

Article

Using the Forestry Reclamation Approach for Reclaimed Surface Mineland in the Western Gulf: Effects on *Pinus taeda* Seedling Growth and Survival

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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, 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 greater 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 scraper ($p = 0.0353$) and control ($p < 0.0001$) plots which likely influenced growth and survival trends. Soil nutrients were increasingly available on the FRA and scraper plots, likely due to 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.

Keywords: forestry reclamation approach; reclamation; silviculture



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1. Introduction

In the United States, coal consumption was 532.1 million Mg in 2020 [1]. Texas contributed 20.5 million Mg 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. The Surface Mining Control and Reclamation Act (SMCRA) of 1977 provided many benefits by better stabilizing reclaimed minelands, but had the unintended consequence of producing reclaimed areas that were heavily compacted and had little productivity for forests [2,3]. The Forestry Reclamation Approach (FRA) was

developed in Appalachia with the aim of encouraging native forest growth by producing a less compacted surface material that would be more suitable for tree growth, and then encouraging proper practices to establish trees. This occurs through a five-step process to reclaim a productive forest: selecting and applying a suitable growth medium (e.g., the best parent material available for tree growth), ensuring the surface soil for at least 1.3 m is uncompacted, sowing seed of a tree-friendly ground cover that will not outcompete seedlings, selecting a mix of early- and late-successional tree species, and using proper tree planting techniques [2]. 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 [4]), has been shown to affect tree growth in Appalachia [5,6]. Machinery involved in the scraper reclamation process may contribute to soil compaction. Despite soil compaction concerns, Hons [7] 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.

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. To test this, soil parameters, tree growth, tree survival and tree ecophysiological variables were measured. 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 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 plantation for pulpwood and sawtimber production.

2. Materials and Methods

2.1. Study Area

This study was conducted on an approximately 1.0 ha site at the unmined Gail Creek Property in Houston County, Texas (31.204719° N, 95.387329° W), which is in east Texas. Given the possibility of increased gully erosion in this region with the untested FRA treatments, mining operators were reticent to test this approach, hence the creation of a simulated surface mine. 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 presently vegetated with grasses and shrubs. The study area had remained unmanaged since planting before installation of these treatments 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 [8]. 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; Figure 1).

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 [9]. 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 between 0 and 3% with a relatively flat topography.

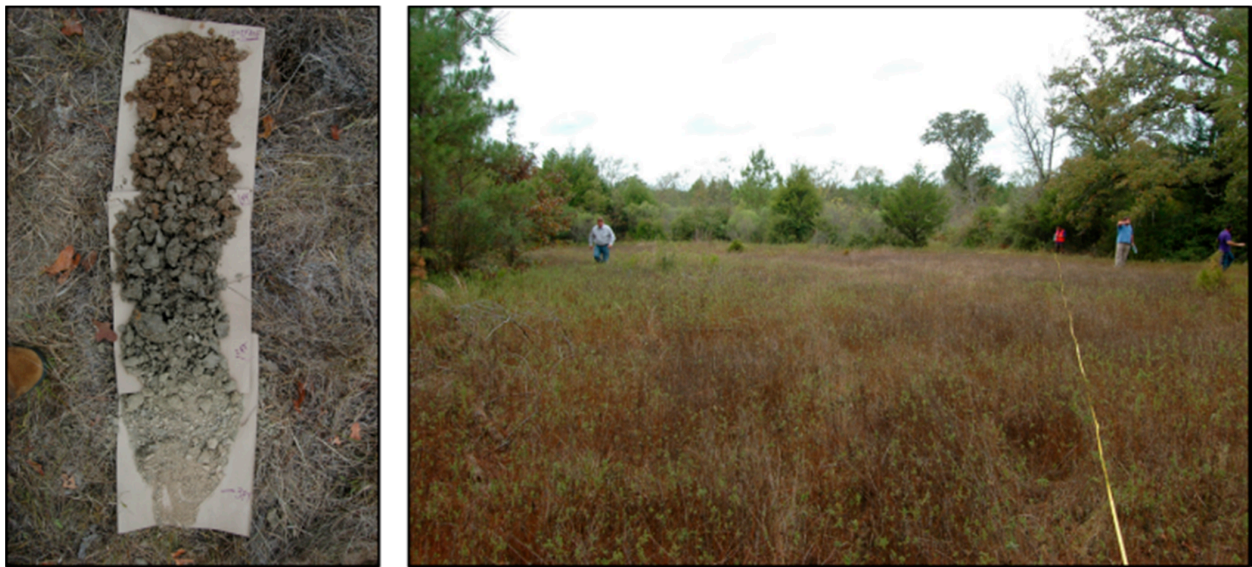


Figure 1. Project site photos taken prior to installation of treatments. Left = photo of soil profile; Right = site photo showing abundance of grasses on the site prior to installation.

