared by two reclamation equipment methodologies; and, 2) evaluating soil physical properties and response of tree seedlings and herbaceous species after one growing season among different tillage treatments installed at a mine site reclaimed by scraper pans.

**Surface Mining and Reclamation Practices in the Gulf Coastal Plain Region**

The area surface mining method for coal is utilized throughout the western, mid-western, and Gulf Coastal Plain regions which have flat to gently undulating topography. A large dragline, or in some cases a cross pit spreader, is used to excavate a pit approximately 30 m wide and several hundred m long through the overburden to expose lignite coal seams. Overburden is all rock and earthen materials lying above the coal seam. This surface mining destroys the original soil profile, creating a mix of often heterogeneous materials sourced from the overburden and known commonly as mine soil. Reclamation of mined lands requires the careful selection, handling, and placement of mine soil in a way that limits erosion and provides suitable substrate for revegetation. After surface mining is complete, mine pits are backfilled and overburden materials are graded to a final configuration that approximates the original contour of the pre-mine
topography. At least 1.2 m of suitable materials are placed on top of the graded overburden as the veneer growth medium for herbaceous and tree seedling establishment. (Railroad Commission of Texas, 1982)

Studies have determined that mixed overburden materials are capable of supporting various types of vegetation in the Gulf Coastal Plain Region and have demonstrated higher productivity potential compared to adjacent undisturbed land when used as a topsoil substitute (Angel, 1973; DeLong et al., 2012; Ng, 2012; Toups, 1986). The resulting chemical and physical soil properties found in the mixed overburden materials contribute to the creation of a desirable rooting medium: containing little or no rock, low sulfur content, optimum pH ranges, suitable soil textures for plant growth, favorable concentrations of most plant available nutrients, and adequate water retention and availability (Angel, 1973). Further research has determined that using mixed overburden as the plant growth medium increases the available water capacity for plants compared to that of unmined native soils (Bearden, 1984; Hons, 1978). Some mined lands contain unfavorable minerals in the overburden such as pyrite (FeS₂) that can lead to increased soil acidity. Typically, deposits of iron sulfides lie in the reduced overburden directly above the lignite coal seam and are deeply buried after mining to prevent oxidization (Jarocki, 1994). When such minerals are detected in the overburden, the oxidized surface materials are separated prior to surface
mining and are used as the plant growth medium in lieu of mixed overburden materials.

There are two reclamation equipment methods commonly used in the Gulf Coastal Plain Region for the selective transport and placement, or haulback, of oxidized surface materials: 1) truck and shovel combination; and, 2) tractor pulled scraper pans. The truck and shovel combination, or truck shovel, uses a hydraulic excavator track hoe to load haul trucks with two 2.5 m cuts of oxidized surface materials to a depth of approximately 5 m or until the oxidation zone ends. Each cut is limed before it is loaded onto haul trucks. Oxidized overburden materials are then transported and dumped at reclamation sites. Bulldozers level at least 1.2 m of oxidized materials, henceforth referred to as mine soil, which serves as the plant growth medium. (Jeff Lamb, Luminant, personal communication)

A scraper pan includes one to two multi-wheeled pans that are typically attached to and pulled by a farm tractor. Scraper pans can either self-load by their moveable bowl that cuts into soil or they can be loaded by a hydraulic excavator track hoe. For each 1.2 m lift, oxidized overburden materials are coated with a liming source and loaded with a track hoe to create a mixing effect for the lime. When scrapers self-load, they carry out short cuts on previously limed areas at 10 cm increments. At full capacity, scraper pans transport
approximately 9.2 m³ of oxidized overburden materials to reclamation sites where
the back panel of the bowl is released, gradually emptying and leveling the mine
soil to a depth of approximately 15 cm with each pass. This method reduces the
need for loading materials with a track hoe and the subsequent leveling with a
bulldozer. (Jeff Lamb, Luminant, personal communication)

Since 1974, the use of improved reclamation techniques on mined lands
owned by the Luminant Mining Company, LLC (Luminant) in Texas have resulted
in over 31,160 ha reclaimed to forests, wildlife habitat, and pastures with
productivity levels similar to those found on unmined lands. Among the total area
of reclaimed mined land, the majority is restored to a forestry post-mining land
use, which includes commercial pine timber and mixed hardwood stands (Dan
Darr, Luminant, personal communication). Reforestation efforts focus largely on
loblolly pine (*Pinus taeda* L.) plantations based on the species high survivability
and growth rates and low seedling costs (Toups, 1986). The Railroad
Commission of Texas (RCT) uses several criteria to evaluate the suitability of
reclaimed mine soils in Texas including soil pH, depth, trace elements, acid-base
relations, cation exchange capacity, texture, and salt content (Railroad
Commission of Texas, 1982). To determine if a reforested site has met bond-
release requirements, a stocking standard is typically used by the state
regulatory authority (Davidson, 1984). In Texas, the RCT requires at least 182
live trees ha⁻¹ for pine and at least 49 live trees ha⁻¹ for hardwoods, which is
maintained for a minimum five year extended responsibility period (Railroad
Commission of Texas, 1990). These stocking standards measure tree survival,
but not the long-term productivity of mine sites.

**Soil Compaction**

Soil physical properties are important in determining revegetation success
as they directly influence available water capacity and aeration, which largely
Soil compaction results from an alteration in pore size and distribution from an
applied force not caused by natural factors (Sutton, 1991). The most influential
physical soil factor limiting tree performance on surface mined lands is likely
mine soil compaction (Burger and Zipper, 2011). The extent and mitigation of soil
compaction is influenced principally by climate, vegetation, and soil-related
organisms such as soil fauna (Miller et al., 2004; Mitchell et al., 1982). Improper
handling and placement of mine soil during reclamation procedures may result in
adverse soil conditions such as high bulk density, reduced water infiltration, low
available water capacity and aeration, reduced plant nutrient availability, and lack
of soil development (Slick and Curtis, 1985). The goal in replacing overburden on
surface mined lands is to create a quality growth medium for plants. However,
replaced overburden materials often become structurally degraded from the
mechanical influences from earth-moving machinery.
Research shows that a minimum of 1.2 meters of non-compacted growth medium is needed to allow trees to reach their full growth potential (Sweigard et al., 2007b; Torbert et al., 1988). The restrictive soil layers formed as a result of heavy machinery operations may severely compromise soil physical properties. Consequently, a lack of soil macroporosity alters water flow, air movement, and plant nutrient uptake in the soil, while decreasing plant growth above and belowground (Kozlowski, 1999; Petelkau and Dannowski, 1990; Siegel-Issem et al., 2005). In the Appalachian Region, research has demonstrated that excessive surface leveling of mined lands adversely affects survival and productivity of pine and hardwood tree species by contributing to factors such as inhibited root penetration and reduced rainfall infiltration (Andrews et al., 1998; Burger and Evans, 2010; Burger and Zipper, 2011; Skousen et al., 2009; Torbert and Burger, 1990; Zeleznik and Skousen, 1996; Zipper et al., 2011).

Soil bulk density, the weight of dry soil per unit of bulk soil volume, is commonly used to evaluate compaction (Sutton, 1991). Mine soils typically have higher bulk densities than those of undisturbed soils because of the excessive movement and grading required by heavy machinery (Slick and Curtis, 1985). The bulk density that reduces root penetration in soil is called the critical bulk density and varies with soil texture and plant species (Sutton, 1991). Daddow and Warrington (1983) described critical values for the following soil textural classes: clays 1.40 Mg m$^{-3}$, clay loams 1.45 Mg m$^{-3}$, sandy clay loams 1.60 Mg m$^{-3}$.
m^{-3}, and sandy loams 1.65 Mg m^{-3}. Soil moisture content is a particularly important factor in determining the degree of compaction under certain soil textures. In mine soils prepared by cross-pit spreader and mixed overburden methods, bulk densities below a 15 cm depth were similar or lower than densities found on unmined lands (Ng, 2012). The author attributed the values to a higher percentage of subsurface clay. Adequate soil fertility, particularly in finer textured soils, has the potential to offset adverse effects of subsoil compaction by increasing root area for soil water extraction (Kozlowski, 1999).

Soil penetration resistance, or soil strength, is recorded as a cone index (CI) value and is another useful determination of compaction especially since these measurements tend to be more predictive of roots ability to penetrate soil (Dunker et al., 1995; Thompson et al., 1987). High soil strength in compacted soils discourages root exploration and proliferation as fewer pore spaces reduce root entry into increased soil volume (Sutton, 1991). Yao and Wilding (1994) reported that scraper pans resulted in a restricted soil layer at a depth of about 10 cm, with subsurface soil zones far exceeding the limiting cone index for root growth (> 2500 kPa). At soil strength above 2,000 kPa, the growth of most plant roots is compromised depending on several other soil related factors (Blouin et al., 2008; Kees, 2005). Barth (2002) found that native soils displayed lower penetration resistance values compared to growth mediums cast by dragline and
cross-pit spreader methods, though vegetation was not limited by higher zones of soil strength.

