Effect of Grading Technique on Forest Productivity of High-Value Tree Species

In Reforested Surface Mine Lands

OSM Cooperative Agreement Number S15AC20026

Reporting Period Start Date – June 2015

Reporting Period End Date – December 2017

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December 2017

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Abstract

Survival, growth and biomass accumulation of 19 year-old trees planted on an Appalachian surface mine site were evaluated to determine the effect of spoil grading and surface amendment treatments. Three spoil grading treatments (loose-dump, strike-off and graded control) were established to create a range of operationally feasible spoil compaction capable of impacting tree establishment and growth. Likewise, three surface amendment treatments (straw/manure mulch, hardwood bark mulch and control) were applied to determine their effects on tree development. Trees grown under low-compaction grading treatment levels (strike-off and loose-dump) consistently outperformed trees planted in a high-compaction control treatment. Loose-dump preparation resulted in higher survival for five of six tree species and greater biomass in the three species for which this metric was estimated. Strike-off preparation generally resulted in higher diameter at breast height (DBH) values. The addition of a straw/manure surface amendment increased biomass for hardwood species for which this value was estimated.

Volunteer woody vegetation growing in the same experimental plots was measured and characterized by species. Loose-dump plots exhibited the highest overall volunteer stem and native stem density and compacted control plots had the lowest volunteer stem density and lowest proportion of native stems. Strike-off plots exhibited intermediate values for both of these measures.

Carbon sequestration both in aboveground biomass and in the soil continues to rise as the trees mature. We found that mean above and belowground sequestration rates increased from 2.92 to 3.46 Mg C ha^{-1} yr^{-1} between years 8 and 18. These rates are comparable and somewhat higher than levels suggested in other mine reclamation studies and higher than those often reported for lands undergoing conversion from agricultural to forest land use. Soil carbon levels in reclaimed FRA soils after 13 and 18 years were similar to those in unmined mature forest, which suggests that soil function can rapidly recover and supports previous findings on these sites by Maharaj et al. (2007) and Littlefield et al. (2013).

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Figure 1.20: Fine resolution soil sample SOC (%) accumulation from time 0 to 18 years since planted on mine sites and in an unmined forested control.

Figure 1.21: Soil C accumulation from a chronosequence of reclamation ages at the Bent Mountain and Starfire mines in eastern Kentucky.

Introduction

Surface mining for coal has left hundreds of thousands of acres of previously forested land across the eastern United States disturbed past the point of recognition (Gilland and McCarthy, 2014). Historically, mining firms were subject to little regulation by state or federal agencies in regards to the reclamation of surface mined land following the completion of coal extraction. During this period, some mine operators voluntarily undertook reforestation efforts on former surface mines and were successful in establishing stands that met or exceeded local non-mined reference sites in terms of economic value and forest productivity (Groninger et al., 2006). Unfortunately, this high level of stewardship was the exception within the industry rather than the rule. Many large firms operating in the mid-20th century heyday of surface mining expended little to no effort or financial resources on reclaiming mines that had ceased to produce coal, leading to widespread occurrence of erosion, landslides and water contamination and the abandonment and devaluation of large tracts of land (Angel, 2009).

The Surface Mining Control and Reclamation Act (SMCRA) of 1977, developed due to increasing concerns on the part of the federal government regarding the environmental effects of mining, set reclamation standards meant to minimize erosion and reestablish vegetation on mine sites following the completion of coal removal (Holl, 2002). These standards must be met before reclamation bonds stipulated by the law can be released to mining firms. Mine operators have historically met SMCRA bond requirements in part by planting rapid-growing, non-native grass and legume species and compacting topsoil or substitute soil materials (Holl 2002). This has led to the replacement of much of the forest eliminated by surface mining since the implementation of SMCRA with grasslands exhibiting little biodiversity or capacity for ecological succession (Holl, 2002, Zipper et al., 2011). Landowners who intend to use former surface mines for livestock grazing or commercial production of hay may prefer such a change in land cover. However, many surface mines converted to treeless grasslands are effectively abandoned following reclamation, meaning they are unmanaged and unproductive, which arguably does not achieve the intent of SMCRA to leave mined lands capable of equal or higher use following reclamation compared to their pre-mined condition (Angel et al., 2005).

Some coal operators attempted to reestablish trees on mined sites in conjunction with high-compaction reclamation techniques. Such efforts were largely unsuccessful, however. Highly compacted soil conditions rendered root expansion difficult while intense competition with herbaceous plants made water and light resources scarce (Torbert et al., 1991). Given the low success of reforestation under such conditions, operators often found planting trees to be financially unattractive (Torbert et al., 1991).

Pre-SMCRA research including Rogers (1949) pointed to the capability for non-compacted mine spoil, a mixture of mostly rocky debris left on the surface after coal extraction, to support native trees and exhibit ecological succession indicative of forest stand development. Growing public and regulatory interest in the reforestation of surface mines during the 1990’s led to new research into the development of reclamation methods compatible with successful tree growth. The University of Kentucky contributed to this growing body of knowledge through the Starfire experiment, which was established in 1996 (Thomas, 1999, Angel, 2009). Data gained from this and other experimental stands led to the Forestry Reclamation Approach, a formalized set of methods in which trees and non-competitive groundcover species are planted on surface mines (Angel, 2009). The Forestry Reclamation Approach calls for site preparation in which spoil is either not compacted (loose-dump) or compacted slightly through a maximum of two passes of heavy equipment (strike-off) (Burger et al., 2005).

Zipper et al. report that the Forestry Reclamation Approach is beginning to be embraced across the eastern United States (2011). Between 2004 and 2012 some 70 million trees were planted over more than 40,000 hectares of land that had recently been mined in the Eastern United States (Angel et al., 2012). Initial studies at the Starfire site showed that both loose-dump and strike-off spoil preparation methods can allow for better tree growth and survival than reclamation methods in which spoil is compacted (Angel et al., 2006, Angel et al., 2012). Another study found that mean height and diameter of ten-year-old white oak (*Quercus alba*) and yellow-poplar (*Liriodendron tulipifera*) trees planted in accordance with the FRA closely resembled those of trees in non-mined regional reference sites (Cotton et al., 2012).

Though such studies illustrate the promise of the Forestry Reclamation Approach, there is currently little published data on growth and development of FRA stands over longer periods of time. The relatively early establishment of the Starfire experiment within this field of research and its permanent nature provide an opportunity to enhance knowledge of the development of FRA plantings. This stand has experienced canopy closure and reached the stem exclusion phase of stand development, in which competition for resources among established trees leads to suppressed growth and eventual decline in some stems (See Figure 1.1) (Oliver and Larson, 1996). Conditions in stands experiencing stem exclusion are generally far different from those in newly-initiated stands. Moreover, little is known about soil development/genesis on sites reclaimed using FRA because there are few sites old enough to thoroughly examine these processes which take decades to develop. The formation of soils over time can be an indicator of the overall health of the system, and to some extent, indicative of how productive the mine has become. There has been shown to be a positive correlation between the amount of soil organic carbon (SOC), and the overall productivity of the soil (Bauer and Black, 1994; Seremesic et al., 2011; Zhao et al., 2016). In addition, SOC has been reported as the single most important indicator of soil quality (National Research Council, 1993). Quantifying soil development through SOC accumulation will provide a better understanding of the influence of FRA on soil genesis and potential for carbon sequestration of mine impacted landscapes.

The first objective of the current study was to assess the influence of grading and surface amendment treatments on trees planted in the Starfire experimental reforestation project on an eastern Kentucky surface mine in the late 1990s. Metrics used to gauge reforestation success included tree survival, height and diameter at breast height (DBH). Our second objective was to develop individual tree and per-area aboveground biomass estimates for selected species through the use of destructive sampling and regression analysis. Additionally, we sought to characterize woody plant colonization on a 19 year-old experimental mine reforestation site through measuring the size and species composition of non-planted woody stems. Effects of grading spoil preparation and surface amendment treatments on stem density and percentage of stems of native species were also investigated. Lastly, we examined carbon accumulation rates in FRA soils to provide an estimate of soil genesis, productivity and carbon sequestration potential.

Executive Summary

Survival, growth and biomass accumulation of 19 year-old trees planted on an Appalachian surface mine site were evaluated to determine the effect of spoil grading and surface amendment treatments. Three spoil grading treatments (loose-dump, strike-off and graded control) were established to create a range of operationally feasible spoil compaction capable of impacting tree establishment and growth. Likewise, three surface amendment treatments (straw/manure mulch, hardwood bark mulch and control) were applied to determine their effects on tree development.

Our results indicated that both strike-off and loose-dump grading preparation methods generally allowed for better survival and growth of planted trees than the conventional, high-compaction method. The loose-dump method appeared to maximize survival, but its resultant undulating topography is likely to present serious challenges for equipment needed to access forestry reclamation stands for silvicultural practices or timber harvest. In fact, even human movement on foot within these cells proved difficult during our data collection efforts. Strike-off preparation may help solve the problem of accessibility without inducing high levels of compaction, as evidenced though bulk density values, though our data indicated somewhat lower mean survival of planted trees. However, our biomass estimates showed that loose-dump preparation resulted in the highest woody biomass levels of any grading method tested.

A large number of volunteer woody species were present on the Starfire site, meaning there is good potential for high biodiversity in these stands as they continue to mature and develop. Unfortunately, two of the species most commonly found volunteering in these stands were noted exotic invaders, namely autumn olive and tree of heaven, each of which has become more common in the stand over the last decade. Invasive species control through chemical or mechanical means could minimize the impact of these species on biodiversity within the stands by retarding their proliferation, and may be advisable on other mine reforestation sites under certain circumstances. Changes in the composition of volunteer species, particularly the replacement of black locust with other species, show that this young stand is already experiencing succession. The number and composition of volunteer trees and shrubs on this site are likely to change in the future and should be re-inventoried to document the rate of such changes.

Carbon sequestration both in aboveground biomass and in the soil continues to rise as the trees mature. We found that mean above and belowground sequestration rates increased from 2.92 to 3.46 Mg C ha^{-1} yr^{-1} between years 8 and 18. These rates are comparable and somewhat higher than levels suggested in other mine reclamation studies and higher than those often reported for lands undergoing conversion from agricultural to forest land use. Soil carbon levels in reclaimed FRA soils after 13 and 18 years were similar to those in unmined mature forest, which suggests that soil function can rapidly recover and supports previous findings on these sites by Maharaj et al. (2007) and Littlefield et al. (2013).

Experimental

Seedling Survival, Growth and Biomass

The study site was located at the Starfire Mine in Knott County and Perry County, KY (37° 24″ N, 83° 08′ W). In 1997, the University of Kentucky (UK) established 9, 1.0 hectare (approximately 70 m by 155 m) experimental reforestation cells on the site (Figures 1.2 and 1.3) (Thomas, 1999). Vegetation and topsoil were removed from the cells by bulldozer (Figure 1.6) (Thomas, 1999). Three of these cells received grading treatment resulting in high compaction of spoil, a state typical of conventional reclamation methods (Control; Figure 1.7); three of the cells were prepared through dumping of spoil in piles by large trucks followed by one pass with a bulldozer in order to partially flatten the piles, resulting in a low degree of compaction (Strike-Off; Figure 1.8 and 1.10); and the remaining three cells were prepared through dumping of spoil into piles but were not levelled off by bulldozer and therefore exhibit minimal compaction (Loose-Dump; Figure 1.9) (Thomas, 1999). Soil bulk density values as measured following construction were significantly ($p \geq .05$) lower for loose-dump cells than strike-off cells, which showed significantly lower bulk density than control cells (Thomas 1999; Table 1.1) The three cells receiving each grading treatment were then randomly assigned one of three surface amendment treatments including hardwood bark mulch (Bark; Figure 1.11), straw and horse manure mulch (Straw; Figure 1.12), or no surface amendment (Control). A tree-compatible groundcover was then hydro-seeded over all cells (Figure 1.13) (Thomas, 1999).

Each cell was then divided into 21. 0.04 hectare plots. Plots within each cell were randomly assigned to be planted with 1 of 7 tree species, for a total of 3 plots per species within each cell (Figure 1.1). Species were hand-planted (Figure 1.14) and included white oak (*Quercus alba*), northern red oak (*Quercus rubra*), white ash (*Fraxinus americana*), eastern white pine (*Pinus strobus*), black walnut (*Juglans nigra*), yellow-poplar (*Liriodendron tulipifera*), and royal paulownia (*Paulownia tomentosa*). Royal paulownia was not included in this study.

In August 2015, DBH of all live planted trees was measured and recorded for all plots occurring in each 1.0 hectare cell using diameter measuring tapes. Survival was subsequently calculated by dividing the number of live planted trees in each 0.04 hectare plot by the number initially planted in each plot. Total heights of live trees were measured following leaf fall in December 2015 and January 2016 using a laser hypsometer. DBH and crown classification (i.e. dominant, codominant, intermediate, and overtopped) were also recorded at this time (crown classification followed Oliver and Larson, 1996). Due to time constraints, a subsample of ten trees representing the range of DBH values for each plot was chosen for height measurement. Sample trees were determined by field personnel. A technician entered each plot from one side and was then instructed to walk aimlessly within its boundaries. A second technician, who faced away from the plot being sampled, waited at least 10 seconds and then instructed the first technician to stop and measure the diameter of the nearest tree. Tree height was then recorded. In cases where DBH of sample trees did not appropriately represent the range of values for a plot, trees were re-chosen using the same methodology until individuals of appropriate DBH were chosen. In cases where less than ten live trees remained in a plot, all trees were measured.

Statistical analysis of height data was limited to those individuals in the overstory (i.e. dominant or codominant). This allowed for comparison of mean heights to site index curves, which are developed using dominant and codominant sample trees (Carmean et al., 1989). The use of site indices to gauge forest productivity is further elaborated in the Discussion section below.

