Federal surface mining regulations require that land disturbed by surface mining be restored to a productive state capable of supporting preexisting land uses. Loblolly pine (Pinus taeda L.) plantations are a widespread reclamation land use in East Texas; however, the productivity of these plantations compared with that of those on unmined lands is not well documented. We quantified the current site qualities of loblolly pine plantations on two mines (Beckville Mine and Oak Hill Mine), which differ in the method of overburden replacement. Substituting mixed overburden for topsoil (done at the Beckville Mine) generally results in no distinction of original soil layers after reclamation, whereas removing and mixing the premining upper, oxidized soil layers for topsoil in the postmining reclamation areas (done at the Oak Hill Mine) creates some stratification. Nonlinear modeling of stem analysis data indicated that the current site indices are 61.1 and 61.9 ft at 25 years for the Beckville Mine and Oak Hill Mine, respectively. The current site indices (postmining) for each mine did not differ statistically from approximated premining site indices nor was height statistically different between premining and postmining at any age. The two mine sites did not statistically differ. These results suggest that mineland reclamation on these mines has successfully restored premining levels of forest productivity.

**Keywords:** reclamation, strip mining, Pinus taeda, productivity, site quality.

Surface mine reclamation is regulated according to the Surface Mining Control and Reclamation Act of 1977 (US Congress 1977). Reclamation requires completion of multiple phases, including soil restoration and vegetation establishment. In brief, the restoration of topsoil generally occurs by two methods in East Texas: the mixed overburden and oxidized material haulback methods. Most mines have documented problems such as high acidity, low nutrient content, poor infiltration and drainage, and disrupted microbial processes, which may lead to reduced vegetative productivity (Sheoran et al. 2010). For reclaimed mineland in East Texas, the mixed overburden is lower in organic matter, nitrogen, phosphorus, and potassium than in oxidized material. However, even the oxidized material tends to show reduced nutrient cycling and altered soil chemistry compared with those for nonmined lands, in part due to being stored in deep stockpiles with little vegetation (Ghose 2005, Harris et al. 1989). The final phase of reclamation is vegetative cover, and successful reclamation is dependent on the ability to support the previous land use without additional amendments beyond general practice for that land use. In East Texas, surface mines occupy vast areas of previously farmed land or natural forestland (Dolezel 1975, Toups 1986, Schmidly 2002). Reclamation of these lands involves returning the vegetation to a previous condition, which includes pasture, pine plantations managed for timber, or mixed hardwood stands managed for wildlife (Railroad Commission of Texas [RCT] 1990).

Forestry reclamation for timber production in East Texas most often consists of loblolly pine (Pinus taeda L.) plantations; this is one of the most common postmining land uses on Luminant Mining Company minelands (38–54%), where this study was conducted (RCT 2009, 2011). Other tree species have been used to a lesser extent, including longleaf pine (Pinus palustris M.) and hardwood mixes (W.B. Martin, Railroad Commission of Texas, Tyler, TX, pers. comm., Oct. 20, 2014). Loblolly pine is preferred because of the extensive research on the species, low-cost seedlings, high survival, and rapid growth rates (Vogel 1981, Toups 1986). Vegetative reclamation is considered successful if pine plantations are maintained at a density of 450 live trees per acre without further inputs during an extended responsibility period of at least 5 years (RCT 1990). Because of the time required to secure bond release, sometimes as long as 15 years, thinning has typically been avoided to ensure that plantations meet the minimum stocking standards. Thinning is a common practice on unmined lands to maintain...
productivity in pine plantations (Sayer et al. 2004), and unthinned stands may be more susceptible to mortality because of competition, drought, insect infestations, or other disturbances (Ruel et al. 1998). Greater timber yields may be possible if the standards for vegetative success were more representative of productivity rather than a function of the number of trees per acre, thus allowing more thinning (Taylor and Fortson 1991).

Site index is one commonly used growth metric that allows comparison of potential productivity across sites (Avery and Burkhart 1983). Quantifying site indices on reclaimed minelands has seldom been done, and in some cases imprecise estimates have been used for calculations because data were not available (Kronrad 2002). Compared with agricultural land uses (e.g., pasture), there is typically little awareness of forest productivity on reclaimed minelands in East Texas by reclamation specialists, land managers, or even researchers. Other regions, such as the Appalachian Mountains, have better documented forest productivity on minelands (Jones et al. 2005). In the Appalachians, Rodrigue and Burger (2004) found that pre-1977 forestry reclaimed minelands attained levels of soil productivity similar to those of unmined lands. Many of the factors Jones et al. (2005) found to influence productivity, such as rooting depth, do not appear to be as important on East Texas reclaimed minelands because of differing geologic and soil conditions.