Pore spaces serve as soil conduits, trafficking root movement, soil oxygen, and moisture content (Sutton, 1991). Compaction reduces total pore space and aeration, and alters the size and distribution of pores, with macropores being the first to decrease in volume (Sutton, 1991; Yao, 1994). Soil compaction by heavy machinery leads to decreased soil water infiltration and percolation, and increased surface runoff (Chong and Cowsert, 1997). Reduced saturated hydraulic conductivity (Ksat) is considered a negative effect of compaction. Yao (1994) found that compaction induced by conventional reclamation practices contributed to a reduction in soil macroporosity and total porosity in subsurface layers, decreasing Ksat to an average value of 0.8 mm hr$^{-1}$, which was estimated to be 10 times lower than values in non-compacted surface treatments (Yao, 1994). Toups (1986) found significantly lower Ksat values with an average of 2.52 cm hr$^{-1}$ compared to a nearby undisturbed site (10.56 cm hr$^{-1}$). Erosion and surface runoff is greater when the infiltration rate is lower than the rainfall rate (Jarocki, 1994). Reclaimed mined land has been shown to have significantly reduced infiltration rates by 53% compared to unmined land (Jarocki, 1994). Additionally, French (1979) attributed low Ksat (10$^{-4}$ cm sec$^{-1}$) to increased soil compressibility following reclamation.
Early studies evaluated tree seedling growth and survival on mined versus unmined sites (Bryson, 1973), and compared loblolly pine seedling performance using different seed sources (Wood, 1985). Toups (1986) found that surface mined lands displayed higher soil bulk density values compared to nearby unmined sites with both sites supporting five-year-old loblolly pine plantations. The author attributed poor soil physical properties as the main contributor to poor tree growth on the reclaimed mined land. Studies regarding loblolly pine seedlings growing in different unmined soil textures showed reduced height growth, nutrient uptake, and root development as a result of compaction (Foil and Ralston, 1967; Lockaby and Vidrine, 1984; Mitchell et al., 1982). Scott and Burger (2014) found that longleaf pine (Pinus palustris) had greater sensitivity to compaction than did loblolly pine as evident by a lower ratio of above to belowground biomass and an overall growth reduction in increased soil bulk densities (>1.5 Mg m$^{-3}$). Loblolly pine roots are generally well adapted to lower oxygen environments allowing for some mitigation in densely packed, low porosity soils (Topa and McLeod, 1986).
Soil Tillage Techniques

Soil tillage techniques are used to improve soil physical properties and have been shown to increase soil porosity, aeration, rooting density, and hydraulic conductivity compared to closely packed soil matrices (Morris et al., 2006; Salem et al., 2015). As soil bulk density increases, the energy required to ameliorate compaction through the use of tillage is greater (Voorhees, 1987). Conventional methods of tillage include disking, or disk harrowing, bedding, chisel plowing, subsoiling, and combination plowing techniques (Miller et al., 2004). These techniques, often used in agricultural settings, address only surface soils with an exception of subsoiling, which loosens soil at the subsurface (55 cm or greater) (Miller et al., 2004). Disking cuts through soil with numerous steel blades to depths of 15 to 35 cm, whereas bedding and chisel plowing typically reach depths of 20 to 40 cm (Miller et al., 2004).

To account for the soil volume needed for tree roots, subsurface tillage is recommended for the long-term management of forests (Burger and Zipper 2011; Miller et al., 2004). In surface mined land revegetation efforts, the U.S. Department of Agriculture advises deep dozer ripping when mine soils are placed using a scraper pan (USDA Forest Service, 1979). The Appalachian Regional Reforestation Initiative, which developed the Forestry Reclamation Approach in the eastern U.S., recommends either ripping in a grid pattern or using a triple-
ripping shank to alleviate mine soil compaction (Sweigard et al., 2007a).
Fracturing subsoil by ripping in two or more directions or with multiple ripping shanks loosens the greatest volume of soil compared to ripping with a single shank in one direction (Sweigard et al., 2007a). Since ripping shanks reach subsoil depths, the terms subsoiling and ripping are often used interchangeably. Timing of tillage operation is crucial in achieving the best results for improved soil physical properties. The effectiveness of the resulting soil fracture is reduced when high soil moisture is present at the time of operation, thus minimizing the benefits of tillage (Morris and Lowery, 1988).

When tillage is implemented under favorable soil conditions, plant survival and growth can be greatly enhanced, setting a positive long-term trajectory in both agricultural and forest management (Miller et al., 2004). However, there are drawbacks to tillage operations. Excessive tillage practices, particularly conventional surface disk ing, have been shown to decrease soil organic carbon (McVay et al., 2006). Aust et al. (1998) found that surface tillage practices alone or in combination with other treatments were ineffective at improving loblolly pine seedlings growing in soils compacted by skid trail trafficking after four years. According to the North Carolina State Forest Nutrition Cooperative, combination plowing (ripping + surface tillage) increased the growth response of loblolly pine seedlings (0.76 m³ha⁻¹) compared to surface tillage (0.22 m³ha⁻¹) (NCSFNC, 2000). Deep tillage techniques, as opposed to surface disk ing, improve the
overall soil volume exploited by roots (Morris and Lowery, 1988). Carlson et al. (2014) reported growth benefits in loblolly pine seedlings after using 3-in-1 combination plowing. However, the growth response accrued by deep tillage compared to the control (no till) was not sufficient enough to offset the costs of the tillage treatment.

Loosening compacted soils using subsurface tillage has been shown to improve tree performance by increasing rooting volume and the subsequent availability of soil nutrients and water (Bateman, 1992; Baumen et al., 2014; Burger and Evans, 2010). Deep ripping was first introduced in the Midwest to increase yield production on prime farmlands reclaimed after the implementation of SMCRA (Sweigard et al., 2007a). Dunker et al. (1995) compared different subsurface tillage treatments at a scraper placed reclaimed mine site in Illinois to evaluate corn and soybean yields compared to an adjacent prime farmland. When tillage depth increased (23 to 122 cm) there was a significant increase in crop yield, water uptake, and a decrease in soil strength. American chestnut (Castanea dentata) tree seedlings planted at a reclaimed mine site in central Ohio showed significantly greater growth and survival when planted on plots that were either cross-ripped (1 m), plowed/disked (30 cm), or cross-ripped and plowed/disked (Bauman et al., 2014). Survival and height growth of black walnut and red oak increased significantly with deep ripping (1.2 m) when compared to non-ripped plots after 12 years on mined land (Ashby, 1996). Casselman et al.
(2006) found that ripping (61 to 91 cm) plus weed control (WC) generally improved tree survival and height compared to the WC only treatment; however, when mine soil physical properties did not impede root growth tillage had no significant effect.

The implementation of deep dozer ripping to ameliorate soil compaction may not prove to be successful in completely reversing long-term effects despite advantages in the short-term. Burger and Evans (2010) showed that after 18 years, single-ripping to a 1 m depth significantly improved tree performance for three hardwood and two pine species growing on post-bond release reclaimed mined land with seedlings planted in or directly near the rip furrows. However, the potential for ripping to increase tree growth was much less compared to average pre-mining productivity based on soil survey site indices. Another study found that initial site preparation using a double-shank ripper making single passes had no advantage on the long-term growth (16 years) of shortleaf pine as it had during an earlier growth stage (Gwaze et al., 2007).

Other studies have found little to no short-term growth response to soil tillage methods (Cleveland and Kjelgren, 1994; Evans et al., 2013; Kelting and Allen, 2000). Cleveland and Kjelgren (1994) found no effect of deep tillage on six different species of tree seedlings planted on surface mined land in Illinois. Growth, survival, and soil water relations differences were greater among tree
species than tillage treatments. Evans et al. (2013) found that ripping was not correlated with success measures of 2, 3, and 4-year old planted trees, indicating that high soil density was not a stressor on a deeply tilled surface mine that was previously compacted. Kelting and Allen (2000) found that water was not a limiting factor for 2-year-old loblolly pine trees growing on tilled soils. The authors found that subsoiling was more effective at reducing bulk density, increasing air-filled porosity, and improving rooting depth for loblolly pine compared to surface disking which can create more tortuous channels for water and roots.

Studies conducted on non-mined lands in the southeast region have generally shown that surface and subsurface soil tillage effects on loblolly pine seedling growth are favorable, although these effects are typically small or variable depending on different soil related factors (Carlson et al., 2006; Furtado et al., 2016; Lincoln et al., 2007; Morris and Lowery, 1998; NCSFNC, 2000; Wheeler et al., 2002; Will et al., 2002). Based on inconsistencies in the literature, further research is needed for an improved understanding of the relationship between soil tillage design and operation, tree seedling root development, and aboveground growth response (Schilling et al., 2004; Will et al., 2002).
CHAPTER II: EFFECTS OF SURFACE AND SUBSURFACE TILLAGE ON MINE SOIL PROPERTIES AND VEGETATION

INTRODUCTION

Reclamation practices are capable of promoting forest productivity similar to that of unmined lands (Amichev et al., 2008). Priest et al. (2015) found that the height growth rates of loblolly pine trees on reclaimed mine soils were similar to the mean height-age curves for the same species on unmined land in east Texas. Soil-survey derived site indices from the same study suggested that Luminant’s reclamation efforts are restoring forest productivity to pre-mining levels. However, alternative backfilling and grading techniques have the potential to create higher tree productivity compared to pre-mining levels (Zipper et al., 2011). The unmined pine plantations used as a comparison to the reclaimed pine plantations in Priest et al. (2015) did not undergo any forest management treatments (i.e., thinning, fertilization) other than herbicide (Coble et al., 2006). Loblolly pine productivity has been shown to increase by an average of 25 percent when fertilizer was applied under proper management (Fox et al., 2007). Thus, the results in Priest et al. (2015) may not represent the full productivity potential that can be achieved for pine plantations in east Texas.
Mined land reclamation practices in Texas may contribute to soil compaction (Barth, 2002; Toups, 1986; Yao, 1994). Yao (1994) compared the effects of mine soil physical properties between three treatments: 1) transporting overburden by scraper pans and leveling by bulldozers; 2) induced compaction layers (30 cm depth) by a loaded scraper pan; and, 3) induced compaction layers (60 cm depth) by a loaded scraper pan. This study found that subsurface bulk density values (1.67 Mg m$^{-3}$) similar to induced compaction layers when scraper pans were used. Additionally, Hons et al. (1980) reported fertilized coastal bermudagrass forage yields from 2,051 kg ha$^{-1}$ to 16,700 kg ha$^{-1}$, whereas Yao (1994) reported fertilized coastal bermudagrass yields from 222 kg ha$^{-1}$ to 445 kg ha$^{-1}$ in the compaction induced treatments listed above. Rooting depths for loblolly pine are based on the soil physical conditions present (Siegel-Issem et al., 2005). After 10 years, taproots for loblolly pine trees growing on reclaimed mined lands in east Texas reached an estimated depth of 98 cm and coarse roots reached an estimated depth of 60 cm, but roots generally occupied 55% of the upper soil layers (0-20 cm) (Priest et al., 2015). Compaction has the potential to shift biomass allocation to aboveground production which can decrease soil carbon and nutrient pools over time (Ludovici, 2008).

A non-compacted and highly aggregated soil encourages root development, biological activity, and the storage of above and belowground carbon over time, especially in conifer stands (Amichev et al., 2008; Shrestha
and Lal, 2006). Voorhees et al. (1987) found that subsoil compaction at a depth of 90 cm was still measurable after heavy axle equipment trafficked four years prior. Conventional tillage methods have been shown to increase soil porosity, aeration, and hydraulic conductivity of compacted soils, especially on mined lands impacted by heavy equipment (Salem et al., 2014). Given favorable soil related factors, equipment design, and timing of operation, the use of soil tillage has the potential to at least partially mitigate the negative long-term effects of soil compaction that persist decades after installation (Dunker et al., 1995; Powers et al., 1999).

