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USING THE FORESTRY RECLAMATION APPROACH FOR RECLAIMED SURFACE MINELAND IN THE WESTERN GULF: EFFECTS ON PINUS TAEDA SEEDLING GROWTH AND SURVIVAL

Cassie Phillips
brassiecassie@gmail.com

Jeremy Stovall
Stephen F Austin State University, stovalljp@sfasu.edu

Hans Williams
Stephen F Austin State University, hwilliams@sfasu.edu

Kenneth Farrish
Stephen F Austin State University, kfarrish@sfasu.edu

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By

CASSIE LYNN PHILLIPS, Bachelor of Science in Biology

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CASSIE LYNN PHILLIPS, Bachelor of Science in Biology

APPROVED:

____
Dr. Jeremy Stovall, Thesis Advisor

____
Dr. Hans Williams, Committee Member

____
Dr. Kenneth Farrish, Committee Member

____
Pauline M. Sampson, Ph.D.
Dean of Research and Graduate Studies

ABSTRACT

While land reclamation efforts of surface mines have considerably increased soil stability since the implementation of SMCRA (Surface Mining Control and Reclamation Act), research suggests that resulting soil compaction hinders the productivity of forests post-mining. The Forestry Reclamation Approach (FRA) was developed to improve forest health in the Appalachian region through a five-step process that minimizes soil compaction and establishes a productive forest. The FRA has not yet been tested in the western Gulf Coastal Plain (GCP). The higher clay content of some GCP soils and the dearth of coarse fragments (e.g. cobbles, stones and boulders) may affect reclamation practices and the ability of these methods to create productive forests. Compaction caused by conventional reclamation methods in the GCP has not been studied in great detail. Thus, this study attempts to provide a comparison of two reclamation methods, the FRA low-compaction method used in the Appalachian region with that of conventional scraper-pan (scraper) methods in the GCP.

This study used the FRA with common silvicultural practices of the western Gulf. The two hectare study site was installed with a randomized complete block design with three replicates comparing conventional scraper reclamation used in the region with that of an unmined control and the FRA-style low compaction treatment. Following soil reclamation, containerized loblolly pine (*Pinus taeda* L.) seedlings of a western Gulf provenance were hand-planted. Soil chemical and physical parameters were assessed on each treatment to determine the effect the FRA and scraper method had on resulting tree seedling growth and survival.

After three growing seasons, seedlings in the FRA plots had significantly higher tree volumes than both the scraper ($p=0.0139$) and the control ($p=0.0247$) treatments. The FRA plots also had a 97% survival rate, while scraper plots had a survival of 86%. The FRA plots had significantly lower soil bulk densities than the scraper ($p=0.0353$) and the control ($p<0.0001$) which likely influenced growth and survival trends. Soil nutrients were increasingly available on the FRA and scraper plots, likely due to the mixing of the soil profile when compared to the unmined control. Leaf-level water potential and gas exchange were not correlated to growth and survival and did not differ among treatments. These results suggest reclamation practices modeled after FRA methods may benefit tree growth and survival in the Western Gulf.

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CHAPTER I: LITERATURE REVIEW

INTRODUCTION

In the United States, coal consumption was 663.24 millions of metric tons (Tonnes) in 2016 (Energy Information Administration, 2017). Texas contributed 35,381 Tonnes of coal to this demand, solely from surface mining operations. Developing new strategies for reclaiming this land is beneficial to land owners, coal mining companies and the general public. To better understand the effects of reclamation techniques in east Texas a site was selected to simulate surface mining and then reclaimed with a modified Forestry Reclamation Approach (FRA) and a more commonly applied scraper method. The two methods were compared to an unmined control area. Loblolly pine (*Pinus taeda* L.) seedlings were planted to demonstrate the post-mining land use of an intensively managed silviculture plantation, a common industry in the area. The FRA was developed in Appalachia with the aim of encouraging native forest growth through a five-step process. These steps promote using a suitable growth medium, uncompacted surface soil, the proper ground cover, and proper tree planting to achieve successful forest reclamation (Angel et al., 2009). This process has not yet been tested in the Gulf Coastal Plain (GCP) where shrink-swell soils and more frequent and severe droughts affect reclamation success. Soil compaction, though not heavily studied in the GCP (but see Angel et al. 2018), has been shown to affect tree growth in Appalachia (Angel 2006, Rodrigue and Burger 2004). Machinery involved in the scraper reclamation process may contribute to soil compaction. Despite soil compaction concerns, Hons 1978 showed that mixed overburden in the GCP increased plant available water on post-mined soil when compared to undisturbed soils. Alleviating soil compaction may further increase soil water availability and lower tree rooting resistance. To test this, soil parameters, tree growth and survival, and tree ecophysiological variables were measured.

The purpose of this research was to provide information on the FRA and its effects on reclaimed mine soils in the Western Gulf Coastal Plain. The Forestry Reclamation Approach had not yet been implemented in this area where shrink-swell clay soils and frequent droughts may affect reclamation success. The main study objectives included: 1) determining the effects of the Forestry Reclamation Approach on soil physical and chemical properties; and, 2) determining tree seedling survival and growth among treatments and define how these response variables are also influenced by tree physiology and competing vegetative cover.

Surface Mining Reclamation Practices in the Gulf Coastal Plain Region

Lignite coal deposits are common in the Gulf Coastal Plain (GCP) in portions of Texas, Arkansas, and Louisiana. For the extraction of lignite, the area mining method is used because of the relatively shallow depth of coal seams, generally 0.9 to 7.5m, of the lignite coal seams, and the flat to gently rolling terrain characteristic of this region (Nelson, 1987). This method involves the removal of the overburden by a dragline or cross pit spreader to expose the coal seam underneath. The overburden, if suitable, may be saved to use as surface material in the reclamation process once mining is complete. Once the coal is removed, the area is backfilled with the overburden using either the scraper method or the "truck and shovel" method. The haulback or "truck and shovel" method uses front end loaders and trucks to transport and place oxidized overburden onto the surface of the mined area. This method of using oxidized material, utilized at mining sites such as Luminant's Oak Hill Mine, generally results in some mine soil stratification. The scraper method accomplishes the same result, but uses one machine: a scraper attached to a tractor to both spread and grade the overburden. Mine soil materials become disturbed as the material is mixed and graded. The scraper method is more cost and time efficient, and therefore is more widely used. This technique restores the land to approximate original contour (AOC). Following this, at least 1.2 m of suitable materials are required to be placed on top of the graded overburden as the growth medium as required by the Railroad Commission of Texas (Railroad Commission of Texas, 1982)

Although erosion due to steep slopes is less common in the GCP compared to Appalachia, heavy rain events and occasional droughts can cause environmental challenges to reclamation (N.O.A.A. 2018). Higher clay contents in some soils may allow for better water holding capacity, but using dozers and heavy equipment on wet fine textured soils increases soil strength (Miller et al., 2004). Attempts at loosening the top soil layers once compacted can cause the creation of ephemeral gullies (Toy et al., 2002). Once these gullies have formed, it is expensive and time consuming to arrest them.

While the scraper reclamation strategy is widely used in the western GCP, it has been shown to cause some undesirable effects on the soil such as compaction (Yao, 1994). In the absence of repeated freezing and thawing cycles, soil compaction in the southern United States often persists for many years. Surface disking is commonly used to alleviate soil compaction and prepare the area for planting but may not be as effective as newer subsoil ripping, or subsoiling, techniques. Angel (2018) showed that cross ripping when compared to surface disking is superior in its influence on soil physical properties affected by compaction, such as bulk density and soil porosity.

Throughout Appalachia, many previously forested areas have been reclaimed to nonnative grasslands after mining operations have ceased (Townsend et al., 2009). This differs from reclamation practices throughout the southern United States in which forestry reclamation, specifically pine plantations, has become the preferred post mining land use (Skousen & Zipper, 2014). A study on loblolly pine allometry by Priest et al. (2015) showed that trees on mined sites had more biomass below ground compared to trees on unmined land. This suggests more environmental stress occurring on the mined sites. After more than 10 years, the differences between unmined and mined tree biomass allocation decreased, demonstrating that loblolly pine plantations can be an equally as productive on mined lands as on unmined lands over time (Priest et al., 2015; Priest et al., 2016).

Surface Mining Reclamation Practices in the Appalachian Region

In the Appalachian region, surface coal mining must face different geologic and climate features than mining in the GCP. Mountaintop removal, contour mining, and area mining are common surface mining methods in that region. Contour mining, a technique similar to the area mining method, involves stripping the soil and rock off of the surface to expose the coal seam underneath in mountains or hillsides. Mountaintop removal involves the use of explosives to remove the overburden that lies above a coal seam on a mountain. The low organic matter and high coarse fragment content of the resulting overburden require specific reclamation strategies that differ from practices in the GCP. Erosion issues must also be addressed in choosing a reclamation strategy, the mountainous or hilly terrain is vulnerable to landslides during and after mining. Though the GCP is relatively flat, ephemeral gullies can occur after heavy rain events. These gullies often occur on reclaimed land when the top layer of mine soils have been tilled or prepped for vegetation while deeper mine soil layers remain heavily compacted (Toy et al., 2002).

Due to the environmental and human safety concerns of mining, the Surface Mining Control and Reclamation Act (SMCRA) was passed in 1977. Surface mining reclamation has resulted in increasingly more stable land use post-mining since the advent of SMCRA. The set of regulations associated with SMCRA attempt to limit the adverse effects on the land and human health due to surface mining. Major components of this law include returning the land to its AOC, establishing a permanent vegetative cover, and reducing impacts on neighboring hydrologic systems (Public Law 95-87). Reclamation regulations also require mining operators to post a bond in order to assure full reclamation of the site is achieved. According to SMCRA, the reclaimed area must be greater or equal to the previous land capability, and returned to its AOC. Land capability must at least meet previous economic or public value (Public Lay 95-87). Post-mining land use is open to interpretation after fulfilling these conditions. Reclaimed land may be returned as pasture land, designated wildlife land, unmanaged forest or managed timber production land. In Appalachia, where areas were previously hilly or mountainous, to return the newly flattened land to grassland or agriculture may constitute a greater use of the land and the AOC requirement can be waived. Reclaiming mined sites to grassland became preferred after SMCRA, as aggressive herbaceous ground-cover reduced erosion, was thought to be less expensive and allowed for a timelier bond release. Tall fescue and clover species are often planted post final grading of the soil and these species remain dominant many years after reclamation (Klemow et al., 2010). In areas where trees and shrubs are planted, compacted and shallow soils stunt tree growth. Herbaceous plants may outcompete trees in these situations and the area may remain in arrested succession (Franklin et al., 2012; Kozlowski, 1999).

While these land reclamation efforts have increased the stability considerably, current research suggests that soil compaction as a result of the implementation of SMCRA hinders the productivity of forests post-mining (Ashby, 1998). Prior to SMCRA reclamation practices varied but many sites were returned to productive forest (Burger & Zipper, 2009; Rodrigue & Burger, 2001). Pre-SMCRA reclamation strategies typically left an exposed highwall and a gently rolling landscape of mine spoils. Mine spoils are defined as the overburden and other accumulated residues removed from atop the coal seam. These spoils were not graded flat and were left as a heterogeneous mixture of rock and soil (Daniels & Zipper, 1988). At some sites, trees were planted to control erosion and mine soils were limed to raise pH, although practices varied by state as there was no federal law. Many of these sites returned to productive forest over time with native trees and shrubs invading the area. SMCRA addressed many problems created using earlier land reclamation techniques including erosion, acid drainage, and associated water quality issues. Current practices of SMCRA use aggressive and nonnative ground covers to rapidly control erosion, but may hinder the ability of trees to colonize the area over time (Holl, 2002). The strict ground cover and stocking rate of 90% required by SMCRA have discouraged the use of reforestation as a method of land reclamation (Sullivan & Amacher, 2010). A study by Groninger et al. (2007) showed that the typical seeding of tall fescue and other fast-growing grasses can prevent trees from colonizing the area. These herbaceous covers compete with tree seedlings for light and nutrients, which increase tree seedling mortality, and in the long-term, can hinder tree growth (Franklin et al., 2012).

