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Technical Progress Report

"Restoring Sustainable Forests on Appalachian Mined Lands for Wood Products, Renewable Energy, Carbon Sequestration, and Other Ecosystem Services"

Quarterly Report

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ABSTRACT

The overall purpose of this project is to evaluate the biological and economic feasibility of restoring high-quality forests on mined land, and to measure carbon sequestration and wood production benefits that would be achieved from forest restoration procedures. We are currently estimating the acreage of lands in Virginia, West Virginia, Kentucky, Ohio, and Pennsylvania mined under SMCRA and reclaimed to non-forested post-mining land uses that are not currently under active management, and therefore can be considered as available for carbon sequestration. To determine actual sequestration under different forest management scenarios, a field study was installed as a 3 x 3 factorial in a random complete block design with three replications at each of three locations, one each in Ohio, West Virginia, and Virginia. The treatments included three forest types (white pine, hybrid poplar, mixed hardwood) and three silvicultural regimes (competition control, competition control plus tillage, competition control plus tillage plus fertilization). Each individual treatment plot is 0.5 acres. Each block of nine plots is 4.5 acres, and the complete installation at each site is 13.5 acres.

Regression models of chemical and physical soil properties were created in order to estimate the SOC content down the soil profile. Soil organic carbon concentration and volumetric percent of the fines decreased exponentially down the soil profile. The results indicated that one-third of the total SOC content on mined lands was found in the surface 0-13 cm soil layer, and more than two-thirds of it was located in the 0-53 cm soil profile. A relative estimate of soil density may be best in broad-scale mine soil mapping since actual D_b values are often inaccurate and difficult to obtain in rocky mine soils. Carbon sequestration potential is also a function of silvicultural practices used for reforestation success. Weed control plus tillage may be the optimum treatment for hardwoods and white pine, as any increased growth resulting from fertilization may not offset the decreased survival that accompanied fertilization. Relative to carbon value, our analysis this quarter shows that although short-rotation hardwood management on reclaimed surface mined lands may have higher LEVs than traditional long-rotation hardwood management, it is only profitable in a limited set of circumstances.

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INTRODUCTION

Public Law 95-87 mandates that mined land be reclaimed in a fashion that renders the land at least as productive after mining as it was before (Torbert et al. 1995). Research has shown that restored forests on mined lands can be equally as or more productive than the native forests removed by mining (Burger and Zipper 2002). Given that most land surface-mined for coal in the Appalachians was originally forested, forestry is a logical land use for most of the reclaimed mined land in the region (Torbert and Burger 1990). However, since implementation of the SMCRA, fewer forests are being restored in the eastern and Midwestern coalfield regions (Burger et al. 1998). In several states, most notably Virginia, the majority of mined land is now being restored to forests. Over eighty percent of Virginia's mined land has been reclaimed to forested post-mining land uses since 1991. However, region-wide, the majority of mined land that was originally forested is not being reclaimed in a way that favors tree establishment, timber production, carbon sequestration, and long-term forest productivity (Torbert and Burger 1990).

We believe that these reclaimed mined lands are producing timber and sequestering carbon at rates far below their potential for reasons that include poor mine soil quality, inadequate stocking of trees, lack of reforestation incentives, and regulatory disincentives for planting trees on previously forested land (Boyce 1999, Burger and Maxey 1998). A number of these problems can be ameliorated simply through intensive silvicultural management. Through established site preparation techniques such as ripping, weed control, fertilizing, and liming, the quality of a given site can be improved. Other management and silvicultural techniques such as site-species matching, correct planting techniques, employing optimal planting densities, post-planting weed control, and thinning can also improve normal development of forest stands, and improve timber production and carbon sequestration.

Similar to the much-debated topic of converting agricultural land to forests, the conversion of reclaimed mined lands to forests carries with it many economic implications. The primary difference between converting agricultural lands to forests and converting reclaimed mined lands to forests is the absence of any obvious extrinsic opportunity cost in the latter scenario; this, of course, assumes that the reclaimed mined land has been abandoned and is not being utilized for any economically beneficial purpose.