2.2. Experimental Design

The 1.0 ha site was set up in a randomized block design (RCBD) totaling nine experimental plots (Figure 2). 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.

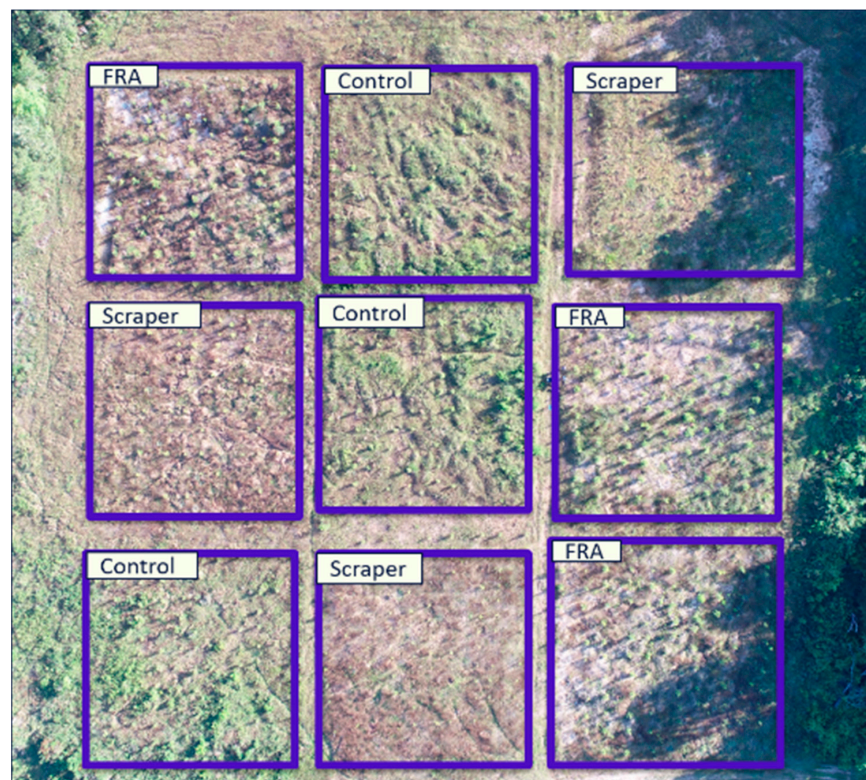


Figure 2. Oblique aerial imagery taken of the site in May 2018 depicting the RCBD design.

2.3. Site Preparation

From January 26 to 1 February 2016 approximately 1.0 ha was cleared of vegetation with a dozer and excavated to a depth of 1.3 m to simulate topsoil replacement following mining as is typical for many mines in the region. Installation of plot treatments included the following:

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 possible. 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 29 January 2016. Pushing the soil back in layers simulated a scraper reclamation due to the frequent trafficking of the dozer and mixing of the subsoil. For the FRA plots, pits approximately 1.3 m deep were dug on 1 February 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 3). For the control treatment, the plots were cleared of all vegetation on 1 February 2016 with a Cat D6T dozer. Plots were not trafficked on further with heavy machinery.