Site index is based on measurements of actual tree growth and is correlated to productivity, so managers can evaluate reclamation success using site index guide curves as long as the curves are properly calibrated for minelands. The use of calibrated site index curves allows for a more direct evaluation of reclamation success rather than evaluation of microbial activity, soil physical and chemical status, or vegetation presence, all of which are more weakly correlated to stand growth (Sheoran et al. 2010). Available curves from which site index is estimated cover a wide range of locations, management strategies, and site characteristics (Carmean et al. 1989). Generalized curves for loblolly pine that allow estimation throughout the species range for either natural or planted stands exist (Coile and Schumacher 1953, US Department of Agriculture Forest Service 1976). Locally calibrated site index curves have also been created for some areas, such as East Texas (Willett and Bilan 1991, Coble and Lee 2006). We are not aware of any specific curves that have been created for reclaimed minelands. Comparisons of height growth between mined and unmined sites have been conducted in East Texas by Toups (1986) and Christian (2013), who studied stands of ages 2–7 and 1–30 years, respectively. In both cases, reclaimed mine sites yielded slight growth reductions in average total height, but neither study was focused on site index.

Currently, little is known about the growth patterns of forest trees on minelands in East Texas and whether or not conventional site index curves are compatible with reclaimed minelands and their inherent variability. The extensive soil disruption caused by strip mining alters the growth of loblolly pine enough to justify creation of site index curves calibrated specifically to mined sites. The objectives of this study are to develop site index curves calibrated to two reclaimed mine sites in East Texas and to use those curves to compare the mines to one another, to their estimated premining site indices, and to site index curves calibrated to unmined stands in the region. First, we hypothesize that the height at an index age of 25 years would be significantly lower on minelands than the height of trees grown on unmined lands. We further hypothesize that the height-age relationship would differ between mines and between mined and nonmined lands. It is suspected from anecdotal evidence that the site index on a mined site that used the oxidized material haulback reclamation method would be greater than the site index on a mined site that used the mixed overburden method of reclamation. This hypothesis is based on evidence that the oxidized material results in a topsoil more similar to unmined soil than the mixed overburden method. Beyond testing these hypotheses, this study sought to develop a simple and useful tool (calibrated site index curves) for land managers at these sites.

**Methods**

**Study Sites**

Our study was conducted at two active mine sites owned and operated by Luminant Mining Company, LLC, in East Texas (Figure 1). Beckville Mine is a lignite coal strip mine located in Rusk and Panola Counties. Average rainfall is 51.4 in. annually, average yearly high temperature is 76.4° F, and average annual temperature...
is 65.2° F (National Oceanic and Atmospheric Administration 2014a). The premining soil series included Bowie, Lilbert, Kirvin, Kullit, Cuthbert, Sacul, Tenaha, Iuka, and Darco (Dolezel 1975). The total area of the mine is approximately 30,000 acres, and it has been in operation since the early 1970s. Oak Hill Mine is also a lignite coal strip mine located in Rusk County. Average rainfall is 49.4 in. annually, average high temperature is 76.0° F, and average annual temperature is 64.7° F (National Oceanic and Atmospheric Administration 2014b). The premining soil series included Bowie, Cuthbert, Kirvin, Lilbert, Pirkey, Redsprings, and Tenaha (Griffith 2000). The total area of the mine is approximately 25,000 acres. Oak Hill began operations 10 years after Beckville, but because of limited forestry reclamation before 1982, the oldest stand at Oak Hill was only 2 years younger than the oldest stand at Beckville. The mine soils on these reclaimed sites differ owing to the parent material and the method of topsoil replacement. Because of greater overburden acidity levels, the oxidized material haulback method is used at Oak Hill, whereas the mixed overburden method is used at Beckville.

### Data Collection

#### Stand Data

In May and June 2013, we installed and measured 72 rectangular 0.248-acre plots (164 ft × 66 ft), with the long axis oriented across the rows. Of these, 48 plots were established at Beckville and 24 plots were established at Oak Hill. Stands of loblolly pine were selected by planting year and to provide as wide a geographic distribution throughout the mine sites as was possible. It should be noted though that stand age and location are generally confounded, as mining at these sites is conducted by beginning at one end of the property progressing toward the other end. Plots were randomly placed in stands that were stratified according to age, with every available age class represented. Stands were excluded if they were smaller than one acre or if an obvious anthropogenic disturbance (e.g., oil/gas drilling well) occurred since planting. Twenty-six of the Beckville stands were selected from a previous study (Christian 2013).

Within each plot, all live trees were tallied and dbh (4.5 ft), total height, live crown ratio, and Kraft crown classification were measured or estimated; dbh was averaged geometrically based on two measurements taken at 90° angles using 32-in. calipers accurate to 0.1 in. For trees shorter than 4.5 ft tall, diameter was measured similarly but at the groundline. This was only necessary in stands younger than 5 years. Total height and height to live crown were estimated using a 2013 TruPulse 360R laser clinometer (Laser Technology, Inc., Centennial, CO). Crown classification was visually assigned based on Kraft (1884). Stand data are shown in Table 1.