A fair amount of research has been conducted regarding the amounts and values of timber produced on reclaimed mined lands. The effect that a carbon market may have on decisions pertaining to the reclamation of mined lands has also been researched. According to previous research, it appears that mined lands are capable of sequestering carbon and producing harvest volumes of equal or greater magnitude to similar non-mined lands. This fact alone, however, does not render afforestation of mined lands economically profitable or feasible in all cases. There is a lack of research pertaining specifically to the conversion of reclaimed mined lands from their current uses to forests and the economic implications of such a land use conversion. Furthermore, the potential for an incentive scheme aimed at promoting the conversion of reclaimed mined lands to forests has yet to be explored in depth.

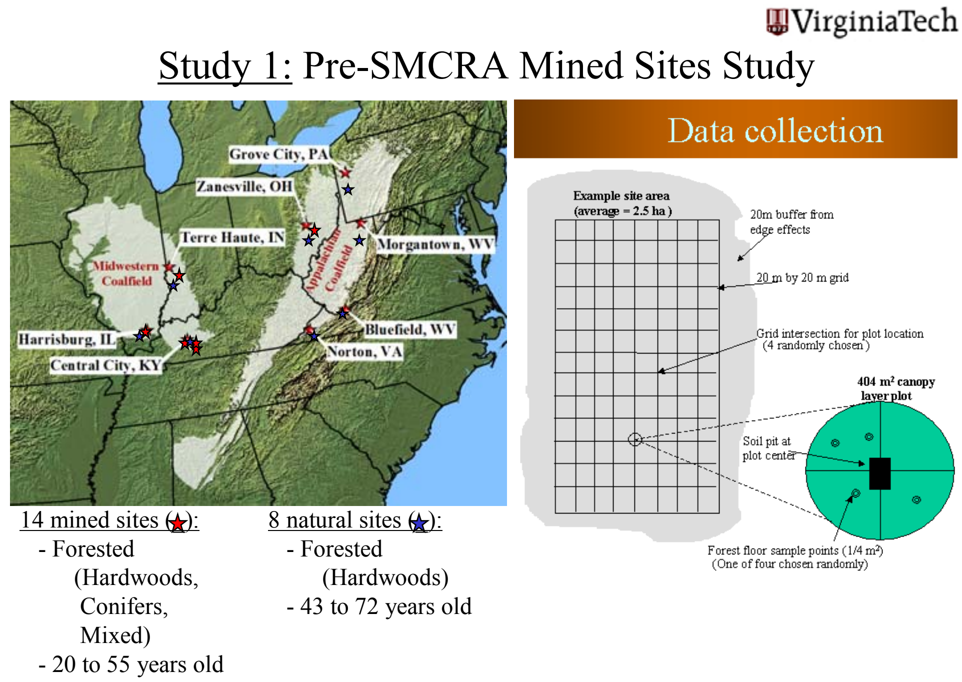
This study ultimately addresses the potential for increasing carbon sequestration on surface-mined land. The overall research objective of this study is to determine the economic feasibility of carbon sequestration through converting reclaimed mined lands to forests using high-value tree species, and to demonstrate the economic and decision-making implications of an incentive scheme on such a land use conversion.

EXECUTIVE SUMMARY

The purpose of this project is to evaluate the biological and economic feasibility of restoring high-quality forests on abandoned mined land, and to measure carbon sequestration and wood production benefits that would be achieved from forest restoration procedures. The project is based on 14 afforested mined sites varying in age from 20 to 56 years located in a seven-state area of the eastern coalfields (Study 1) (Fig. 1), and a new field study, which is a 3 x 3 factorial in a random complete block design with three replications at each of three locations: Ohio (Fig. 1), West Virginia (Fig. 2), and Virginia (Study 2) (Fig. 2). For Study 2, which is the emphasis of this report, the treatments included three forest types (white pine, hybrid poplar, mixed hardwood) and three silvicultural regimes (competition control, competition control plus tillage, competition control plus tillage plus fertilization). Each individual treatment plot is 0.5 acres. Each block of nine plots is 4.5 acres, and the complete installation at each site is 13.5 acres.

Measuring carbon on mined land has additional challenges compared to measuring it on undisturbed soils. Soil carbon analysis is complicated by coal contamination, and mine soils are highly variable. Regression models of chemical and physical soil properties were created in order to estimate the SOC content down the soil profile. Soil organic carbon concentration and volumetric percent of the fines decreased exponentially down the soil profile. The results indicated that one-third of the total SOC content on mined lands was found in the surface 0-13 cm soil layer and more than two-thirds of it was located in the 0-53 cm soil profile. The results for a hypothetical scenario indicated that at assumed value for costs of SOC content analysis down the soil profile equal to \$24 per 1 cm thick spoil layer per 1 m^2 area and for price of the estimated SOC content equal to \$60 per Mg C, the maximum cost-effective sampling depth was 15 cm.