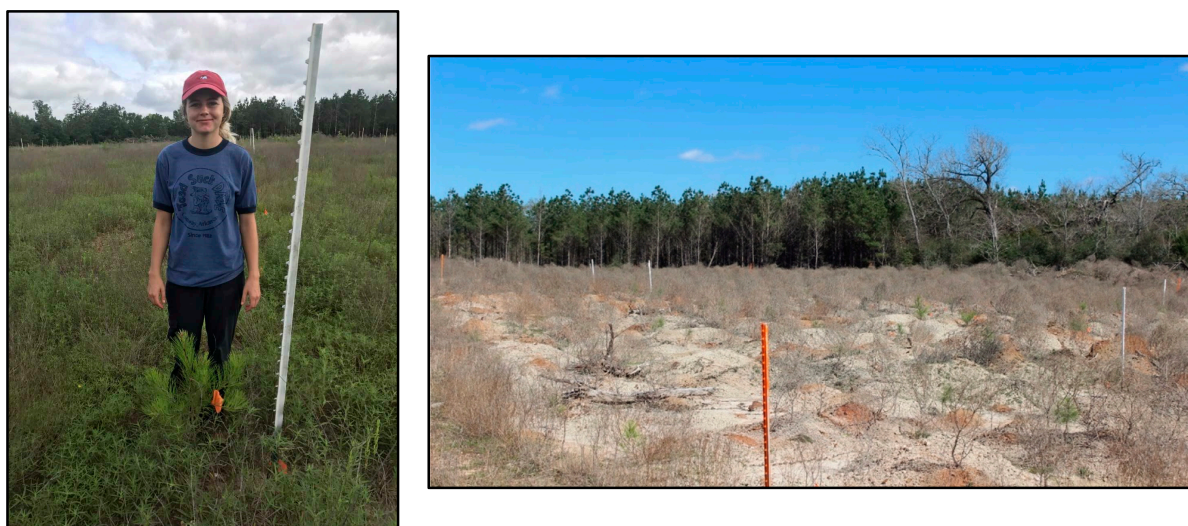


Figure 3. A photo taken in June 2017 of a scraper plot (left) contrasted with a photo taken in January 2017 of FRA style reclamation plots showing uncompacted loose soil piles (right).

International Forest Company containerized, genetically improved western Gulf provenance loblolly pine seedlings were planted on 23 February 2016 as observational units following treatment installation in each plot. Each seedling was hand planted on a 2.4×2.7 m spacing. Trees were planted regardless of slope location on FRA plots. Each plot was approximately 0.10 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 to mitigate edge effects in the measurement plots.

2.4. Data Collection

2.4.1. Soil Sampling

Soil nutrients and pH were determined using composite samples of the upper 15 cm from each plot taken with an augur, with a total of 27 samples analyzed. These were collected in February 2018 at the four corners of a 1 m^2 quadrant and combined as one sample, with this procedure replicated at three locations in each plot. This scale matched the pit and mound topography of the FRA plots, so soils were collected and mixed across a range of microsites (mound top, midslope, pit bottom). Samples were bagged and stored at room temperature until processing in the lab. Ca, Mg, K and P were quantified with an

IRIS Intrepid II XSP inductively coupled plasma (ICP) analyzing unit (Thermo Scientific, Waltham, MA, USA) following extraction by the Mehlich 3 extraction procedure [10]. 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 measurements were taken in June 2017. Soil bulk density was sampled and measured using the slide hammer method [11]. Soil cores were sampled using four 5.08 cm × 2.54 cm aluminum liners (AMS Inc., American Falls, ID, USA) inserted into the slide hammer. Thus, 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 was oven dried at 105 °C until reaching a constant weight.

Soil strength measurements were taken in July 2017. Soil strength was calculated using the cone index [12]. Using a FieldScout 900 SC Soil Compaction Meter electronic cone penetrometer (Spectrum Technologies, Inc., Aurora, IL, USA) 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.

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:

$$\theta_{vw} = \text{Bulk Density} \times \text{Gravimetric Moisture Content} \quad (1)$$

Soil texture samples were collected in December 2017. Samples 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 50 g subsamples which were used to determine sand, silt, clay content using the hydrometer method [13].

Slope location on FRA plots were quantified categorically to determine the location on the mound of each seedling: 1 = top of mound, 2 = upper mound, 3 = middle mound, 4 = swale or bottom of mound.

2.4.2. Vegetation Sampling

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, where d is the tree seedling ground line diameter and h is the tree seedling height.