Soil Properties

Since the introduction of SMCRA, soil compaction due to grading by heavy machinery has become an issue of concern for reclamation success (Ashby,1991; Ashby,1998). The physical and chemical properties of soil are altered when the land is disturbed by heavy equipment. The reclamation method used can greatly influence the productivity of the area. In the GCP where soils tend to have higher levels of clay content reclamation can increase water holding capacity and soil organic matter when compared to native unmined soils (Skousen et al., 1990).

The soil particles are pushed closer together when the land is heavily graded causing an increase in soil strength. Reduced soil porosity decreases aeration and water storage. This, in turn, limits soil gas exchange, infiltration and percolation rates, and saturated hydraulic conductivity (Greacen & Sands, 1980). Bulk density can give an indication of the rooting volume of a soil thus influencing structure, texture, and porosity soil. A high bulk density can decrease available water capacity and nutrient availability, which can limit tree growth (Linder, 1987). Alternatively, a low bulk density would allow for more efficient root growth and development. The relationship between bulk density and soil strength can indicate the degree of compaction in the soil. This relationship allows for a better comparison of compaction across different soil textures (Hakansson & Lipiec, 2000). The effects of soil compaction have been shown to persist for more than three years, during which time tree seedlings are at their most vulnerable (Lowery & Schuler, 1991). In the long term, compacted soil may decrease aboveground biomass due to the lower storage capacity and availability of soil nutrients because of restricted root growth (Ludovici, 2008). Root volumes have been shown to decrease with compacted soils however results are unclear as to its effect on above ground biomass of Douglas-fir (*Pseudotsuga menziesii*) and western white pine (*Pinus monticola*) (Page-Dumroese et al., 1998). Scott and Burger (2014) found a negative linear relationship with increasing in soil bulk densities (>1.5 Mg m^{-3}) and root length density of loblolly and longleaf pine (*Pinus palustris*). That is, increased soil bulk densities decreased root length density. Longleaf pine was shown to have a greater degree of reduction in growth in response to soil compaction and soil moisture changes when compared to loblolly pine.

Another important factor in determining a soil's suitability for reclamation is soil nutrient content. Most nutrients are exchanged from the soil to the plant through two primary means: mass flow and diffusion (Barber, 1962). Nutrients that are transported through diffusion, mainly phosphorus and potassium, have slower rates of diffusion in compacted soils due to the decrease in overall pore space (Arvidsson, 1999). Nutrient deficiencies often result in smaller leaves, leaf growth inhibition, chlorosis and an increase in leaf abscission (Kozlowski & Pallardy 1997). Less leaf area for photosynthesis further reduces plant productivity and growth. In an agricultural setting, gaseous loss of nitrogen have been shown to be at their greatest when soils are heavily compacted (Douglas & Crawford 1993). Already low levels of nitrogen in reclaimed mine sites due to a low level of organic matter can be worsened by soil compaction. There are other means that trees may acquire nutrients, many trees employee mycorrhizal symbiosis (Chen et al., 2016). Microbial diversity and biomass are negatively affected by the mining and reclamation process and may further hinder the nutrient cycling process in the first few years of reclamation (Ingram et al., 2005). However, within 5 to 14 years the soil microbial community has been shown to return to predisturbance levels (Dangi et al., 2012; Mummey et al., 2002). However, it is unclear how these factors may be impacted by compaction during reclamation.

Reducing the compaction that is caused by heavy machinery on mined sites is of interest to landowners, especially those interested in using reclaimed lands to grow commercially valuable forests. Strategies for reducing soil compaction include ripping (subsoiling), tillage, and using ungraded overburden as the primary growth medium. Subsurface ripping has been shown to be a beneficial method for decreasing heavy soil compaction, which typically uses a ripping bar or a similar tool mounted onto a dozer. Burger and Evans (2010) showed that this subsurface ripping process improved the survival of several species (e.g. *Platanus occidentalis*, *Liquidambar styraciflua*, *Liriodendron tulipifera*, *Pinus taeda*) when compared to a compacted unripped plot. While beneficial, it also does not fully mitigate the effects of soil compaction (Burger & Evans, 2010), leaving more room for improvement. Avoiding compacting the soil during the reclamation process may be more cost effective and efficient than attempts at compaction mitigation.

Rodrigue & Burger (2001) found that most sites they sampled, in which pre-SMCRA reclamation strategies had been implemented, had tree productivity levels similar to that of their unmined counter parts. Two sites in their study showed lower productivity values, estimated by site index (SI). This result was attributed to a higher level of soil compaction, increased coarse fragment content, and low base saturation. As base saturation is positively correlated with site productivity, low base saturation may indicate that the soil has less available nutrients and a higher amount of exchangeable acidity (Rodrigue & Burger 2004). The resulting lack of available water and nutrients ultimately limits forest growth (Linder, 1987).

The use of scraper as a primary method of reclamation is relatively new, therefore little is known about the effects to the soil from this method. However, research conducted with agricultural systems (which use heavy machinery similar to that used on reclamation sites) may give insight to what the effects scraper methods may have on reclaimed lands. For example, the increased use of heavy machinery results in increased soil compaction, which has been linked to decreased agricultural crop yields (Håkansson et al., 1987). Mechanical resistance or soil strength increases stomatal closure in wheat seedlings, reducing photosynthetic output (Masle & Passioura, 1987). Compacted soil creates a response in seedlings that causes widely spreading roots instead of deep roots; this can increase the absorption of nutrients per unit length of root. However, because root penetration is decreased, the total absorption of nutrients also decreases (Kozlowski, 1999). Overall, these results suggest that the heavy machinery used in agriculture can have significant negative consequences on soil properties, which ultimately influence crop output. Likewise, heavy machinery used on scraper reclaimed mined sites may impose a similar degree of soil strength increases which could potentially limit root penetration.

Forestry Reclamation Approach in Appalachia

The Forestry Reclamation Approach (FRA) was created to address some of the problems brought on by implementation of SMCRA. These techniques developed by Burger et al. (2005) were applied in an attempt to increase the survival rates and productivity of trees planted following SMCRA guidelines. The

FRA consists of a five-step process, which is based on current research, that promotes the long-term productivity and health of forest ecosystems. In order to achieve soil conditions that are favorable for forest establishment, it often more cost and time efficient to address post-mining reclamation problems before they begin.

The first step of the FRA is to ensure a suitable growth medium is used that is at least 1.2 m deep and has a pH between 5 and 7. This growth medium is to be the best material available and may include a mix of overburden (Burger et al., 2005). If possible, native topsoil should be saved during the mining processes to be used as the primary growth medium when available. Oxidized brown sandstone has also been shown to provide a high quality growth medium conductive to forest growth and should be used when available (Angel et al., 2008). Other soil types such as unweathered, high coarse fragment, and unoxidixed overburden should be avoided due to their lack of water holding capacity and nutrient availability (Sena et al., 2014; Emerson et al., 2009). Natural revegetation occurs slower on these less desirable types of soils, so the soil must undergo the weathering processes in order to become suitable for most plant species. This weathering process is expensive (in time and cost), so these soils are generally less recommended. The soil type and texture that is used as the growth medium in reclamation can play a large role in the time and cost it takes to ensure bond release of the land.

The second step of the FRA is to loosely grade the topsoil to provide an uncompacted growth medium for trees. This step involves the use of end dumping, or a method known as “dozer push-up,” to create a loose substrate. The end dumping method can be used on a flat to gently rolling surface and involves dumping at least 1.2 m of suitable soil into piles on filled-in mine pits. These piles should be closely spaced and should not be trafficked over more than twice. Using the “dozer push-up” method accomplishes the same result but the overburden is pushed into parallel piles which are kept loose. This method may be more efficient when the mine spoils are only moved a short distance. Both methods allow the soil to be loose, which saves time and money that would otherwise be spent grading the land while also promoting tree root growth (Sweigard et al., 2007). Trees not only have higher survival rates, but are also more productive when planted on loosely graded plots compared to conventionally graded plots (Angel et al., 2006; Rodrigue and Burger 2004). This step is consistent with SMCRA regulations, 30 CFR 715.14—Backfilling and Grading, which requires: “Transport, backfill, grade, and revegetate to achieve an ecologically sound land use compatible with the prevailing land use in unmined areas surrounding the permit area.” Small depressions and uneven slopes are allowed if they are compatible with the post-mining land use specifications. The overburden may be graded to meet stability requirements, the top 1.2 m of topsoil is the only portion that should be left loose. Topographically, natural landscapes are often never completely flat, this allows the land be in a steady state or an equilibrium state with subsurface water (Toy & Chuse, 2004). Land that is in this equilibrium state will typically not have erosion problems.

This method must also be compliant with the third step, which is to use ground cover that will not outcompete tree seedlings (Sweigard et al., 2007; Groninger et al., 2007). This involves planting trees that are suited to the area, and planting low growing native grasses as initial ground cover. A combination of legumes and grasses are typically applied post-mining along with lime, as is deemed necessary. These practices allow for the area to be quickly revegetated to reduce erosion of the area. However, these herbaceous plants can compete with tree seedlings for soil nutrients, light, and water. While soil properties can influence tree growth and development in the long-term, in the short-term dense herbaceous cover can increase tree seedling mortality and growth (Franklin et al., 2012). Alternatively, planting herbaceous ground cover has been shown to be unnecessary unless the area is anticipated to have an erosion problem (Sena et al., 2014; Miller et al., 2012). Planting native tree species and relying on native plant invasion to cover the reclaimed area is preferred in these areas; this can increase tree survival rates and help to decrease the cost of reclamation (Burger et al., 2009).

Step four of the FRA is to plant two types of trees, this involves planting early and late successional species to speed up the successional process (Groninger et al., 2007). Mine sites do not usually contain the seed banks found in natural soils, therefore many species must be planted to speed up the regeneration of forests (Bell & Unger, 1981; Carter & Unger, 2002). Early successional species colonize the area and provide a more habitable site for late successional species. “Arrested succession”, when late successional species cannot colonize a site, can occur in areas where only herbaceous or early successional species are planted. Natural reforestation of the area can take decades when a site has entered “arrested succession.” Late successional species do not spread as easily and naturally will take many years to colonize an area; by planting them at the beginning of reclamation, adequate forest cover can be achieved. This process also speeds up reclamation by promoting the invasion of native vegetation ensuring a timely bond release.

The fifth and final step is to use proper tree planting techniques – planting trees at the correct time in the season and proper handling of the tree seedlings. To ensure trees are planted at the correct depth and firmness, tree planting by professional tree planters is preferred in the Appalachian region. Shallow and loosely planted seedlings tend to have the lowest survival rates, therefore, achieving proper rooting depth is essential (Long, 1991). The loose soil material created in the previous steps of the Forestry Reclamation Approach allows for the seedlings to be planted at an adequate depth for root growth (Sweigard et al., 2007; Burger et al., 2009).

Reclamation techniques such as leaving soil ungraded and foregoing heavy seeding of fast growing herbaceous cover come from pre-SMCRA reclamation techniques. Pre-SMCRA mined sites have shown forest productivity at or above non-mined areas (Rodrigue et. al., 2002). These sites used less competitive ground covers and did not heavily grade the land, instead the soils were left loose. Current and future reclamation practices need to address soil physical and chemical properties, soil compaction, tree selection and ground cover competition in order to succeed (Emerson et al., 2009). The five steps of the FRA help to address these issues, encourage a successful reforestation, and meet SMCRA regulatory requirements. Geomorphic processes can take hundreds of years to reform adequate soil profiles on land that is disturbed but when properly reclaimed, mine sites can be returned to conditions similar to that of undisturbed land (Toy & Chuse, 2004). The overall goal of the FRA is to mimic these natural processes in order to achieve a successful reforestation.