Short-rotation hardwood management was examined as an alternative to white pine and traditional hardwood management options examined earlier. As in earlier analyses, land expectation value (LEV) was considered the metric for financial viability, and LEVs were calculated for short-rotation hardwood management under a range of site classes, reforestation intensities, interest rates, and timber prices. Findings indicate that the short-rotation option is only slightly more attractive financially than earlier-examined traditional hardwood management, and that the short-rotation management is only profitable (LEV > 0) under a limited combination of circumstances, including better sites, high prices, low interest rates. In addition, an analysis of carbon payment options demonstrates that the payment required to make reforestation profitable under short-rotation hardwood management may be substantially lower than payments required under traditional hardwood management, if those payments are based upon incremental carbon added to the site each year.



VirginiaTech

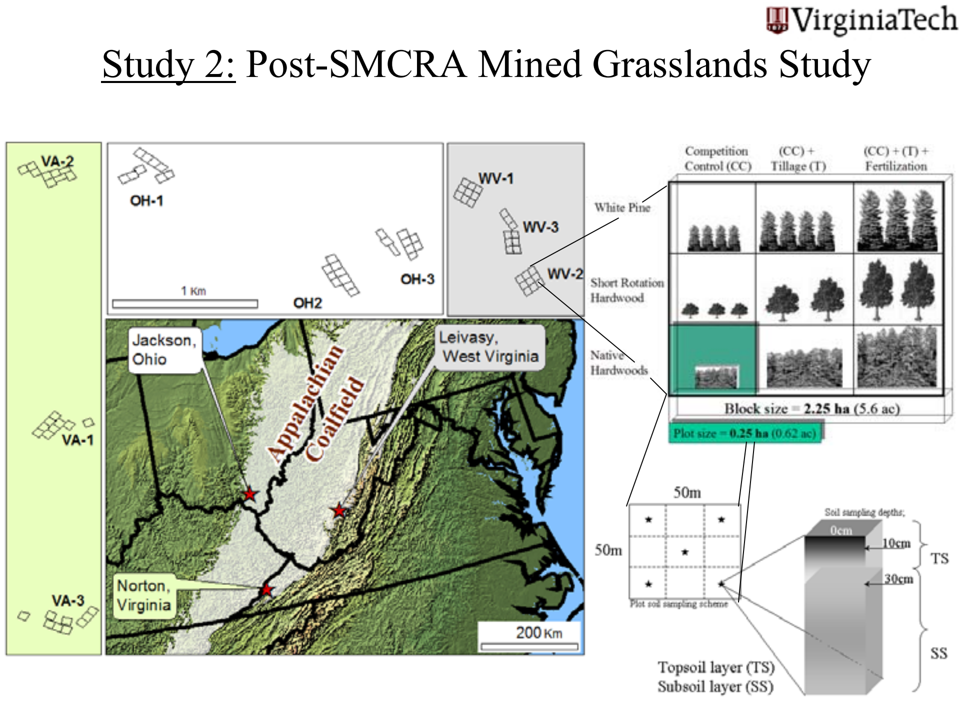
Study 1: Pre-SMCRA Mined Sites Study

Data collection

14 mined sites (★):
- Forested (Hardwoods, Conifers, Mixed)
- 20 to 55 years old

8 natural sites (★):
- Forested (Hardwoods)
- 43 to 72 years old

Figure 1. Location and layout of experimental sites for Study 1 across a seven-state region.



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Study 2: Post-SMCRA Mined Grasslands Study

Figure 2. Location and layout of experimental sites for Study 2 in Ohio, West Virginia, and Virginia.

TASK 1: Estimate forest productivity and carbon sequestration potential on mined lands supporting abandoned grasslands. (Burger et al.)