#### Destructive Sampling

Based on the stand data, all trees were stratified by height, age, and crown class for each plot. In each plot, one dominant or codominant tree was randomly selected from the list of the 10 tallest trees for the plot. Randomization was done by finding the first tree from plot center that met these criteria along a randomly generated azimuth. If no such tree was located, a second randomly generated azimuth was used, and the process was repeated until a tree was found. Selected trees were destructively harvested in the field. The total sample size included 47 trees at Beckville Mine (one stand was not sampled due to limited access) and 24 trees at Oak Hill, yielding a total sample size of 71.

Aboveground destructive sampling of these 71 trees occurred in December 2013 through January of 2014, before bud break for the 2014 growing season. Each selected tree was marked clearly at dbh and felled by chainsaw as near to groundline as possible or between stem section disc sampling heights for larger trees when safety was a concern. The bole was cut by chainsaw into 4-ft increments using the mark at dbh as the origin. The use of 4-ft increments approximates maximum annual height growth and permits a maximum height estimation error of 2 ft, using the stem analysis equation by Carmean (1972). Carmean’s equation places annual growth term in the center of the increment. A 4-ft increment is also consistent with previous stem analysis work (Carmean 1972, Dyer and Bailey 1987, Tasissa and Burkhart 1998). Another cut was made at 1.5 ft above the groundline. Stem section discs approximately 2 in. thick were then removed by chainsawn from the upper end of each sectioned bolt. The stem section discs were labeled as to their position on the tree and bagged for transport to the laboratory.

The diameters inside and outside the bark were recorded for each sectioned bolt. The stem section discs were labeled as to their position on the tree and bagged for transport to the laboratory.

#### Statistical Analyses

Data were analyzed in SAS 9.3 (SAS Institute, Cary, NC). All variables were found to meet assumptions of normality checked using a 2013 TruPulse 360R laser clinometer (Laser Technology, Inc., Centennial, CO). Crown classification was visually assigned based on Kraft (1884). Stand data are shown in Table 1.

### Table 1. Summary stand data by age class for study sites on Luminant’s Beckville and Oak Hill Mines.

<table>
<thead>
<tr>
<th>Mine site</th>
<th>Age class (yr)</th>
<th>Sample size (unitless)</th>
<th>QMD (in.)</th>
<th>BA (sq ft/ac)</th>
<th>Density (trees/ac)</th>
<th>HT (ft)</th>
<th>Stands thinned (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beckville</td>
<td>2–5</td>
<td>8</td>
<td>3.4 (1.8)</td>
<td>31.1 (29.8)</td>
<td>328.8 (149.3)</td>
<td>4.4 (2.1)</td>
<td>0.0</td>
</tr>
<tr>
<td>Beckville</td>
<td>6–10</td>
<td>10</td>
<td>3.8 (0.7)</td>
<td>90.3 (26.0)</td>
<td>348.4 (115.1)</td>
<td>17.5 (8.7)</td>
<td>0.0</td>
</tr>
<tr>
<td>Beckville</td>
<td>11–15</td>
<td>7</td>
<td>5.0 (0.7)</td>
<td>89.4 (27.8)</td>
<td>324.5 (187.9)</td>
<td>32.1 (8.6)</td>
<td>0.0</td>
</tr>
<tr>
<td>Beckville</td>
<td>16–20</td>
<td>11</td>
<td>7.5 (1.0)</td>
<td>110.6 (63.2)</td>
<td>296.1 (189.7)</td>
<td>46.3 (4.8)</td>
<td>0.0</td>
</tr>
<tr>
<td>Beckville</td>
<td>21–25</td>
<td>6</td>
<td>8.5 (1.7)</td>
<td>126.4 (33.0)</td>
<td>267.9 (143.3)</td>
<td>47.8 (4.7)</td>
<td>0.0</td>
</tr>
<tr>
<td>Beckville</td>
<td>26–30</td>
<td>5</td>
<td>9.7 (1.6)</td>
<td>97.4 (180.2)</td>
<td>368.6 (204.2)</td>
<td>58.0 (7.2)</td>
<td>0.0</td>
</tr>
<tr>
<td>Beckville</td>
<td>31–32</td>
<td>1</td>
<td>12.5</td>
<td>89.4</td>
<td>105.2</td>
<td>69.6</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Oak Hill