CHAPTER II:

EFFECTS OF THE FORESTRY RECLAMATION APPROACH AND PAN SCRAPER RECLAMATION ON SOIL PROPERTIES AND VEGETATION

INTRODUCTION

The implementation of the Surface Mining Control and Reclamation Act of 1977 (SMCRA) created a process for keeping coal mining companies accountable for reclamation of their mined land and promoted land stability practices post-mining (Public Law 95-87). SMCRA was created out of concern that surface mines were negatively impacting the environment and public safety. Prior to SMCRA, reclamation practices varied but it was not uncommon to leave mine spoils in heterogeneous, ungraded piles (Daniels & Zipper, 1988). Tree planting occurred on some sites but was not required. When tree planting did occur, forests became mature, diverse, and productive over time (Rodrigue et al., 2002). In order to comply with SMCRA regulations, reclamation strategies changed and typically included grading the land to return it to its approximate original contour (AOC) and planting fast growing, non-native herbaceous cover. Until recently, many coal mine reclamation areas throughout Appalachia were returned to non-native grasslands as opposed to native forest. However, pine plantations have become the preferred post-mining land use throughout the southern United States, thus practices that can increase pine tree growth and survival are of high economic and interest (Skousen & Zipper, 2014).

The scraper technique has shown to be one of the most cost efficient methods of the commonly used reclamation methods in the Gulf Coastal Plain (GCP) but has been shown to cause soil compaction (Yao, 1994). Loblolly pine is commonly used in east Texas reclamation due to its low cost, rapid growth rates, ability to tolerate acidic and nutrient poor soils, and high timber value (Toups, 1986). While Priest et al. (2015) showed similarities in above ground tree growth on mined and unmined sites, allometry showed mined site trees had more below ground biomass than their unmined counterparts in the first 10 years of growth. This suggests a larger amount of environmental stress being placed on tree seedlings growing on mined sites (Priest et al., 2015; Priest et al. 2016).

An additional stressor for seedling success is the physical and/or chemical properties of the soil. Although there is limited research on soil compaction of reclaimed minerals in the GCP (but see Yao 1994 and Angel et al., 2017), it has been heavily studied in the Appalachian region (Kozlowski, 1999; Angel 2006; Sweigard et al., 2007). The forestry reclamation approach (FRA) was developed in the interest of preserving soil physical and chemical properties. In Appalachia, implementing the five steps of the FRA has been shown to be more efficient in producing higher survival and growth rates than conventional methods (Angel et al., 2006; Rodrigue and Burger 2004).

Though the FRA has been shown to be beneficial in the Appalachian region, its effects have not yet been studied in the GCP. The GCP has many factors that affect land reclamation and forestry practices including more erodible soils, higher clay content soils, some with shrink-swell properties, and frequent summer droughts. Clay and clay-loam textured soils tend to have high runoff and low infiltration rates which increase erosion rates. Fine textured soils, when wet, are also more easily compacted than that of coarser textured soils. This can create an issue for implementing practices more commonly used in the Appalachian region where soils tend to be higher in coarse fragments and thinner (Haering et al., 2004). Drought conditions can develop rapidly, typically occurring every five years, with an extreme to exceptional drought covering much of the Gulf Coastal Plain as recently as 2011(N.O.A.A., 2018). These factors must be considered when implementing and adapting any of the five steps of the FRA.

The primary focus of this study was to determine the effects of two different reclamation strategies, the FRA and the traditional scraper method, on tree growth and survival and select soil properties using a simulated reclamation site in the GCP. Priest et al. (2015 & 2016) documented that productivity and site index of unmined sites are being met by current reclamation practices, however using the FRA in the GCP presents an opportunity to potentially increase this productivity beyond unmined levels. Land owners, who may have a personal interest in the intrinsic or economic value of the land, and coal companies are legally bonded to land reclamation until revegetation requirements are met, have a shared interest to increase tree productivity on these reclamation areas. This simulated mine study reclamation was set up in order to determine if there are more efficient reclamation methods of accomplishing afforestation.

In this study an unmined control was set up to be used as a baseline to compare the two reclamation strategies. Four alternative hypothesis were tested in order to understand the effects of conventional and FRA reclamation methodologies in the GCP. First, we hypothesized there are differences observed in select soil physical and chemical properties between treatment methods. Based on similar studies, soil physical properties such as bulk density and soil strength would be expected to be lower on FRA treatments due to the lack of frequent heavy equipment trafficking (Angel et al., 2006; Thomas et al., 1999). Soil chemical properties in the control treatments would be expected to be different from the two reclamation treatments because they remained undisturbed. Secondly, we hypothesized there is a difference among treatments in seedling growth and survival. This hypothesis is based on previous studies done using the FRA in which tree growth and survival are improved (Angel et al., 2006; Rodrigue and Burger 2004; Torbert & Burger, 1994). Third, we hypothesized water potential and leaf-level gas exchange of seedlings would differ among treatments. Differing soil reclamation strategies may influence tree physiology and how tree seedlings deal with moisture stress. Fourth, tree physiology properties are correlated to seedling growth and survival. Tree physiology properties such as water potential and leaf-level gas exchange may influence the growth and survival of tree seedlings. Tree seedlings under less moisture stress, therefore having a higher water potential value, would be expected to have higher volumes and survival rates. A vegetative cover component will also be tested to determine if differences exist across treatments.

METHODS

Study Site

This study was conducted on an approximately 1 ha site at the unmined Gail Creek Property in Houston County, Texas (31.204719, -95.387329; Figure 1), which is located in east Texas.

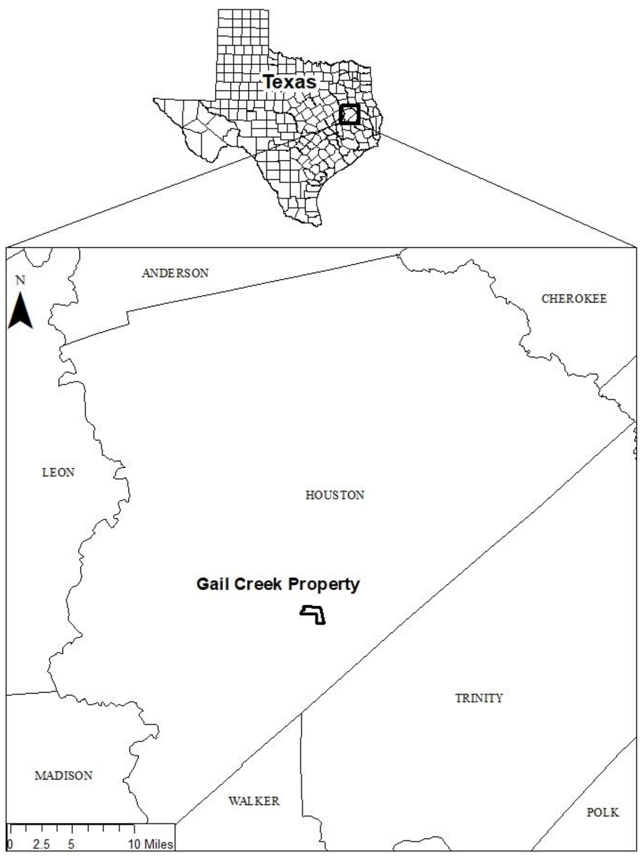

Figure 1. Location of the study site at the Gail Creek Property in Houston County, Texas.

Approximately 15 years prior to installation of the mine simulation Gail Creek Property was planted with loblolly pine trees. Much of the study site had poor seedling survival rates and was taken over by grasses and was converted to pasture use. The study area had remained as an unmanaged pasture land for several years before installation of treatment occurred. The area consisted of mainly grasses, forbs, and shrubs. Houston County annually receives an average of 1219 mm of rainfall with an average temp of 19°C (N.O.A.A., 2018). It was determined that Gail Creek Property consisted mostly of the Moswell Soil Series (very fine, smectic, thermic Vertic Haplaudalfs) with a smaller component consisting of the Kurth Soil Series (fine-loamy, siliceous, semiactive, thermic Oxyaquic Glossudalfs; Soil Survey Staff, 2019; Figure 2).

Figure 2. Project site photos taken prior to installation of treatments. Left = photo of soil profile; Right = site photo showing abundance of grasses on the site prior to installation.

The climate of east Texas is sub-tropical humid, with the major eco-region of the area being referred to as the Pineywoods. The native vegetation of the area is dominated by several pine species as well as various hardwoods including oaks. Loblolly pine is commonly used as a commercial timber species in the Pineywoods due to its ease of availability and rapid growth rates (Toups, 1986). To implement the final land use as an intensively managed plantation, loblolly pine was planted as the reclamation species. No cover crop was planted and no herbicide was applied to any treatments. Slope of the site was approximately 3% with a relatively flat topography.

Experimental Design

The one ha site was set up in a randomized block design (RCBD) totaling nine experimental plots (Figure 3). Treatments were randomly assigned to each of the plots. Three FRA treatment plots were a low compaction methodology simulating end dumping, but using a tracked excavator rather than a rock truck. Three scraper plots simulated the conventional method of reclamation commonly used in the GCP. Three control plots were used to measure conditions on unmined soil and vegetation parameters.

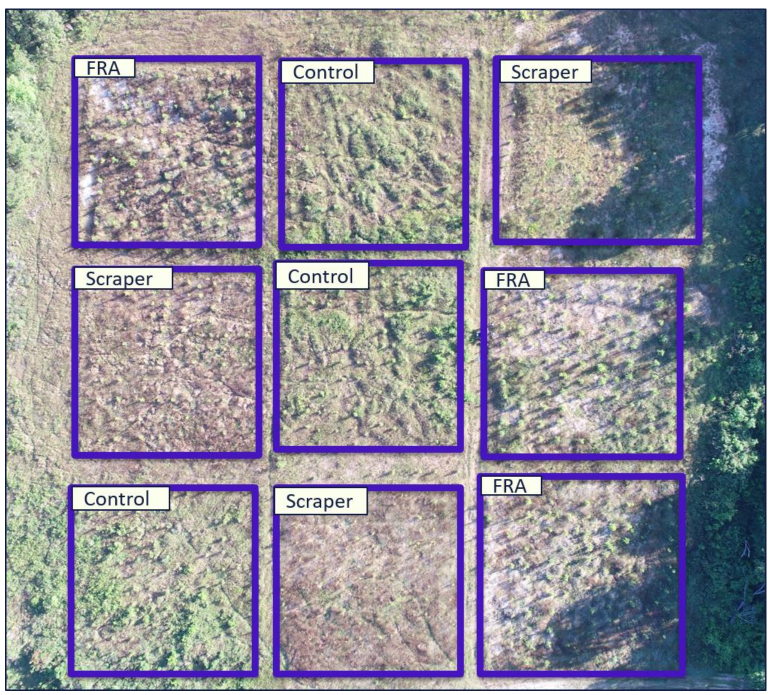

Figure 3. Oblique aerial imagery taken of the site in May 2018 depicting the RCBD design.

Site Preparation

From January 26 to February 1, 2016 approximately 1 ha was cleared of vegetation and excavated to simulate mine activity, encompassing nine total plots. Installation of plot treatments included the following:

Scraper-Pan Plots. A traditional scraper treatment involves using a tractor to pull a scraper-pan that layers soil into the pits approximately 15 cm at a time. Due to the high clay content of soils with vertic properties and high soil moisture at the time of trial installation, a traditional scraper grading of the surface was not used. Instead, a Cat D6T dozer pushed the soil back into 1.3 m pits and replaced in thin (15 cm) layers. Installation of scraper plots was completed on January 29, 2016. Pushing the soil back in layers adequately simulated a scraper reclamation due to the frequent trafficking of the dozer and mixing of the subsoil (Figure 4).

FRA Style Plots. Pits approximately 1.3 m deep were dug on February 1, 2016 using a Cat excavator. Buckets of soil were then dropped into the pits adjacent to but overlapping the pile of the last bucket. The resulting soil was left in loose piles and not trafficked on further (Figure 5).

Control Plots. For the control treatment, the plots were cleared of all vegetation on February 1, 2016 with a Cat D6T dozer. Plots were not trafficked on further with heavy machinery (Figure 4).

International Forest Company containerized, genetically improved western Gulf provenance loblolly pine seedlings were planted on February 23, 2016 as observational units following treatment installation in each plot. All tree seedlings were planted at the same time on all plots to allow for comparison of tree seedling response to each treatment. Each seedling was hand planted using 2.4 X 2.7 m spacing. Trees were planted regardless of slope location on FRA plots.Each plot was approximately 0.25 ha and comprised of approximately 50 tree seedlings to be used as experimental units. Two border rows were also installed on all four sides of each plot were also planted to mitigate edge effects but were not measured for any variables.