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

Leaf-level gas exchange measurements were taken monthly from May to November 2018 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 and 10:30 a.m. Within five minutes of excision, the mid-section of two fascicles were placed into the leaf cuvette. Internal conditions were sustained at a saturating light level of 1600 $\mu\text{mol m}^{-2} \text{s}^{-1}$ PPFD, ambient temperature, mixer rate of 400 $\mu\text{mol CO}_2 \text{mol}^{-1}$ air and flow rate at 300 $\mu\text{mol s}^{-1}$. Diameter (mm) of

each 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 [14]:

$$LA = (n \times l \times d) + (\pi \times d \times l) \quad (3)$$

where l was the length of the needles, d was the fascicle diameter and n was the number of needles per fascicle. This allowed estimation of intercellular CO₂ concentration (C_i), light-saturated photosynthetic rate (A_{sat}) stomatal conductance (g_s) and leaf transpiration (E).

Plant water potential measurements were taken with a Model 600 Pressure Chamber (PMS Instrument Company, Albany, Oregon) using portable N₂ gas. Measurements were taken pre-dawn and midday using the pressure chamber method [15]. The pressure chamber method involves extracting one fascicle per tree, fitting the fascicle through a tightly fitting rubber stopper with the fascicle 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 (i.e., three fascicles, each from a different tree). 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 a.m. and mid-day day were taken between 10:30–11:45 a.m. Soil moisture content samples were taken in conjunction with pressure chamber measurements.

Percent cover of herbaceous vegetation was visually estimated using 1 m² quadrats in triplicate per experimental plot for a total of 27 samples [16]. Percent cover was estimated in year 1 and year 2 during the growing season. Vegetative productivity was determined using 1 m² quadrats randomly placed in each plot in triplicate. All above ground vegetation inside the 1 m² 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.

2.5. Statistical Analysis

A randomized complete block design (RCBD) was used to control for variations in location on the site. One-way (ANOVA) was used to determine if significant differences existed for each dependent variable. Two-way ANOVA was used test leaf-level measurements along with the date of each measurement and their interaction effects. Analyses were performed with SAS (SAS 9.4, SAS Institute, Cary, NC, USA). 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, with block as a random effect. Tukey's post-hoc test was used to determine differences among treatments where the ANOVA was significant. PROC GLIMMIX was used to analyze tree survival data using the logit function link.

Analysis of covariance (ANCOVA) was used to examine the impact of water potential on tree seedling volume following model (4).

$$Y_{ijk} = \mu + \text{Treatment}_j + \text{Block}_i + \text{WaterPotential}_k + \text{Treatment}_j * \text{WaterPotential}_k + \text{Block}_i * \text{Treatment}_j + \epsilon \quad (4)$$

The relationship between water potential as the dependent variable and leaf-level gas exchange was examined using ANCOVA and the following model (5).

$$Y_{ijk} = \mu + \text{Treatment}_j + \text{Block}_i + \text{Leaf-LevelGasExchange}_k + \text{Block}_i * \text{Treatment}_j + \epsilon \quad (5)$$

3. Results

3.1. Soil Properties

3.1.1. Physical

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. 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 ($p = 0.0013$). Treatment effects were observed in both bulk density and soil strength, with FRA treatments having the lowest values of both variables (Figure 4a,b).

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 (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

¹ Means followed by the same letter are not different ($\alpha = 0.05$).

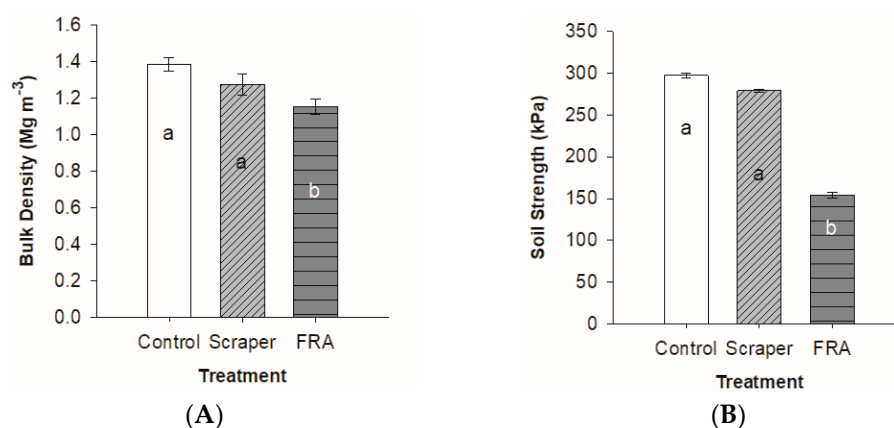


Figure 4. (A) Bulk density of each treatment followed by standard error bars. (B) Mean soil strength followed by standard error bars. Shared letters are not statistically different ($\alpha = 0.05$).