<table>
<thead>
<tr>
<th>Age class (yr)</th>
<th>Sample size (unitless)</th>
<th>QMD (in.)</th>
<th>BA (sq ft/ac)</th>
<th>Density (trees/ac)</th>
<th>HT (ft)</th>
<th>Stands thinned (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2–5</td>
<td>6</td>
<td>8.5 (1.7)</td>
<td>110.6 (63.2)</td>
<td>296.1 (189.7)</td>
<td>47.8 (4.7)</td>
<td>0.0</td>
</tr>
<tr>
<td>6–10</td>
<td>6</td>
<td>8.5 (1.7)</td>
<td>89.4 (27.8)</td>
<td>324.5 (187.9)</td>
<td>47.8 (4.7)</td>
<td>0.0</td>
</tr>
<tr>
<td>11–15</td>
<td>10</td>
<td>5.2 (1.6)</td>
<td>80.0 (43.8)</td>
<td>488.1 (74.6)</td>
<td>28.0 (8.7)</td>
<td>0.0</td>
</tr>
<tr>
<td>16–20</td>
<td>3</td>
<td>8.1 (1.0)</td>
<td>157.4 (42.0)</td>
<td>469.4 (203.4)</td>
<td>48.7 (6.6)</td>
<td>0.0</td>
</tr>
<tr>
<td>21–25</td>
<td>4</td>
<td>8.7 (0.4)</td>
<td>113.7 (72.5)</td>
<td>282.3 (204.2)</td>
<td>53.3 (3.7)</td>
<td>0.0</td>
</tr>
<tr>
<td>26–30</td>
<td>2</td>
<td>10.9 (1.3)</td>
<td>100.0 (20.0)</td>
<td>153.8 (5.7)</td>
<td>59.0 (2.5)</td>
<td>0.0</td>
</tr>
</tbody>
</table>

SDs are displayed in parentheses. QMD, quadratic mean diameter; BA, basal area; HT, height of dominant and codominant trees.
using PROC UNIVARIATE, and models were fit using PROC NLIN. The 95% confidence intervals for each model were used for comparisons of height. Model parameter estimates were analyzed by two-sample t-tests to determine whether the height-age relationship differed.

Site indices were created following the methods of Curtis (1964) and Carmean (1972). Curtis’ method involves correcting for bias in differently aged stands when site index curves are created with mean height at a common age. Carmean’s stem analysis method uses the following equation:

\[
H_{ij} = h_i + \frac{h_{i+1} - h_i}{2(r_i - r_{i+1})} + \frac{(j-1)(h_{i+1} - h_i)}{(r_i - r_{i+1})} \tag{1}
\]

where \(H_{ij}\) is the total height at age \(t_j\) in feet, \(h_i\) is the height at the \(i\)th stem section disc in feet (e.g., 1st disc, \(h = 1.5\) feet), and \(t_j\) is the age of the tree associated with the \(j\)th inner ring of the \(i\)th disc in years. Note that the \(j\)th inner ring refers to an annual height growth terminating within the section above the \(i\)th stem section disc (e.g., the first annual height growth terminating within a section \(j = 1\)).

Curtis’ methodology provides a correction for calculated site index when the sample trees are located on sites of inherently different site indices. Dyer and Bailey (1987) found these equations to be less accurate and more labor intensive. A total of 1,029 height-age observations produced from the stem analysis for Equation 1 were used to fit the model in Equation 2. Based on these calculations and a nonlinear height-age equation such as that found in Coble and Lee (2006), average site indices were developed for both mines. Distinct site index classes were created through grouping of similar sites (e.g., 35–45, 45–55, 55–65, and 65–75 ft at 25 years). We used the algebraic difference approach, which allows simple derivation of the fitted model to each site index level, but site index equations derived from this method are constrained to anamorphic or single asymptote guide curves (i.e., developed curves may vary only in the asymptote parameter or the shape parameter, not in both) (Diéguez-Aranda et al. 2006). Coble and Lee (2006) used the Chapman-Richards (Chapman and Richards 1959) model for height at a given age:

\[
H_t = \beta_0 (1 - e^{-\beta_1 t}) + \beta_2 \tag{2}
\]

where \(H_t\) is the total height at age \(t\) in feet, \(t\) is the age of the tree in years, \(\beta_0\) is the asymptotic height parameter, \(\beta_1\) is the shape parameter that dictates rate of growth, and \(\beta_2\) is the shape parameter that dictates early growth patterns.

Coble and Lee (2006) produced anamorphic guide curves for determining site index in loblolly pine plantations in East Texas. These curves have the same shape, and only the \(\beta_0\) parameter in Equation 2 changes for various site indices. This attribute allows a specific guide curve derived from the model to easily fit any desired site index and base age by determining the appropriate \(\beta_0\) value:

\[
\hat{\beta}_0 = H_{IA} \cdot (1 - e^{-\hat{\beta}_1 \cdot \text{base age}})^{-\hat{\beta}_2} \tag{3}
\]

where \(\hat{\beta}_0\) is the index age and the height is therefore site index. Any height-age pair can be used to determine the corresponding site index curve. The site index model is therefore found by substituting Equation 3 into the fitted Equation 2:

\[
H = SI \cdot (1 - e^{-\hat{\beta}_1 \cdot \text{base age}})^{-\hat{\beta}_2} \tag{4}
\]

where SI (site index) is the height (ft) at index age 25 (years) of the 10 tallest trees in the plot.