Figure 4. Photos of installation of treatment plots from January 26 to February 1, 2016. Top = from left to right - control, scraper and FRA plots; bottom left = digging to a depth of 1.3 m to simulate mining; bottom right = soil replaced back in 15 cm layers to simulate scraper-pan reclamation.

Figure 5. Photo taken in January 2017 of FRA style reclamation plots showing uncompacted loose soil piles.

Data Collection

Tree seedling measurements were made at the end of each growing season for three years (in February 2017, February 2018, and December 2018). Measurements using a Model 600 Pressure Chamber (PMS Instrument Company, Albany, Oregon) to assess seedling water potential were collected once each month for eleven months in 2018 (all months except September). Leaf level gas exchange was measured with a LICOR 6400 XT and a 6400-02b LED Light Source (LI-COR Environmental, Lincoln, Nebraska) in May, June, July, August, October, November and December 2018. Herbaceous cover was estimated with 1 m^2 quadrants randomly placed in each experimental plot in July 2017 and June 2018. Above ground biomass was sampled within 1 m^2 quadrants randomly placed in each plot on July 2017 and June 2018 during the peak of the growing season. Herbaceous composition was categorized using 1 m^2 quadrants randomly placed in each plot in June 2018.

Weather conditions. All weather condition data were collected from the Crockett, Houston County Airport N.O.A.A. station (2018) (Figure 6). The total rainfall for 2016 and 2017 was 1,008 mm and 1,398 mm, respectively. Average temperature of July 2017 was 29°C with a total precipitation of 61.72 mm, which was lower than average. Typical rainfall for May, June and July was also well below average in 2018, the low precipitation and warm conditions contributed to a slight summer drought for the area. Occasionally droughts in the area are not uncommon and typically occur every 5-10 years (N.O.A.A., 2018).

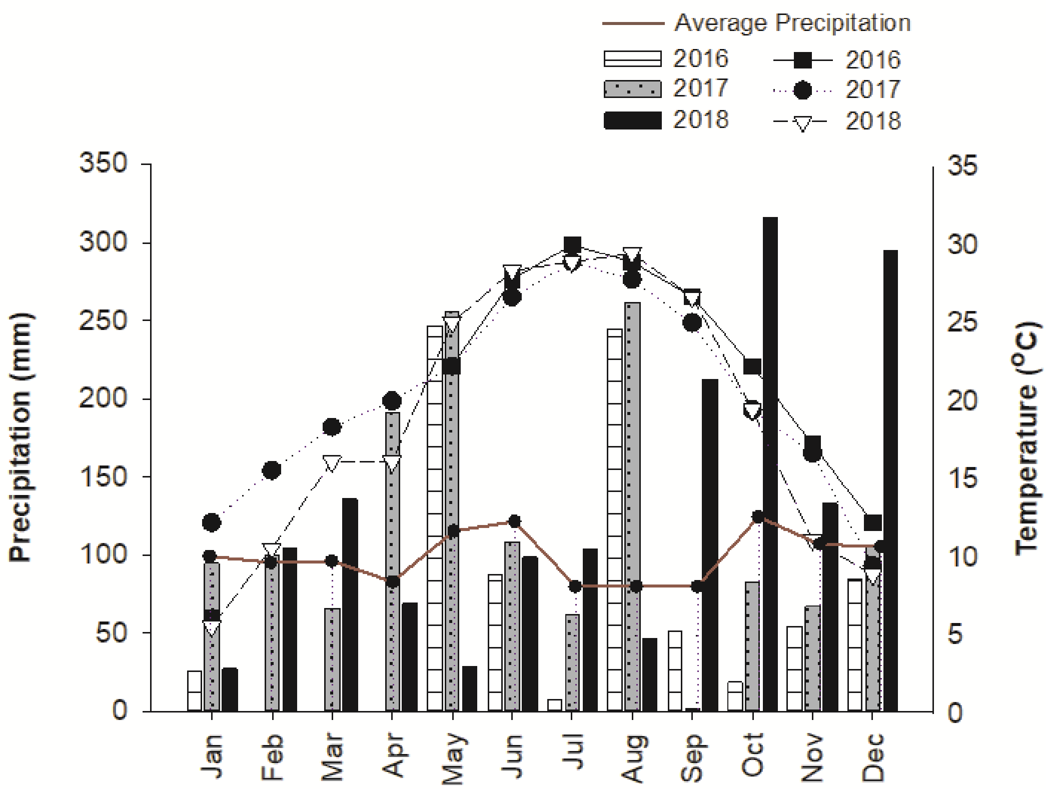

Figure 6. Monthly total precipitation and mean temperature data from 2016-2018 for Crockett, Texas (N.O.A.A., 2018). Due to a lack of available data, precipitation and temperature data from February to April of 2016 were not included.

Soil Sampling

Soil Nutrients and pH. Soil nutrients and pH were determined using composite samples of the upper 15 cm from each plot, a total of 27 samples were analyzed (i.e., three from each experimental plot). Ca, Mg, K, and P were quantified with an IRIS Intrepid II XSP inductively coupled plasma (ICP) analyzing unit (Thermo Scientific, USA) following extraction by the Mehlich 3 extraction procedure (Mehlich,1984). A glass electrode pH meter determined soil pH. Soil nutrient analysis was conducted by the Stephen F. Austin State University Soil, Plant and Water Analysis Laboratory.

Bulk Density. Bulk density measurements were taken in June 2017. Soil bulk density was sampled and measured using the slide hammer method (Blake and Hartge, 1986). Soil cores were sampled using 5.08 cm x 2.54 cm aluminum liners (AMS Inc., American Falls, Idaho). Four soil bulk density cores were extracted per sample; the two interior cores were used for bulk density analysis at a depth of 15 cm. Four samples were taken from each treatment plot. Bulk density was calculated by weighing dry soil from sampled from the soil core and dividing it by the total volume of the soil core. Bulk density soil cores taken from a slide hammer were oven dried at 105°C until reaching a constant weight. The density of the soil was then determined using the following equation (1):

(1) Density = Mass / Volume

Soil Composite Samples. Composite soil samples were collected in February 2018). The upper 15 cm in was collected at four corners of a 1 m^2 quadrant and combined as one measurement at three locations in each plot for later analysis of P, K, Ca, Mg, S, Na and pH.

Soil Strength. Soil strength measurements were taken in July 2017. Soil strength was calculated using the cone index (Bradford 1986). Using a FieldScout 900 SC Soil Compaction Meter electronic cone penetrometer (Spectrum Technologies, Inc., Aurora, IL) soil strength measurements were taken at a depth of 15 cm using a 30° angle cone 1.3 cm diameter cone tip. Four randomly selected areas of each experimental plot were sampled during January 2017. For each randomly selected area, three measurements were taken and then averaged to produce a single measurement.

Soil Water. Soil moisture samples were taken for eleven months in 2018 (all months except September). One soil moisture measurement was taken on each experimental plot in conjunction with leaf-level water potential measurements at a depth of 15 cm using a slide hammer. Gravimetric soil moisture was determined by weighing samples directly taken from the field, and then again after oven drying at 105°C until reaching constant weight. Gravimetric soil moisture was later converted to volumetric water concentration (θ_{vw}) from average bulk density values using the following equation (2):

$$(2)\ \theta_{vw} = \textit{Bulk Density}\ \times\ \textit{Gravimetric Moisture Content}$$

Soil Texture. Soil texture samples were collected in December 2017. Measurements were taken by using a slide hammer at a depth of 15 cm in three randomly selected locations across all plots for a total of 27 samples (i.e., three from each experimental plot). Soil samples were oven dried at 105°C until they reached a constant weight and pulverized using a SA-45 soil grinder (Gilson Company, Lewis Center, Ohio). Soil samples were measured into 50g subsamples which were used to determine sand, silt, clay content using the hydrometer method (Bouyoucos, 1951).

Vegetation

Tree Seedlings. Height and ground-line diameter (GLD) of living tree seedlings were taken at one, two, and three years post planting. All dead seedlings were counted but not measured to give a survival rate of each plot. Tree seedling volume index data was used to determine the growth of tree seedlings between measurement dates. Tree seedling volume index (VI) was calculated from the following equation (3):

$$(3)\ VI = d^2h$$

d = tree seedling ground line diameter

h = tree seedling height

Tree seedling measurements were conducted at the end of the growing season in 2016, 2017 and 2018. Slope location on FRA plots were quantified categorically to determine the location on the mound: 1 = top of mound, 2 = upper mound, 3 = middle mound, 4 = swale or bottom of mound.

<u>Leaf-level measurements.</u> Leaf level gas-exchange was measured with the following variables: intercellular CO_2 concentration (C_i), light-saturated photosynthetic rate (A_{sat}) stomatal conductance (g_s) and leaf transpiration (E). All measurements were taken with the LICOR 6400 XT and 6400-02b LED Light Source (LI-COR Environmental, Lincoln, Nebraska) from two young, fully expanded, current year's flush, detached needle fascicles per sample between 9:30-10:30 am. Within five minutes of extraction, the mid-section of two fascicles were placed into the leaf cuvette. Internal conditions were sustained at a saturating light level of 1600 µmol m^{-2} s^{-1} PPFD, ambient temperature, mixer rate of 400 µmol CO_2 mol^{-1} air and flow rate at 300 µmol s^{-1}. Diameter (mm) of each needle fascicle was taken post sampling to estimate the total needle surface area

(SA) inside the chamber. The following equation was used to calculate total leaf surface area (4) (Ginn et al., 1991):

$$(4)\ LA = (n \times l \times d) + (\pi \times d \times l)$$

l = length of needle,

d = fascicle diameter

n = number of needles on the fascicle

Plant water potential measurements were taken with a Model 600 Pressure Chamber (PMS Instrument Company, Albany, Oregon) using portable N_2 gas. Measurements were taken pre-dawn and midday using the pressure chamber method (Scholander et al., 1965). The pressure chamber method involves extracting one leaf fascicle per tree, fitting the fascicle through a tightly fitting rubber stopper with the leaf sheath protruding out, and then sealing with the pressure chamber metal lid. Pressure is increased into the chamber causing sap to move upwards along the protruding surface until it spills out. The pressure at which sap comes to the surface is recorded. Each treatment plot was measured in triplicate. Tree seedlings were randomly selected each sampling date; however, the same trees were sampled for both pre-dawn and midday measurements. Samples were measured within five minutes of extraction from the seedling. A pilot study was conducted in June 2017 to determine the peak pre-dawn and mid-day sampling times at the site, pre-dawn sampling times were taken between 5:30-6:30 am and mid-day day were taken between 10:30-11:45 am. Soil moisture content samples were taken in conjunction with pressure chamber measurements.

Herbaceous Cover and Density. Percent cover was measured using 1 m^2 quadrats in triplicate per experimental plot conducting a visual estimate for a total of 27 samples (Daubenmire 1959). Percent cover was measured in year 1 and year 2 during the growing season. Vegetative productivity was determined using 1 m^2 quadrats randomly placed in each plot in triplicate. All above ground vegetation inside the 1 m^2 quadrats was collected using hand-held grass clippers. Clipped vegetation was oven-dried at 60°C until samples reached a constant weight to determine total dry biomass.

Statistical Analysis

A randomized complete block design (RCBD) was used to control for variations in location on the site. One-way analysis of variance (ANOVA) was used to determine if significant differences existed for each dependent variable (Table A1). Two-way ANOVA was used test leaf-level measurements along with the date of each measurement and interaction effects (Table A2).

Analyses were performed with SAS (SAS 9.4, SAS Institute, Cary, North Carolina). Probability of significant differences was tested at an alpha of 0.05. Assumptions of normality were verified using residual plots. Data did not require transformation. PROC MIXED was used to analyze RCBD data. Tukey's post-hoc test was used to determine differences among treatments. PROC GLIMMIX was used to analyze tree survival data using the logit function link. A pearson correlation, PROC CORR, was used to determine if any significant relationships existed between leaf-level gas exchange variables and volume and survival.