As new and alternative reclamation methods of operation for surface mining develop, it is important to determine the effects of mine soil compaction which may persist for decades if not avoided or lessened (Burger and Zipper, 2011). Additionally, it is equally as important to investigate the potential productivity benefits associated with reversing or alleviating mine soil compaction using soil tillage techniques (Sweigard et al., 2007a). While ample research demonstrates the benefits of alleviating soil compaction using tillage, there are currently no studies that examine the effects of surface and subsurface tillage on mined lands in the Gulf Coastal Plain Region.

Historically, the truck shovel method has been used as the conventional reclamation method of operation in Texas. Due to the improved cost savings
associated with operating scraper pans, there is interest in establishing the scraper pan method as the primary haulback methodology in lieu of the truck shovel method. However, there is limited information on the use of scraper pans in terms of mine soil compaction and tree seedling growth. Thus, this study was initiated to develop strategies for mitigating compaction induced by heavy reclamation equipment. The impact of reclamation equipment operating at Luminant’s Oak Hill Mine and the subsequent improvement of current practices through soil tillage were examined in this study by testing the following null hypotheses:

H0: 1) There will be no difference in soil physical properties by depth at a truck shovel reclaimed mined site or between tillage treatments at a scraper pan reclaimed mined site.

H0: 2) There will be no difference in the establishment and aboveground biomass production of the herbaceous plant species or in the survival, growth, and biomass of tree seedlings after one growing season between tillage treatments at a scraper pan reclaimed mined site.
METHODS

Study Site

This study was conducted at the Oak Hill Mine (Figure 1), a 10,000 ha active lignite surface mine operated by Luminant and located in Rusk County, Texas (N 32° 12’ 50.007”, W 94° 43’ 57.6942”).

Figure 1. Location of the Oak Hill Mine research site in Rusk County, Texas.
Oak Hill Mine has been in operation since the early 1980s and is one of three mines supplying lignite coal to the nearby Martin Lake Power Plant. Among these mines, 76% of mined lands are reclaimed to forestry post-mining land uses (Dan Darr, Luminant, personal communication). Immediately following final leveling on reclaimed mined sites, herbaceous cover crops (i.e., wheat and clover) are established to control erosion. In mixed hardwood plantings, native grasses, legumes, and forbs are inter-planted to enhance wildlife habitat. Loblolly pine plantations are the most common forestry post-mining land use. The climate and cover type of east Texas is described as sub-tropical humid with mixed hardwood and evergreen forest land. Rusk County averages 1,255 mm of rainfall annually with a temperature average high of 24°C and an average annual temperature of 18°C (NOAA, 2016a). The dominant pre-mining soils by land area comprising the Oak Hill Mine are the Cuthbert (fine, mixed, semiactive, thermic Typic Hapludults), Redsprings (fine, kaolinitic, thermic Ultic Hapludalfs), and Tenaha (loamy, siliceous, semiactive, thermic Arenic Hapludults) soil series, respectively (Griffith, 2000).

Reference Site. A recently clearcut unmined area was selected from the Redsprings soil series, serving as a reference area for measurements (N 32° 16' 17.9106", W 94° 41' 34.9254"). An area reclaimed using the conventional truck shovel haulback methodology served as a case study and another reference area for previous reclamation methodologies (2 ha). Five 0.20 ha sample plots
(60 m x 34 m) were used to measure response variables and account for any within site variability. Two-year-old loblolly pine trees were present at the time of measurements. The truck shovel site is not replicated and confounding factors include age since reclamation and duration of cover crop and tree seedlings; thus, we do not make statistical comparisons between the two reclamation haulback methodologies.

Scraper Pan Site. A randomized complete block design testing three forms of tillage and an untilled control was installed in a nearby area reclaimed using scraper pans (3.6 ha). The four treatments were installed in 0.08 ha plots and replicated five times for a total of 20 plots (Figure 2). The purpose of this experimental design was to evaluate the effects soil tillage as a site preparation technique on early reclamation success.
Figure 2. Map showing the schematic design for the scraper pan site (5 blocks x 4 treatments = 20 replicate plots) and the plot layout for the truck shovel site (5 total plots; stars represent sampling locations).
Experimental Design

Prior to treatment installation, the scraper pan site remained un-vegetated with no cover crop or site preparation treatments for approximately 18 months. In consultation with mine personnel, soil tillage techniques were implemented with increasing levels of intensity in August 2015 during dry and favorable soil conditions (Appendix A). The overall treatment plots were approximately 21 m x 38 m in size (20 total). One measurement plot (15 m x 15 m) occurred in the middle section of each treatment plot (Figure 2). Tillage treatments included the following:

1) No tillage (control) – This treatment excluded any type of tillage operation.
2) Disking (D) – A tractor pulled Rome disk plow with 16 blades was used to install one pass of the disking treatment to a depth of approximately 30 to 35 cm.
3) Single-Ripping/D – Deep ripping was accomplished using a Cat D-8 bulldozer with a single 90 cm ripping shank. Single-ripping was installed with one dozer pass at 2 m spacing. Disking was performed after single-ripping per normal operating procedure as described above.
4) Cross-Ripping/D – For this treatment, the bulldozer made additional single passes perpendicular to the pre-existing single rips to a 90 cm depth on a 2 m grid pattern. Disking was performed after cross-ripping per normal operating procedure.
Site Preparation

Following tillage treatments the entire experimental design received similar chemical and mechanical site preparation in accordance with Luminant’s normal reclamation operating procedures. Oxidized surface materials were treated with agricultural lime at approximately 181 to 335 Mg ha\(^{-1}\) for each 2.5 m cut prior to transportation and placement at the scraper pan site in winter 2014.

In November 2015, the following site preparation techniques were distributed evenly across the scraper pan study site over the course of two days and under dry conditions. One final disking treatment (15 cm depth) was installed at each treatment plot except for control plots to smooth out ruts and prepare the seed bed for planting. The site was then broadcast with a mix of winter wheat (\textit{Triticum} spp.) and 17-17-17 pelletized fertilizer at 0.14 Mg ha\(^{-1}\) using a 4.5 metric ton tractor pulled buggy. Next, the site was roller packed with a Brillion seeder, applying crimson clover (\textit{Trifolium incarnatum}) at 0.03 Mg ha\(^{-1}\) and tracking in the seed and fertilizer mix. Finally, the site was lightly mulched using locally grown mine site hay.

In January 2016, 1-0 bare root loblolly pine tree seedlings were machine planted at 2.1 m x 3.0 m spacing. A coulter blade was attached to the machine planter to create a narrow planting slit in the ground to a 30 cm depth. Tree planting was accomplished on a sunny, partly cloudy day with a high of 16°C.
Soil conditions were generally favorable. In wetter areas, a ground crew ensured proper spacing and planting techniques. Tree seedlings were planted across the site without regard to rip placement.

Data Collection

At the unmined reference site, two soil test pits and four surface soil sampling locations were randomly located to measure soil chemical and physical properties in July 2016. At the truck shovel site, two soil test pits (July 2016) and four surface soil sampling locations (November 2015) were randomly located to measure soil chemical and physical properties per sample plot (60 m x 34 m). At the scraper pan site, two soil test pits (July 2016) and four surface soil sampling locations (March 2016) were randomly located to measure soil chemical and physical properties per measurement plot (15 m x 15 m). Three sampling locations were installed in each measurement plot for soil strength. Two sampling locations were used for Ksat measurements. Data were collected for each type of vegetation after one growing season at the scraper pan site. Percent cover for the cover crop was recorded in March 2016, aboveground biomass production of the cover crop was collected in May 2016, and tree seedling measurements and a destructive seedling biomass harvest occurred in October and November 2016. No vegetation data were collected at the unmined and truck shovel sites.
Weather Conditions. In November 2015, March 2016, and July 2016, total rainfall was 387 mm, 575 mm, and 39 mm, respectively. Measurements for the cover crop and tree seedlings occurred during mild weather conditions with average air temperatures at 21.2°C and 21.3°C, respectively. Rainfall for the entire year of 2016 totaled 1,346 mm with the highest amounts occurring in April, August, and March, respectively. (NOAA, 2016b)

Soil Sampling

Mined and reference sites were sampled for the following soil properties at surface and subsurface zones. For this study, the soil depth was defined as 0 to 30 cm for the surface and below 30 cm for the subsurface. Texas mining companies are required by state regulatory authority to replace at least 1.2 m of growth medium (Railroad Commission of Texas, 1982). Sampling occurred above this required depth and the greatest sampling depth of 90 cm reflected the depth of the single ripping shank.

Bulk Density. Soil bulk density was measured using the slide hammer method (Blake and Hartge, 1986a). Soil sample volumes, or cores, were retained in 5.08 cm x 2.54 cm aluminum liners (AMS Inc., American Falls, ID, USA). Between the unmined reference, truck shovel, and scraper pan sites, a total of 52 soil test pits were dug and 156 bulk density determinations made. A small track hoe was used to excavate soil pits with dimensions of approximately 1.22 m (H) x
1.22 m (W) x 1.07 m (D). A sharp shooter spade was used to shave off approximately 5 cm of soil before sampling. The pit sides were sampled at the middle to reduce edge effects. Soil cores and samples were taken at 15-, 45-, and 75 cm to represent the midpoints of the three main sampling depths: 0-30, 30-60, 60-90 cm. Four soil bulk density cores were extracted per sample; the interior two cores were used to measure bulk density, total pore space, particle density, field capacity, and wilting coefficient. The soil collected in exterior cores was used for texture analysis.

**Soil Composite Samples.** A soil mass water concentration was measured gravimetrically as a one-time measurement (Gardner, 1986). Using a hand-held soil auger, composite samples were collected vertically (0-30 cm) for surface soil sampling. For the soil test pit sampling, soil samples were collected horizontally (0-30 cm) and composited by depth (0-30, 30-60, 60-90 cm) to determine pH and nutrient concentration, and to provide additional soil if needed. Mass water concentration values from soil surface and pit sampling were later converted to volumetric water concentration using average bulk density values from the corresponding sample location. At the scraper pan site, samples were taken only between the planted tree rows.

**Soil Strength.** Penetration resistance, or soil strength, was calculated using the cone index which is defined as the force exerted to a cone, or steel tip,
divided by the cone’s basal area (Bradford, 1986). Soil strength was measured with a FieldScout electronic cone penetrometer equipped with a 30° angle cone and a 1.3 cm diameter cone tip (SC 900 Soil Compaction Meter, Spectrum Technologies, Inc., Aurora, IL, USA). At the surface, soil strength was recorded between and within tree planting rows with depths ranging from 0-20 cm as the ease of insertion for the penetrometer was highly variable. Three insertions were taken at each surface sampling location and averaged for one value. These values correspond to soil samples collected at that time for soil water concentration between planting rows. Additionally, soil strength was recorded horizontally in soil test pits at the middle of 10 cm intervals to a depth of 90 cm. Two insertions were taken and averaged for one value per depth interval.