**Determining Premining Site Indices**

No premining stand data were available for either mine, so we determined the premining average site index from the US Geological Survey Web Soil Survey that uses Coile and Schumacher (1953) base age 50-year site index curves for natural loblolly pine stands. To convert this site index to a modern 25-year index age for plantations, we found the height at age 25 along the appropriate Coile and Schumacher (1953) base age 50-year site index curve and added 10 ft to approximate gains from improved silviculture and genetics of planted loblolly pine similar to the stands in Coble and Lee’s study. The 10-ft estimate is an estimation based on anecdotal information only and is likely to vary in real stands, depending on silvicultural intensity and realized genetic gain of the planting stock. Another available method to derive the base age 25 site index uses an equation that multiplies the base age 50 site index by two-thirds and adds a constant of 7 ft (Barry 2011). Site index estimates using this method produced lower estimates of premining site index than the plus-10-foot method. Alternatively, an earlier Luminant study by Willett and Bilan (1991) observed site indices on native soils of the same soil series as those found on the mine sites ranging from 60 to 65 ft at 25 years. However, these site indices are not truly premining site indices for the locations of this study because they were developed for different locations. Thus, we did not use these approaches as they were less conservative. Using a site index estimation method with a tendency to overestimate the premining site index relative to these alternative methods makes it less likely that we will spuriously conclude that forest productivity increased after mineland reclamation or that we will underestimate potential reductions in productivity. Specific guide curves for those premining site index values could then be calculated from an East Texas site index model of Coble and Lee (2006) for full comparison of premining and postmining site indices.

**Results**

We developed height-age models for the Beckville and Oak Hill Mines (Figure 2) and used those models to evaluate our hypotheses. We estimated the original average site index from soil survey data (Dolezel 1975, Griffith 2000) in base age 50 years to be 88 and 82 ft for Beckville and Oak Hill, respectively. Our approximated base age 25-year original site index values were thus 70 and 66 ft for Beckville and Oak Hill, respectively. The average unmined site index in East Texas found by Coble and Lee (2006) was 70.9 ft. We compared the current average site index from the height-age models with the estimated original average site index and determined that neither mine’s site index was statistically different from the estimated premining site index (Figure 3). We then compared the two sites’ height-age models to determine whether any statistical difference occurred between the two sites (Figure 4). On finding no statistical difference between Beckville and Oak Hill, we combined the data sets to develop a height-age model representative of these
reclaimed minelands. The site index curves for reclaimed minelands were developed from this combined data set model. The parameter estimates and associated goodness-of-fit data for each site index model can be located in Table 2.

The combined data set height-age model was compared with Coble and Lee’s (2006) East Texas unmined height-age model. Statistically significant differences in height for ages 16 through 25 years were observed, with the reclaimed minelands slightly underperforming the unmined model representing much of East Texas (Figure 5). We then compared our site index curves to those developed by Coble and Lee on unmined lands in East Texas. There were statistically significant differences between all of the model parameters for our guide curves and those developed by Coble and Lee ($P < 0.001$). Curtis’ (1964) method determined that no bias existed as a result of planting stock of lower genetic quality in older stands.

Beckville Mine

The model fit to the Beckville Mine stem analysis data predicted a mean height at 25 years of 61.05 ft. The upper and lower 95% confidence intervals for the model at 25 years are 70.87 and 51.28 ft, respectively (Figure 2). The current site index is therefore not statistically significantly lower than the estimated Beckville Mine original site index of 70.0 ft at base age of 25 years (Figure 3). Using 95% confidence intervals to again compare current site index height-age model and the estimated original site index height-age model, we found that the current predicted heights at a given age are not statistically different from original site index model predicted heights at the same age (Figure 3). Statistical differences in height were only tested in the age range available in this study (2–32 years) instead of projecting the model beyond the age of our oldest trees.
The model showed overall good fit, with a fairly normal residual plot that did not require weighting, although some sample tree growth patterns deviated from the model. Pseudo-$R^2$ for the model was 0.9817 and RMSE was 4.31 ft. At Oak Hill, 7 of the 24 trees had at least one data point outside of the 95% confidence intervals. All of those data points fell outside the lower confidence interval and were in trees 16 years old or younger at the time of harvest. These outliers were not removed. The reduced growth rates in recent years for our sample trees are most likely attributable to an extensive drought in East Texas that occurred primarily in 2011.

**Comparing Reclamation Methods**

The site indices were not statistically different between the two mines as indicated by the 95% confidence intervals (Figure 4). The differences in height between the two models was less than 2 ft for any of the ages evaluated (1–32 years), and the difference was never significant for any age. The parameter estimates for the two models

\[
\text{Height} = 94.7364 \cdot (1 - e^{-0.0494 \cdot \text{Age}^{1.1378}}) \tag{6}
\]

The model showed overall good fit, with a fairly normal residual plot that did not require weighting, although some sample tree growth patterns deviated from the model. Pseudo-$R^2$ for the model was 0.9817 and RMSE was 4.31 ft. At Oak Hill, 7 of the 24 trees had at least one data point outside of the 95% confidence intervals. All of those data points fell outside the lower confidence interval and were in trees 16 years old or younger at the time of harvest. These outliers were not removed. The reduced growth rates in recent years for our sample trees are most likely attributable to an extensive drought in East Texas that occurred primarily in 2011.