Analysis of covariance was used due to the significance of each slope (slope ≠ 0) using the following model (5). Water potential was treated as a covariate to determine effects of each treatment on tree seedling volume.

$$(5)\ Y_{ijk} = \mu + Treatment_j + Block_i + WaterPotential_k + Treatment_j*WaterPotential_k$$
$$Block_i*Treatment_j + \varepsilon$$

Significant differences between water potential and leaf-level gas exchange were determined using ANOVA and the following model (6):

$$(6)\ Y_{ijk} = \mu + Treatment_j + Block_i + LeafLevelGasExchange_k + Block_i \times Treatment_j + \varepsilon$$

RESULTS

Soil Physical Properties

The Moswell soil series typically has a dominant textural class of loam from 0 to 12 cm and clay texture 12 cm to 177 cm (Soil Survey Staff, 2019). This soil series profile aligns with the textural classes observed of each treatment: the control had a clay loam texture, and the scraper and FRA treatments had significantly more clay, in turn being classified as clay. The control treatment had a lower clay content at the sampled depth of 15 cm than both the scraper (p=0.0334) and FRA treatments (p=0.0067; Table 1). Sand content differences were also exhibited between the FRA and control treatments (p=0.0013).

Table 1. Mean soil particle size distribution and textural class for each treatment followed by the standard error in parenthesis.

Treatment	Sand	Silt	Clay	Texture
	------------------	%	----------------	
Control	36_{a}† (1.9)	26 (2.5)	38_{a} (3.0)	clay loam
Scraper	28_{ab} (3.4)	22 (3.2)	50_{b} (2.6)	Clay
FRA	21_{b} (2.0)	26 (3.4)	53_{b} (1.9)	Clay

† Means followed by the same letter are not different (α = 0.05).

Treatment effects were observed in both bulk density and soil strength, with FRA treatments having the lowest values of both variables (Figure 7A and B). Bulk density was significantly lower in FRA plots when compared with scraper plots ($p=0.0353$) and control plots ($p<0.0001$), but scraper and control plots bulk density measurements did not differ ($p=0.0619$; Figure 7A). Soil strength did not differ between control and scraper treatments ($p=0.8057$), but FRA soil strength differed from scraper ($p=0.0009$) and control ($p=0.0002$; Figure 7B). Soil strength measurements may differ depending on soil moisture and may be higher during drought periods; however, bulk density and soil strength were taken in early summer 2017 when rainfall amounts were at a seasonal average. Observationally, despite the equal clay contents of both FRA and scraper plots (Table 1), the ease of sampling (i.e. insertion of slide hammer or cone penetrometer) was improved on FRA treatments. Root length in loblolly pines has been shown to have a negative linear relationship as soil bulk densities increase (>1.5 Mg m^{-3}; Scott & Burger, 2014). While all treatment means were below the 1.5 Mg m^{-3} threshold, control plots experienced a mean bulk density of 1.4 Mg m^{-3} (Figure 3A).

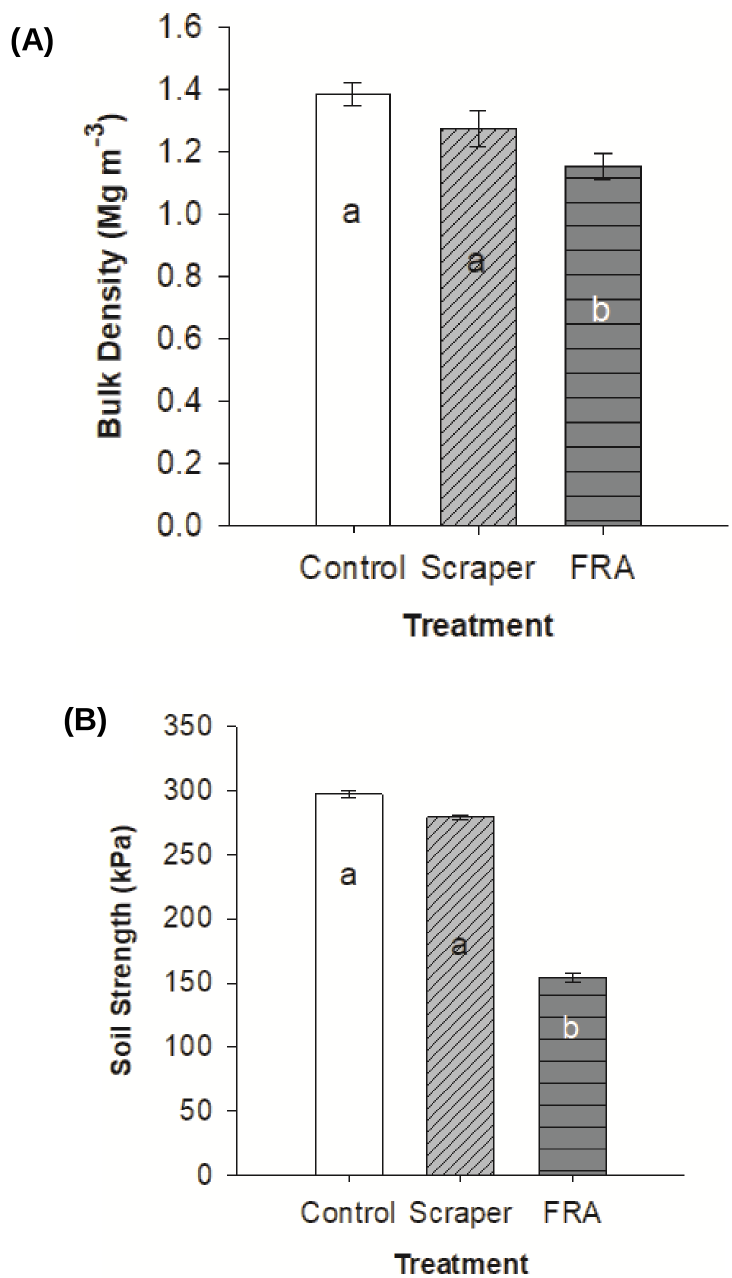

Figure 7. Mean soil strength (A) and bulk density (B) of each treatment followed by standard error bars. Shared letters are not statistically different (α= 0.05).

The lowest soil moisture percentages occurred on the control plots at 13% during the months of June and August, while the scraper and FRA treatments experienced their lowest moisture at 17% and 18% during August (Table 2). This is consistent with weather data during those months that indicate low rainfall and high temperatures inducing a mild drought. Overall soil moisture was not significant between treatments (Table 3).

Table 2. Volumetric water concentration means by month in 2018 per treatment taken in conjunction with pressure chamber measurements.

Volumetric Water Concentration			
Date	**Control**	**Scraper**	**FRA**
	-------------------- m^3 m^{-3} --------------------		
January	0.29	0.32	0.29
February	0.36	0.33	0.30
March	0.27	0.33	0.30
April	0.35	0.31	0.31
May	0.30	0.28	0.31
June	0.17	0.25	0.24
July	0.24	0.23	0.21
August	0.18	0.21	0.21
September	N/A	N/A	N/A
October	0.35	0.32	0.33
November	0.29	0.34	0.34
December	0.37	0.34	0.35

Table 3. Total mean, minimum and maximum soil moisture percentages.

Soil Moisture			
Treatment	**Min**	**Max**	**Mean**
	---------------------%--------------------		
Control	13	27	20
Scraper	17	27	23
FRA	18	31	24

Soil Chemical Properties

Differences were found between FRA and scraper treatments when compared to the control in pH, calcium, and magnesium (Table 4). When compared to the control, FRA (p=0.0029) and scraper (p=0.0261) treatments had higher pH values. This was expected due to the more basic soil materials found lower in the profile being mixed with the moderately acidic surface horizons in the FRA and scraper treatments. FRA treatments exhibited higher Na values than the control (p=0.0002) and scraper (p=0.0449). No significant differences were found for phosphorus, potassium or sulfur among treatments. Nitrates were tested but were undetectable in all treatment plots.

Table 4. Mean soil pH, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), and sodium (Na) by treatment measured at a depth of 15 cm.

Treatment	pH	P	K	Ca	Mg	S	Na
		----------------------------mg kg-1 ---------------------------					
Control	5.93	7	125	2826	557	10	214
Scraper	7.05	3	120	4516	691	10	273
FRA	7.43	3	106	4453	740	13	445

Vegetation

Tree Seedlings

Tree seedling survival across all treatments in the first growing season (2016) ranged from 73 - 98% (Figure 8). Differences in survival rates were observed between FRA and control plots (p=0.0275) during the first year with a similar trend continuing in 2017 and 2018. Seedling mortality rates were highest in the first growing season, with almost no seedling mortality occurring in the successive growing seasons.

Tree seedling heights and diameters differed between treatments in all three years (Table 5). During the first growing season, tree seedling diameters in the FRA experimental plots were significantly larger than control (p=0.0266) and scraper treatments (p=0.0222). Height followed a similar trend as FRA treatments were taller than both scraper and control treatments all three growing seasons (Table 5). Though control and scraper treatments heights and diameters were not significantly different from 2016-2018, p-values decreased from p=0.7807 for heights in the first year to p=0.1764 by the third year.

Tree seedlings volumes followed the same trend as height and diameter, and differed significantly by treatment all three growing seasons (Figure 8). FRA treatments had higher tree volumes than the control (p=0.0201) and the scraper (p=0.017) seedlings in 2016. The FRA tree seedlings had significantly higher tree volumes than the control (p=0.017) and scraper (p=0.0111) at the end of the second growing season (2017). The third growing season (2018) followed a similar pattern with larger tree volumes on the FRA treatments than both the control (p=0.0247) and scraper (0.0139). The control and scraper treatments did not significantly differ from each other during any year.

Table 5. Tree seedling heights and diameter by treatment over three growing seasons (2016-2018) followed by standard error in parentheses.

Treatment	Year	Height (cm)	Diameter (mm)
Control	**2016**	36.07a† (0.584)	7.32a (0.184)
Scraper	**2016**	35.27a (0.542)	7.17a (0.171)
FRA	**2016**	43.06b (1.008)	10.71b (0.31)
Control	**2017**	76.58a (1.851)	16.78a (0.468)
Scraper	**2017**	63.15a (1.916)	13.72a (0.446)
FRA	**2017**	114.54b (2.873)	27.01b (0.778)
Control	**2018**	147.36a (3.215)	30.28a (0.794)
Scraper	**2018**	114.50a (4.005)	22.36a (0.826)
FRA	**2018**	211.92b (5.17)	46.93b (1.317)

† Means followed by the same letter are not statistically different (α=0.05).