In order to develop biomass accumulation estimates for white oak, yellow-poplar and eastern white pine, trees representing the range of DBH values exhibited by each of these species were destructively sampled during the summer of 2016. Sample trees were determined by field personnel. A technician entered each plot from one side and was then instructed to walk aimlessly within its boundaries. A second technician, who faced away from the plot being sampled, waited at least 10 seconds and then instructed the first technician to stop and measure the diameter of the nearest tree. Tree height was then recorded. In cases where DBH of sample trees did not appropriately represent the range of values for a plot, trees were re-chosen using the same methodology until individuals of appropriate DBH were chosen

Two trees were harvested from each of the 18 white oak and yellow-poplar plots in strike-off and loose-dump cells (n=36). Control cells were not sampled due to their virtual lack of overstory trees. The eastern white pines on our study site were larger and more difficult to process than the sampled hardwood species. Due to time constraints, only one tree was selected from each white pine plot within the same cells (n=18). Trees chosen for sampling were felled, subdivided into component classes (bole, large branches (≥2.5 cm); twigs (<2.5 cm); foliage; and, where applicable, cones) and then weighed in the field using a bench scale or large hanging scale (Figure 1.15). Subsamples from each class were then collected and green weights were recorded. These subsamples were subsequently placed in a drying oven at 60 degrees Celsius for a minimum of 5 days before being reweighed. The ratio of dry weight to green weight for each component of a given tree was then applied to the total field green weight for that component to determine its overall dry mass (woody, foliage, and woody and foliage combined).

Subsamples of the dried material from the species white pine, yellow-poplar and white oak were ground with a Wiley mill equipped with a 20-**μ**m screen and analyzed for total C and N using a LECO CHN 2000 analyzer (Leco Corp., St. Joseph, MI). Aboveground carbon sequestration for each of the respective species was obtained by taking the total biomass and multiplying by the % C of each tree component (biomass C), dividing that by the age of that tree (by evaluating bole samples taken), then multiplying by the number of surviving trees per hectare (metric tons/hectare/year).

Natural Colonization of Woody Vegetation

Volunteer woody vegetation within each of these 0.04 ha plots was recorded. All woody plants with height greater than 1 m and diameter at breast height (DBH) greater than 1.0 cm were measured and included in this study. Ground line diameter (GLD) and DBH were determined using diameter tapes and plants were identified to species, with the exception of sumac (*Rhus*) species, which were identified to genus. All recorded stems were later categorized as being either “native” or “exotic” in origin.

Soil Carbon Accumulation

Five study sites distributed at two coal mines, Starfire and Bent Mountain, were used in this part of the study (Figure 1.4). Three of these sites were located on the Starfire mine, and two were on the Bent Mountain mine in Pike County, KY (Table 1.2). All of these sites were reforested after reclamation using strike-off FRA techniques. These sites were chosen to extend the time series data produced by Maharaj et al. (2007 a, b). For further information about site descriptions see Maharaj et al. (2007b) and Agouridis et al. (2012).

Soil samples were collected from the reclaimed coal mine sites of various ages post-reclamation. Samples were taken from a “time 0” site, which was reclaimed during the year of sampling, and then sites reclaimed 10, 12, 13, and 18 years old. Both bulk and high-resolution soil sampling was conducted at all sites. For bulk sampling, the method of sampling was replicated from Maharaj et al. (2007b). The intervals used were 0-10, 10-40, and 40-50 cm, where there were no impediments to reaching those depths. For the purpose of studying the variability of soil characteristics over each individual site, three sets of composite samples from the aforementioned intervals were taken via soil auger. To examine possible variability over relatively small areas, these sets were taken from within 5-10 m of each other.

For high-resolution sampling, a soil pit was dug to 50 cm, where no impediments were present. Samples were taken at 2 cm intervals down to 20 cm, and then at 5 cm intervals down to 50 cm. A tape measure was placed inside the trench; each interval depth was measured down from the surface, and then samples were taken with a masonry trowel and bagged. In between sample collections, the masonry trowel was wiped clean to avoid contamination. Approximately 200 g of soil was collected from each interval. Samples were oven dried and visible stems, roots, and coal pieces removed, and samples were then homogenized using a Retsch Mortar Grinder RM 200.

Soil organic carbon on the soil samples was determined using thermogravimetric analysis (TGA), a technique that measures mass loss during incremental heating of a sample (Coats and Redfern, 1963). TGA was analyzed at the University of Kentucky using a TA Instruments TGA Q50. Standards with known carbon percentages were run with the soil samples for quality control. Weight loss was recorded as temperature was incrementally raised to 1000 °C. The weight (%) of the sample and the temperature (°C) was plotted using the Universal Analysis 2000 TGA program. Taking the derivative of this thermal curve yields the derivative thermogravimetry (DTG) thermal curve. The advantage of having the DTG curve is that it brings out subtle inflections of the TG plot, which allows for thermal events, or peaks on the graph, to be better distinguished (Maharaj et al., 2007a; Figure 1.5). The peaks on the DTG curve represent areas where the sample’s weight is changing at the fastest rate. Thermogravimetry has been shown to be effective in differentiating between organic and inorganic forms of carbon (Maharaj et al., 2007b; Kristl et al., 2016). This differentiation is useful as it can distinguish between “old” carbon, such as coal, and “new” carbon, such as root exudates and detrital matter (Maharaj et al., 2007a). Soil carbon sequestration rates were determined for the upper 10-cm of the soil using the %SOM, soil bulk density and time since reclamation (metric tons/hectare/year).

Soil samples will also be analyzed for total elemental content. To prepare samples for elemental analysis, approximately one gram of sediment was completely digested using concentrated HF, HCl, and HNO_3 acids in a Teflon beaker over heat and quantified for the following elements by high-resolution inductively coupled plasma mass spectrometry (ICPMS): Al, Ca, Fe, K, Mg, Mn, and Na.

Statistical Analysis

Means of survival proportion, overstory height (m) and DBH (cm) data were calculated by 0.04 ha plot for each species. Overstory height for a given plot was calculated as the mean total height of dominant and codominant crown class trees. ANOVA models were then completed for these three dependent variables using PROC MIXED (SAS 9.4), with surface amendment, grading treatment and their interaction as fixed effects. Cell was added to the model as a random effect in order to address challenges imposed by the study design, in which both treatments were applied at the same level, resulting in a modified complete block design. An arcsine transformation was applied to survival data in order to correct for the non-normal distribution found in proportional datasets. Mean comparisons were carried out using the Tukey-Kramer method to account for multiple comparisons ($\alpha = 0.05$).

PROC GLM (SAS 9.4) was used to develop tree-level biomass equations for each destructively sampled species with DBH and woody biomass dry weight as the independent and dependent variables, respectively. Residual analysis suggested a non-linear relationship between variables, so data were log-transformed to meet assumptions of linear regression. The resulting regression equations were applied to collected DBH data for all live trees within plots of the three destructively sampled species. Resulting values were then back-transformed with calculated Baskerville corrections and mean tree and per area aboveground woody biomass estimates were calculated for each plot (Baskerville, 1972). Mean per tree and per area woody biomass values for each species were tested using PROC MIXED (SAS 9.4) with surface amendment, grading treatment and their interaction as fixed effects and plot as a random effect. As above, the Tukey-Kramer post hoc test for multiple comparisons was employed for the ANOVA results.

Measured woody plants were totaled and the proportion contributed by each species was calculated. Mean volunteer stem density was calculated by plot and analyzed using PROC MIXED (SAS 9.4), with surface amendment, grading treatment and their interaction as fixed effects and plot as a random effect. The Tukey-Kramer method was employed for post hoc mean comparisons. Mean proportions of native species stems were calculated and analyzed using a similar model and the Tukey-Kramer method was employed for post hoc comparisons.

Figure 1.1: View of Starfire plots from above in 2016 (Matt Barton)

Figure 1.2: Diagram of Starfire experimental reforestation plots (not representative of relative plot position)

Cell number → Cxx
USFS species code → XXX
Plot number → Pxx

Starfire Cell Key

1 602 7	1 129 14	1 833 21	2 602 28	2 541 35	2 129 42	3 802 49	3 602 56	3 541 63
1 602 6	1 621 13	1 802 20	2 833 27	2 129 34	2 541 41	3 129 48	3 712 55	3 129 62
1 712 5	1 802 12	1 541 19	2 712 26	2 802 33	2 833 40	3 602 47	3 621 54	3 621 61
1 712 4	1 621 11	1 541 18	2 602 25	2 712 32	2 541 39	3 541 46	3 833 53	3 541 60
1 621 3	1 712 10	1 129 17	2 802 24	2 712 31	2 621 38	3 712 45	3 802 52	3 712 59
1 541 2	1 833 9	1 602 16	2 802 23	2 602 30	2 129 37	3 802 44	3 833 51	3 621 58
1 802 1	1 833 8	1 129 15	2 621 22	2 833 29	2 621 36	3 129 43	3 602 50	3 833 57

USFS SPECIES CODE

129 white pine
541 white ash
602 black walnut
621 yellow-poplar
833 northern red oak
802 white oak
712 royal paulownia

4 833 70	4 621 77	4 712 84	5 602 91	5 129 98	5 602 105	6 541 112	6 541 119	6 712 126
4 541 69	4 129 76	4 621 83	5 621 90	5 833 97	5 802 104	6 129 111	6 541 118	6 129 125
4 129 68	4 602 75	4 541 82	5 602 89	5 833 96	5 802 103	6 833 110	6 802 117	6 602 124
4 712 67	4 602 74	4 621 81	5 802 88	5 833 95	5 621 102	6 802 109	6 621 116	6 621 123
4 833 66	4 833 73	4 541 80	5 129 87	5 129 94	5 541 101	6 621 108	6 602 115	6 712 122
4 802 65	4 129 72	4 802 79	5 621 86	5 712 93	5 712 100	6 602 107	6 833 114	6 833 121
4 712 64	4 802 71	4 602 78	5 541 85	5 541 92	5 712 99	6 712 106	6 129 113	6 802 120

TREATMENT PER CELL

1--- Strike-off control
2--- Loose dump control
3--- Loose dump bark
4--- Loose dump straw
5--- Strike-off straw
6--- Strike-off bark
7--- Compacted straw
8--- Compacted bark
9--- Compacted control

7 129 133	7 712 140	7 833 147	8 833 154	8 802 161	8 129 168	9 621 175	9 833 182	9 129 189
7 621 132	7 802 139	7 129 146	8 712 153	8 833 160	8 129 167	9 129 174	9 802 181	9 802 168
7 833 131	7 129 138	7 802 145	8 602 152	8 833 159	8 712 166	9 541 173	9 602 180	9 802 187
7 602 130	7 602 137	7 541 144	8 541 151	8 802 158	8 621 165	9 541 172	9 129 179	9 712 186
7 712 129	7 541 136	7 802 143	8 802 150	8 621 157	8 602 164	9 833 171	9 602 178	9 602 185
7 712 128	7 602 135	7 621 142	8 621 149	8 712 156	8 541 163	9 541 170	9 712 177	9 621 184
7 833 127	7 541 134	7 621 141	8 129 148	8 602 155	8 541 162	9 621 169	9 712 176	9 833 183

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Figure 1.3: Map of Starfire Plots

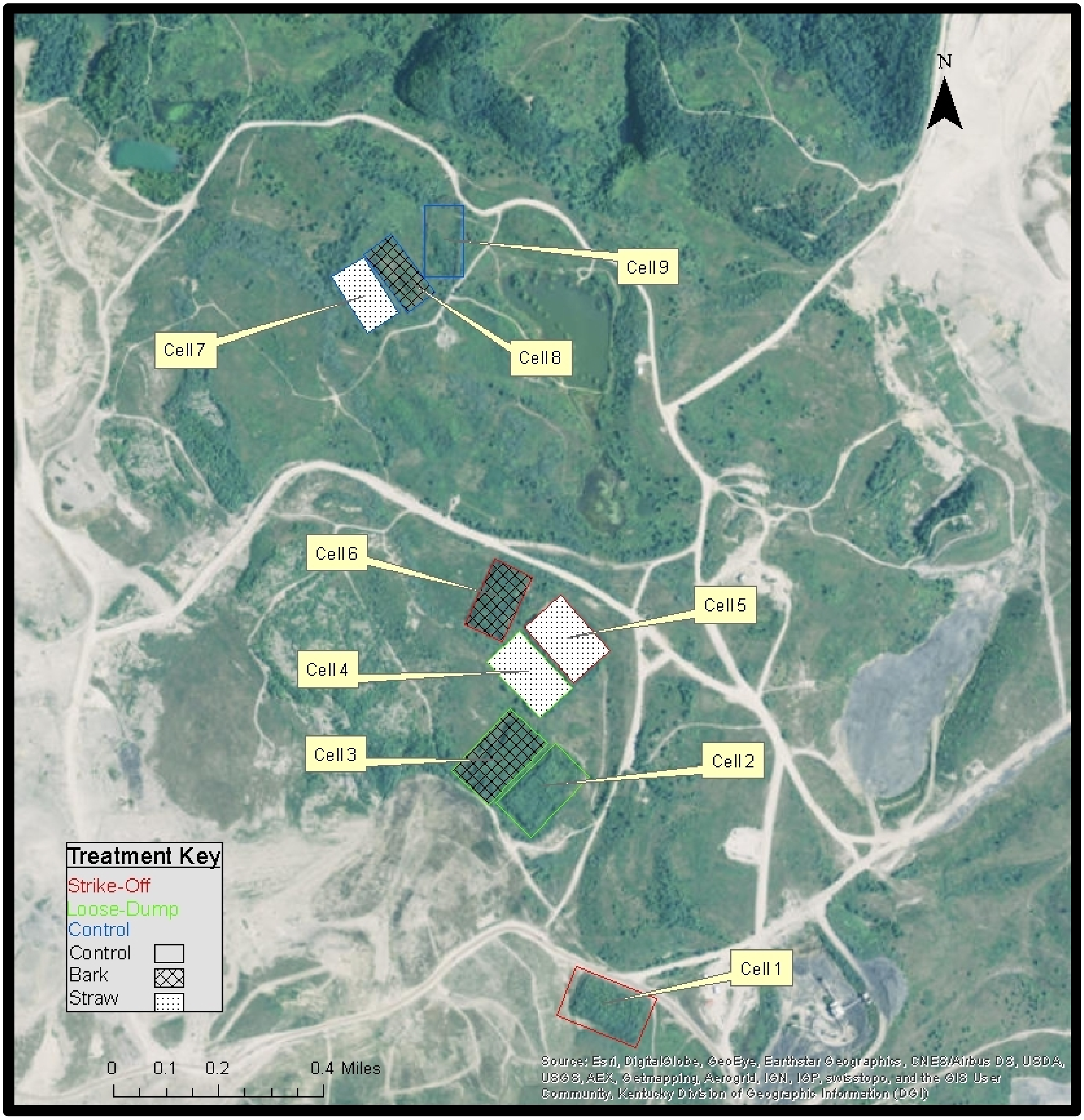

Figure 1.4: Location of soil carbon study sites.