Executive Summary

When coal companies do not have any plans for future land use on reclaimed areas they choose the least expensive site reclamation methods, such as hydroseeding to grass, to gain release of their performance bonds. Mine soil samples of the surface and the subsurface overburden material were collected to approximately 2 m depth; chemical and physical soil properties were determined on the less-than-2 mm fine sample fraction. Results are presented for the vertical distribution of $SOC\_C_{wt\%}$, $Fines_{vol\%}$, $Coal\_C_{wt\%}$, and $BD_{fines,\ g\ cm^{-3}}$ down the mine soil profile. The $SOC\_C_{wt\%}$ concentration ranged between 0.0 and 0.767% and the $Coal\_C_{wt\%}$ concentration ranged between 0.0294 and 4.53% among all samples. The R^2 of the SOC predictions (g C m^{-2}) was estimated at 60.6%, and the shape of the prediction model resembled that of an exponential function. The results for a hypothetical scenario indicated that at assumed value of \$24 per 0.01cm^3 excavated spoil, labeled as cost of SOC content analysis down the soil profile, and \$60 per Mg of elemental C as the price of the analyzed SOC content, the maximum cost-effective sampling depth was 15cm.

Experimental

Tens of thousands of hectares of previously productive forestland in the Appalachian region of the United States presently exist as grassland and highland pasture as a result of surface coal mining operations. When coal companies do not have any plans for future land use on reclaimed areas they choose the least expensive and easiest to apply methods for site reclamation. Hydroseeding to grass (Booze-Daniels et al. 2000) is the most commonly used practice to gain release of their performance bonds (Daniels and Stewart 2000). A major drawback of reclaiming mined sites to grassland is that this practice is limiting the potential of the land to grow productive native forests (Skousen et al. 1994) that would produce high-value timber, more extensive wildlife habitat, and improved watershed control.

The grand total C accumulations in the form of biomass, litter layer, and soil organic matter (SOM) (Rodrigue 2001, Rodrigue et al. 2002), as well as the prolonged C storage time, such as standing timber and long-term forest products (IPCC 2003, Skog and Nicholson 1998, Spinney et al. 2005), greatly increase the function of forests in reducing atmospheric CO_2. In his summary of the global carbon cycle, Schlesinger (1995) suggests that the potential for enhanced carbon sequestration in terrestrial ecosystems is much greater in forest vegetation than in soils, which makes reforestation and forest fertilization attractive short-term practices for atmospheric CO_2 sequestration on land.

While improved forest management practices may lead to an increase of the forest productivity (Rodrigue et al. 2002) and the carbon sequestration potential of reclaimed forest lands in the Appalachian and Midwestern coalfields of the United States (Amichev et al. 2004), there are several challenges associated with verifying C stock changes, especially in the soil component of these forest ecosystems. Many soil factors have an effect on SOM accumulation and decomposition in mine soils, including the methods of mine spoil placement and site reclamation after coal mining and the subsequent development of mine soils largely influenced by the vegetation they support and weathering processes (Chichester and Hauser 1991).

The objective of this report was to determine (1) the distribution pattern and accumulation of soil organic carbon (SOC) down the mine soil profile; and (2) the maximum cost-effective depth of SOC analysis on mined lands supporting abandoned grasslands.

We identified and located three project sites in the Appalachian coalfields. At each study site we established three replications (blocks) of nine forest establishment treatments (Fig. 1-1). An extensive description of the experimental treatments, and tree survival and growth data from the first growing season, were presented in our previous reports.

We collected soil samples at five ocations on each plot (Fig. 1-1) to two sampling depths, 0-10 cm and 10-30 cm. All soil samples were stored in paper bags, or open plastic bags in a well-ventilated area, and were air- or oven-dried at 50-60^{o}C in order to shorten the drying time. We passed the soil samples through sieve No. 10 (<2 mm) in order to separate the fine earth fraction from the coarse rock fragments. Then the fine earth component of each soil sample (<2 mm) was used for soil carbon content estimation. Total soil carbon was determined with a carbon-nitrogen auto-analyzer (Vario MAX CNS analyzer, elementar, Hanau, Germany).

Two to four deep pits were excavated with a backhoe to approximately 2 m depth in representative locations at each site. Each horizon was described and sampled (Jones 2005). Multiple bulk density samples were collected in each horizon using a modified version of the excavation method of (Blake and Hartage 1986). A metal cylinder approximately 5 cm in diameter was used to extract soil from each horizon. The hole was then lined with a thin plastic bag and filled with lead BBs to the original surface level in order to determine the volume of the excavated hole (Jones 2005). The whole soil bulk density, coarse fragment content (CFC) (>2 mm particle size), and moisture content of the excavated soil were then used to determine the bulk density of the fine earth fraction, BD_{fines} in g cm^{-3} on the oven-dry weight of the soil.