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 4a). 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 4b).

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.

3.1.2. Chemical

Differences were found between FRA and scraper treatments when compared to the control in pH, calcium and magnesium (Table 3). 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.

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

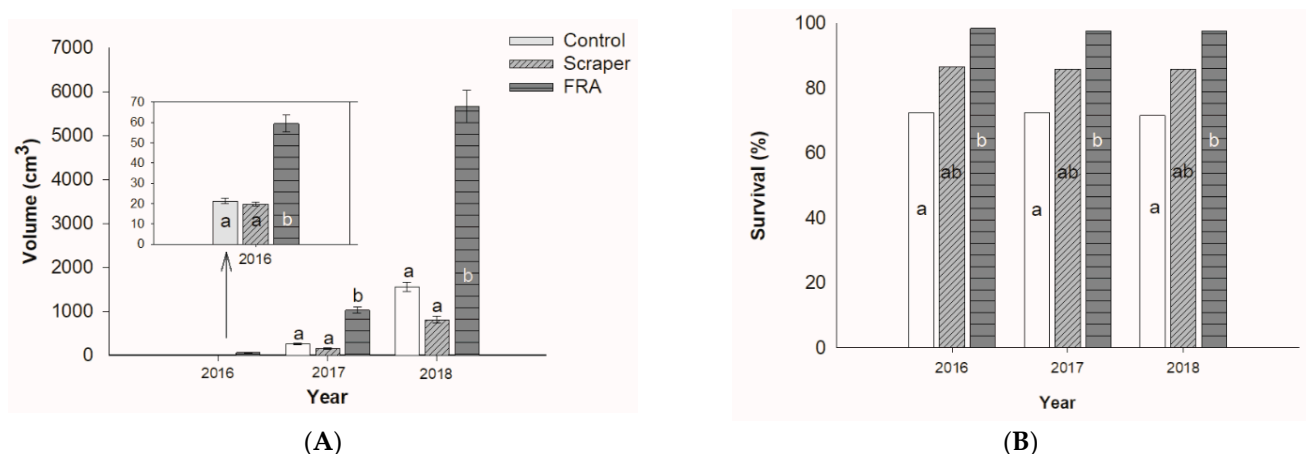
Date	Volumetric Water Concentration		
	Control	Scraper	FRA
	----- m ³ m ⁻³ -----		
January	0.29	0.32	0.29
February	0.36	0.33	0.30
March	0.27	0.33	0.30
April	0.35	0.31	0.31
May	0.30	0.28	0.31
June	0.17	0.25	0.24
July	0.24	0.23	0.21
August	0.18	0.21	0.21
September	N/A	N/A	N/A
October	0.35	0.32	0.33
November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

Table 3. 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

3.2. Tree Seedlings

Tree seedling survival across all treatments in the first growing season (2016) ranged from 73–98% (Figure 5). 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.

**Figure 5.** Mean tree seedling volumes by treatment with standard error bars (A) and mean survival rates by treatment (B). Shared letters are not statistically different ($\alpha = 0.05$).

Tree seedling heights and diameters differed between treatments in all three years (Table 4). 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 4). Even 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.

Table 4. 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	36.07 ^{a1} (0.584)	7.32 ^a (0.184)
Scraper		35.27 ^a (0.542)	7.17 ^a (0.171)
FRA		43.06 ^b (1.008)	10.71 ^b (0.31)
Control	2017	76.58 ^a (1.851)	16.78 ^a (0.468)
Scraper		63.15 ^a (1.916)	13.72 ^a (0.446)
FRA		114.54 ^b (2.873)	27.01 ^b (0.778)
Control	2018	147.36 ^a (3.215)	30.28 ^a (0.794)
Scraper		114.50 ^a (4.005)	22.36 ^a (0.826)
FRA		211.92 ^b (5.17)	46.93 ^b (1.317)

¹ Means followed by the same letter are not statistically different ($\alpha = 0.05$).

Tree seedlings volumes followed the same trend as height and diameter, and differed significantly by treatment all three growing seasons (Figure 5). 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.