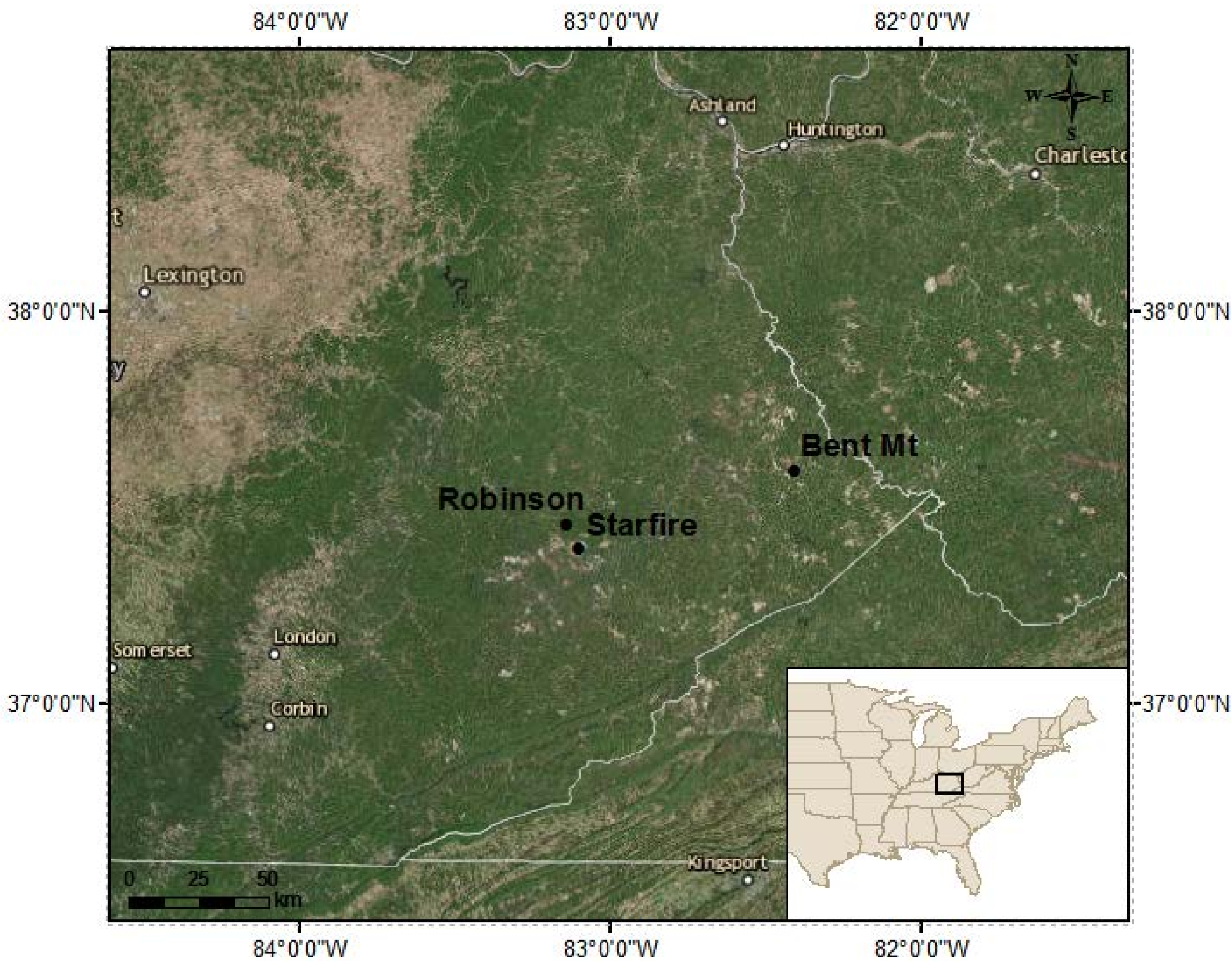

Figure 1.5. Representative TG (I) and DTG (II) plot for grass litter, coal, and limestone (from Maharaj et al., 2007a).

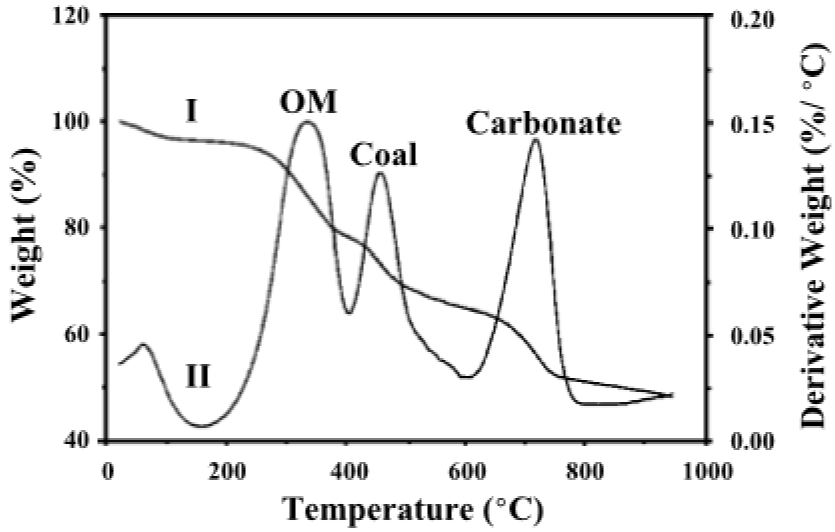

Table 1.1: Average bulk density values for all plots by compaction level in Mg/m^3. Note that strike-off cells are referred to here as "strike-over cells." Average values with different letters are significantly different ($p<0.05$). (From Thomas, 1999)

Loose-dumped cells	Mg/m^3	Strike-over cells	Mg/m^3	Compacted cells	Mg/m^3
# 2	1.49	# 1	2.32	# 7	2.12
# 3	1.32	# 5	1.60	# 8	2.01
# 4	1.38	# 6	1.52	# 9	2.69
Average and SE	1.4^a (SE=0.05)	Average and SE	1.8^b (SE=0.25)	Average and SE	2.3^c (SE=0.21)

Table 1.2: Descriptions of the control and reclaimed mine sites.

Site Name	Years Post-Reclamation	Latitude/Longitude	County
Robinson Forest	Undisturbed	37.464° N, 83.141° W	Breathitt
Starfire Mine	0	37.39851° N, 83.09879°W	Knott
Bent Mountain	10	37.59942° N, 82.408140°W	Pike
Bent Mountain	12	37.60211° N, 82.41103° W	Pike
Starfire Mine	13	37.40977° N, 83.11844° W	Perry
Starfire Mine	18	37.41151° N, 83.12571° W	Knott

Figure 1.6: Construction of experimental cells (from Thomas, 1999).

Figure 1.7: Grading of control cells to achieve compaction typical of conventional reclamation (from Thomas, 1999).

Figure 1.8: Dumping of spoil carried out for loose-dump and strike-off cells (from Thomas, 1999).

Figure 1.9: View of two loose-dump cells following construction (from Thomas, 1999).

Figure 1.10: View of a strike-off cell following grading. The surface is less irregular than in loose-dump cells (from Thomas, 1999).

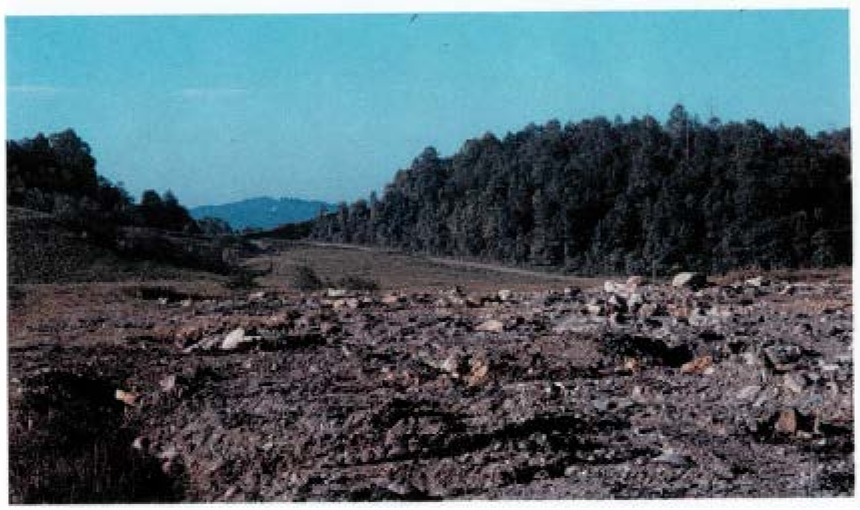

Figure 1.11: Application of bark mulch amendment (from Thomas, 1999).

Figure 1.12: Application of straw mulch amendment (from Thomas, 1999).

Figure 1.13: Hydro-seeding herbaceous groundcover in 1996 (from Thomas, 1999).

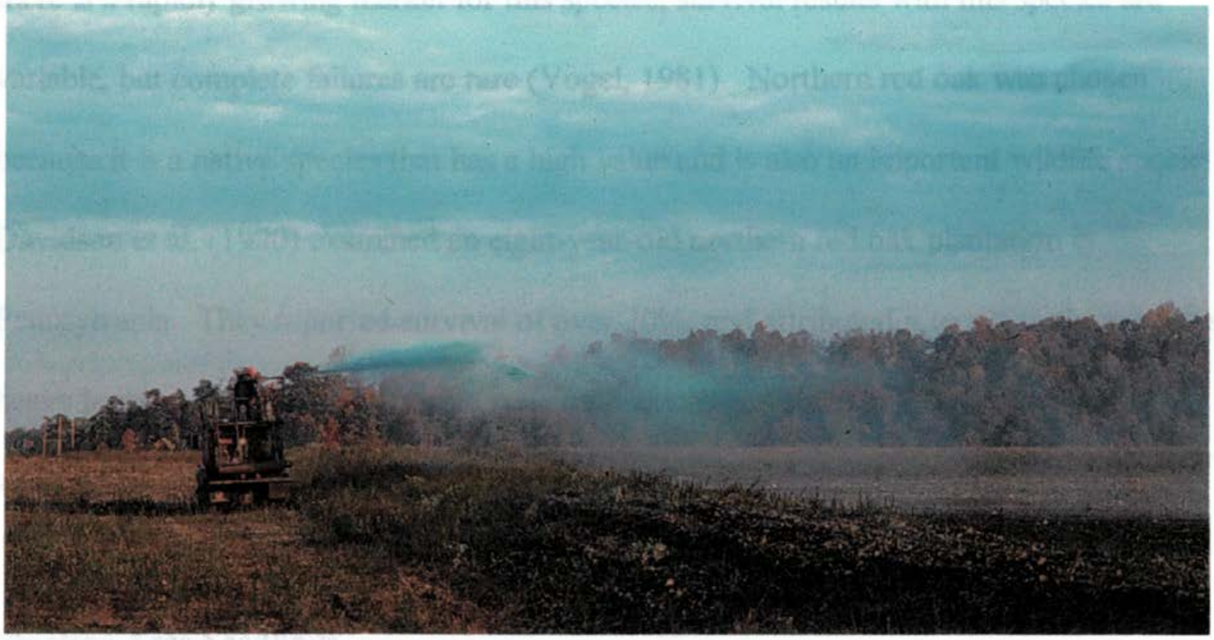

Figure 1.14: Professional tree planters planting trees in a control compacted cell (from Thomas, 1999).

Figure 1.15: Field technicians process an eastern white pine for biomass measurements.

Results and Discussion

Results

Survival

Survival rates for all species combined can be seen in Table 1.3. This measure showed a significant interaction effect between grading and surface amendment treatments. Values ranged from 9.376 % for control/straw plots to 85.574 % for loose-dump/straw plots. Survival for loose-dump plots exceeded 80% regardless of surface amendment, while survival for strike-off plots ranged from 51.5% to 67.333%.

Our ANOVA model indicated that grading treatment was the only variable with a significant effect on survival for eastern white pine. The mean proportion of surviving trees of this species ranged from 2.9% for control plots to 84.0% for loose-dump plots, with strike-off plots exhibiting an intermediate value at 49.5% (Table 1.4). Each of these proportions was significantly different from the other two.

The interaction of grading treatment and surface amendment was statistically significant for white ash; differences in survival were therefore been tested across levels of one variable while holding the other constant (Table 1.5). This species exhibited the highest overall survival with values ranging from 58.7% for cells receiving control grading treatment and straw surface amendment to 97.4% for cells receiving loose-dump and straw treatments. While there were few statistically significant differences within our comparisons, both loose-dump and strike-off treatments showed generally higher survival than the control grading treatment.

As in the case of white ash, the interaction between grading and surface amendment treatments significantly affected survival of black walnut. Proportions of surviving trees of this species were likewise presented across levels of one variable while holding the other constant (Table 1.6). The minimum and maximum survival for this species were again seen in cells with control grading treatment and straw surface amendment (0.8%) and cells with loose-dump and straw amendment (77.0%). A general trend toward higher survival for strike-off and loose-dump treatments versus the control grading treatment was also apparent for black walnut.

Yellow-poplar survival, which exhibited a significant interaction effect, ranged from 2.2% for the control/straw treatment combination to 86.3% for cells with loose-dump and control treatments (Table 1.7). This species exhibited a clear positive trend in survival across control (2.2 - 16.6%), strike-off (40.5 - 59.3%), and loose-dump (78.1 – 86.3%) grading treatment levels.

White oak survival was significantly affected by the interaction of grading and surface amendment treatments and is presented in the same manner as the three species above (Table 1.8). Survival values for this species varied from 4.0% for the control/straw treatment level combination to 92.2% for the loose-dump/straw treatment level combination. As was the case for yellow-poplar, white oak survival was lowest for the control level of grading treatment (4.0 – 44.9%) and highest for the loose-dump level (79.8 - 92.2), with strike-off falling between (56.4% - 77.5%).

Survival of northern red oak was significantly affected by grading treatment alone (Table 1.9). Cells receiving the control level of this treatment showed a mean proportion of 0.174 trees surviving. Strike-off cells exhibited 54.2% survival, while loose-dump cells had 81.7% survival. As was the case for eastern white pine, each of these results was significantly different than the others.

Mean Overstory Height

Mean overstory height (MOH) values for all species can be seen in Table 1.10. Heights were lowest in control graded plots (6.902 to 7.684 m). Heights for strike-off and loose-dump plots were generally not statistically different from one another and ranged from 9.034 to 11.817 meters. All strike-off and loose-dump cells significantly exceeded control graded cells for this metric except for the strike-off/control treatment combination.