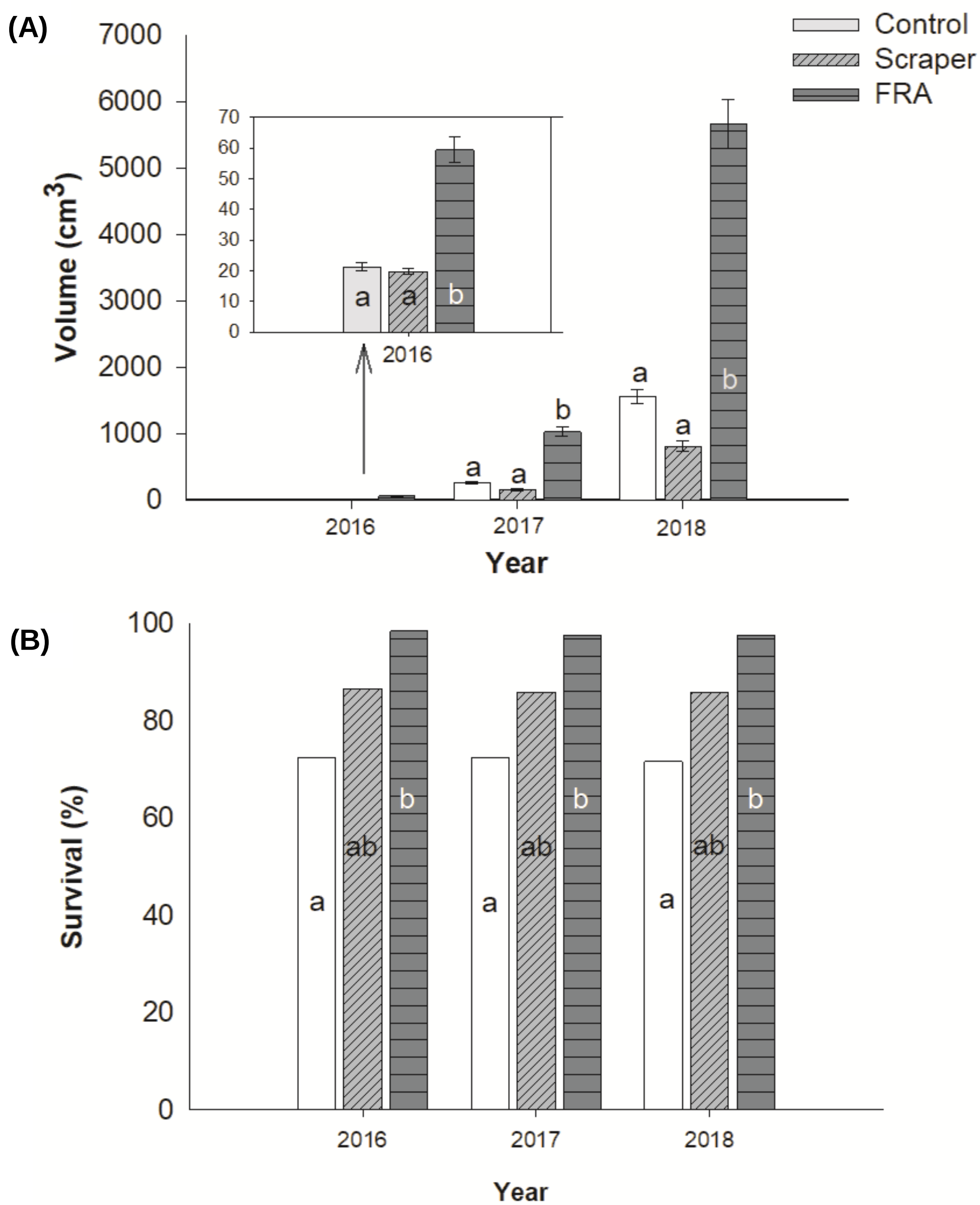

Figure 8. Mean tree seedling volumes by treatment with standard error bars (A) and mean survival rates by treatment (B). Shared letters are not statistically different (α= 0.05).

Figure 9. Photos of tree seedlings in each plot taken during the growing season of 2018. Top left = FRA style plot tree; Top right = scraper reclamation style plot tree; Bottom middle = control style plot tree.

FRA seedlings were also categorized by slope location on each mound; slope location was denoted with the four following categories: 1 = top of mound, 2 = upper mound, 3 = middle mound, 4 = swale or bottom of mound. No significant differences were observed between slope location and tree volume. Observationally, slope location shifted throughout 2016-2018 due to the settling of soil. The number of trees at a slope location of 1 was 31 in 2018 compared to only 13 in 2016 and 2017 (Table 6). Dead trees slope location was not quantified therefore survival rates across slope location were not tested. Overall FRA tree survival was 98% regardless of slope location, indicating slope location may not be a factor in determining tree seedling survival or growth.

Table 6. FRA tree seedlings volume and number of trees per slope location.

Year	Slope Location	Volume (cm^3)	Number of Trees
2016	1	65.64	13
	2	46.51	25
	3	63.01	35
	4	61.56	51
2017	1	1292.37	13
	2	967.44	24
	3	961.33	35
	4	1037.05	51
2018	1	5660.95	31
	2	5256.46	18
	3	5448.56	26
	4	5916.9	48

Water Potential

Water potential measurements taken on the same date did not differ among treatments. Low moisture stress was observed in all treatments during periods of high rainfall during the months of May, October, November and December (Figure 10). Higher mid-day moisture stress was observed from March to July, during which a mild drought occurred. While FRA treatment seedlings tended to have less negative pre-dawn and mid-day water potentials during low precipitation months, they were not significantly different from the other treatments (Figure 10).

Soil moisture did not differ significantly among treatments on the same day, and interaction effects between treatment and moisture were not significant for either pre-dawn or mid-day water potential measurements; therefore, moisture effects were not included as a factor to determine water potential (Tables 2 & 3).

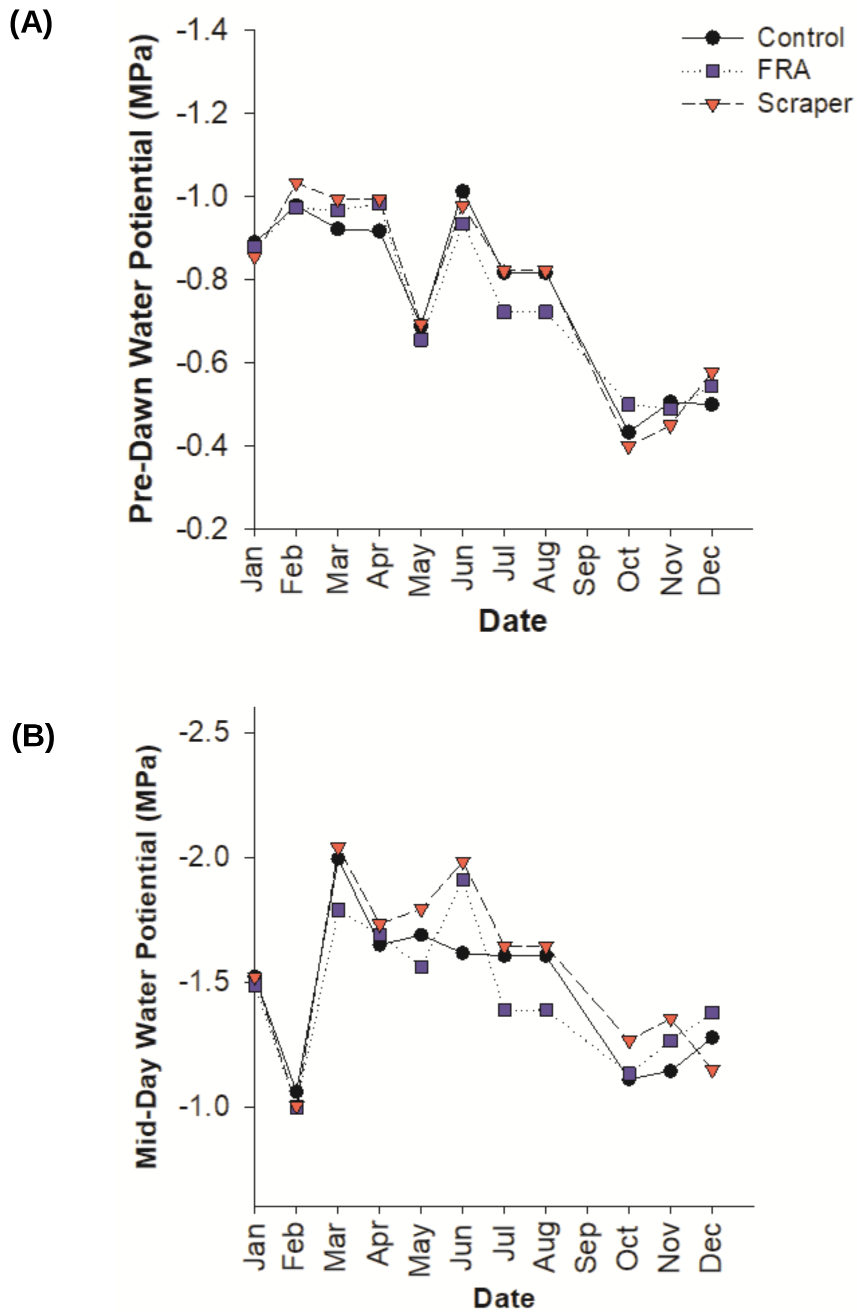

Figure 10. Pre-dawn (A) and mid-day (B) plant moisture stress measurements taken with a PMS Chamber presented by date, treatment, and time of sampling.

No significant effects were observed between pre-dawn and mid-day water potential and volume or survival of tree seedlings. Pre-dawn or mid-day water potential were not significant predictors for volume or survival between treatments. Interaction between water potential at pre-dawn or mid-day levels with treatments were not significant (Table 7).

Table 7. ANCOVA p-values between pre-dawn and mid-day water potential and volume and survival.

Effects	Volume	Survival
Treatment	0.1644	0.1886
Pre-dawn	0.1964	0.3055
Treatment*Pre-dawn	0.1876	0.1959
Treatment	0.1605	0.5738
Mid-day	0.3352	0.6684
Treatment*Mid-day	0.3407	0.5727

Level-level Gas Exchange

Leaf-level gas exchange variables were significantly different by date but not by treatment and date. C_i, A_{sat}, g_s, and E were not different among treatments on the same sampling date (Figure 11). Scraper treatments C_i values were not included for the months of October and November; therefore, no comparisons can be made for that parameter during that time. Same treatments did differ among themselves on different dates; this is likely due to seasonal temperature and rainfall changes. Variables overall fluctuated over time but no significant impacts of treatments were observed. Treatments did not appear to be impacting leaf-level gas exchange.

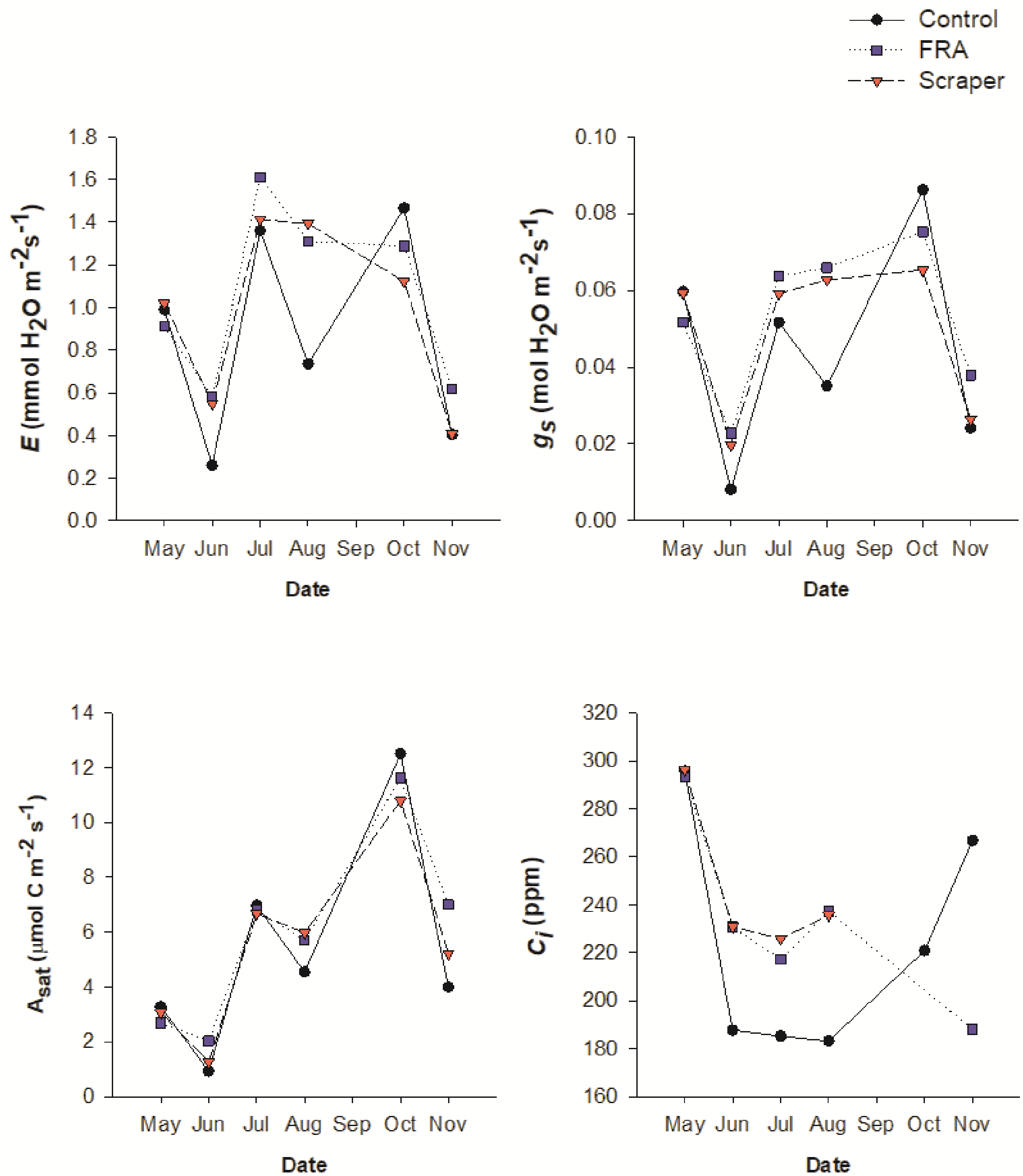

Figure 11. Leaf-level measurements taken with the LICOR 6400 XT sorted by date, treatment and variable measured. †

† C_i = intercellular CO_2 concentration; A_{sat} = light-saturated photosynthetic rate; g_s = stomatal conductance; *E* = leaf transpiration

ANOVA determined there was no significant relationship between pre-dawn or mid-day water potential and leaf level gas exchange parameters (Table 8).