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 and 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 5). The slope location of dead trees 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 5. 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

Table 5. Cont.

Year	Slope Location	Volume (cm ³)	Number of Trees
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

3.3. Ecophysiological Variables

3.3.1. 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 6). 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 6).

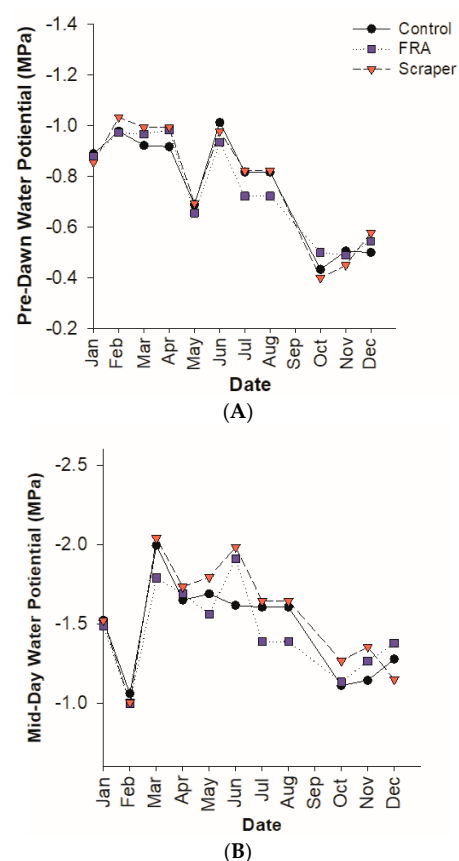


Figure 6. Pre-dawn (A) and mid-day (B) plant moisture stress measurements taken with a PMS Chamber presented by date, treatment and time of sampling.

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.

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 6).

Table 6. 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

3.3.2. Leaf-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 7). 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. Treatments did not appear to be impacting leaf-level gas exchange in the third growing season of the study. ANOVA determined there was no significant relationship between pre-dawn or mid-day water potential and leaf level gas exchange parameters (Table 7). Pearson's correlation determined there was a significant positive correlation between C_i and tree seedling volume (Figure 8A). There was also a significant negative correlation between A_{sat} and tree seedling survival (Figure 8B). There were no other significant correlations between any other leaf-level gas exchange variables and volume or survival (Table 8).

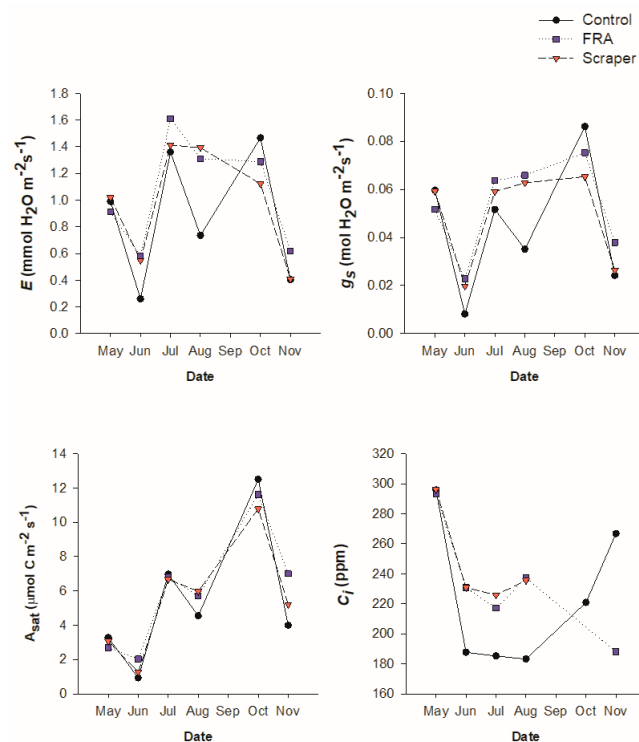
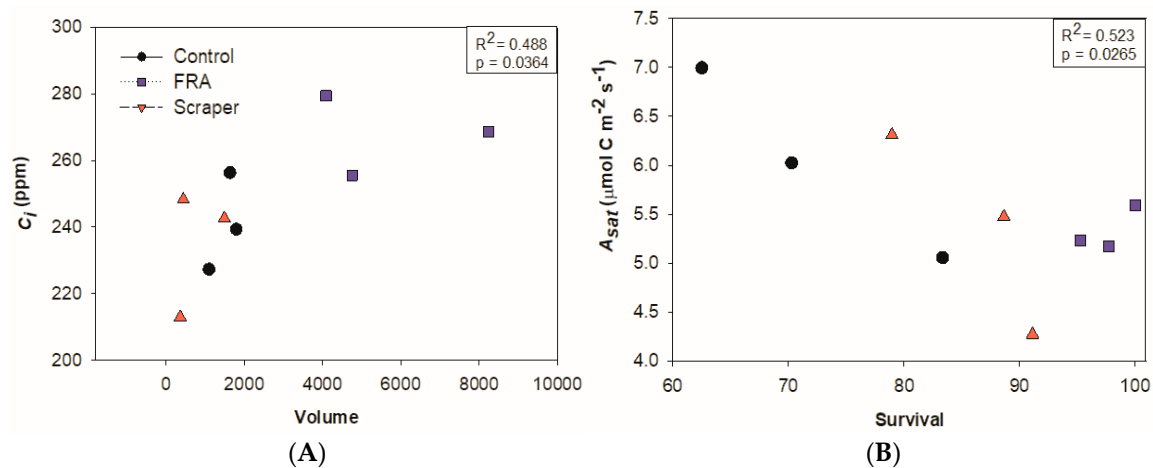