MOH values for eastern white pine are presented in Table 1.11. The mean value for the control level of this treatment was non-estimable due to its very low survival (0.029). Strike-off and loose-dump levels exhibited mean heights of 12.551 and 13.509 meters respectively, which were not significantly different.

MOH values for white ash showed a significant interaction between grading and surface amendment treatments and were presented across levels of one variable while holding the other constant (Table 1.12). Values ranged from 6.131 meters for control/bark cells to 11.849 meters for strike-off/straw cells.

Black walnut MOH values (Table 1.13) were significantly affected by grading treatment alone. As was the case for eastern white pine, the value for this measure was not estimable for the control level due to its very low survival. MOH values for strike-off and loose-dump levels of this treatment were 8.849 and 9.002 meters, which are not significantly different.

Yellow-poplar MOH values were significantly affected by both grading and surface amendment treatments but do not show a significant interaction between these two variables. Means were therefore presented for the levels of one treatment while pooling values of the other (Table 1.14). Strike-off and loose-dump levels of grading treatment exhibited significantly higher MOH than the control level of this treatment. When grading treatment was pooled, the straw level of surface amendment treatment was significantly greater than control and bark treatments.

As with yellow-poplar, MOH values for white oak were significantly affected by grading and surface amendment treatments but did not show a significant interaction between these two variables and have been presented in Table 1.15 for levels of one treatment while pooling values of the other. MOH values for white oak across grading treatment levels followed the same trend as yellow-poplar, with strike-off and loose-dump levels significantly higher than control. Both bark and straw levels of surface amendment treatment significantly exceeded MOH values for this treatment's control.

MOH values for northern red oak have been presented in the same manner as those for yellow-poplar and white oak due to the presence of a significant effect of both grading and surface amendment treatments and the absence of a significant interaction between the two (Table 1.16). Once again, both strike-off and loose-dump cells significantly exceeded cells receiving control level of grading treatment. Surface amendment values followed the pattern seen for yellow-poplar, with straw cells exhibiting a significantly higher MOH than both control and bark cells.

Mean DBH

DBH means for all species combined are listed in Table 1.17. Values ranged from 4.243 cm for control/straw plots to 11.175 cm for strike-off/straw plots. Strike-off/straw and loose-dump/straw (10.664 cm) plots were statistically similar to each other but greater than all other treatment combinations. No other significant differences were evident for these values.

The ANOVA model for eastern white pine DBH indicated a significant interaction between grading treatment and surface amendment type. Means are therefore presented in Table 1.18 for levels of one variable while holding the other constant. Mean values ranged from 0 cm in control/straw cells to 20.235 cm in strike-off/straw cells.

Mean DBH values for white ash are presented in Table 1.19 and have been pooled for levels of one treatment in order to view the effects of the other. Strike-off cells exhibited a significantly higher mean DBH (6.817 cm) than control and loose-dump cells (5.199 and 5.775 cm respectively). Cells receiving straw surface amendment significantly exceeded control and bark cells (7.649, 5.030 and 5.113 cm respectively).

Black walnut DBH data indicated a significant interaction between grading and surface amendment treatments and are presented for levels of one variable while holding the other constant in Table 1.20. Values ranged from 1.567 cm for control/straw cells to 7.694 cm for loose-dump/straw cells.

Yellow-poplar DBH values were significantly affected by both grading and surface amendment treatments but do not show a significant interaction between these two variables. Means are therefore presented for the levels of one treatment while pooling values of the other (Table 1.21). Values ranged from 7.504 cm for control grading cells to 9.890 cm for cells receiving straw surface amendment, but no significant differences in DBH were seen across either treatment.

White oak DBH values were significantly affected by grading treatment alone; mean values are presented in Table 1.22. Values for strike-off and loose-dump cells (8.367 and 7.502 cm respectively) did not differ significantly but are both significantly larger than the mean value for control cells (3.882 cm).

Northern red oak DBH values were significantly affected by both grading and surface amendment treatments but do not show a significant interaction between these two variables. Means are presented for the levels of one treatment while pooling values of the other (Table 1.23). Greatest mean DBH within levels of grading treatment was observed in strike-off cells (10.300 cm) and the lowest mean value was exhibited in control cells (5.176 cm). Loose-dump cells had an intermediate mean value of 7.924 cm. The greatest mean value within surface amendment treatment was 9.409 cm, which was exhibited in cells receiving straw. Bark and control cells had means of 6.818 and 7.173 cm respectively.

Basal Area

Estimated basal area per hectare values for eastern white pine are shown in Table 1.24. This variable was significantly affected by grading treatment alone. Cells receiving no mulch amendment showed significantly larger values for strike-off and loose-dump (45.502 and 50.487, respectively) grading levels than for the control grading level (5.980). For both bark and straw amended plots, control graded plots had significantly lower basal areas than strike-off plots, which were in turn significantly lower than loose-dump plots receiving the same type of mulch.

Basal area per hectare for white ash (Table 1.25) showed a significant interaction between grading and amendment variables. Basal area values for this species varied less widely than was the case for eastern white pine, ranging from 5.069 to 18.505. Plots receiving the strike-off/straw treatment combination (18.505) showed significantly higher basal area than control/straw plots and strike-off/control plots (8.719 and 5.069, respectively).

Black walnut also exhibited a significant interaction between treatment variables for this metric. Values are reported in Table 1.26. Basal area for this species was greatest in loose-dump/straw cells (12.413) and strike-off/bark plots (10.784) and lowest in control/straw (0.015) and control/bark plots (0.809).

Basal area per hectare for yellow-polar is presented in Table 1.27. This species also showed a significant interaction effect between grading and amendment treatments, and values ranged from 1.902 in control/straw plots to 28.988 in loose-dump/straw plots. Values for strike-off/straw plots (25.199) and loose-dump straw plots were statistically similar to each other but significantly higher than those for other treatment combinations. Regardless of surface amendment, strike-off and loose-dump plots showed generally higher values for this metric.

White oak basal area values are presented in Table 1.28. This species shows a significant interaction effect between grading and amendment treatments. Values range from 0.466 for control/straw plots to 21.326 for loose-dump/straw plots, with the latter significantly greater than the former but statistically similar to strike-off/straw cells at 16.629. As was the case for yellow-poplar, values were generally higher for strike-off and loose-dump plots than for control graded plots.

Basal area values for northern red oak are presented in Table 1.29. As was the case for the other hardwoods, this species showed a significant interaction effect between grading and amendment treatments. The lowest value, 1.102, occurred for control/bark plots, while the highest occurred for loose-dump/straw plots (25.078). Strike-off and loose-dump plots again exhibited generally higher values for this metric than their control counterpart regardless of surface amendment.

Aboveground Biomass Estimation

Plots of log-transformed values for total dry biomass by DBH and lines of best fit for eastern white pine, white oak and yellow-poplar are presented in Figures 1.16 – 1.18. Calculated regression equations for destructively sampled species are listed in Table 1.30. The R-squared value for the eastern white pine regression was lowest at 0.8428, likely owing to the smaller sample size for this species. Root mean square error (RMSE) for this species’ regression was 0.11297. The regression for yellow-poplar explained nearly 95% of the variability in the data (R-squared = 0.9477) and had RMSE of 0.15515. For white oak, the regression had an R-squared of 0.9358 and RMSE of 0.13129.

Table 1.31 shows mean dry biomass for individual eastern white pine trees. These data are presented for each level of grading and surface treatments across the levels of the other due to a significant interaction effect. Values ranged from 83.628 kg for control/straw cells to 174.12 kg for loose-dump/straw cells.

Mean individual dry biomass for white oak was significantly affected by grading treatment alone (Table 1.32). Strike-off and loose-dump levels of this treatment both significantly exceeded the control.

Mean individual biomass for yellow-poplar is presented for each treatment while pooling the other (Table 1.33). Mean values ranged from 18.143 kg for bark cells to 41.525 kg for straw cells. Individual biomass did not differ significantly among levels of grading treatment or surface treatment.

Per-area, mean dry woody biomass (Mg/ha) for eastern white pine was significantly affected by grading treatment alone (Table 1.34). Values for control, strike-off and loose-dump levels of this treatment (7.698 Mg/ha, 144.92 Mg/ha and 192.85 Mg/ha respectively) were all significantly different from the other levels.

Table 1.35 shows mean biomass per hectare for white oak for each level of grading and surface treatments across the levels of the other due to a significant interaction effect. The smallest mean value was seen in control/straw cells (1.707 Mg/ha) while the largest was seen in loose-dump/straw cells (80.012 Mg/ha).

Mean values for per hectare biomass in yellow-poplar showed a significant interaction of the two treatments and are therefore presented in much the same manner as values for white oak in Table 1.36. The smallest and largest values (6.982 and 98.546 Mg/ha) were again exhibited by control/straw and loose-dump/straw treatment combinations. Both strike-off/straw and loose-dump/straw treatment combinations significantly exceeded the control/straw combination.

Aboveground Carbon Accumulation

Mean aboveground C for the three species examined was 44,938 Kg ha^{-1} (Table 1.37). Aboveground C varied by tree species as reflected by differences in aboveground biomass with white oak exhibiting the lowest rates (mean = 25,845 Kg ha^{-1}) and white pine with the highest (mean = 66,136 Kg ha^{-1}). Mean C sequestration rates for the period were 3.48, 2.25 and 1.36 Mg ha^{-1} yr^{-2} for white pine, yellow-poplar and white oak, respectively. Overall mean C sequestration rate for the 19 year period for the three species combined was 2.36 Mg ha^{-1} yr^{-2}.

Soil Carbon Accumulation

In bulk soil samples we saw the % SOC increase from less than 0.2% at time 0 to greater than 2% by year 13 and a drop to 1.5% by year 18 at the surface (0-10 cm) (Figure 1.19). The 13 and 18 year SOC levels compare well to that observed in an unmined second growth forest (1.7% SOC). SOC increases in the 10-40 cm and 40-50 cm depths showed a similar increasing trend over time, but levels were much lower than at the surface where root turnover is high and litter accumulates. In the fine resolution soil sampling we observed a similar trend as that exhibited in the bulk samples (Figure 1.20). At the 2-cm soil depth we find SOC enrichment to levels above 2% in the 12-year and older stands. We also observe a general increase in SOC in the upper 20-cm in those older stands. Below 20-cm, only the 18 year stand and the forest control exhibit SOC levels greater than 0.5% suggesting that C is accumulating due to increased rooting depth.

Using previously collected data (Maharaj et al., 2007), a chronosequence of soil carbon accumulation was developed for the Bent Mountain and Starfire locations (Figure 1.21). Soil C increased from 324 to 19,565 Kg ha^{-1} at Bent Mountain over a 12-year period. At Starfire, soil C increase from 1,035 to 26,185 Kg ha^{-1} between years 3 and 13, suggesting a higher accumulation rate than Bent Mountain. Oddly, C accumulated in year 18 at Starfire drops to 17,343 Kg ha^{-1}, which could be a function of stand dynamics or sampling relic. Regardless, soil C is exhibiting a general increase over time as the forest stands grow.

Volunteer Woody Vegetation

A total of 5,092 woody plants of 36 species were identified within the experimental plots, as shown in Table 1.38. Thirty-one of the recorded species were native to the region while five were exotic and potentially invasive species. Approximately half of the recorded stems (2,543) were American sycamore (*Platanus occidentalis*). The non-native and invasive autumn olive (*Elaegnus umbellata*) accounted for approximately 13 percent of the volunteer plants with a total of 663 stems recorded. Red maple (*Acer rubrum*) comprised slightly less than 13 percent of measured stems with a total of 659 individuals. A total of 277 stems of the non-native tree of heaven (*Ailanthus altissima*) were found, accounting for approximately five percent of measured stems. The remaining species recorded on site comprised the final nineteen percent of surveyed stems.

Included in Table 1.39 is a summary of woody colonizing plants identified on the study site after eight growing seasons in a previous study. At that time, 4,877 stems of 24 species were found. As was the case in the current study, sycamore was the most prevalent colonizer with a total of 2607 stems or approximately 53 percent of the total stems. Red maple was the second-most prevalent species with 721 stems or approximately 15 percent of total stems. 333 black locust (*Robinia pseudoacacia*) individuals were found, representing approximately 7 percent of total stems found. Sumac species (*Rhus* species) and tree of heaven each comprised about 4 percent of the total stems, with 212 and 192 individuals, respectively. The remaining species comprised the final 17 percent of identified stems.

<u>Mean volunteer stem density</u>

Mean volunteer stem density exhibited a significant interaction between grading and surface amendment treatments; values are therefore presented for levels of one variable across levels of the other (Table 1.40). Values ranged from 179 stems per hectare for the control/straw treatment level combination to 1,695 stems per hectare for cells receiving loose-dump/straw treatments. For both control and bark levels of amendment treatment, stem density was significantly higher in loose-dump cells than in strike-off cells, which exhibited significantly higher stem density than control cells.

This pattern of statistically significantly increases in stem density as compaction decreases was not shown in cells receiving the straw amendment; while values for strike-off/straw and loose-dump/straw were greater than the control/straw combination, the values were not significantly different. Overall, the control level of grading treatment showed the lowest values (179 to 228) and the loose-dump level exhibited the highest values (453 to 1695), with strike-off cells intermediate (444 to 744).

Percentage of volunteer stems of native species

As in the case of mean stem density, mean percentages of native species stems exhibited a significant interaction between grading and surface amendment treatments. Values are therefore presented in much the same way as for mean stem density in Table 1.41. Values ranged from 31.2 percent native stems for cells with control/control treatment combination to 95.5 percent for cells receiving the loose-dump/bark treatment combination.