**Saturated Hydraulic Conductivity.** Saturated infiltration, or hydraulic conductivity, is the flow of water into soil under saturated conditions and provides indirect information about the soil physical condition (Bouwer, 1986). A double ring cylinder infiltrometer was used to determine Ksat (IN8-W Turf Tec International Model, Tallahassee, FL, USA) (ASTM, 2009). Water depth was measured in the inner ring using a ruler until a steady state was reached. The inner and outer cylindrical rings were 15 cm and 30 cm in size, respectively, with a height of 18 cm. A steel driving plate was used to force the infiltrometer approximately 5 cm into the ground (IN6-W Turf Tec International Model, Tallahassee, FL, USA). Prior to recording, herbaceous vegetation was cut and
sponges were used as a splash guard to limit soil disturbance when adding water.

**Vegetation**

**Herbaceous Species.** Percent cover of the winter cover crop was visually estimated using the six cover class ranges described by the Daubenmire method (Daubenmire, 1959). The cover classes are as follow: Class 1 (0 – 5%); Class 2 (5 – 25%); Class 3 (25 – 50%); Class 4 (50 – 75%); Class 5 (75 – 95%); Class 6 (95 – 100%). Tree planting rows were used as intersects, which served as the sampling units. The midpoint for each cover class was multiplied by the number of times a designated cover class was observed in each measurement plot. These values were totaled and divided by the sum of total transects used for each treatment to determine percent cover. Aboveground biomass production was collected at three randomly located sample points per measurement plot for a total of 60 samples. Using grass clippers, herbaceous vegetation was cut within a 1 m x 1 m quadrat at the soil surface.

**Tree Seedlings.** Height and ground-line diameter of loblolly pine seedlings were measured immediately after tree planting on approximately 42 trees per subplot (15 m x 15 m). Tree seedling volume index, the product of squared ground-line diameter and height, was determined after tree planting in January and after one growing season in October 2016. Initial tree seedling volume index
was used to determine the relative growth rates of tree seedlings after one year of growth. Survival was recorded during growth measurements. Four pine seedlings were randomly chosen per treatment plot and destructively harvested in the field at the root collar to determine aboveground biomass. Of the four harvested tree seedlings, one was selected at random for belowground harvesting. Due to a lack of larger seedlings randomly selected for belowground harvest, additional seedlings were harvested in February 2017. The protocol included harvesting the largest tree in each treatment (four trees total) in a randomly selected block to extend the range of interpolation for the total tree and root biomass models. For all belowground harvests, shovels were used to excavate pits with a diameter equal to seedling height and to a 0.5 m depth or until the end of the taproot.

**Laboratory Work**

**Soil**

Soil Physical Properties. Intact soil cores and composite samples were transferred from the field to the Stephen F. Austin State University Forest Soils Laboratory. Soil cores were oven-dried to a constant weight at 105°C and weighed. Soil bulk density ($D_b$) was calculated as the weight of oven-dried soil divided by soil volume (Blake and Hartge, 1986a). After dry weights were obtained, $D_b$ soil cores were placed in a 250 mL graduated cylinder of known
water volume and thoroughly stirred. The volume of solid particles was determined by finding the difference between the two water volumes. Particle density \( D_p \) can then be calculated as the weight of oven-dried soils over solid particle volume (Blake and Hartge, 1986b). Once the \( D_b \) and \( D_p \) values were determined, the following formula was used to calculate total pore space:

\[
\%	ext{ Total Pore Space} = 100 - \left( \frac{D_b}{D_p} \right) \times 100
\]  

(1)

Samples for soil texture were composited by depth and treatment, thoroughly mixed, and passed through a 2-mm sieve. Soil was oven-dried at 105°C before 50 g of fine textured soil and 100 g of coarse textured soil was used to determine sand, silt, and clay content using the standard hydrometer method (Bouyoucos, 1951).

Soil Water. Soil water concentration was determined using the gravimetric or mass approach \( \theta_{gw} \). Soil samples were weighed to obtain wet weights and then oven-dried to a constant weight at 105°C. Water concentration was calculated as the difference between initial wet weight and dry weights. Soil surface and pit samples were later converted to volumetric water concentration \( \theta_{vw} \) from average \( D_b \) values using the formula:

\[
\theta_{vw} = D_b \times \theta_{gw}
\]  

(2)
Field capacity and wilting coefficient were determined using the pressure plate apparatus method (Klute, 1986) from additional intact soil cores taken with $D_b$ samples. Pressure plates were pre-wetted to saturate the porous ceramic surface. Intact soil samples were placed in small rubber rings ensuring flush contact with the plate. The soil was wetted to saturation and placed in each plate’s respective chamber using a 2,000 kPa compressor (Soilmoisture Equipment Corp., Model 505, USA). After 12 hours in the pressure chamber, samples were scooped into aluminum weighing tins. Field capacity at -0.03 MPa (FC) and wilting coefficient -1.5 MPa (WC) were determined by calculating $\theta_{vw}$ for each set of samples. Available water capacity (AWC) was calculated as the difference between FC and WC.

**Soil Chemical Properties.** A glass electrode pH meter was used to measure soil pH (McLean, 1982). Concentrations of calcium, magnesium, potassium, and phosphorous were measured with an Optical Emission Spectrometry Inductively Coupled Plasma (ICP-OES) analyzing unit (Thermo Scientific, USA) following extraction by the Mehlich III extraction procedure (Mehlich, 1984). Soil carbon and nitrogen were measured using a LECO CHN628 Series Elemental Determinator (St. Joseph, MI). Cation exchange capacity (CEC) was estimated from the soil analysis using Mehlich III for exchangeable Ca, Mg, K, and Na, and the Moore-Sikora buffer for exchangeable acidity (Sikora and Moore, 2008). Base saturation was calculated as the quantity
of exchangeable base cations divided by the CEC. Stephen F. Austin State University Soil, Plant and Water Analysis Laboratory performed the soil pH and chemical analyses.

Vegetation

Aboveground cover crop samples were transferred to the lab and oven-dried to a constant weight at 60°C and weighed to determine herbaceous aboveground biomass production. Dry weights were scaled to a per hectare basis. After tree planting in January, a sample of 30 loblolly pine seedlings was taken from the planting stock, transferred to campus and placed in cold storage. In the laboratory, pine seedlings were separated by biomass component (i.e., needles, stems + branches, and roots), measured for aboveground height, root collar, and diameter, and oven-dried at 60°C to constant weight. Seedling roots were rinsed off over a wire screen to catch broken fine roots. The same procedure was used for tree seedlings harvested in October 2016 and February 2017.
Statistical Analyses

A randomized complete block design (RCBD) was used at the scraper pan site to control for variations in topography. Depending on the dependent variables tested, the RCBD used either a one-way or two-way factorial analysis of variance (ANOVA). A two-way ANOVA for testing the effects of two main factors, soil tillage and depth, and an interaction effect is represented in Table 1. When soil depth was used as a factor level, three main depths were used except for soil strength measurements, which consisted of nine depths.

**Table 1.** Analysis of variance table for a randomized complete block design for response variables sampled by depth.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sums of Squares (SS)</th>
<th>Degrees of Freedom</th>
<th>Mean Square (MS)</th>
<th>F statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocks</td>
<td>SSB</td>
<td>4</td>
<td>SS (B)</td>
<td>MS(B)/MSE</td>
</tr>
<tr>
<td>Tillage Treatments</td>
<td>SST</td>
<td>3</td>
<td>SS(T)</td>
<td>MS(T)/MSE</td>
</tr>
<tr>
<td>Depth</td>
<td>SSD</td>
<td>2</td>
<td>SS(T)</td>
<td>MS(T)/MSE</td>
</tr>
<tr>
<td>Tillage x Depth</td>
<td>(T-1)(D-1)</td>
<td>6</td>
<td>SS(TxD)</td>
<td>MS(TxD)/MSE</td>
</tr>
<tr>
<td>Error</td>
<td>SSE</td>
<td>44</td>
<td>SS(Error)</td>
<td>MS(Error)/MSE</td>
</tr>
<tr>
<td>Total</td>
<td>TSS</td>
<td>59</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2 represents a one-way ANOVA used for the RCBD without an interaction effect. Table 3 represents a one-way ANOVA used at the truck shovel site.

**Table 2.** Analysis of variance table for a randomized complete block design for samples collected at the surface.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sums of Squares (SS)</th>
<th>Degrees of Freedom</th>
<th>Mean Square (MS)</th>
<th>F statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocks</td>
<td>SSB</td>
<td>4</td>
<td>SS(B)</td>
<td>MS(B)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DF(B)</td>
<td>MSE</td>
</tr>
<tr>
<td>Tillage Treatments</td>
<td>SST</td>
<td>3</td>
<td>SS(T)</td>
<td>MS(T)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DF(T)</td>
<td>MSE</td>
</tr>
<tr>
<td>Error</td>
<td>SSE</td>
<td>12</td>
<td>SS(Error)</td>
<td>DF(Error)</td>
</tr>
<tr>
<td>Total</td>
<td>TSS</td>
<td>19</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.** Analysis of variance table to test effects of soil depth and response variables at the truck shovel site.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sums of Squares (SS)</th>
<th>Degrees of Freedom</th>
<th>Mean Square (MS)</th>
<th>F statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>SSD</td>
<td>2</td>
<td>SS(D)</td>
<td>MS(D)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DF(D)</td>
<td>MSE</td>
</tr>
<tr>
<td>Error</td>
<td>SSE</td>
<td>12</td>
<td>SS(Error)</td>
<td>DF(Error)</td>
</tr>
<tr>
<td>Total</td>
<td>TSS</td>
<td>14</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
All analyses were performed in SAS (SAS 9.2, SAS Institute, Cary, NC). Probability of significant differences was tested at an alpha of 0.10. Assumptions of normality and homogeneity of variance were verified using PROC UNIVARIATE and a Levene’s test, respectively. Response variables did not require transformation. The data analysis for the RCBD was performed using PROC MIXED. The least squares means were calculated for variables with significant differences. PROC GLIMMIX was used to assess tree survival as binary data. PROC GLM and Tukey’s post hoc test were used at the truck shovel site. Analysis of covariance was used to determine effects of soil strength using volumetric water concentration as a covariate.