Figure 7. Leaf-level measurements taken with the LICOR 6400 XT sorted by date, treatment and variable measured. C_i = intercellular CO₂ concentration; A_{sat} = light-saturated photosynthetic rate; g_s = stomatal conductance; E = leaf transpiration.

Table 7. *p*-values of pre-dawn and mid-day mean water potential from simple linear regressions with 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

**Figure 8.** 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).**Table 8.** Correlation coefficients for each leaf-level gas exchange variable compared to volume and survival.

Volume				
Variable	P	R	β_0	β_1
E	0.797	0.100	1.008	5.79×10^{-6}
C_i	0.036	0.698	233.274	0.005
g_s	0.887	−0.056	0.051	$−1.79 \times 10^{-7}$
A_{sat}	0.525	−0.245	5.769	$−7.5 \times 10^{-5}$
Survival				
Variable	P	R	β_0	β_1
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	$−4.0 \times 10^{-4}$
A_{sat}	0.027	−0.727	9.417	−0.045

3.4. 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 9B). 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.

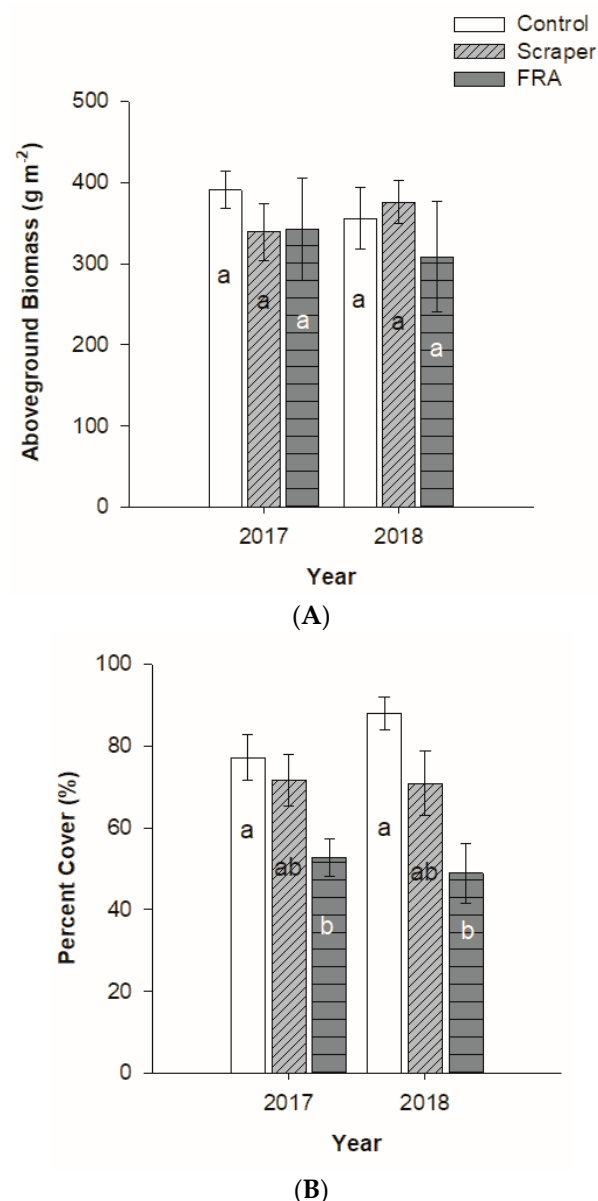


Figure 9. Mean aboveground biomass (A) and percent cover (B) of all non-pine herbaceous and woody species followed by standard error bars. Shared letters are not statistically different ($\alpha = 0.05$).

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 9A). 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 (*Gleditsia 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 fewer woody plants present than the FRA and control plots.

4. Discussion

4.1. Soil

4.1.1. 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 [17], such as this study site. Bulk density measurements for all treatments were below thresholds ($>1.5 \text{ Mg m}^{-3}$) at which levels have been shown to cause negative effects on root and growth habits [18]. 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. Even though, Priest et al. [19] showed that site index projections on loblolly trees under six years old on reclaimed minelands in the region were inaccurate, trees in this study were only measured up to three years old and therefore precise predictions about future tree volumes cannot be made.

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 similar to an average year. 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. 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 4a).

Shrestha and Lal [20] showed that bulk densities significantly increased from $0.98\text{--}1.41 \text{ Mg m}^{-3}$ on undisturbed sites to $1.11\text{--}1.69 \text{ Mg m}^{-3}$ 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 [21] 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 [22]. Loose soil present on FRA treatments has been also been shown to increase plant available water and decrease surface runoff [23]. 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 [6,24].

Other soil physical properties, such as lower soil strength and higher soil porosity, have been positively correlated with higher tree survival [25]. 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 [26]. 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.

4.1.2. 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 [27,28]. 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 [25]. 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. It has been shown that over time, reclaimed soils in east Texas return to acidity levels present in unmined soils [29].

4.2. Vegetation

4.2.1. Herbaceous Cover and Density