Table 8. P-values of pre-dawn and mid-day mean water potential compared to mean leaf-level gas exchange measurements.

Effects	Pre-Dawn	Mid-Day
g_s	0.2411	0.9719
A_{sat}	0.0705	0.6546
C_i	0.4671	0.8223
E	0.2358	0.6860

Pearson's correlation determined there was a significant positive correlation between C_i and tree seedling volume (Figure 12A). There was also a significant negative correlation between A_{sat} and tree seedling survival (Figure 12B). There was no other significant correlations between any other leaf-level gas exchange variables and volume or survival (Table 9).

Table 9. Correlation coefficients for each leaf-level gas exchange variable compared to volume and survival.

Volume				
Variable	P	R	β0	β1
E	0.797	0.100	1.008	5.79E-06
C_i	0.036	0.698	233.274	0.005
g_s	0.887	-0.056	0.051	-1.79E-07
A_{sat}	0.525	-0.245	5.769	-7.5E-05
Survival				
Variable	P	R	β0	β1
E	0.133	-0.541	1.562	-0.006
C_i	0.379	0.335	202.471	0.532
g_s	0.066	-0.636	0.085	-4.0E-04
A_{sat}	0.027	-0.727	9.417	-0.045

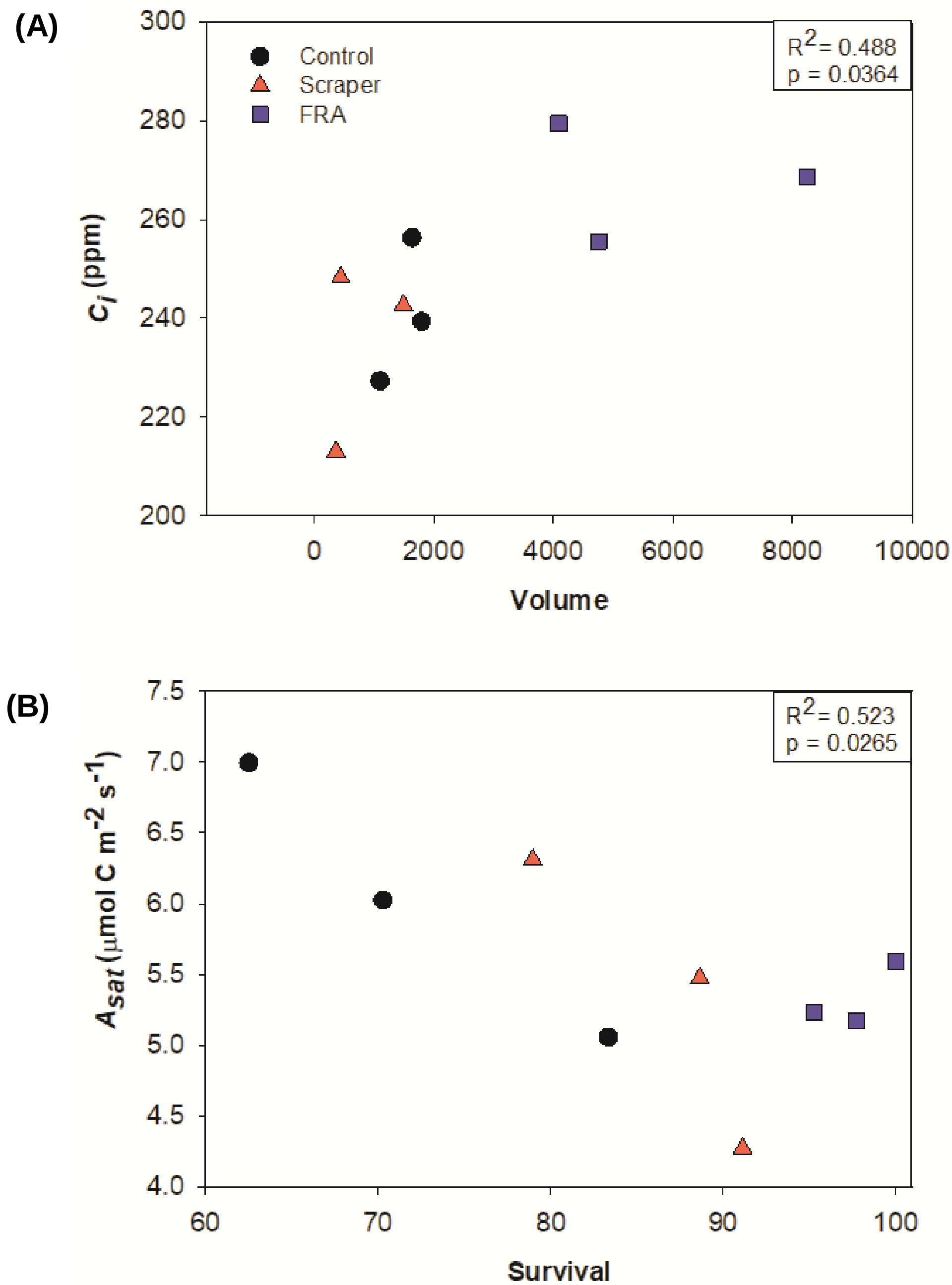

Figure 12. C_i correlated with volume (A) and A_{sat} correlated with seedling survival (B) sorted by treatment, measurements were taken during the third growing season (2018).

Herbaceous Cover and Density

In 2017, percent of aboveground herbaceous and woody cover differed significantly between FRA and control plots (p=0.0065) and between FRA and scraper plots (p=0.0373). In the 2018 growing season, cover followed the same pattern with FRA plots being different from both control (p=0.0010) and scraper (p=0.0682) plots (Figure 13B). Mean percent cover followed the trend of having the highest percentages at 77% in 2017 and 88% in 2018 on the control treatments. This may be attributed to the seed bank present in the surface soil on those treatments.

No significant differences were observed in aboveground biomass among treatments. In 2017, FRA plots had a mean percent cover of 50% while control plots had cover at around 80%. However, above ground biomass was not different between the two treatments (Figure 13A). This indicates that FRA plots had taller and more densely clumped biomass, which is consistent with what was observed across all plots.

During the 2018 sampling period, drought conditions occurred that did not occur in 2017. Therefore, percent cover and above ground biomass were not compared between the two sampling dates.

Rubus spp. was present more often on FRA plots than the other treatments. The control plots tended to have more woody species, such as honey locust (*Gledistsia triacanthos* L.), post oak (*Quercus stellata* Wangenh.) and yaupon (*Ilex vomitoria* Sol.). A common invasive tree in the area, Chinese tallow (*Triadica sebifera* L.), was noted on several FRA plots. Scraper plots tended to have less woody plants present than the FRA and control plots (Table A3).

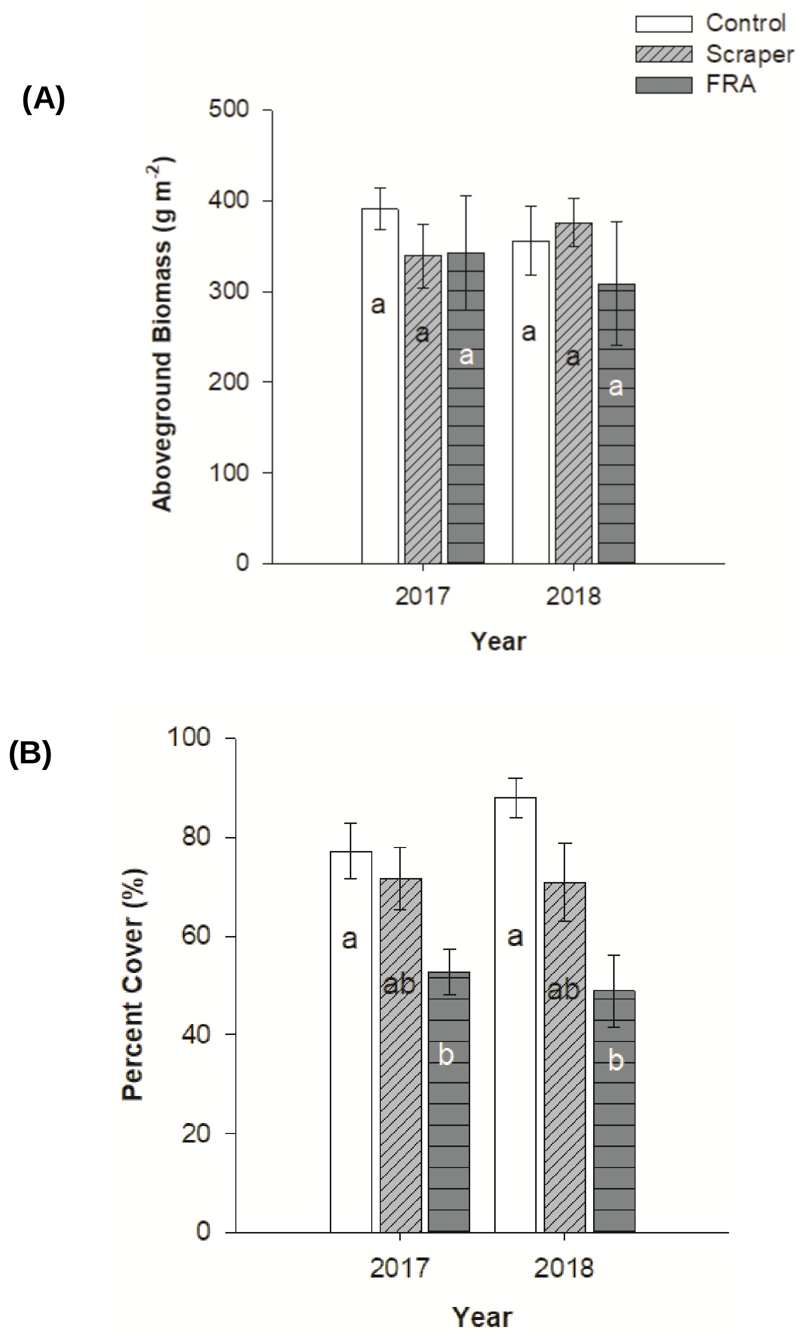

Figure 13. Mean aboveground biomass (A) and percent cover (B) of all non-pine herbaceous and woody species followed by standard error bars. Shared letters are not statistically different (α=0.05).

DISCUSSION

Soil

Physical Properties

As expected, the lowest bulk densities and soil strength measurements were found on FRA treatments, which indicates a lower degree of soil compaction on these plots. Bulk density may also increase when reclamation is implemented during wet conditions on soils with high clay contents (Miller et al., 2004), such as this study site. Bulk density measurements for all treatments were below thresholds (>1.5 Mg m^{-3}) at which levels have been shown to cause negative effects on root and growth habits (Scott & Burger, 2014). While bulk density levels found in this study may be under certain thresholds, levels present in this study may still cause enough stress to limit overall tree volumes. Though, Priest et al. (2016) showed that index projections on trees under six years old were inaccurate, trees in this study were measured up to thre years old and therefore precise predictions about future limitations on tree volumes cannot be made.