Table 1.3: Mean survival percentage for all species and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	33.166a* ± 0.724	51.500a* ± 0.069	81.346b* ± 0.202
Bark	19.916a*† ± 0.619	67.333b* ± 0.128	81.057b* ± 0.095
Straw	9.376a† ± 0.516	60.882b* ± 0.178	85.574c* ± 0.147

Table 1.4: Eastern white pine mean survival percentage and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	7.442a* ± 3.39	45.417ab* ± 0.169	87.990b* ± 0.835
Bark	2.180a* ± 0.157	59.865b* ± 0.268	86.544b* ± 0.031
Straw	0.826a* ± 0.000	43.152ab* ± 0.457	76.678b* ± 0.337

Table 1.5: White ash mean survival percentage and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	76.973a* ± 0.359	66.960a* ± 0.018	88.658a* ± 2.983
Bark	77.518a* ± 0.105	84.540a* ± 0.560	78.938a* ± 0.810
Straw	58.745a* ± 1.336	81.827ab* ± 0.218	97.415b* ± 0.662

Table 1.6: Black walnut mean survival percentage and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	47.012a* ± 1.567	45.447a* ± 0.048	67.548a* ± 1.719
Bark	7.479a*† ± 1.408	75.981b* ± 0.690	64.623b* ± 0.263
Straw	0.826a† ± 0.000	47.661b* ± 0.010	76.796b* ± 1.110

Table 1.7: Yellow-poplar mean survival percentage and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	9.306a* ± 1.368	40.479b* ± 0.045	86.290c* ± 0.433
Bark	16.582a* ± 0.849	54.634b* ± 0.492	79.158b* ± 0.080
Straw	2.157a* ± 0.317	59.276b* ± 0.134	78.150b* ± 0.163

Table 1.8: White oak mean survival percentage and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	44.869a* ± 1.238	56.432ab* ± 0.785	79.772b* ± 0.825
Bark	17.621a*† ± 0.667	69.167b* ± 0.027	88.702b* ± 0.850
Straw	4.041a† ± 0.347	77.460b* ± 0.539	92.187b* ± 0.104

Table 1.9: Northern red oak mean survival percentage and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	20.591a* ± 3.121	54.006ab* ± 0.606	74.427b* ± 0.644
Bark	12.337a* ± 0.227	56.512b* ± 0.131	85.129b* ± 0.005
Straw	19.876a* ± 0.617	52.130ab* ± 0.421	84.843b* ± 0.193

Table 1.10: Overstory height means (m) and standard errors for all species by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Grading		
Amendment	Control	Strike-Off	Loose-Dump
Control	7.451a* ± 0.524	9.034ab* ± 0.415	9.800b* ± 0.546
Bark	6.902a* ± 0.438	10.401b*† ± 0.294	10.596b* ± 0.461
Straw	7.684a* ± 0.812	11.817b† ± 0.441	11.483b* ± 0.445

Table 1.11: Eastern white pine overstory height means (m) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Grading		
Amendment	Control	Strike-Off	Loose-Dump
Control	8.448a* ± 0.961	11.849ab* ± 0.326	13.032b* ± 0.430
Bark	8.799a* ± 2.174	11.872ab* ± 0.056	13.794b* ± 0.250
Straw	Non-estimable	13.931a* ± 0.239	13.701a* ± 0.112

Table 1.12: White ash overstory height means (m) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Grading		
Amendment	Control	Strike-Off	Loose-Dump
Control	7.115a* ± 0.498	7.965a* ± 0.284	9.875a* ± 0.088
Bark	6.131a* ± .0.455	9.717b* ± 0.151	10.376b* ± 1.665
Straw	6.411a* ± 0.371	11.849b† ± 0.350	10.615b* ± 0.409

Table 1.13: Black walnut overstory height means (m) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Grading		
Amendment	Control	Strike-Off	Loose-Dump
Control	8.317a* ± 0.666	7.273a* ± 0.349	8.240a* ± 1.296
Bark	Non-estimable	9.943a* ± 0.525	9.388a* ± 0.837
Straw	Non-estimable	9.332a* ± 0.848	9.380a* ± 0.166

Table 1.14: Yellow-poplar overstory height means (m) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Grading		
Amendment	Control	Strike-Off	Loose-Dump
Control	8.261a* ± 2.719	9.636a* ± 0.185	10.250a* ± 1.300
Bark	7.365a* ± 0.505	11.048a* ± 0.407	11.002a* ± 0.359
Straw	10.642a* ± 1.425	13.762a* ± 0.092	13.584a* ± 0.574

Table 1.15: White oak overstory height means (m) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Grading		
Amendment	Control	Strike-Off	Loose-Dump
Control	5.001a* ± 0.540	7.305a* ± 0.106	7.354a* ± 1.110
Bark	7.237a* ± 0.028	8.802a* ± 0.882	9.567a* ± 0.128
Straw	5.151a* ± 1.054	10.195b* ± 0.592	9.897b* ± 0.328

Table 1.16: Northern red oak overstory height means (m) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Grading		
Amendment	Control	Strike-Off	Loose-Dump
Control	8.231a*† ± 0.772	10.174a* ± 0.126	10.043a* ± 0.930
Bark	5.721a* ± 0.780	11.025b* ± 0.253	9.447b* ± 0.068
Straw	9.380a† ± 0.742	11.834a* ± 0.381	11.721a* ± 0.960

Table 1.17: DBH means (cm) and standard errors for all species by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$).

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	6.080a* ± 1.034	9.698a* ± 1.200	7.360a* ± 0.897
Bark	5.279a* ± 0.880	9.374a* ± 0.792	7.756a* ± 0.921
Straw	4.243a* ± 1.228	11.175b* ± 1.085	10.664b* ± 0.905

Table 1.18: Eastern white pine DBH means (cm) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	7.527a* ± 7.527	19.883b* ± 1.047	14.966ab* ± 0.593
Bark	8.756a* ± 4.660	15.832b* ± 0.310	15.847b* ±0.574
Straw	Non-estimable	20.235b* ± 0.097	18.325b* ± 0.461

Table 1.19: White ash DBH means (cm) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	5.432a* ± 0.317	4.984a* ± 0.191	4.673a* ± 0.278
Bark	3.797a* ± 0.676	6.486a*† ± 0.285	5.055a* ± 0.398
Straw	6.367a* ± 1.523	8.982a† ± 0.450	7.598a* ± 0.273

Table 1.20: Black walnut DBH means (cm) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	5.696a* ± 0.848	5.979a* ± 0.601	3.987a* ± 0.840
Bark	5.075a* ± 0.658	6.942a* ± 1.181	4.606a* ± 0.169
Straw	1.567a* ± 1.567	6.610b* ± 0.594	7.694b* ± 0.469

Table 1.21: Yellow-poplar DBH means (cm) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	9.769a* ± 2.604	8.542a* ± 0.628	7.167a* ± 0.922
Bark	6.458a* ± 0.600	8.825a* ± 0.080	7.277a* ± 0.084
Straw	6.283a* ± 6.283	12.176a* ± 0.857	11.211a* ± 0.335

Table 1.22: White oak DBH means (cm) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	4.214a* ± 1.306	8.523a* ± 0.275	6.323a* ± 0.417
Bark	3.898a* ± 1.062	7.887a* ± 0.838	7.193a* ± 0.557
Straw	3.536a* ± 1.742	8.691b* ± 0.664	8.991b* ± 0.572

Table 1.23: Northern red oak DBH means (cm) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	4.198a* ± 1.949	10.274b* ± 0.236	7.046ab* ± 0.164
Bark	3.624a* ± 1.051	10.273b* ± 0.273	6.558ab* ± 0.269
Straw	7.707a* ± 2.547	10.353a* ± 0.711	10.166a* ± 0.817

Table 1.24: Eastern white pine basal area per hectare (m^2/ha) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$).

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	5.980a* ± 5.980	45.502b* ± 1.894	50.487b* ± 3.932
Bark	0.964a* ± 0.524	38.516b* ± 3.869	57.911c* ± 4.148
Straw	4.690×10^{-13}a* ± 0	45.666b* ± 6.183	65.057c* ± 3.640

Table 1.25: White ash basal area per hectare (m^2/ha) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	7.341a* ± 1.405	5.069a* ± 0.369	5.662a* ± 1.017
Bark	5.856a* ± 1.340	10.483a*† ± 1.358	6.752a* ± 1.473
Straw	8.719a* ± 3.640	18.505b† ± 2.233	16.035ab† ± 0.694

Table 1.26: Black walnut basal area per hectare (m^2/ha) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	5.424a* ± 2.442	4.865a* ± 0.978	4.399a* ± 2.384
Bark	0.809a* ± 0.567	10.784b* ± 2.675	4.315ab* ± 0.568
Straw	0.015a* ± 0.015	6.281ab* ± 0.966	12.413b* ± 2.060

Table 1.27: Yellow-poplar basal area per hectare (m^2/ha) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	4.233a* ± 3.775	8.532a* ± 1.006	13.936a* ± 2.379
Bark	2.711a* ± 1.310	12.044a* ± 1.513	13.169a* ± 0.340
Straw	1.902a* ± 1.902	25.199b† ± 3.896	28.988b† ± 2.722

Table 1.28: White oak basal area per hectare (m^2/ha) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	3.951a* ± 2.376	11.420a* ± 2.052	9.389a* ± 1.952
Bark	1.966a* ± 1.263	12.700b* ± 2.379	13.171b*† ± 2.060
Straw	0.466a* ± 0.243	16.629b* ± 2.937	21.326b† ± 1.857

Table 1.29: Northern red oak basal area per hectare (m^2/ha) and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	3.588a* ± 1.976	15.526b* ± 1.236	11.045ab* ± 0.598
Bark	1.102a* ± 0.795	16.029b* ± 1.190	10.923b* ± 0.981
Straw	6.880a* ± 3.327	15.394ab*±0.688	25.078b† ± 3.010

Table 1.30: Regression equations for log-transformed biomass sampling data.

	Equation	R^2	**Root Mean Square Error**
Species			
Eastern White Pine	y= -1.485 + 2.047*(x)	0.843	0.113
White Oak	y= -1.937 + 2.285*(x)	0.936	0.131
Yellow-Poplar	y= -2.199 + 2.317*(x)	0.948	0.155

Figure 1.16: Scatterplot with regression line for eastern white pine biomass.

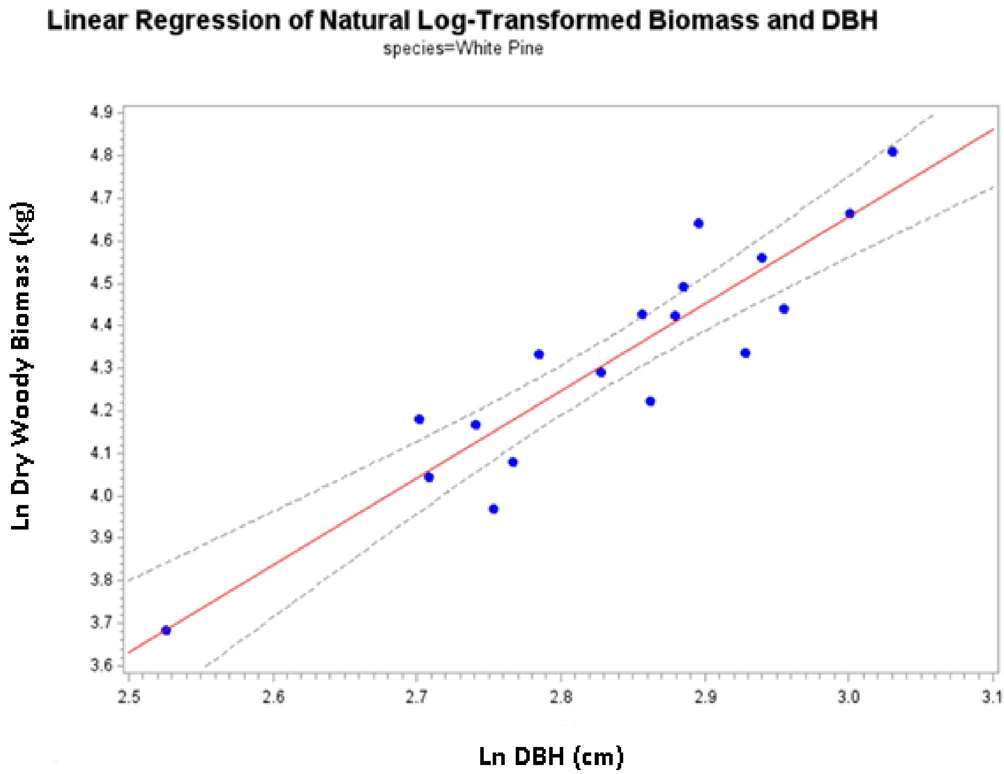

Figure 1.17: Scatterplot with regression line for white oak biomass.

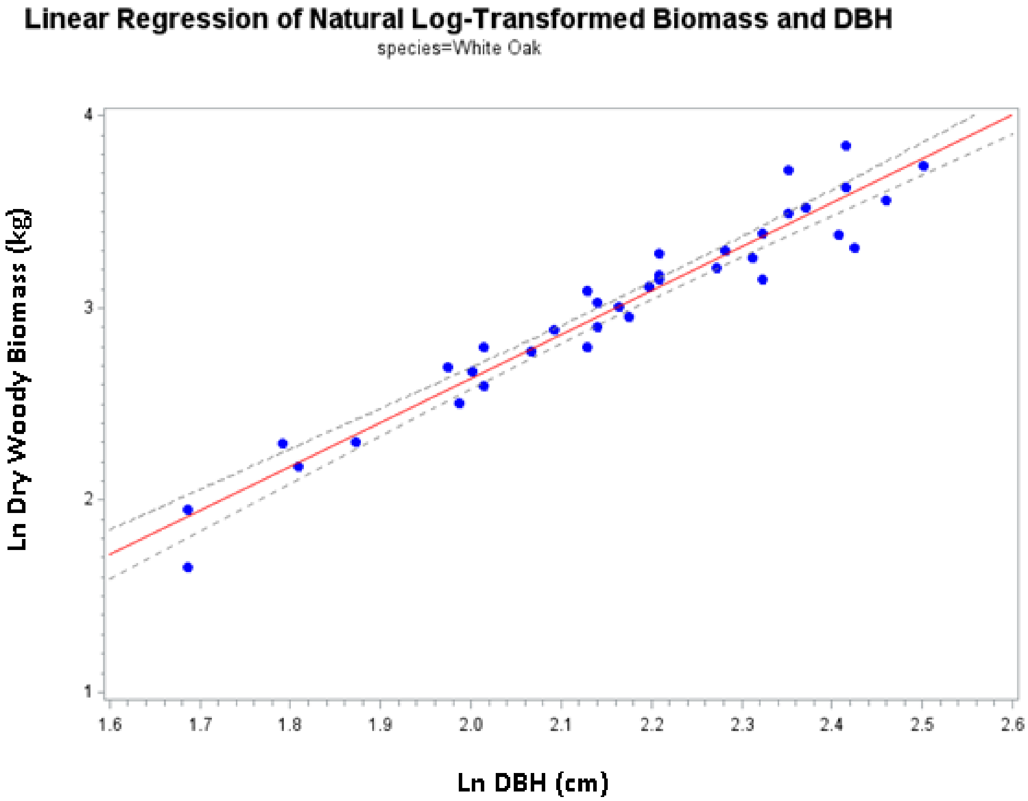

Figure 1.18: Scatterplot with regression line for yellow-poplar biomass.