**Oak Hill Mine**

The height-age model fit to the Oak Hill Mine data predicted a mean height at 25 years of 61.94 ft. Upper and lower 95% confidence intervals at 25 years are 70.56 and 53.28 ft, respectively (Figure 2). Results were similar to those for Beckville: the current site index at the Oak Hill Mine was not statistically significantly different from the estimated Oak Hill original site index of 66.0 ft at base age 25 years (Figure 3). The heights predicted by the Oak Hill site index model are not statistically different from the original site index represented using the Coble and Lee (2006) guide curves at any of the age ranges in this study (2–32 years). Again, there are differences in the shape of the Oak Hill site index curve and unmined site index curve. The $\hat{b}_0$ asymptote parameter is not statistically different from Coble and Lee’s (2006) model for site index of 66.0 ft ($P = 0.13$) or the East Texas average site index model ($P = 0.41$). However, the $\hat{b}_1$ and $\hat{b}_2$ model parameters are statistically different from those for the Coble and Lee’s model ($\hat{b}_1/ P = 0.0002$, $\hat{b}_2/ P = 0.0018$). Both mines exhibited similar results compared with their respective estimated original site indices: height was not statistically different at any age, including site index age, and curves exhibited forms different from the estimated original site index curves. The parameterized Oak Hill Mine height-age model, which represents the average site index curve for the mine, is

\[
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\]

The model showed overall good fit, with a fairly normal residual plot that did not require weighting, although some sample tree growth patterns deviated from the model. Pseudo-$R^2$ for the model was 0.9817 and RMSE was 4.31 ft. At Oak Hill, 7 of the 24 trees had at least one data point outside of the 95% confidence intervals. All of those data points fell outside the lower confidence interval and were in trees 16 years old or younger at the time of harvest. These outliers were not removed. The reduced growth rates in recent years for our sample trees are most likely attributable to an extensive drought in East Texas that occurred primarily in 2011.
were not statistically different for any parameter \( \hat{\beta}_0 = 0.80, \hat{\beta}_1 = 0.88, \hat{\beta}_2 = 0.28 \). The two data sets were combined for further analysis.

**Reclaimed Mineland Site Index**

As a result of statistical similarities in growth rates between the two mine sites, a single height-age model incorporating data from both mines could be created to approximate site index on reclaimed minelands in East Texas.

The fitted model was

\[
\text{Height} = 93.0255 \cdot (1 - e^{-0.0482 \cdot \text{Age}^{1.1699}}) \tag{7}
\]

The model showed overall good fit, with a normal residual plot and no weighting necessary. Pseudo-\( R^2 \) for the model was 0.9794, and RMSE was 4.76 ft. This East Texas reclaimed mineland model predicted a mean height at base age 25 years of 61.32 ft. The upper and lower 95% confidence intervals at the base age were 70.74 and 51.95 ft, respectively. Although there is no statistical difference between current site index and site index before mining, there is a statistical difference between the average reclaimed mineland site index of 61.32 ft and the average East Texas site index of 70.95 ft reported by Coble and Lee (2006) for unmined lands. This difference is determined using the 95% confidence intervals of the model, and the heights are statistically different between the reclaimed mineland model and Coble and Lee’s unmined model for ages 16–25 years (Figure 5). Coble and Lee’s unmined model predicted taller heights than the reclaimed mineland model with the largest difference (10.1 ft) occurring at 20 years. The differences in height for only these midrotation ages were supported by differences in Equation 7 and Coble and Lee’s average site index model. The \( \hat{\beta}_0 \) asymptote parameter is not statistically different from Coble and Lee’s (2006) site index model \( (P = 0.30) \). However, the \( \hat{\beta}_1 \) and \( \hat{\beta}_2 \) model parameters are statistically different from the unmined comparison \( (P < 0.0001) \).

**Site Index Guide Curves**

From this single model (Equation 7), anamorphic site index guide curves were created (Figure 6) to approximate a range of possible site indices for reclaimed minelands in East Texas. As these are anamorphic guide curves (i.e., shape parameters remain constant across all levels of site index), the equation for each site index level or any height-age value can be found by correcting the \( \hat{\beta}_0 \) parameter. Therefore, the \( \hat{\beta}_0 \) value for a level of site index can be found by Equation 8:

\[
\hat{\beta}_0 = H \cdot (1 - e^{-0.0482 \cdot \text{t}^{1.1699}}) \tag{8}
\]

where \( H \) is height (feet) at time \( t \) (years). When Equation 8 is substituted into Equation 7, the final site index model is found:

\[
\text{Height} = \text{SI} \cdot (1 - e^{-0.0482 \cdot 25})^{1.1699} \cdot (1 - e^{-0.0482 \cdot \text{Age}^{1.1699}}) \tag{9}
\]

where SI (site index) is height (ft) at base age 25 (years) of the 10 tallest trees in the plot.