Shrestha & Lal (2011) showed that bulk densities significantly increased from 0.98-1.41 Mg m^{-3} on undisturbed sites to 1.11-1.69 Mg m^{-3} on reclaimed mined sites. Overall bulk density levels were similar in this study to previous research, conclusions, however, did differ. The control unmined plots did not differ in their bulk density values from the traditional scraper reclamation method which is not typical of most reclamation areas. Limstrom (1960) showed that infiltration rates on ungraded minespoil were greater than that on natural soils and on graded spoils. Higher bulk density values have been associated with lower infiltration, this suggests that ungraded mine spoils have the potential to decrease bulk density levels below that of unmined areas (Lindstrom et al., 1981). Loose soil present on FRA treatments has been also been shown to increase plant available water and decrease surface runoff (Torbert & Burger, 1994). The lower compaction levels (i.e. bulk density and soil strength) present in the FRA treatments is consistent with examples of the FRA used in Appalachia (Angel et al., 2006; Thomas et al., 1999).

Other soil physical properties, such as lower soil strength and higher soil porosity, have been positively correlated with higher tree survival (Kelting & Allen, 2000). Several factors may influence soil properties, such as texture and water concentration. For instance, bulk density and soil strength may change depending on the water content present at the time of sampling (Sutton, 1991). Therefore, caution should be used when comparing bulk densities across studies in which soil textures differed. Overall, however, this study is consistent with findings that relatively lower soil strength and bulk density measurements were positively correlated with higher tree volumes.

Chemical Properties

Soil analysis revealed that many essential plant nutrients increased after either scraper or FRA treatment implementation. This increase in nutrients may suggest that treatments implemented in this study may benefit reclaimed sites by increasing the availability of soil nutrients without the use of fertilizer. This study supports previous studies that have shown soil mixing can be beneficial to GCP soils, Texas minesoils generated from overburden can be more productive than that of unmined sites (Angel, 1972; Dixon et al., 1980). This increase in productivity is a product of nutrients and deeper clay soils that have been leached to the lower soil profile layers over time and through the reclamation process can be brought back to the top, where they are accessible to seedlings. Higher plant-available nutrients has been shown to reduce stress in tree seedlings that is induced by periods of low-moisture (Kelting et al. 2000). This is beneficial in times of high moisture stress during drought periods, similar to the one experienced during this study and that is common in the GCP. Native surface soils also tend to be more acidic, and the increase in pH in the two implemented treatments likely also reflects the mixing of nutrients from lower in the soil profile with nutrients in the upper profile (Steptoe, 2002). It has been shown that over time, reclaimed soils in east Texas return to acidity levels present in unmined soils (Ng, 2012).

Vegetation

Herbaceous Cover and Density

Herbaceous cover such as wheat and clover are often used in order to quickly control erosion on reclamation areas. However, there is evidence to suggest that this strategy hinders reforestation in the long term (Holl, 2002). The FRA method does not necessarily increase soil erosion which is a major concern when attempting to reduce the amount of competitive herbaceous cover that is planted on a mined site (Jeldes et al., 2013). The practice of planting no cover crop in this study may have allowed all treatments to have high survival rates overall. When used in combination with the FRA low soil compaction reclamation method, fast-growing ground covers are not required unless erosion is expected to be an issue (Sena et al., 2014; Miller et al., 2012). While no ground cover was planted, all plots had percent cover at or above 50%. This indicates many grasses and shrubs were able to effectively colonize the area.

Leaf-level Measurements

High moisture stress corresponds with more negative leaf-level water potentials, which is what was expected to be observed during a period of slight drought in 2018. In contrast with study, other studies have shown that soil water shortage causes a reduction in photosynthesis (Teskey et al., 1986). Studies vary in their conclusions of photosynthesis and stomatal conductance levels being influenced by water stress, indicating there may be variation among species in their physiological responses to water stress (Kozlowski, 1999). In this study there were no differences in photosynthesis by treatment, however soil compaction has been shown to reduce the rate of photosynthesis in *Rubus spp.* (Wieniarska et al., 1987). Temperature is also a factor in predicting g_s values which influence net photosynthesis. Properties such as g_s typically increase with temperature, however many studies are done in controlled environments and other research has shown conflicting results involving temperature and stomata effects in field experiments (Urban et al., 2017). This study did present similar water-potential levels and g_s levels experienced by loblolly pine in Urban et al. (2017) in a range of normal to heat stressed conditions. Field conditions vary thus research regarding field versus greenhouse experiments are often conflicting. For example, has been shown that below freezing temperatures during the night reduce leaf conductance the following day despite warming day temperatures (Teskey et al., 1987). Weather conditions, among other, factors are often difficult to account for in a greenhouse setting. This may account for some of the variation in photosynthesis and g_s levels in previous studies.

Measurements from both leaf water potential and leaf-level gas exchange were not significant among treatments and were not accurate predictors of volume or survival differences among treatments. Plant moisture potential and leaf-level gas exchange were not correlated. While this is uncommon in much of the literature, there are many possible causes. Studies have shown that the amount of foliage a tree possess is a major determinant in its above ground net productivity (Teskey et al., 1987). This suggests that larger trees present on the FRA treatments total foliage should be taken into account and may be an important part of determining total photosynthesis per seedling (Boltz et al., 1986). A_{sat} was negatively correlated with tree seedling survival, this could indicate differing photosynthesis rates of trees of different sizes. For example FRA trees had a higher survival rate but had lower A_{sat} rates per needle-area.Total photosynthesis per seedling may differ by treatment when the total foliage measurement, rather than just needle-area, is used. Clay content of the soil might also play a role in leaf-level measurements. Clay application has been show to increase soil moisture and water use efficiency in cucumbers (Ismail & Ozawa, 2007). This could indicate that high clay levels present in GCP soils help to reduce moisture stress regardless of soil compaction.

Tree seedlings

It has been shown that pre-SMCRA sites in the Eastern U.S. have been able to achieve pre-mining tree productivity (Rodrigue et al., 2002). This was likely due to the low soil compaction experienced on these sites that were not heavily graded and lack of introduced highly competitive ground covers. In east Texas, Priest et al. (2016) showed that reclaimed mine land was also able to produce tree productivity equal to unmined areas after at least 6 years. The FRA has shown that in the GCP productivity levels of unmined areas can be met within the first three years. Tree seedling volumes and survival in this study has produced similar results to that of several FRA implementations in Appalachia (Angel et al., 2006; Rodrigue and Burger 2004; Torbert & Burger, 1994). With proper implementation of a low-compaction reclamation technique, tree growth and survival may be able to meet and possibly exceed that of an unmined control.

This study may not represent the full aspects of using the FRA on current mine sites due to the use of a small mine-simulated study site and lack of post-reclamation site preparation. Gully erosion, though not an issue in this study, is a common problem for land reclamation post-mining. Ephemeral gullies often form in the area when soil is compacted and there is little vegetation to prevent erosion, this may require implementation of adapted FRA strategies (Toy et al., 2002). High clay content combined with wet soil conditions may make large scale proper implementation of the FRA difficult. Many reclamation strategies may also employ ripping as a form of tillage which has been shown to decrease soil compaction and improve tree volumes at least in the first six years (Angel et al., 2018; Carlson et al., 2006; Burger & Evans, 2010). Mulching is also a common post reclamation amendment that has been shown to alleviate compaction and increase soil nutrients (Plass, 1978; Evangelou, 1981). Cost comparison between using the scraper treatment and FRA treatment has not been conducted and cost-effectiveness is an important factor for land owners in determining a reclamation strategy. Possible preparation needed after FRA or scraper treatments could enhance or diminish any gains determined in this study between the treatments.

CONCLUSIONS

The use of the FRA low compaction treatment resulted in soil with lower soil bulk density and strength. This allowed the tree seedlings on the FRA treatments to achieve a higher overall volume by the third growing season (Appendix A, Figure A4). The largest growth differences were evident between the FRA and scraper treatments. The highest survival was reported on the FRA plots; however, all plots exhibited relatively high survival rates. In order to meet bond release in Texas, stocking standards are set on a permit by permit basis, however, common stocking standards typically require at least 1120 live trees per ha^{-1} (450 live trees per ac^{-1}) for pine (Railroad Commission of Texas, 1982). Each treatment had survival rates that would have allowed all plots to meet this standard.

Due to the relatively new use of the FRA in the GCP, research is limited on its cost in comparison to the scraper-pan strategy. Costs for reclamation continue to rise as new tillage techniques are implemented in order to relieve soil physical problems such as compaction. Many studies have shown current tillage techniques may not alleviate compaction to pre-mining levels or improve tree seedling growth and survival to a degree at which they are cost effective (Burger & Evans, 2010; Carlson et al. 2014; Lincoln et al., 2007; Angel et al., 2018). Prevention of soil compaction, such as using the end dump method of the FRA, may be more cost effective and efficient solution. This study has shown that implementation of the five-step process of the FRA is possible in the GCP and can increase growth and survival rates versus conventional reclamation practices.

Prior to SMCRA, long-term soil stability was negatively impacted by a lack of proper reclamation. Research has shown that the FRA method of low-compaction does not compromise long-term slope stability and should be considered a viable alternative to heavily compacting soil to increase stability (Jeldes et al., 2013). Based on this study, we recommend that the FRA be implemented in at a larger scale in mining operations as a reclamation strategy. If growth trends continue, FRA treatment seedlings could produce more productive pine stands more quickly than seedlings grown using conventional reclamation methods such as the scraper.

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APPENDIX A

Table A1. Analysis of variance table for a randomized complete block design for all samples excluding leaf-level measurements.

Source of Variation	Sum of Squares (SS)	Degrees of Freedom	Mean Square (MS)	F Statistic
Blocks	SSB	2	$\frac{\text{SS(B)}}{\text{DF(B)}}$	$\frac{\text{MS(B)}}{\text{MSE}}$
Treatment	SST	2	$\frac{\text{SS(T)}}{\text{DF(T)}}$	$\frac{\text{MS(T)}}{\text{MSE}}$
Error	SSE	4	$\frac{\text{SS(Error)}}{\text{DF(Error)}}$	
Total	TSS	8		

Table A2. Analysis of variance table for randomized complete block design for select leaf-level response variables sampled by date.

Source of Variation	**Sum of Squares (SS)**	**Degrees of Freedom**	**Mean Square (MS)**	**F Statistic**
Blocks	SSB	2	$\frac{SS(B)}{DF(B)}$	$\frac{MS(B)}{MSE}$
Treatment	SST	2	$\frac{SS(T)}{DF(T)}$	$\frac{MS(T)}{MSE}$
Date	SSD	11	$\frac{SS(T)}{DF(T)}$	$\frac{MS(T)}{MSE}$
Treatment x Date	(T-1)(D-1)	22	$\frac{SS(TxD)}{DF(TxD)}$	$\frac{MS(TxD)}{MSE}$
Error	SSE	284	$\frac{SS(Error)}{DF(Error)}$	
Total	TSS	321		

Table A3. Observational woody species by treatment followed by their count located in 1 m^2 quadrants used to determine vegetative cover and density in 2018.

Treatment	Tree/Shrub Species	Count	Woody Vines	Count
Control	*Gleditsia triacanthos*	2	*Smilax spp.*	4
	Ilex vomitoria	2	*Rubus spp.*	3
	Quercus stellata	1		
Scraper	*Quercus stellata*	1	*Rubus spp.*	2
	Eastern Baccharis	1		
FRA	*Eastern Baccharis*	1	*Rubus spp.*	7
	Triadica sebifera	1	*Smilax spp.*	2

VITA

Cassie Lynn Phillips was born on July 10, 1994, in Little Rock, Arkansas to Lisa Baker Phillips and Michael Vanness. Cassie grew up in Little Rock and graduated from eSTEM High School in 2012. She then attended Arkansas State University in Jonesboro, Arkansas where she obtained her Bachelor of Science in Biology in 2016. Following her undergraduate studies, she moved to Nacogdoches, Texas to attend Stephen F. Austin State University. Cassie completed a Master of Science in Environmental Science in May 2019. Support for her project came from the Office of Surface Mining Reclamation and Enforcement.

Permanent address: 16 Rocky Valley Cove
Little Rock, AR 72212

Soil Science Society of America

This thesis was typed by Cassie L. Phillips.