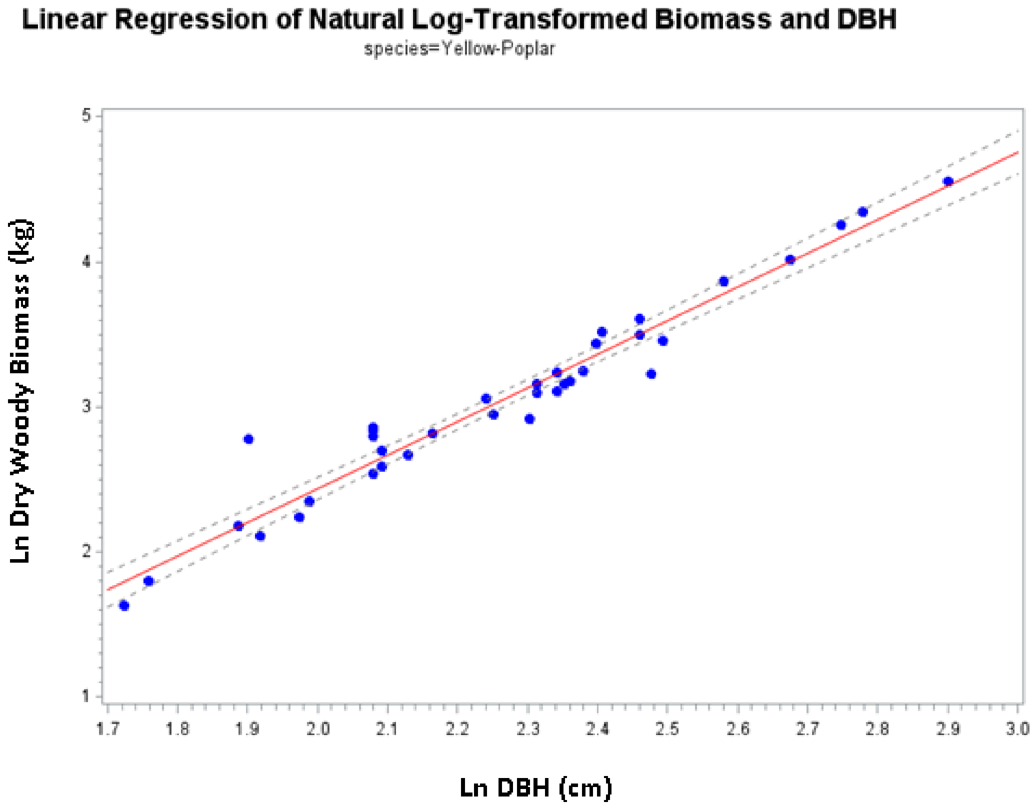

Table 1.31: Eastern white pine dry biomass means (kg) and standard errors for individual trees by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	139.34a* ± 87.330	121.88a* ± 12.714	86.846a* ± 21.105
Bark	134.36a* ± 79.497	140.79a* ± 57.878	104.55a* ± 26.998
Straw	83.628a* ± 68.829	174.12a* ± 46.678	137.88a* ± 36.717

Table 1.32: White oak dry biomass means (kg) and standard errors for individual trees by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	8.137a* ± 4.024	24.277a* ± 3.630	13.201a* ± 1.759
Bark	10.328a* ± 4.490	21.955a* ± 3.630	17.702a* ± 3.229
Straw	8.576a* ± 4.281	26.345ab* ± 3.630	28.874b* ± 3.380

Table 1.33: Yellow-poplar dry biomass means (kg) and standard errors for individual trees by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	32.814a* ± 16.814	21.517a* ± 2.445	17.000a* ± 4.305
Bark	14.847a* ± 2.502	22.649a* ± 0.301	16.932a* ± 0.771
Straw	34.910a* ± 34.910	48.022a* ± 6.464	41.642a* ± 2.941

Table 1.34: Eastern white pine dry biomass means (Mg) per hectare and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different. ($p < 0.05$)

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	19.893a* ± 19.893	152.900ab* ± 6.304	167.630a* ± 13.084
Bark	3.202a* ± 1.737	128.14b* ± 12.951	193.120c* ± 14.184
Straw	2.840a* ± 0.311	153.730b* ± 20.687	217.790c* ± 12.276

Table 1.35: White oak biomass means (Mg) per hectare and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	13.643a* ± 8.439	41.479ab* ± 7.487	32.204a* ± 7.111
Bark	7.488a* ± 4.991	46.301b* ± 9.381	46.654b*† ± 8.171
Straw	1.707a* ± 0.921	61.624b* ± 11.937	80.012b† ± 7.739

Table 1.36: Yellow-poplar biomass means (Mg) per hectare and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	14.938a* ± 13.736	26.335ab* ± 3.320	42.942b* ± 8.396
Bark	8.232a* ± 3.942	37.324a* ± 4.535	40.430a* ± 1.374
Straw	6.982a* ± 6.982	86.649b† ± 14.615	98.546b† ± 10.104

Table 1.37: Aboveground biomass carbon and carbon sequestration rates for yellow-poplar, white pine and white oak.

Plot #	**Species***	**Biomass** (Kg)	**Biomass C** (Kg)	**Trees per Plot**	**Aboveground C** (Kg ha^{-1})	**Sequestration Rate** (Mg C ha^{-1} yr^{-2})
13	YP	26.02	12.00	44	13,204	0.69
83	YP	64.41	28.85	102	73,570	3.87
102	YP	46.77	21.68	77	41,728	2.20
AVG	***YP***				***42,834***	***2.25***
17	WP	87.43	43.59	46	50,126	2.64
62	WP	60.07	28.95	107	77,429	4.08
68	WP	70.62	35.15	83	70,853	3.73
AVG	***WP***				***66,136***	***3.48***
20	WO	15.04	7.03	87	15,281	0.80
104	WO	30.13	13.88	81	28,113	1.48
117	WO	34.55	15.88	86	34,141	1.80
AVG	***WO***				***25,845***	***1.36***
Combined AVG	**All**				**44,938**	**2.36**

*YP = yellow-poplar, WP = white pine, WO = white oak

Figure 1.19: Bulk soil SOC (%) accumulation from time 0 to 18 years since planted on mine sites and in an unmined forested control.

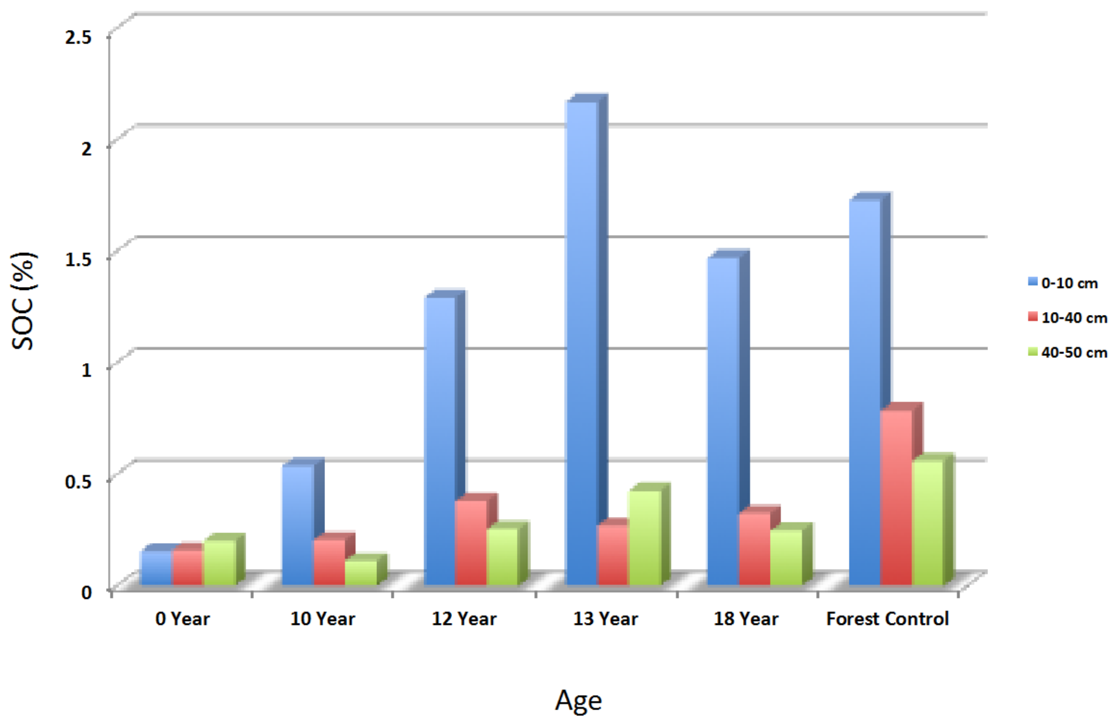

Figure 1.20: Fine resolution soil sample SOC (%) accumulation from time 0 to 18 years since planted on mine sites and in an unmined forested control.

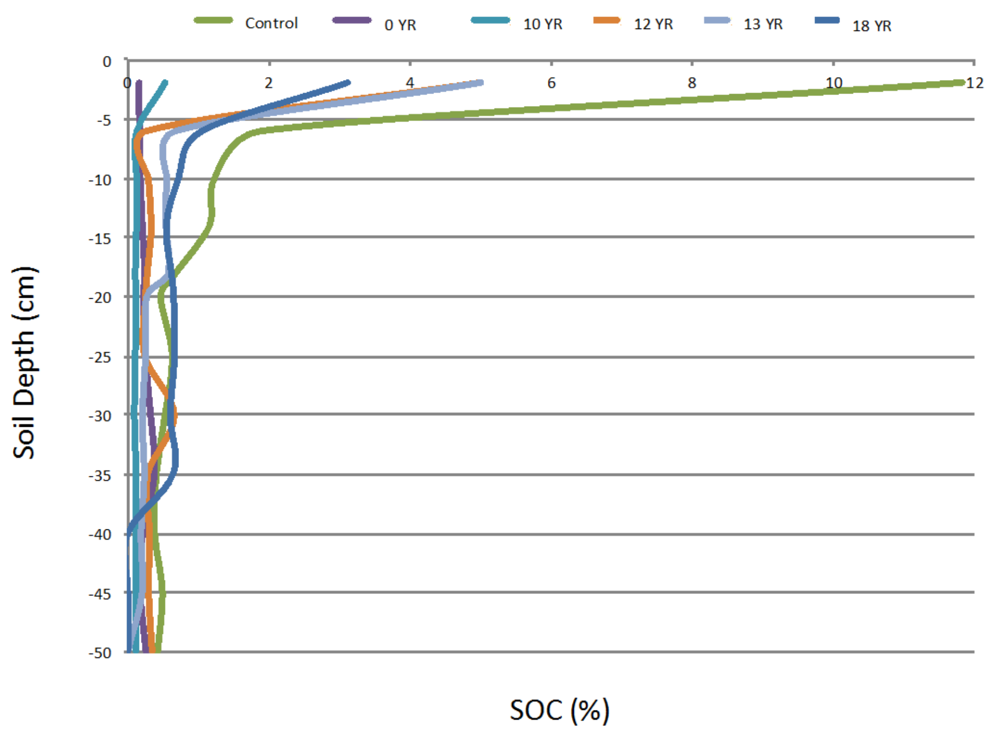

Figure 1.21: Soil C accumulation from a chronosequence of reclamation ages at the Bent Mountain and Starfire mines in eastern Kentucky.

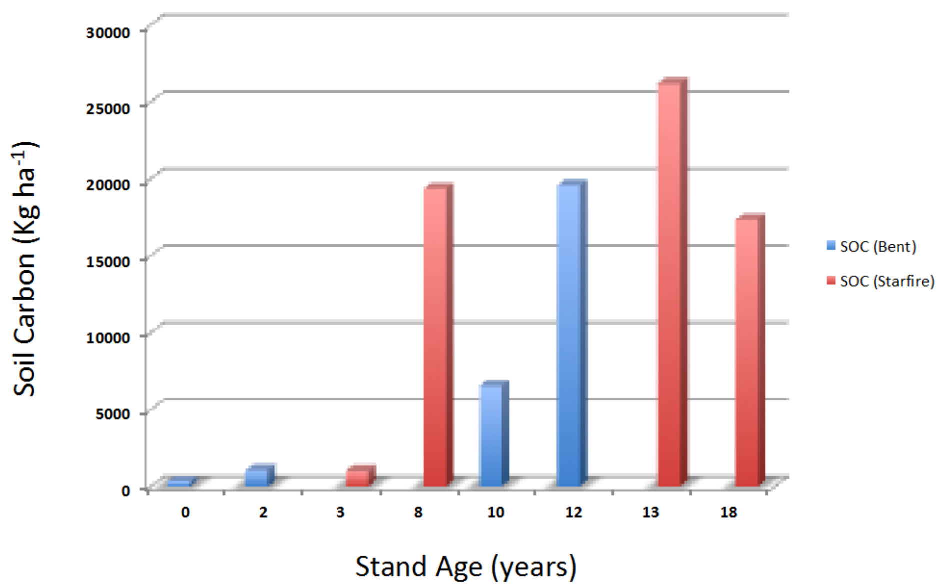

Table 1.38: Summary of volunteer woody plants identified at the Starfire Experimental site in the current study.