Nonlinear regression was used to create allometric relationships for the harvested seedlings to predict the above and belowground biomass of all planted tree seedlings after one growing season. Regression coefficients were estimated from the non-linear model form in equation (3) using PROC NLIN. The model form has similarly been used in other loblolly pine allometric analyses (Priest et al., 2015). Height and ground-line diameter were used as predictor variables. Response variables included needle, stem, root, aboveground and total tree biomass components. The model to be fit is shown in the equation below (3):

\begin{equation}
\end{equation}
\begin{equation}
Y = \beta_0 * (GLD^{\beta_1}) * (HT^{\beta_2})
\end{equation}

Where,

$Y$ = Dry weight biomass component (g)

$GLD$ = Ground line diameter (mm)

$HT$ = Total seedling stem height (mm)

$\beta_0, \beta_1, \beta_2$ = Regression parameters to be estimated
RESULTS

Soil Physical Properties

The unmined soil had high clay content at subsurface depths (> 30 cm) (Table 4). As the taxonomy suggests, the Redsprings soil series (fine, kaolinitic, thermic Ultic Hapludalfs) ranges from fine sandy loam to clay textures throughout the A, Bt, and C/Bt horizons. Clay content in this series generally ranges from 35 to 50% (Griffith, 2000). The Redsprings series profile displayed a red, highly oxidized soil (Appendix A). The truck shovel site had a sandy clay loam texture across all depths ($p > 0.10$) (Table 4). At this site, differences in mine soil color were common (Appendix A).

Similar to the truck shovel site, the dominant soil texture across treatment and soil depth at the scraper pan site was sandy clay loam (Table 4). A significant increase in clay content was apparent between surface and subsurface depths ($p = 0.0013$). Sand decreased with depth ($p = 0.0050$) while silt remained consistent ($p = 0.3396$). Observationally, differences in soil color were common; rock content was variable at surface depths. As a casual observation, the ease of soil sampling (i.e., probe, auger, and hammer insertion) was improved with increasing levels of tillage intensity (Appendix A).
Table 4. Mean soil texture at the unmined, truck shovel, and scraper pan sites followed by standard error in parentheses.

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (cm)</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0-30</td>
<td>60</td>
<td>9</td>
<td>31</td>
<td>sandy clay loam</td>
</tr>
<tr>
<td></td>
<td>30-60</td>
<td>44</td>
<td>11</td>
<td>45</td>
<td>clay</td>
</tr>
<tr>
<td></td>
<td>60-90</td>
<td>46</td>
<td>10</td>
<td>44</td>
<td>sandy clay</td>
</tr>
<tr>
<td>Redsprings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unmined</td>
<td>0-30</td>
<td>66</td>
<td>9</td>
<td>25</td>
<td>sandy clay loam</td>
</tr>
<tr>
<td></td>
<td>30-60</td>
<td>68</td>
<td>7</td>
<td>25</td>
<td>sandy clay loam</td>
</tr>
<tr>
<td></td>
<td>60-90</td>
<td>63</td>
<td>12</td>
<td>25</td>
<td>sandy clay loam</td>
</tr>
<tr>
<td>Truck Shovel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mined</td>
<td>0-30</td>
<td>60_a</td>
<td>12</td>
<td>28_a</td>
<td>sandy clay loam</td>
</tr>
<tr>
<td></td>
<td>30-60</td>
<td>56_a</td>
<td>11</td>
<td>33_b</td>
<td>sandy clay loam</td>
</tr>
<tr>
<td></td>
<td>60-90</td>
<td>53_b</td>
<td>14</td>
<td>33_b</td>
<td>sandy clay loam</td>
</tr>
<tr>
<td>Scraper Pan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mined</td>
<td>0-30</td>
<td>60_a</td>
<td>12</td>
<td>28_a</td>
<td>sandy clay loam</td>
</tr>
<tr>
<td></td>
<td>30-60</td>
<td>56_a</td>
<td>11</td>
<td>33_b</td>
<td>sandy clay loam</td>
</tr>
<tr>
<td></td>
<td>60-90</td>
<td>53_b</td>
<td>14</td>
<td>33_b</td>
<td>sandy clay loam</td>
</tr>
</tbody>
</table>

† Means followed by the same letter are not different (α = 0.10).
As a reference comparison, the unmined site had lower soil bulk density and strength across more soil depths, and higher Ksat values when compared to the truck shovel and scraper pan reclaimed mined sites (Table 5). At the truck shovel site, soil physical properties showed no differences at surface and subsurface depths ($p > 0.10$) (Tables 5 and 6). There were no differences detected in soil strength across the nine 10 cm depth intervals at the conventional site ($p = 0.2949$) despite a difference in water concentration at 60-90 cm (Table 6). Soil strength slightly exceeded 2,000 kPa at lower depths which is considered limiting to root growth in conifers (Blouin, et al., 2008). Surface soil strength at the truck shovel site averaged 2,100 kPa in November 2015, likely as a result of the high soil water concentration ($0.30 \text{ m}^3 \text{ m}^{-3}$) measured after a heavy rainfall.
Table 5. Mean soil physical properties at the unmined and truck shovel sites followed by standard error in parentheses. There were no significant differences by depth.†

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (cm)</th>
<th>( D_b )</th>
<th>( D_p )</th>
<th>Total Soil Porosity (%)</th>
<th>Ksat (mm hr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-30</td>
<td>1.38</td>
<td>2.54</td>
<td>46</td>
<td>50.8</td>
</tr>
<tr>
<td><strong>Redsprings</strong></td>
<td>30-60</td>
<td>1.22</td>
<td>2.41</td>
<td>49</td>
<td>-</td>
</tr>
<tr>
<td><strong>Unmined</strong></td>
<td>60-90</td>
<td>1.31</td>
<td>2.52</td>
<td>48</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0-30</td>
<td>1.43</td>
<td>2.67 (0.07)</td>
<td>46 (3.16)</td>
<td>9.20 (3.10)</td>
</tr>
<tr>
<td><strong>Truck Shovel</strong></td>
<td>30-60</td>
<td>1.49 (0.05)</td>
<td>2.70 (0.09)</td>
<td>45 (1.86)</td>
<td>-</td>
</tr>
<tr>
<td><strong>Mined</strong></td>
<td>60-90</td>
<td>1.53 (0.04)</td>
<td>2.61 (0.04)</td>
<td>41 (2.28)</td>
<td>-</td>
</tr>
</tbody>
</table>

† \( D_b \) = soil bulk density; \( D_p \) = soil particle density; Ksat = saturated hydraulic conductivity.
Table 6. Mean soil strength by soil depth at unmined and truck-shovel sites followed by standard error in parentheses. There were no significant differences by depth.

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (cm)</th>
<th>Soil Strength (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redsprings</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Unmined</strong></td>
<td>0-10</td>
<td>914</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>1327</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>1160</td>
</tr>
<tr>
<td></td>
<td>30-40</td>
<td>1660</td>
</tr>
<tr>
<td></td>
<td>40-50</td>
<td>1376 (112)</td>
</tr>
<tr>
<td></td>
<td>50-60</td>
<td>2172 (143)</td>
</tr>
<tr>
<td></td>
<td>60-70</td>
<td>1917 (167)</td>
</tr>
<tr>
<td></td>
<td>70-80</td>
<td>2527 (145)</td>
</tr>
<tr>
<td></td>
<td>80-90</td>
<td>2422 (170)</td>
</tr>
<tr>
<td><strong>Truck Shovel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mined</strong></td>
<td>0-10</td>
<td>1835 (112)</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>2039 (143)</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>2181 (167)</td>
</tr>
<tr>
<td></td>
<td>30-40</td>
<td>2235 (145)</td>
</tr>
<tr>
<td></td>
<td>40-50</td>
<td>2257 (116)</td>
</tr>
<tr>
<td></td>
<td>50-60</td>
<td>2275 (160)</td>
</tr>
<tr>
<td></td>
<td>60-70</td>
<td>2135 (145)</td>
</tr>
<tr>
<td></td>
<td>70-80</td>
<td>2225 (170)</td>
</tr>
<tr>
<td></td>
<td>80-90</td>
<td>2098 (141)</td>
</tr>
</tbody>
</table>
At the truck shovel site, there were no differences detected for soil water relations across depths ($p > 0.10$) except for volumetric water concentration between surface and subsurface soil depths ($p < 0.0001$) (Table 7).

**Table 7.** Mean soil water relations at truck shovel site followed by standard error in parentheses.†

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (cm)</th>
<th>FC</th>
<th>WC</th>
<th>AWC</th>
<th>$\theta_{vw}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m³ m⁻³</td>
<td>m³ m⁻³</td>
<td>m³ m⁻³</td>
<td>(m³ m⁻³)</td>
</tr>
<tr>
<td></td>
<td>0-30</td>
<td>0.28 (0.02)</td>
<td>0.12 (0.01)</td>
<td>0.16 (0.01)</td>
<td>0.15ₐₜ⁺</td>
</tr>
<tr>
<td>Truck Shovel</td>
<td>30-60</td>
<td>0.29 (0.02)</td>
<td>0.13 (0.01)</td>
<td>0.16 (0.02)</td>
<td>0.17ₜ</td>
</tr>
<tr>
<td>Mined</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.01)</td>
</tr>
<tr>
<td></td>
<td>60-90</td>
<td>0.29 (0.01)</td>
<td>0.15 (0.01)</td>
<td>0.14 (0.01)</td>
<td>0.24ₜ⁺</td>
</tr>
</tbody>
</table>

† FC = field capacity; WC = wilting coefficient; AWC = available water capacity; $\theta_{vw}$ = volumetric water concentration.

‡ Means followed by the same letter are not different ($\alpha = 0.10$).
Soil Response to Tillage

There were no treatment x depth interactions for soil response variables ($p \geq 0.10$). Differences existed either between depth and/or tillage treatment (Table 8). As the level of tillage intensity increased, soil bulk density decreased (Figure 3). Values ranged from 1.55 Mg m$^{-3}$ to 1.36 Mg m$^{-3}$ for Control and Cross-Rip/D, respectively ($p < 0.0001$). Soil depth increased bulk density values across all treatments ($p = 0.0833$). Soil particle density showed no differences between treatments or depths with fairly consistent values ranging from 2.63 Mg m$^{-3}$ to 2.80 Mg m$^{-3}$ ($p > 0.10$).