The majority of soil minerals in the Appalachian region were assumed to have a specific gravity of 2.65 g cm^{-3} representing that of quartz and approximately the specific gravity of kaolinite (2.6 g cm^{-3}). This assumption seems valid for most mine soils where an overburden material mostly comprised of crushed sandstone and siltstone material was used as a soil substitute material. Soils derived from sandstone overburden material are mostly comprised of sand-size quartz particles and in the clay fraction of soils derived from siltstone material is dominated by kaolinite.

Pedogenic soil C exists in two forms, soil organic matter and/or plant residues. A unique property of mine soils is the presence of coal and carboniferous rock particles, commonly referred to as geogenic carbon. Depending on their particle size and quality, geogenic carbon particles could have chemical and physical properties resembling those of soil organic matter, such as their ability to be chemically oxidized (Daniels and Amos 1982) and to be decomposed by soil microorganisms (Faison 1993). Because size and quality of geogenic carbon particles is usually a function of their moisture content and amount of impurities contained within the individual coal macerals (Faison 1993), it is nearly impossible to predict the presence and distribution of geogenic carbon in the mine soil profile. Unfortunately, there is no existing method in the literature that may be of use for quantitative estimation of SOC that can successfully differentiate between pedogenic and geogenic carbon forms in mine soils.