The guide curves were compared on the basis of an equal site index, in this case using Equation 7 and the anamorphic guide curve equal to a site index of 61.32 ft derived from the East Texas average site index model (Coble and Lee 2006). The reclaimed mineland site index guide curves were statistically different from the East Texas guide curves developed by Coble and Lee (2006) for all model parameters \( (\hat{\beta}_0 = 0.0009, \hat{\beta}_1 < 0.0002, \hat{\beta}_2 < 0.0001) \). See Figure 7 for a comparison of the two site index guide curves.

**Discussion**

**Site Index Comparison**

We found that the site index after mining was not statistically different from the premining site index (Figure 3). This result does not support our first research hypothesis that site index would be lower on reclaimed mineland. We did find an overall difference in the shape of the site index curves (Beckville, Oak Hill, and combined reclaimed mineland models) from those of models created on unmined land (Coble and Lee 2006). These differences in shape are
mine sites have been planted with a range of genetic stock over the northwestern limits of the population sampled by Coble and Lee (2006). The difference was not particularly large, but it is notable. Other than planting stock genetics and site characteristics, model parameters and curve shape may have also been affected by the use of algebraic difference approach techniques as opposed to the generalized algebraic difference approach used by Coble and Lee (2006). In addition, the panel data collected by Coble and Lee in their reestablishment study could also contribute errors dissimilar to those from the stem analysis data used here. Our definition of site index mimicked Coble and Lee’s by selecting one of the 10 tallest trees in each plot and probably yielded higher site index estimates than a definition of site index that includes all dominant and codominant trees. Sample trees averaged 1.5 ft greater than the average height of dominant and codominant trees in each plot. However, this height difference remained constant over all ages, which indicates that site index would decrease by less than 2 ft when a greater number of trees was included in the definition of site index.

The East Texas reclaimed mineland model (Equation 7) predicted that the average site index on mine sites was statistically less than the East Texas average found on unmined lands (Coble and Lee 2006). The difference was not particularly large, but it is notable. This comparison is not the same as comparing pre- and postmining conditions and could be partially due to the mine site’s location at the northwestern limits of the population sampled by Coble and Lee (2006). The genetics of the two populations differ greatly as the mine sites have been planted with a range of genetic stock over multiple decades of operation, whereas the East Texas Pine Plantation Research Project plantings were somewhat uniform in genetic makeup. Nevertheless, this result indicates that reclaimed mineland site index does not have site quality similar to that of much of East Texas (Figures 5 and 7). Increasing silvicultural intensity may improve site index on reclaimed minelands to levels comparable to those for the region.

Reclamation Method Comparison

The two mines had similar site indices, which were not statistically different. We inferred that sites that have acid-forming materials in the overburden either require oxidized material haulback as a necessary countermeasure to attain postmining site quality similar to that on mixed overburden reclaimed mine sites or gain no added benefit to site quality from higher-cost oxidized material haulback over mixed overburden reclaimed mine sites. It was not possible to test this hypothesis with our data. Essentially, the oxidized material haulback (“red dirt”) reclamation method should only be used for the purpose of preventing surface acidity. If acid-forming materials are not present, there is no reason to expect that the use of oxidized material as a topsoil substitute will improve site quality after mining compared with mixed overburden as a topsoil substitute (Haywood et al. 1993). The oxidized material haulback method is typically only required to prevent surface acidity due to oxidation of pyrites, and management practices for that objective should continue. Alternative methods of controlling pyrite oxidation should be considered to determine whether the haulback of oxidized material is both the most cost-effective and environmentally conscious method for controlling this problem. This research has found no difference in productivity between the two reclamation methods as implemented on these two mine sites.

Guide Curve Development

The two mine sites were not statistically different in reference to their height-age models, so a single model could be created for reclaimed minelands in East Texas. This single model provides a tool for land managers and researchers to properly quantify growth of trees on East Texas mine sites (Figure 6). Although this study only uses two sites that are in relatively close proximity to one another, the clumped spatial pattern of East Texas mines suggests that application of this research to other reclaimed minelands in the area will not be limited by distance (see Railroad Commission of Texas Permitted Coal Mining Locations’s). The applicability of this research is instead more limited by changing reclamation strategies and silvicultural methods that are not currently regulated by the Texas Railroad Commission (i.e., genetically improved planting stock, fertilization, timing of operations, and others).