Table 8. P-values for tillage treatment, soil depth, and fixed effects interactions of soil physical and water properties at the Oak Hill Mine, Rusk County, Texas ($\alpha = 0.10$).†

<table>
<thead>
<tr>
<th>Effects</th>
<th>$D_b$</th>
<th>$D_p$</th>
<th>Soil Strength</th>
<th>Total Porosity</th>
<th>FC</th>
<th>WC</th>
<th>AWC</th>
<th>$\theta_{vw}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>&lt;0.0001</td>
<td>0.9318</td>
<td>&lt;0.0001</td>
<td>0.0031</td>
<td>0.4703</td>
<td>0.1251</td>
<td>0.7603</td>
<td>0.0789</td>
</tr>
<tr>
<td>Depth</td>
<td>0.0833</td>
<td>0.8556</td>
<td>&lt;0.0001</td>
<td>0.5946</td>
<td>0.0128</td>
<td>0.0196</td>
<td>0.0551</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Tillage x Depth</td>
<td>0.8932</td>
<td>0.8393</td>
<td>0.9850</td>
<td>0.8442</td>
<td>0.7838</td>
<td>0.7880</td>
<td>0.9764</td>
<td>0.3476</td>
</tr>
</tbody>
</table>

† $D_b =$ soil bulk density; $D_p =$ soil particle density; FC = field capacity; WC = wilting coefficient; AWC = available water capacity; $\theta_{vw} =$ volumetric water concentration.
Figure 3. Mean soil bulk density by tillage treatment (A) and soil depth (B) with standard error bars. Shared letters are not different ($\alpha = 0.10$).
Soil strength decreased with increasing tillage intensity ($p < 0.0001$) and varied by depth ($p < 0.0001$) when measured in soil test pits (Figure 4). Highest soil strength occurred at the 20-50 cm depth range, whereas lowest strength occurred at 70-90 cm. Penetrometer readings were taken vertically from the surface during the wet soil season (March 2016) and showed reduced soil strength as treatment intensity increased. Values were much lower during the summer season (July 2016), though measurements were taken horizontally by depth and are not directly comparable.

During the spring season, soil strength values were measured vertically. Soil strength between the planted trees differed among tillage treatments ($p = 0.0497$) when adjusted for variability in water concentration ($p = 0.0070$) (Figure 4). Volumetric water concentration sampled at the time strength was measured between tree rows showed no treatment effects, ranging from 0.25 to 0.32 m$^3$ m$^{-3}$ ($p = 0.8962$). During this same period, soil strength was also measured within planted tree rows ($p = 0.0840$), though water concentration was not measured within the tree rows (Figure 4). Soil strength within planted tree rows showed lower values compared to between row values likely as a result of the narrow furrow created by machine planting.
Figure 4. Mean soil strength by treatment or depth in March and July 2016 followed by standard error bars. Shared letters are not different ($\alpha = 0.10$).
Total porosity followed a similar trend to that of bulk density shown in Figure 3. As tillage intensity increased, total pore space significantly increased \((p = 0.0031)\) (Table 9). A 6% overall reduction in total pore space was evident when the two treatment extremes, Control and Cross-Rip/D, were compared. Ksat was not significant across tillage treatments \((p = 0.5569)\) (Table 9).

**Table 9.** Mean total soil porosity and Ksat between tillage treatments followed by standard error in parentheses.

<table>
<thead>
<tr>
<th>Total Soil Porosity (%)</th>
<th>Control</th>
<th>Disk (D)</th>
<th>Single/Rip/D</th>
<th>Cross-Rip/D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>43\textsuperscript{a†} (1.0)</td>
<td>45\textsuperscript{ab} (1.2)</td>
<td>46\textsuperscript{b} (1.2)</td>
<td>49\textsuperscript{c} (1.2)</td>
</tr>
</tbody>
</table>

| Ksat (mm hr\textsuperscript{-1}) ‡ | 17.60 (4.63) | 23.17 (8.87) | 21.27 (6.04) | 23.42 (6.21) |

\(†\) Means followed by the same letter are not different \((\alpha = 0.10)\).

\(‡\) Ksat = saturated soil hydraulic conductivity.

Volumetric water concentration increased with depth \((p < 0.0001)\) and varied between treatments \((p = 0.0789)\) (Table 10). When compared to the Control, volumetric water concentration was decreased in Cross-Rip/D by 0.04 m\(^3\) m\(^{-3}\). Disk and Single-Rip/D produced intermediate effects. The 60-90 cm depth displayed the highest water concentration at 0.31 m\(^3\) m\(^{-3}\). Soil water relations produced similar results across treatments (Table 11). Differences were found for FC \((p = 0.0128)\), WC \((p = 0.0196)\), and AWC \((p = 0.0551)\) by depth,
though in each case the magnitude of the difference was relatively small.

Generally, soil water retention properties increased with depth (Table 11).

**Table 10.** Mean volumetric soil water concentration by tillage treatment and soil depth followed by standard error in parentheses.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Control (m$^3$)</th>
<th>Disk (D) (m$^3$)</th>
<th>Single-R/D (m$^3$)</th>
<th>Cross-R/D (m$^3$)</th>
<th>Mean (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
<td>0.23 (0.01)</td>
<td>0.22 (0.03)</td>
<td>0.17 (0.02)</td>
<td>0.19 (0.01)</td>
<td>0.20*</td>
</tr>
<tr>
<td>30-60</td>
<td>0.30 (0.02)</td>
<td>0.26 (0.03)</td>
<td>0.28 (0.02)</td>
<td>0.25 (0.02)</td>
<td>0.27</td>
</tr>
<tr>
<td>60-90</td>
<td>0.30 (0.01)</td>
<td>0.33 (0.01)</td>
<td>0.31 (0.01)</td>
<td>0.29 (0.01)</td>
<td>0.31</td>
</tr>
<tr>
<td>Mean</td>
<td>0.28* (0.01)</td>
<td>0.27* (0.02)</td>
<td>0.25* (0.01)</td>
<td>0.24* (0.01)</td>
<td>-</td>
</tr>
</tbody>
</table>

*† Treatment means (column) followed by the same letter are not different ($\alpha = 0.10$).
‡ Depth means (row) followed by the same letter are not different ($\alpha = 0.10$).
Table 11. Mean soil water relations by tillage treatment and soil depth followed by standard error in parentheses.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Control</th>
<th>Disk (D)</th>
<th>Single-R/D</th>
<th>Cross R/D</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m⁻³</td>
<td>m⁻³</td>
<td>m⁻³</td>
<td>m⁻³</td>
<td></td>
</tr>
<tr>
<td>0-30</td>
<td>0.33</td>
<td>0.30</td>
<td>0.29</td>
<td>0.28</td>
<td>0.30ₐ†</td>
</tr>
<tr>
<td></td>
<td>(0.02)</td>
<td>(0.02)</td>
<td>(0.01)</td>
<td>(0.01)</td>
<td></td>
</tr>
<tr>
<td>30-60</td>
<td>0.33</td>
<td>0.35</td>
<td>0.33</td>
<td>0.31</td>
<td>0.33ₐₗ</td>
</tr>
<tr>
<td></td>
<td>(0.02)</td>
<td>(0.02)</td>
<td>(0.02)</td>
<td>(0.01)</td>
<td></td>
</tr>
<tr>
<td>60-90</td>
<td>0.33</td>
<td>0.34</td>
<td>0.35</td>
<td>0.33</td>
<td>0.34ₐₗ</td>
</tr>
<tr>
<td></td>
<td>(0.01)</td>
<td>(0.02)</td>
<td>(0.01)</td>
<td>(0.01)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wilting Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>30-60</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>60-90</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Available Water Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>30-60</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>60-90</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

*† Treatment means (column) followed by the same letter are not different (α = 0.10).*
Soil Chemical Properties

A summary of soil chemical properties is reported below to serve as baseline information for the study sites. As expected for natural soils in the southeast, the unmined reference soil exhibited a lower pH at 0-30 cm, especially contrast to the recently limed and fertilized mined site reclaimed by scraper pans which showed the highest pH and base saturation (Table 12).

Table 12. Mean soil chemical properties by depth at all sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (cm)</th>
<th>pH</th>
<th>C</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
<th>CEC (cmol kg⁻¹)</th>
<th>BS† (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-----</td>
<td>-----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>-----------------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red-springs Unmined</td>
<td>0-30</td>
<td>5.7</td>
<td>1.33</td>
<td>0.14</td>
<td>0.2</td>
<td>72</td>
<td>703</td>
<td>158</td>
<td>35</td>
<td>9.1</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>30-60</td>
<td>7.7</td>
<td>1.06</td>
<td>0.15</td>
<td>ND</td>
<td>49</td>
<td>777</td>
<td>257</td>
<td>42</td>
<td>11.2</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>60-90</td>
<td>6.0</td>
<td>0.96</td>
<td>0.14</td>
<td>ND</td>
<td>47</td>
<td>730</td>
<td>256</td>
<td>44</td>
<td>10.0</td>
<td>30</td>
</tr>
<tr>
<td>Truck-Shovel Mined</td>
<td>0-30</td>
<td>7.2</td>
<td>0.67</td>
<td>0.11</td>
<td>0.7</td>
<td>32</td>
<td>1125</td>
<td>181</td>
<td>46</td>
<td>7.8</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>30-60</td>
<td>6.5</td>
<td>0.60</td>
<td>0.11</td>
<td>0.4</td>
<td>34</td>
<td>776</td>
<td>158</td>
<td>47</td>
<td>6.5</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>60-90</td>
<td>6.6</td>
<td>0.60</td>
<td>0.10</td>
<td>0.7</td>
<td>35</td>
<td>724</td>
<td>138</td>
<td>45</td>
<td>7.0</td>
<td>36</td>
</tr>
<tr>
<td>Scraper Pan Mined</td>
<td>0-30</td>
<td>8.1</td>
<td>0.95</td>
<td>0.11</td>
<td>1.6</td>
<td>63</td>
<td>3855</td>
<td>304</td>
<td>52</td>
<td>14.5</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>30-60</td>
<td>8.1</td>
<td>0.88</td>
<td>0.11</td>
<td>0.9</td>
<td>62</td>
<td>4044</td>
<td>350</td>
<td>57</td>
<td>15.4</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>60-90</td>
<td>8.1</td>
<td>1.01</td>
<td>0.12</td>
<td>0.6</td>
<td>58</td>
<td>4461</td>
<td>322</td>
<td>57</td>
<td>16.4</td>
<td>78</td>
</tr>
</tbody>
</table>

† BS = Soil base saturation; sum of Ca, Mg, K, and Na occupying total CEC.
‡ ND = Below detection limit.
Vegetative Response to Tillage