Species	Latin Name	Number	Percent
Sycamore	*Platanus occidentalis*	2543	49.94
Autumn Olive	*Elaeagnus umbellata*	663	13.02
Red Maple	*Acer rubrum*	659	12.94
Tree of Heaven	*Ailanthus altissima*	277	5.44
Sweet Birch	*Betula lenta*	172	3.38
Black Cherry	*Prunus serotina*	148	2.91
Sourwood	*Oxydendrum arboreum*	109	2.14
Slippery Elm	*Ulmus rubra*	60	1.18
Black Locust	*Robinia pseudoacacia*	57	1.12
White Ash	*Fraxinus americana*	46	0.9
River Birch	*Betula nigra*	45	0.88
Royal Paulownia	*Paulownia tomentosa*	43	0.84
Yellow-Poplar	*Liriodendron tulipifera*	41	0.81
Redbud	*Cercis canadensis*	35	0.69
Black Willow	*Salix nigra*	25	0.49
Box Elder	*Acer negundo*	24	0.47
Eastern Red Cedar	*Juniperus virginiana*	23	0.45
Virginia Pine	*Pinus virginiana*	23	0.45
Sassafras	*Sassafras albidum*	20	0.39
Sumac	*Rhus spp.*	19	0.37
American Elm	*Ulmus americana*	12	0.24
Flowering Dogwood	*Cornus florida*	9	0.18
Sugar Maple	*Acer saccharum*	5	0.1
Yellow Birch	*Betula alleghaniensis*	5	0.1
Eastern White Pine	*Pinus strobus*	4	0.08
Winged Elm	*Ulmus alata*	3	0.06
Cottonwood	*Populus deltoides*	2	0.04
Tag Alder	*Alnus serrulata*	2	0.04
Callery Pear	*Pyrus calleryana*	1	0.02

Flowering Crabapple	*Malus hopa*	1	0.02
Eastern Arborvitae	*Thuja occidentalis*	1	0.02
Elderberry	*Sambucus canadensis*	1	0.02
Mapleleaf Viburnum	*Viburnum acerifolium*	1	0.02
Mimosa	*Albizia julibrissin*	1	0.02
Paper Birch	*Betula papyrifera*	1	0.02
Red Mulberry	*Morus rubra*	1	0.02

Table 1.39: Summary of volunteer woody plants identified at the Starfire Experimental site after eight growing seasons.

Species	**Latin Name**	**Number**	**Percent**
Sycamore	*Platanus occidentalis*	2607	53.45
Red Maple	*Acer rubrum*	721	14.78
Black Locust	*Robinia pseudoacacia*	333	6.82
Sumac	*Rhus spp.*	212	4.35
Tree of Heaven	*Ailanthus altissima*	192	3.94
Sweet Birch	*Betula lenta*	170	3.49
Black Willow	*Salix nigra*	122	2.50
River Birch	*Betula nigra*	79	1.62
Black Cherry	*Prunus serotina*	78	1.60
Autumn Olive	*Elaeagnus umbellata*	65	1.33
Redbud	*Cercis canadensis*	53	1.09
Royal Paulownia	*Paulownia tomentosa*	50	1.03
Sourwood	*Oxydendrum arboreum*	45	0.92
White Ash	*Fraxinus americana*	43	0.88
Virginia Pine	*Pinus virginiana*	25	0.51
Sassafras	*Sassafras albidum*	16	0.33
Eastern White Pine	*Pinus strobus*	16	0.32
Box Elder	*Acer negundo*	12	0.25
Slippery Elm	*Ulmus rubra*	11	0.23
Cottonwood	*Populus deltoides*	10	0.21
American elm	*Ulmus americana*	9	0.18
Eastern Red Cedar	*Juniperus virginiana*	4	0.08
Pitch Pine	*Pinus rigida*	3	0.06
Mimosa	*Albizia julibrissin*	1	0.02

Table 1.40: Mean volunteer stems per hectare and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	228.570a* ± 47.600	744.050b* ± 58.015	1545.240c* ± 120.670
Bark	189.290a* ± 28.114	614.290b* ± 81.897	1695.240c* ± 212.284
Straw	179.760a* ± 37.899	444.050a* ± 39.260	453.570a† ± 98.369

Table 1.41: Mean percentage of native woody species and standard errors by surface amendment within grading treatment levels. For each row, means with same letter are not significantly different. For each column, means with same symbol are not significantly different ($p < 0.05$). A significant interaction was present between grading and surface amendment treatments for this species.

	Treatment		
Amendment	Control	Strike-Off	Loose-Dump
Control	31.241a* ± 6.048	89.432b* ± 3.277	91.140b*† ± 1.525
Bark	52.817a* ± 7.259	74.101b* ± 4.823	95.501b† ± 0.765
Straw	44.945a* ± 8.785	81.201b* ± 3.963	68.894b* ± 5.942

Discussion

Survival

Five of the six species measured (eastern white pine, black walnut, yellow-poplar, white oak and northern red oak) showed a general positive trend in survival rates as grading compaction decreased from control to loose-dump treatment levels. This trend was apparent in a 2006 inventory of this experimental site, which showed survival rates very near those seen at present (Angel et al., 2006). This suggests that survival of trees on mined sites can be stable during the second decade following planting if conditions are favorable.

White ash, which exhibited high survival rates for all levels of grading preparation, is an exception to the trend seen in other species planted at the Starfire site. High survival rates for white ash and other *Fraxinus* species have been noted in multiple short-term mine land reforestation studies on this site and others (Angel et al., 2006, Sena et al., 2015). Our data suggests that this phenomenon can persist through 20 growing seasons. Unfortunately, white ash is susceptible to the invasive emerald ash borer, which is currently causing widespread mortality in ash species across the eastern United States (Flower et al., 2013). For this reason, it may be unadvisable for this species to be included in reclamation mixtures until either cost-effective methods of controlling this pest have been developed or its population has otherwise decreased. Discussion of productivity of this species is therefore not included below.

Mean Overstory Height

Mean overstory height across measured species was generally greater in those cells receiving strike-off and loose-dump levels of grading treatment than in those receiving the control level of this treatment. In their 2006 study on this site, Angel et al. (2006) found that mean height for all crown classes increased significantly across treatment levels as compaction decreased for all species except white oak and red oak, for which strike-off and loose-dump levels showed significantly greater height than control cells but were not significantly different from each other. While some variation in height was apparent based on surface amendment, it appears that all species now exhibit the pattern previously limited to the oak species. In other words, growth rates of dominant and co-dominant trees in strike-off cells since the previous study have increased to the extent that these trees are no longer significantly shorter than dominant and co-dominant trees in loose-dump cells. This apparent trend may be partially attributable to differences in methodology; the earlier study did not limit measurements to the overstory due to lack of differentiation in the young stand.

Since height growth of dominant and codominant trees is closely tied to volume growth, this metric is employed to estimate site quality and is represented in height index tables, which are most often standardized to heights in feet at 25 years for pine species and 50 or more for hardwood species (Carmean et al., 1989). In the case of eastern white pine, heights for both strike-off and loose-dump spoil preparations exceeded a 25 year plantation site index of 50 feet, which is intermediate for this species on such sites (Carmean et al., 1989). Given that the study site does not offer the favorable growing conditions (i.e. well-drained, fertile soil on lower slopes) of a commercial plantation, this value is promising.

Black walnut heights for strike-off and loose-dump plots indicated a 50-year site index of approximately 40 feet, which falls on the low end of values seen in plantations in the Central states (Carmean et al., 1989). As discussed above, the study site represents a harsher growing environment than that experienced in a plantation. The apparent sensitivity of this species to site quality may indicate that it is not likely to grow at acceptable rates for commercial purposes on FRA sites.

Yellow-poplar heights on the study site indicated a 50-year site index of approximately 75 feet based on curves developed from Appalachian forests in West Virginia (Carmean et al., 1989). This value indicated an intermediate level of productivity on the study site compared to the reference forests. Again, given the harsh nature of the study site, this value is promising.

White oak heights in strike-off and loose-dump cells indicated a site index of about 65 feet based on curves developed from upland sites in eastern Kentucky and surrounding states (Carmean et al., 1989). This value falls on the upper end of the range seen for this species (30 to 80 feet). The study site therefore appears to be highly productive for white oak, which is perhaps not surprising given their ability to tolerate the dry and thin soils often found on upland sites.

Site index for northern red oak on the study site also indicated high productivity, with a 50-year value of 65 feet, which is near the maximum range given for values of this species (40 to 70) as determined on sites in southwestern Wisconsin (Carmean et al., 1989). Again, it is not surprising that oak species would compete well on the study site.

In a 2012 study, Cotton et al. developed height projections for white oak and yellow-poplar on the study site after eight growing seasons as well as regional reference overstory height ranges for these species. White oak overstory heights for strike-off and loose-dump treatments fell squarely in the reference range and exceeded the heights predicted for the site. The same pattern held for height values for yellow-poplar. This suggests that white oak and yellow-poplar height growth has accelerated in the time between Cotton et al.'s study and the current study, and that height growth for these species on the study site has been similar to that seen in regional forests.

Mean DBH

Strike-off and loose-dump levels of grading preparation generally exhibited higher values for DBH for all species except yellow-poplar, which showed no significant difference in DBH growth across levels of either treatment. In the case of white ash and northern red oak, strike-off cells showed significantly higher DBH than loose-dump cells. This general trend was also seen in other species in which there is no significant difference in DBH between strike-off and loose-dump preparations.

Observed differences in mean DBH between strike-off and loose-dump treatment levels is likely due to the lower initial survival (and resultant lower tree densities) seen in strike-off plots. Since individual trees within the strike-off treatment generally experienced lower competition for growing space than trees in the more crowded (higher survival) loose-dump treatment, they are likely to produce more photosynthate unless they receive extremely limited amounts of water or nutrients, which could be the case for trees planted in control plots (Oliver and Larson, 1996). A previous study on the Starfire site found that, at year ten, white oak and yellow-poplar in both strike-off and loose-dump plots tended toward higher DBH to height ratios than trees of the same species on local reference sites but that the effect was more pronounced in strike-off plots (Cotton et al., 2012). These findings reflect that even when survival is high, stem densities on FRA plantings are lower than that often seen in naturally regenerating stands.

Aboveground Biomass Estimation

The highest values for individual tree mean biomass belonged to eastern white pine. This is unsurprising given that trees of this species have larger mean DBH and height values than either white oak or yellow-poplar (see Tables 1.7 and 1.13; 1.10 and 1.16 ; 1.11 and 1.17 for comparison). Eastern white pine has been noted for its relatively fast rate of growth on a variety of site types, and grows particularly quickly between 15 and 45 years of age (Beck, 1971). This suggests that these young trees will continue to grow and accumulate biomass quickly in the coming decades.

For all species, the largest mean individual tree mass occurred within strike-off cells. This is likely attributable to the lower overall survival seen in these cells, which, as discussed above, should afford individual trees a greater amount of theoretical growing space than would be available in the more crowded loose-dump cells. While strike-off plots tend to exhibit higher average per-tree biomass, there is a strong trend toward higher per-area aboveground biomass accumulation evident in loose-dump plots. This aligns with the generally accepted concept that biomass accumulation within a given stand increases as stem density increases (Oliver and Larson, 1996).

There was also a clear trend toward higher aboveground biomass values in plots receiving mulch, particularly in the case of the straw and manure mulch mixture. Cotton et al., 2012 found similar trends on the study site after ten years of growth, and postulated that the addition of mulch served to improve nutrient availability and jumpstart microbial activity in the rocky spoil. This assertion seems to be supported by another study at this site, which found no significant effect of mulches on soil dry bulk density and penetration resistance after ten years (Conrad et al., 2008). If trees are not better able to establish roots and access water in plots receiving mulch, as one might assume given their very similar bulk density values, then the greater growth seen in these plots may be attributable to some other effects of mulch, such as the addition of nutrients and microorganisms.

Control/Straw Treatment Combination

A portion of the species included in this study exhibited a significant interaction effect between grading and surface amendment treatments for one or more measured variables. In the majority of these cases, the interaction appeared to be driven by the combination of control grading and straw surface amendment treatment levels. While the addition of a straw amendment tended to improve all measured variables when paired with strike-off or loose-dump grading preparation, this trend was reversed when straw was present in control grading cells. This phenomenon may be partially attributable to random effects (within the context of this study) related to edaphic or hydrological properties of the plot receiving the control/straw treatment combination. However, Angel et al. 2006 noted that plots receiving straw mulch exhibited higher levels of competition from aggressive grasses and legumes than other plots and speculated that this mulch had both transported seeds and fostered growth of these species. This unintended introduction of competition for growing space likely led to lower initial survival and appears to have retarded growth of some species to the present.

Soil Carbon Accumulation

The combination of global fossil fuel use and the degradation of vegetated lands has caused a dramatic flux of carbon dioxide (CO_2) to the atmosphere (Vitousek et al., 1997; Lal, 2004), and is potentially responsible for the 0.85 °C increase in average global surface temperature since the late nineteenth century (IPCC, 2014). This release of CO_2 into the atmosphere will continue throughout the next century due to projected increases in human population, known fossil fuel reserves, present trends in energy use, and increases in urban development (Littlefield et al., 2013). Three strategies exist to lowering CO_2 emissions: (i) reducing global energy consumption, (ii) developing clean energy, and (iii) sequestering CO_2 from point sources and/or the atmosphere through natural or engineering techniques (Lackner, 2003; Schrag, 2007; Figueroa et al., 2008). Terrestrial carbon sequestration is one subtype of strategy (iii), which takes place in wetlands, forests, and soils (Oren et al., 2001; Chmura et al., 2003; Lal, 2004, 2008). Sequestering carbon by the restoration of degraded soils is a strategy which can reduce net CO_2 emissions (Lal, 2008).

Due to their definite ages, or time since reclamation, mine soils represent an excellent way to study soil development and carbon sequestration changes over relatively short temporal scales (i.e., years to decades) (Chaudhuri et al., 2012). Observable differences in soil parameters are apparent when studying mine soil chronosequences. Through at least the upper 30 cm, SOC concentrations generally show an increase with time since reclamation (Sever and Makineci, 2008; Chaudhuri et al., 2012; Chatterjee et al., 2009; Shukla and Lal, 2005; Akala and Lal, 2000, 2001; Adeli et al., 2013). Akala and Lal (2000) showed that a reclaimed mine soil can sequester up to 30 Mg C ha^{-1} in 25 years. Maharaj et al. (2007b) found that a mine soil in eastern Kentucky was sequestering SOC at an average rate of 2.92 Mg ha^{-1} yr^{-1} after eight years, and had a SOC content of 13 Mg C ha^{-1}. Over time, it has been shown that mine soils begin to approach values of those that are undisturbed, in terms of SOC inventories, or in some cases, surpass them (Akala and Lal, 2001). Akala and Lal (2001) found that within 30 years, a reforested mine site had greater SOC inventories as compared to a forested non-mined site, in both the upper 0-15 and 15-30 cm intervals.