Our results indicated that although the shapes of the height-age curves are different after mining, trees on reclaimed mineland reach the same height as trees on unmined land by the end of a typical rotation. This could be explained by aggrading site quality as a function of time since disturbance (Ng 2012). In some cases, aggradation is influenced by the vegetation used to reclaim the site (Mukhopadhyay et al. 2013). Further research could evaluate how reclamation success in East Texas is dependent on the choice of vegetation. Improving site index and early growth on reclaimed minelands depend on reducing limiting factors, some of which are naturally improved over time (i.e., restoration of nutrient cycling, mycorrhizal propagation, increasing soil organic matter, and lowering pH to premining levels) (Blake 2003, Ng 2012) whereas others...
require correction during reclamation (i.e., decreasing compaction, reducing acid-forming materials, and selecting topsoil materials of appropriate soil texture) (Burger et al. 2005, Wheeler 2009).

Aggrading site quality could be a factor contributing to significant differences between mined and unmined site index model parameters. Figure 8 illustrates this possibility by depicting the apparent effect of age at which site index is estimated and the resulting site index prediction. A random sample should have revealed a horizontal scatter with a clear trend, yet lower site index predictions occurred with use of younger trees. These were estimations based on final height and age at the time of destructive sampling, which allows the possibility that recent climatic conditions are responsible for the trend. Recent drought from 2011–2012 in East Texas (Hoerling et al. 2013) could have slowed height growth of our sample trees. The effects of drought could have had a stronger impact on young trees, which would explain both the trend and the reason that our height-age model would not have followed a similar pattern. This phenomenon may occur independently of environmental conditions and instead as a result of young loblolly pine growth patterns. This occurrence has been documented for loblolly on unmined sites in East Texas by Lenhart and Allen (1997), where trees younger than age 5 years poorly predicted site index on moderate- to high-quality sites.

**Implications for Management**

Toups (1986) predicted that site index would be considerably lower after mining based on 7- and 8-year-old stands and utilizing site index curves developed for unmined land. We found similar results during preliminary assessments, although this was partly due to incorrectly estimated stand ages derived from mining company records. The planting data contained inaccuracies that may have resulted from replanting practices. Stem analysis reduced the effects of the recent drought, obtained accurate estimates of age, and allowed us to create site index models specifically for reclaimed minelands in East Texas. There is potential for error in estimates of site index from unmined site index guide curves (Figure 7). As an example, a 30-ft-tall tree at age 10 would be approximated to reach a height of 65.4 ft at age 35 using unmined guide curves (Coble and Lee 2006). With our guide curves to estimate the height of the same tree at age 35, the height would be 72.7 ft. The predicted height at age 25 for this individual tree would be 58.0 and 60.9 ft using unmined and mined site index guide curves, respectively. Some research on mine sites has found that site quality returns to approximately the same level as premining (Jones et al. 2005), which is supported by our data. Site quality as measured by site index is not statistically different from estimated premining site index.

A suggestion for evaluating reclamation success is to determine site index before clearing and mining when stands are available. If site index is to be implemented in regulations, determining approximate productivity is necessary at or near the mine. Statewide levels of site index or height growth for regulatory standards are not recommended. Site index varies widely, so an accurate measurement before mining at each mine site (or a nearby area) is necessary to ensure that standards are both feasible and that reclaimed mineland is capable of supporting the same level of premining land use.

Our findings on the comparison of site index between two different methods of topsoil replacement seem to contrast with findings in the Appalachian region where topsoil substitutes have been ranked according to productivity and are not interchangeable (Skousen et al. 2011). In addition, Burger et al. (2007) found that not only was growth and survival of pine strongly affected by mine soil composition but a second rotation of northern red oak (*Quercus rubra* L.) planted after removal of the pines was also inversely influenced by mine soil type (i.e., soils most productive for pine were poor for red oak and vice versa). The same study by Burger et al. (2007) also supports the need to match species to site characteristics as red oak performed better on a mix of sandstone and siltstone, whereas pine performed best on pure sandstone and decreased with additional siltstone.

**Conclusion**

For loblolly pine plantations on two reclaimed minelands in East Texas, average site index was statistically similar to approximated premining site indices. This similarity indicates that current site quality on these reclaimed minelands is similar to the original site quality and productivity as measured by site index for loblolly pine. Therefore, current reclamation practices are validated for the purpose of restoring forestry plantations of loblolly pine as a postmining land use. Site index is a viable alternative to density-based reclamation standards currently in place for forestry land uses, barring that trees younger than approximately 6 years are not relied on to determine site index. We recommend that site index be accounted for in premining site evaluations. Estimation of site index before mining accurately determines premining productivity, which is a requirement of SMCRA (1977) for developing reclamation plans. From a research and management standpoint, the estimate of site quality provided by site index can further be correlated to soil conditions to guide reclamation processes and improve productivity on reclaimed mineland (Jones et al. 2005).

**Endnote**

1. For more information, see www.tceq.texas.gov/mining.

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