Herbaceous Species

Observationally, winter wheat was more abundant across the scraper pan site compared to crimson clover. Volunteer herbaceous species prevalently colonized the site following winter wheat and clover, though cover by species was not quantified for each plot. Percent cover of all herbaceous species was significantly greater on tilled plots ($p = 0.0003$) (Figure 5). Overall, the control had significantly lower percent cover (54%). Final diskng during the site preparation appeared to increase percent herbaceous ground cover. Aboveground biomass production of the herbaceous species after one growing season (November-May) ranged from 1.0 Mg ha$^{-1}$ on Control plots to 3.0 Mg ha$^{-1}$ on Cross-Rip/D plots showing significant differences ($p = 0.0102$) (Figure 5).
Figure 5. Mean percent cover (A) and aboveground biomass (B) of herbaceous species followed by standard error bars. Shared letters are not different ($\alpha = 0.10$).
**Tree Seedlings**

Survival of loblolly pine seedlings ranged from 85 – 97% during the first growing season with highest survival in the two ripped treatments ($p < 0.0001$) (Table 13). Feral hog browse was evident on several tree seedlings across the site; impacts on survival were minimal. Based on personal communication with the operator, machine tree planting in Control plots was more difficult due to increased soil strength. As a result, there were several instances of shallow planting (poor soil-to-root contact), which may have contributed to lower survival. Tree seedlings growing on Cross-Rip/D treatments outgrew lower intensity tillage treatments in height, diameter, and seedling volume index after one growing season (Table 13). Control and Single-Rip/D exhibited similar diameter and seedling volume index ($p < 0.0001$). Height was similar for Disk and Single-Rip and for Disk and Control ($p < 0.0001$). The Disk treatment had the smallest tree seedlings.
Table 13. Mean relative tree seedling growth and survival after one growing season followed by standard error in parentheses.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Survival (%)</th>
<th>Height Growth (cm)</th>
<th>Diameter Growth (cm)</th>
<th>Volume Index Growth (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>85a† (0.03)</td>
<td>17a (0.6)</td>
<td>0.26b (0.01)</td>
<td>19b (1.1)</td>
</tr>
<tr>
<td>Disk (D)</td>
<td>91b (0.02)</td>
<td>17ab (0.5)</td>
<td>0.18a (0.01)</td>
<td>14a (0.8)</td>
</tr>
<tr>
<td>Single-Rip/D</td>
<td>95bc (0.02)</td>
<td>18b (0.6)</td>
<td>0.25b (0.01)</td>
<td>18b (1.1)</td>
</tr>
<tr>
<td>Cross-Rip/D</td>
<td>97c (0.01)</td>
<td>30c (0.06)</td>
<td>0.35c (0.02)</td>
<td>32c (2.7)</td>
</tr>
</tbody>
</table>

† Means followed by the same letter are not different (α = 0.10).

The trend in loblolly pine seedling relative growth was similar for above and belowground biomass between treatments. Treatment effects and p-values are given in Table 14. Cross-Rip/D biomass production increased stem, root, aboveground, and total tree components compared to the other treatments (p < 0.10). Disk produced the lowest stem biomass. No differences existed in root biomass between Control, Disk, and Single-Rip/D (p > 0.10). Control was second highest in aboveground biomass production and exhibited no differences in needle biomass compared to Cross-Rip/D.
Table 14. Mean relative tree seedling above and belowground biomass after one growing season followed by standard error in parentheses.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Needles</th>
<th>Stem</th>
<th>Roots</th>
<th>Above-ground</th>
<th>Total Tree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>8.9a† (0.5)</td>
<td>5.11a (0.1)</td>
<td>6.0a (0.4)</td>
<td>14.1a (0.6)</td>
<td>22.3a (1.1)</td>
</tr>
<tr>
<td>Disk (D)</td>
<td>5.5b (0.3)</td>
<td>3.5b (0.1)</td>
<td>7.2a (0.5)</td>
<td>9.3b (0.4)</td>
<td>21.6a (1.2)</td>
</tr>
<tr>
<td>Single-Rip/D</td>
<td>5.7b (0.3)</td>
<td>4.8a (0.2)</td>
<td>6.7a (0.9)</td>
<td>10.3b (0.5)</td>
<td>19.5a (1.1)</td>
</tr>
<tr>
<td>Cross-Rip/D</td>
<td>8.7a (0.6)</td>
<td>6.8c (0.5)</td>
<td>12.4b (1.9)</td>
<td>15.5c (0.9)</td>
<td>27.9b (2.9)</td>
</tr>
<tr>
<td>Pr &gt; F</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>0.0002</td>
<td>&lt;.0001</td>
<td>0.0066</td>
</tr>
</tbody>
</table>

† Means followed by the same letter are not different (α = 0.10).

Allometric regression coefficients for biomass components per treatment were all significant (p < 0.10) (Table 15). Weight variables were initialized at a value of 1.0 and subsequently modified. The final weights represent the best starting values that minimized the error sum of squares, decreased computation time, and produced appropriate estimates for the parameters (Table 15).
Table 15. Regression coefficients for tree seedling biomass components based on the model (equation 3): $Y = \beta_0 \cdot (\text{GLD}^{\beta_1}) \cdot (\text{HT}^{\beta_2})$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control</th>
<th>Disk</th>
<th>Single-R/D</th>
<th>Cross R/D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Needles</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>5.2E-06</td>
<td>2.7E-11</td>
<td>2.1E-05</td>
<td>0.0326</td>
</tr>
<tr>
<td>$\beta_1$</td>
<td>2.3334</td>
<td>0.9816</td>
<td>1.7751</td>
<td>2.5020</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>1.5590</td>
<td>3.9232</td>
<td>1.4641</td>
<td>0.0314</td>
</tr>
<tr>
<td>Weight</td>
<td>2.0</td>
<td>4.0</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Stem</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>0.0030</td>
<td>1.4E-05</td>
<td>1.4E-05</td>
<td>4.0E-05</td>
</tr>
<tr>
<td>$\beta_1$</td>
<td>0.9738</td>
<td>0.6877</td>
<td>0.7996</td>
<td>0.8868</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>0.8935</td>
<td>1.8156</td>
<td>2.1871</td>
<td>1.6370</td>
</tr>
<tr>
<td>Weight</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Roots</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>5.0E-13</td>
<td>4.9E-07</td>
<td>1.6E-10</td>
<td>3.0E-13</td>
</tr>
<tr>
<td>$\beta_1$</td>
<td>0.9569</td>
<td>2.9477</td>
<td>1.6152</td>
<td>2.4752</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>4.5465</td>
<td>1.7538</td>
<td>3.4307</td>
<td>4.0782</td>
</tr>
<tr>
<td>Weight</td>
<td>1.0</td>
<td>0.5</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>Aboveground</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>1.8E-04</td>
<td>2.9E-08</td>
<td>1.7E-05</td>
<td>0.0023</td>
</tr>
<tr>
<td>$\beta_1$</td>
<td>1.6989</td>
<td>0.9087</td>
<td>1.4049</td>
<td>1.6824</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>1.2777</td>
<td>2.9020</td>
<td>1.7139</td>
<td>0.8389</td>
</tr>
<tr>
<td>Weight</td>
<td>2.0</td>
<td>3.0</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total Tree</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>9.0E-08</td>
<td>4.9E-04</td>
<td>2.3E-06</td>
<td>7.6E-07</td>
</tr>
<tr>
<td>$\beta_1$</td>
<td>1.1310</td>
<td>2.7556</td>
<td>1.3777</td>
<td>2.4912</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>2.7603</td>
<td>0.8789</td>
<td>2.1492</td>
<td>1.9017</td>
</tr>
<tr>
<td>Weight</td>
<td>3.0</td>
<td>1.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>
DISCUSSION

Soil

Chemical Properties

Compared to the truck shovel and scraper pan sites, the unmined site (Redsprings series) displayed a lower pH and base saturation, which is consistent with regional soil characteristics in east Texas (Griffith, 2000). At the unmined site, the soils developed under forest vegetation, contributing organic matter and resulting in the higher soil carbon content at 0-30 cm compared to values found at the reclaimed mined sites. In order to meet regulatory compliance, the somewhat higher soil acidity present at the Oak Hill Mine is addressed with agricultural lime application (Railroad Commission of Texas, 1990). This explains the higher soil pH and base saturation at the recently reclaimed scraper pan site. Loblolly pine trees do not tend to naturally grow in alkaline soils (Baker and Langdon, 1990). Soil pH on reclaimed mined lands typically decreases after a few years as natural processes begin to alter soil chemical properties (Ng, 2012). The lower base saturation at the truck shovel site was probably caused by the increased window of time that allowed for leaching of base cations such as Ca to occur (Donahue et al., 1976).
Physical Properties

Studies comparing mined versus unmined lands show either similar soil physical properties or more favorable properties at unmined locations (Barth, 2002; Jarocki, 1994; Ng, 2012; Toups, 1986). These observations were consistent to what we found at the unmined site — a soil that reflected a loose, uncompacted rooting medium. Unmined soil physical properties were more favorable in terms of lower soil bulk density and soil strength, and increased Ksat rates which are properties considered favorable for root growth and soil biological activity (Shrestha and Lal, 2006). The truck shovel site did not drastically vary in soil texture or physical properties throughout the three main sampling depths, indicating that the conventional method of operation used to reclaim this site three years prior produced a relatively homogenous mine soil.

Increasing levels of tillage intensity at the scraper pan site resulted in a less compacted mine soil in terms of lowered soil bulk density and strength and increased total porosity compared to the more densely packed soil matrix at the untilled plots. Siegel-Issum et al. (2005) found that loblolly pine trees growing in soils of lower bulk densities are capable of growing across a broader range of soil water concentrations. The Control treatment exhibited a soil bulk density within the limiting range for sandy clay loams (1.55 to 1.70 Mg m$^3$) (Daddow and Warrington, 1983). While long-term effects were not quantified, it is possible that
soil bulk densities close to this limiting range may cause added stress to planted trees, especially during years with seasonal droughts.