As with these previous studies, data from the FRA sites examined show a similar trend. The Starfire mine showed that the soil was capable of storing over 25 Mg C ha^{-1} in the upper 10-cm in 13 years and the Bent Mountain site stored nearly 20 Mg C ha^{-1} in 12 years. Using the same chronosequence as Maharaj et al. (2007b), we found that mean above and belowground sequestration rates increased from 2.92 to 3.46 Mg C ha^{-1} yr^{-1} between years 8 and 18.

Volunteer Woody Vegetation

This site was found to be generally well-stocked with volunteer woody plants. A few species dominated the site, with *Platanus occidentalis* (American sycamore) by far the most prevalent at nearly 50% of the 5092 measured stems. Sycamore is often associated with the banks of streams and rivers, where it thrives in alluvial soils and tolerates prolonged wet conditions (Burns and Honkala, 1990). However, this adaptable species is also sometimes a pioneer on disturbed upland sites such as abandoned fields and was valued for its ability to grow on surface mines by reclamation specialists as early as the 1940s (Burns and Honkala, 1990; Brothers, 1988). Sycamore's lightweight (1/441,000 kg), wind-dispersed seeds and rapid seedling growth under high light conditions explain its ability to reach and successfully compete in the Starfire stand (Burns and Honkala, 1990). In fact, many individuals appeared to be of dominant or co-dominant crown class and in some cases were taller than the planted trees surrounding them. The number of individuals measured at year eight (2607) slightly exceeded the current number, suggesting that this species was a very early colonizer of the site.

The non-native and invasive shrub autumn olive was the second-most prevalent volunteer species on our study site, making up some 13% of measured stems. This Asian species tolerates shade well and was planted on surface mines for decades due to its ability to fix atmospheric nitrogen and thrive on marginal sites (Michigan DNR 2012, Plass 1975). This species has low palatability for deer and other browsing species (Michigan DNR, 2012). Its small fruits, however, are eaten by many bird species; seeds that pass through birds' digestive tracts have been found to be more likely to germinate than seeds that simply drop to the ground (LaFleur et al., 2009). Avian use of this species as a food source therefore facilitates both spread of seed across the landscape and successful establishment of new stems. This species increased by a factor of ten in the eleven years between the earlier study and the current study, a fact which supports its prolific reproductive potential. Given its characteristics, this species appears likely to remain common on the study site in the foreseeable future.

Acer rubrum (red maple) was the third most common volunteer species found across our site, comprising approximately 13% of all recorded individuals. Red maple is a generalist species that can survive under a wide variety of conditions and produces a large number of wind-dispersed seeds (Burns and Honkala, 1990). Its presence in the Starfire stand is therefore not surprising. While red maple sometimes acts as a pioneer species, it is longer-lived (up to 150 years) and more shade tolerant than many early-successional species (Burns and Honkala, 1990). Seedlings can persist as advance regeneration in the understory for years before disturbance allows for their recruitment into the overstory (Burns and Honkala, 1990). Red maple has become more prevalent in Appalachian forests in recent decades due to a variety of factors (see Alexander and Arthur, 2010; Nowacki and Abrams, 2008). It decreased in prevalence slightly between the year eight study and the current study, from 721 individuals to 659. However, it is likely that this species will continue to occupy a significant portion of the growing space in the Starfire stand in the future and may increase in prevalence.

Ailanthus altissima (tree-of-heaven) comprised approximately five percent of the volunteer stems found on our study site. Tree-of-heaven is a naturalized Asian species known for its ability to tolerate harsh conditions and pioneer disturbed sites through its prolific production of wind-dispersed seeds (Burns and Honkala, 1990). Its vigor on marginal sites led to research on its value in reclamation in past decades, and this species was planted on many surface mines (Plass, 1975). Tree-of-heaven's silvical characteristics often make it a problematic species following forest disturbance, when increased light leads to prolific root spouting that may deprive favored species of growing space (Burns and Honkala, 1990). Its numbers on the study site have increased modestly since year eight, from 192 stems to 277. However, the tree is relatively short-lived and does not tolerate shade well, meaning that any individuals in the Starfire stand that have not reached the overstory will likely decline as the stand continues to mature (Burns and Honkala, 1990).

Of all the species recorded in both of the colonization studies on our site, *Robinia pseudoacacia* (black locust) declined most precipitously, from 333 individuals or some 7 percent of all stems to 57 individuals or approximately 1 percent of all stems. This species initiates growth quickly on disturbed sites with high light availability and tolerates poor soil conditions well, in part due to its ability to fix atmospheric nitrogen (Burns and Honkala, 1990). Such conditions would have existed in the early years of this study, and many others have noted that black locust thrives on harsh strip mine sites (Burns and Honkala, 1990). However, locust is extremely intolerant of shade, being found in closed forests only if it can maintain a dominant crown position (Burns and Honkala, 1990). The growth of planted trees and other volunteer species likely doomed black locust to an early decline in this experimental stand. This species therefore serves as an example of succession in this experimental stand after less than two decades of growth.

The remainder of the species found on site shared many of the characteristics of those described above, including: light seeds dispersed by wind or wildlife; early- or mid-successional status; and relatively short lifespan. Virtually no individuals of heavy-seeded species important to the regional timber industry (i.e. oaks and hickories) were found growing voluntarily. This pattern reinforces the prescription by ARRI researchers to include such late-successional species in FRA plantings in order to accelerate their establishment (Adams, 2017).

The large number of overall species found suggests a high level of diversity within these stands. In the case of an outbreak of a host-specific pest or some other factor leading to mortality in some species, it is reasonable to assume that non-affected species already present on-site would become more competitive. These species would likely utilize newly released growing space and grow in size and number of stems, thereby ensuring sustained stand productivity (Oliver and Larson, 1996). Resilience of forest systems, which can be partially attributed to their biodiversity, is of particular importance given recent widespread mortality events caused largely by invasive pests and the threat of future climate change; neither of these pressures on forests is likely to abate in the near future.

Mean Stem Density

Values for mean stem density varied widely, with the highest value exceeding the lowest by nearly a factor of ten. Mean stem density in loose-dump cells receiving control or bark levels of surface amendment (1545.24 and 1695.24 stems/ha, respectively) exceeded strike-off cells receiving the same surface amendment (744.05 and 614.29 stems/ha) by a factor of two. Cells receiving the control level of grading preparation showed the lowest stem density regardless of surface amendment, with values ranging from 179.79 to 228.57 stems per hectare. This general pattern of increased volunteer stem density as spoil compaction is reduced has been noted in other studies including Gillard and McCarthy, 2014 and Skousen et al., 2006.

Gillard and McCarthy and Skousen et al., however, did not directly compare density of woody species recruitment in loose-dump and strike-off preparations. Our data suggest that even the low degree of compaction exhibited in struck-off cells may result in significantly lower recruitment than in cells left entirely ungraded. The greater heterogeneity associated with loose-dump preparation may in and of itself lead to a wider range of microtopographic conditions suitable for the establishment and growth of various woody species. In the case of loose-dump/control and loose-dump/bark treatment level combinations, the number of volunteer stems alone would exceed Kentucky bond standards for forest post-mining land use, which stipulate that at least 450 woody stems per acre or approximately 1,112 stems per hectare be present at time of bond release (Kentucky DSMRE, 1991).

A previous study on this site gauged the density of volunteer woody stems after eight growing seasons following methods similar to those employed in the current study. The authors found that, after pooling surface amendment treatment, loose-dump plots averaged approximately 1150 stems per hectare, strike-off plots averaged approximately 620 stems per hectare, and control plots averaged about 125 stems per hectare. Pooling surface amendment treatment levels for the current study yields average values of 1231, 601, and 200 stems per hectare for loose-dump, strike-off and control plots, respectively. These values reflect a remarkable stability in the number of volunteer stems for each treatment type over an 11-year period.

Interestingly, neither strike-off nor loose-dump cells receiving the straw surface amendment followed the general pattern of increased colonization with decreased compaction. In fact, even compacted cells receiving straw mulch exhibited lower stem densities than their control or bark mulch counterparts. In their 2006 study on the Starfire site, Angel et al. (2006) speculated that the straw and manure mulch mixture had served to introduce seeds of herbaceous species and foster the growth of such species, leading to heightened competition for resources between these plants and the trees planted on site. In some cases, these cells exhibit decreased survival, height, and DBH for planted trees that is detectable to the present (see Chapter 1). The entirety of this study site was bare of vegetation at the time of tree planting. Given that volunteer woody vegetation could not have become established until after seedling planting and application of mulch treatments, any effects on these stems would likely be enhanced due to their relatively late arrival to the site. While random factors could contribute to differences in volunteer stem density, the occurrence of lower observed values for cells receiving straw mulch across all levels of grading treatment suggests a real phenomenon arising from this amendment type.

Proportion of Stems of Native Species

While comparing volunteer stem density between the various treatment combinations provides important information, it is key to further characterize these stems as either native and therefore desirable, or exotic and therefore potentially invasive and undesirable as part of a functional Appalachian forest ecosystem. Surprisingly, treatment combinations with the highest observed stem density (loose-dump/control and loose-dump/bark) also exhibited the highest proportion of stems of native species (91.1 and 95.5, respectively). The lowest values for this metric were seen in compacted control cells, which ranged from 31 to 58 percent native stems. This reinforces the views of FRA supporters, who have long held that the high compaction and intense herbaceous competition associated with grassland reclamation greatly deters native woody growth. Woody species able to persist under such harsh conditions are likely to be exotic and therefore largely undesirable (Webster et al., 2006).

Conclusions

Our results indicated that strike-off and loose-dump grading preparation methods generally allow for better survival and growth of planted trees than the conventional, high-compaction method. The loose-dump method appeared to maximize survival, but its resultant undulating topography is likely to present serious challenges for equipment needed to access forestry reclamation stands for silvicultural practices or timber harvest. In fact, even human movement on foot within these cells proved difficult during our data collection efforts. Strike-off preparation largely solves the problem of accessibility without inducing high levels of compaction, as evidenced though bulk density values, though our data indicated somewhat lower mean survival of planted trees. However, our biomass estimates showed that loose-dump preparation resulted in the highest woody biomass levels of any grading method tested.

The interpretation of a portion of the data presented above was complicated by the significant interaction of grading and surface amendment treatments. Nonetheless, our results indicated that strike-off and loose-dump grading methods generally allowed for better survival and greater productivity of planted trees. Furthermore, the addition of organic surface amendments (either bark or straw) generally fostered greater growth, with the strongest effect often seen in cells receiving straw and manure mulch. However, it is important to note that competition from grass and legume species introduced or bolstered by a surface amendment can have a strong effect on tree seedling survival and growth. Future research should focus on quantifying the impact of such competition, but even with the limited knowledge gleaned from this project, it appears that control of non-woody plant growth on forestry reclamation sites through physical or chemical means may be well worth its cost.

Carbon sequestration both in aboveground biomass and in the soil continues to rise as the trees mature. We found that mean above and belowground sequestration rates increased from 2.92 to 3.46 Mg C ha^{-1} yr^{-1} between years 8 and 18. These rates are comparable and somewhat higher than levels suggested in other mine reclamation studies and higher than those often reported for lands undergoing conversion from agricultural to forest land use. Soil carbon levels in reclaimed FRA soils after 13 and 18 years were similar to those in unmined mature forest, which suggests that soil function can rapidly recover and supports previous findings on these sites by Maharaj et al. (2007) and Littlefield et al. (2013).

Summary of Volunteer Woody Vegetation

A large number of volunteer woody species were present on the Starfire site, meaning there is good potential for high biodiversity in these stands as they continue to mature and develop. Unfortunately, two of the species most commonly found volunteering in these stands were noted exotic invaders, namely autumn olive and tree of heaven, each of which has become more common in the stand the last decade. Invasive species control through chemical or mechanical means could minimize the impact of these species on biodiversity within the stands by retarding their proliferation, and may be advisable on other mine reforestation sites under certain circumstances.

Given the costs associated with invasive species removal, the targeting of shade-tolerant invasive species such as autumn olive may be an effective means of maximizing long-term results with minimal effort. In the case of less shade-tolerant invaders such as tree of heaven, selective removal of individual stems that have grown into the overstory may be advisable. Smaller individuals may simply be monitored to ensure that they do not achieve a crown class that would allow for their long-term success.

Changes in the composition of volunteer species, particularly the replacement of black locust with more shade-tolerant species, show that this young stand is already experiencing succession to a degree. The number and composition of volunteer trees and shrubs on this site are likely to change in the future and should be re-inventoried to document the rate of such changes.

Mean Stem Density

Compaction of soil or soil substitute material appears to have had a strong negative effect on the density of volunteer stems on our study site, with mean values for uncompacted loose-dump cells exceeding highly-compacted control cells by nearly a factor of ten in some cases. Given that bond requirements do not differentially value planted and volunteer stems, operators employing the forestry reclamation approach could see any volunteer woody growth initiating prior to bond release as a buffer against mortality of planted trees. Measured stem densities resembled those seen on the study site after eight growing seasons. While some of the stems measured in this study may have initiated growth following the earlier study, the steady level of stocking indicates that the site was colonized significantly within the first decade following the establishment of the study.

The effects of surface amendment treatment on volunteer stem density are less clear, though the straw/manure amendment does appear to retard establishment of woody seedlings, likely due to the introduction and support of seeds of herbaceous species. More research on the role of herbaceous competition in the long-term growth and development of mine reforestation sites should be carried out, including a characterization of herbaceous communities and ground cover levels within the Starfire experimental stand. More detailed investigations of the effects of surface amendments applied at differing rates could also be helpful in developing ideal application recommendations to coal operators and contractors.

Proportion of Stems of Native Species

The greatest proportions of volunteer stems of native species were generally observed in experimental cells in which soil material was left entirely uncompacted (loose-dump). While maximizing native stems could be a goal of land managers, in some cases the production of timber through planted trees is the primary goal. In such cases, strike-off preparation is likely preferable for two reasons. As discussed in Chapter One, sites prepared through the loose-dump method have heterogeneous, undulating topography that renders equipment access for harvest or silvicultural practices difficult or even impossible. Additionally, land managers desiring to maximize wood production in planted target species might wish to minimize competition from non-target species of lesser perceived value.

While the strike-off cells in our study exhibited a higher proportion of non-native volunteer stems than loose-dump cells, the majority of stems found in these cells are still native. While invasive species control may be advisable in stands utilizing the strike-off method, our data suggest that they are not likely to be inundated with invasive woody plants after nearly twenty years of growth and development. Therefore, striking off loosely dumped spoil material may represent a viable compromise between maximizing colonization and stand development and maximizing timber production from a few target species.

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