Herbaceous cover such as wheat and clover are often used to quickly control erosion on reclamation areas. However, there is evidence to suggest that this strategy hinders reforestation in the long term [30]. 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 [31]. 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 [32,33]. 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.

4.2.2. 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 this study, other studies have shown that soil water shortage causes a reduction in photosynthesis [34]. 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 [35]. 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. [36]. 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 accomplished in controlled environments and other research has shown conflicting results involving temperature and stomata effects in field experiments [37]. This study did present similar water-potential levels and g_s levels experienced by loblolly pine in Urban et al. [37] in a range of normal to heat stressed conditions.

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, such as differences in the temporal scaling of measurements taken at different times on only a few dates and then compared to season-long growth. Studies have shown that the amount of foliage a tree possess is a major determinant in its above ground net productivity [38]. This suggests that larger trees present on the FRA treatments with greater total foliage should be taken into account and may be an important part of determining total photosynthesis per seedling [39]. A_{sat} was negatively correlated with tree seedling survival, this could indicate differing photosynthesis rates of trees of different sizes, although it is rarely viable to scale leaf-level measurements to the tree scale. 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 seedling-level, rather than just leaf-level, is used. We did not quantify foliar area per seedling in this study. Clay content of the soil might also play a role in leaf-level measurements. Clay application has been shown to increase soil moisture and water use efficiency in cucumbers [40]. This could indicate that high clay levels present in GCP soils help to reduce moisture stress regardless of soil compaction.

4.2.3. Tree Seedlings

It has been shown that pre-SMCRA sites in the Eastern U.S. have been able to achieve pre-mining tree productivity [41]. 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. [19,42] 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 have produced similar results to that of several FRA implementations in Appalachia [5,6,23]. 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 range of operational treatments required to implement 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 in a region with few coarse fractions [43]. High clay content combined with wet soil conditions may make large scale 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 [4,44,45]. Mulching is also a common post reclamation amendment that has been shown to alleviate compaction and increase soil nutrients [46,47]. 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.

5. 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 (Figure 5A). 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. 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 for pine [48]. 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 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 [4,44,45,49]. 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 [31]. 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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