One of the main factors influencing soil strength, or resistance to soil penetration, is soil moisture content (Zou et al., 2001). Soil strength is a useful corollary to bulk density; however, a range of soil-related factors must be considered such as texture, pore space, and bulk density (Gomez et al., 2002; Yao, 1994). Morris et al. (2006) showed that increased soil strength occurred at several treatment-depth intervals at higher water concentrations for non-tilled soils, whereas the opposite trend was found on tilled soils. Furtado et al. (2016) found that soil strength exceeded the critical value of 2,500 kPa in no tilled versus tilled soils (surface + subsurface tillage) in similar water concentrations, including the wettest soil water range. These findings are consistent with the soil strength results in this study (Figure 4). Critical soil strength for root growth depends on the plant species and soil physical properties such as bulk density, pore size distribution, water concentration, and texture (Sutton, 1991). Gerard et al. (1982) found higher soil strength values in coarse textured soils compared to finer textured soils. The higher clay and water contents at our two lowest soil depth intervals (70-80, 80-90 cm) may have contributed to the decreased soil strength found at those depth ranges. Upper soil layers should have been most impacted by site preparation equipment.
Volumetric water concentration was higher in the Control compared to Cross-Rip/D, with intermediate levels found in Disk and Single-Rip/D, although it is important to note that this reflects the sampling of a temporally-variable parameter on a single measurement date. Will et al. (2002) attributed decreased soil water in tillage treatments, especially bedding, to increased soil macroporosity (decreased bulk density) creating larger pathways for water percolation through the soil and/or greater usage of water by vigorous tree seedlings. This finding is supported by others who found a decrease in volumetric water concentration in tilled soils as attributed to a greater presence of macro or non-capillary pores created by tillage (Furtado et al., 2016; Lincoln et al., 2006). Additionally, the lack of vegetative cover at the control plots may have led to lower evapotranspirative demand compared to the greater amount of herbaceous cover growing on ripped plots (Ashby, 1996; Franklin and Buckley, 2009; Ludovici, 2008; Wittwer et al., 1986).

Plant water availability is a function of rooting depth and soil moisture, oxygen, and physical impedance (Dougherty and Gresham, 1988). While it is possible for compaction to create a more or less favorable pore size distribution (Gomez et al., 2002; Ponder et al., 2012), we found that the dynamics between mine soil texture, pore space, and tillage created similar water retention characteristics among treatments. Lincoln et al. (2007) showed that changes in loblolly pine seedling growth were correlated to reductions in soil strength and
increases in macroporosity as a result of tillage. They suggested that volumetric water availability was similar between tilled and no till treatments and had less impact on tree seedling growth rates. Other studies found slight increases in plant available water in compacted soils (Seigel-Issem et al., 2005) or soils prepped with a bedding plow (Page-Dumroese et al., 1997).

Although air filled porosity was not quantified in this study, a lack of soil aeration may not translate into a growth issue if soils are not frequently wetted beyond field capacity (Gomez et al., 2002). A significant difference in total pore space was found between the two treatments extremes, Control and Cross-Rip/D. Pore size, shape, and distribution are the most important factors dictating soil air and water movement (Sutton, 1991). Lenhard (1986) found that the void volume of a compacted soil remained constant while pore size distribution differed. An increase in flow channels created by deep tillage may increase the storage of plant available water lower in the profile as a result of increased infiltration and decreased runoff which may be an important factor during years of drought (Morris and Lowery, 1988). One possible explanation for the similarity in Ksat rates could be the occurrence of surface sealing or crusting as a result of raindrop impact and the subsequent disruption of macropore space (Ahuja et al., 1998).
Vegetation

Herbaceous Species

The scraper pan reclamation equipment method without tillage created a mine soil that was not favorable to the establishment and growth of the herbaceous species. Lower percent cover of herbaceous species on the untilled versus tilled plots may have been a product of either poor germination of the seed or increased mortality post germination as a result of the increased soil bulk density on untilled plots. Wiersum (1957) showed that root penetration of several herbaceous plant species was discouraged in soils with rigid pores less than 0.2 mm in size. Soil pore size and arrangement is more crucial in determining soil plant relationships than the number of pores (Sutton, 1991). Aboveground herbaceous biomass production followed a similar trend as percent cover. Thorup-Kristensen et al. (2009) found that winter wheat can root up to 2.2 m deep and provide efficient nitrogen return to the soil. In another study, deep ripping was shown to increase aboveground wheat grain yields and root extension rates resulting in increased nitrogen use efficiency (Delroy and Bowden, 1986).
**Tree Seedlings**

Across all treatments, survival of the loblolly pine tree seedlings exceeded the pine stocking standard for surface mined lands in Texas (Railroad Commission of Texas, 1990). The high survival may have been partly due to the greater than average amount of rainfall for Rusk County, Texas in 2016 (1,346 mm total rainfall in 2016 compared to the 1,255 mm average). Wittwer et al. (1986) also showed higher first year survival due to increased rainfall. Aboveground growth of the tree seedlings improved with increasing tillage intensity. Loosening the mine soil in a grid pattern (cross-ripping) significantly improved relative tree seedling growth during the first growing season compared to other treatments. It is important to note that tree seedlings were not planted directly in the dozer rip furrows. The ability of tree seedlings to root in response to increased macroporosity has been correlated to greater water, nutrient, and oxygen availability (Kelting et al., 2000). As a result, tree seedlings may have been able to exploit soil resources more quickly leading to increased growth and vigor (Coyle et al., 2008; Will et al., 2002). Additionally, a soil with reduced mechanical impedance or soil strength will increase the rate at which tree seedling roots begin to exploit soil outside of the planting furrow (Morris and Lowery, 1988). Generally, studies show that mechanical impedance reduces root growth (Sutton, 1991). High soil strength within or surrounding the planted tree
rows on the less intensive treatments may have impeded root penetration and elongation.

Similar to our study, Lincoln et al. (2006) found a positive relationship between loblolly pine seedling height and biomass production that showed significant increases in tilled soil compared to no till areas. Foil and Ralston (1967) found a significant negative correlation between loblolly pine root growth and soil bulk density. They showed that lower soil densities resulted in higher root length and weight of loblolly pine seedlings across different soil textures. Further, Zou et al. (2001) found that soil strength had a greater effect on reducing Monterey pine (Pinus radiata) seedling root elongation rate than texture or soil matric potential. Planted tree seedlings on a reclaimed mine in Appalachia followed a similar positive response to deep tillage. Fast-growing yellow-poplar (Liriodendron tulipifera) tree seedlings yielded significantly higher growth and total biomass in dozer ripped and fertilized soils (Casselman et al., 2006).

Additionally, the Least Limiting Water Range is characterized as a range of soil water concentrations where growth limitations are minimal including available soil air, water, and strength (Kelting et al., 2000). Kelting et al. (2000) found a strong positive relationship between the soil physical environment (i.e., soil aeration) and two-year-old loblolly pine seedling growth with nutrient availability showing less relevance on the growth response. They stressed that changes in growth limitations would probably occur over time.
Biomass partitioning in tree seedlings arises from indirect and direct factors including ontogenetic development and environmental conditions (Coyle et al., 2008). For example, Bongarten and Teskey (1987) showed that higher soil water concentration resulted in lower allocation of resources aboveground in loblolly pine seedlings sourced from different regions. The greater total aboveground biomass observed in the Cross-Rip/D treatment may have been a result of the tree seedlings’ ability to respond more quickly to increased resources, thus partitioning similar belowground biomass as a consequence (Coyle et al., 2008). However, we did not measure different root classes; thus, inferences based on our belowground data are limited. Additionally, since soil strength and bulk density were higher in less intensive tillage treatments, it may be possible that root systems were under sampled in those treatments. Emphasis is generally placed on soil physical properties (i.e., improved resource availability) for explaining changes in early tree seedling growth patterns which is consistent with findings in our study (Sands et al., 1979).
CONCLUSIONS

The use of surface and subsurface soil tillage at the mine site reclaimed using scraper pans resulted in a less compacted mine soil (i.e., lower soil bulk density and strength, higher total porosity). Intermediate effects on soil physical properties were generally shown between the Disk and Single-Rip/D treatments. The greatest effects on soil physical properties were evident between the two treatment extremes, Control (no tillage) and Cross-Rip/D. Overall, the Cross-Rip/D treatment was superior in terms of alleviating the greatest amount of compaction among treatments. There were no interactive effects between tillage treatments and soil depth within the first 90 cm.

Both surface and subsurface tillage treatments resulted in increased tree survival during the first growing season compared to Control plots. Additionally, all tillage treatments resulted in higher percent ground cover of herbaceous species. The ripped treatments showed the highest aboveground biomass production of herbaceous species after one growing season compared to the Control and Disk only treatment. Relative growth and biomass production of loblolly pine tree seedlings was lowest in the Disk only treatment, while intermediate levels were found in Control and Single-Rip/D treatments. Cross-
ripping and disking accrued the greatest relative growth during the first growing season.

Based on these results, we recommend that at a minimum surface disking be used prior to tree planting and seeding of herbaceous species after operating scraper pans on mined lands in the Gulf Coastal Plain Region. If trends in tree growth continue, a combined treatment of surface and subsurface tillage may serve to enhance long-term site and loblolly pine tree productivity on mined lands. Studies suggest that the positive effects of intensive soil tillage on tree seedling growth may not be substantial enough to justify initial site preparation costs (Carlson et al., 2014; Schilling et al., 2004; Wheeler et al., 2012). Additionally, the favorable soil properties associated with soil tillage may decrease over time (Ahuja et al., 1998). Ultimately, the use of tillage to ameliorate potentially long-lasting mine soil compaction should be a consideration of short and long-term reforestation goals and objectives.
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Tillage on the Piedmont and Upper Coastal Plain of Georgia: Tree 
Allometry, Foliar Nitrogen Concentration, Soil Bulk Density, Soil Moisture, 


Figure A1. Photos of tillage treatments installed in August 2015 at the scraper pan site. Top left = control (no tillage); bottom left = disking only (30-35 cm); top right = single-ripping (90 cm on 2 m centers); bottom right = cross-ripping (90 cm on 2 m grid pattern). One pass of disking was delivered to the ripped treatments after dozer operation (30-35 cm).
Figure A2. Photos of soil profiles at the scraper pan site. Top left = control (no tillage); bottom left = disk; top right = single-rip/disk; bottom right = cross-rip/disk.
Figure A3. Photos of soil profiles at the conventional truck shovel site.
Figure A4. Photo of the Redsprings soil series profile at the unmined site.
VITA

Hannah Zoe Angel was born on May 28, 1992 in London, Kentucky to Patrick Nicholas and Glenna Sue Angel. Hannah lived on her family’s sheep farm in London until she graduated from South Laurel High School in 2010. From there she moved to Lexington, Kentucky and attended the University of Kentucky (UK) from 2011 to 2014. In May 2014, she graduated with a Bachelor of Science in Forestry at UK. After her undergraduate studies, she moved to Nacogdoches, Texas and completed a Master of Science in Forestry at Stephen F. Austin State University in May 2017 with support to conduct her research from the Luminant Environmental Research Program.

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