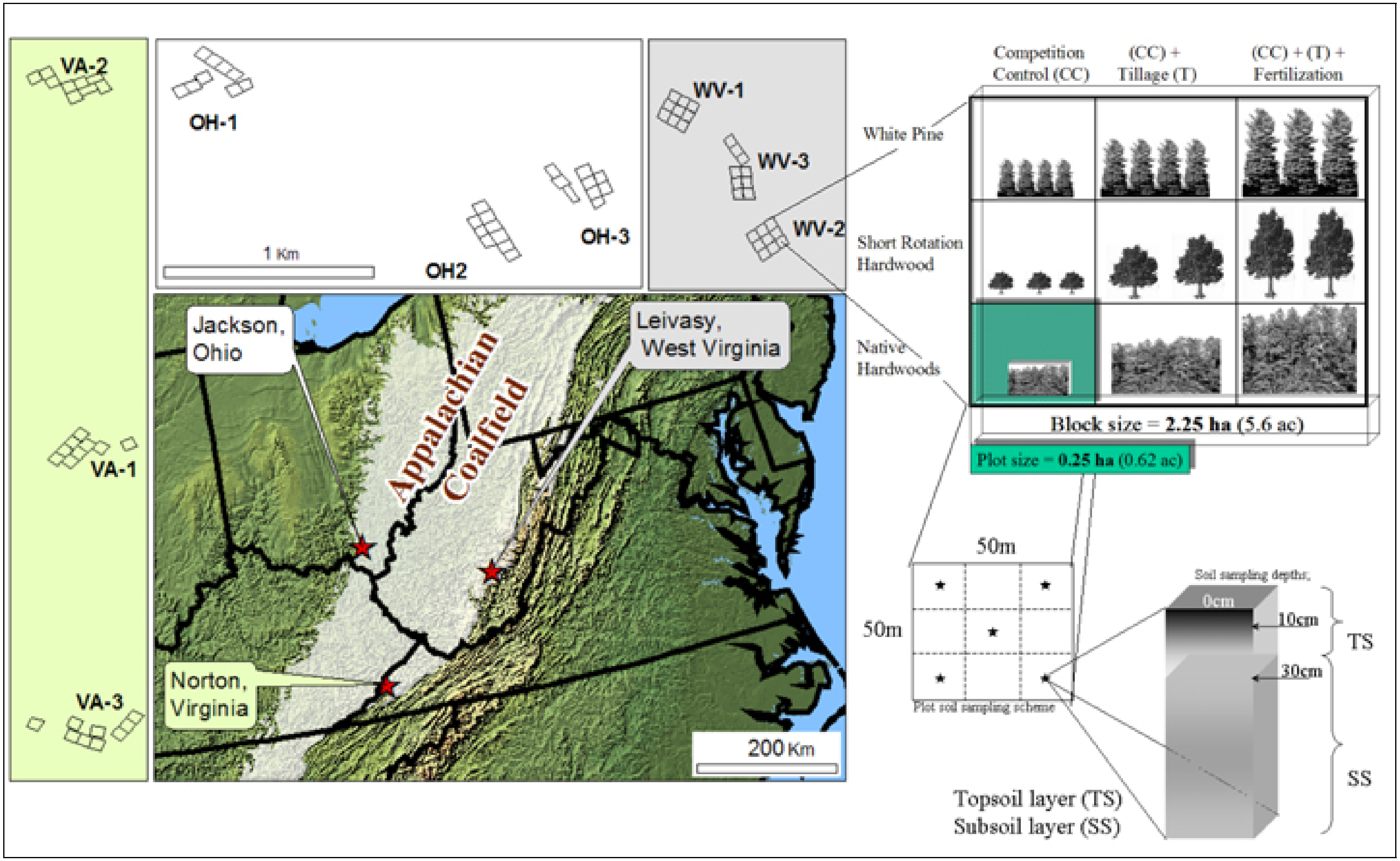


Figure 1-1. Study site locations, treatment blocks spatial distribution, and data collection scheme for 9 study areas located in Virginia, West Virginia, and Ohio.

The SOC results in this paper are based on the following assumptions: (i) there is an insignificant amount of carbonates present in the mine soil samples; and (ii) the total nitrogen is present in organic forms, such as SOM or coal particles, with negligible or no amounts present as inorganic nitrogen, such as NH_4^+ or NO_3^-.

The first assumption was reasonable due to the facts that carbonate particles tend to leach very rapidly from young mine soils, which was the case for the study areas in Virginia, and that the average pH values of these soils was at below-neutral (pH = 7) levels (Jones 2005). The second assumption was also considered reasonable because of the fact that all of the study sites were in their 3+ growing season, a long enough period for potentially all nitrogen applied as fertilizer at the time of hydroseeding to be either acquired by the vegetation or to leach out of the soil system (Li 1991).

These two assumptions were used to correct the total soil carbon values measured at combustion temperatures of 900°C by a carbon-nitrogen auto-analyzer machine, the results of which included all pedogenic and geogenic carbon forms present in the soil. A C/N ratio of 52.2 for pure coal particles, CN_{coal}, was adopted from previous research work carried out at the same study sites (Li 1991). An average C/N ratio of 12.0 for the soil organic matter of a grassland soil, CN_{soil}, that is free of carboniferous particles (Chichester and Hauser 1991, Insam and Domsch 1988) was adopted for the total C correction procedure depicted below.

The total soil carbon values ($Total\_C_{wt\%}$) were corrected for coal-derived carbon by solving for the weight percent soil organic carbon concentration, $SOC\_C_{wt\%}$, and for the weight percent of coal-derived carbon, $Coal\_C_{wt\%}$, in the following simultaneous equations:

$$\left| \begin{array}{l} (Total\_N_{wt\%}) = \dfrac{(Coal\_C_{wt\%})}{CN_{coal}} + \dfrac{(SOC\_C_{wt\%})}{CN_{soil}} \\ (Total\_C_{wt\%}) = (Coal\_C_{wt\%}) + (SOC\_C_{wt\%}) \end{array} \right.$$

For example, for a soil sample with measured C/N ratio of 15.0 (CN_{sample}) and a total sample nitrogen ($Total\_N_{wt\%}$) of 0.075% (note that $Total\_C_{wt\%}=CN_{sample}*Total\_N_{wt\%}=1.125\%$), the $SOC\_C_{wt\%}$ is 0.8328, which is estimated as $[Total\_N_{wt\%}*(CN_{sample}-CN_{coal})/(1-CN_{coal}/CN_{soil})]$ and the $Coal\_C_{wt\%}$ is 0.2922, which is estimated as $[Total\_N_{wt\%}*(CN_{sample}-CN_{soil})/(1-CN_{soil}/CN_{coal})]$. For mine soil samples with C/N ratios lower that 12.0, the sample $SOC\_C_{wt\%}$ was assigned the estimate of the $Total\_C_{wt\%}$ and for samples with C/N ratios greater than 52.2 the $SOC\_C_{wt\%}$ was assigned a value of 0. The latter could occur when denser coal particles with lower moisture content and coal particles of higher aromatic nature dominate the soil sample (Vorres, 1998).

Soil organic carbon content per soil horizon (or per soil layer) with identified upper and lower boundaries was estimated in g m^{-2} using total soil carbon concentration measurements corrected for coal content, bulk density of the fine earth fraction, percent of the fine earth fraction on a soil volume basis, and horizon depth, as depicted in the equation below:

$$SOC_{g\ m^{-2}} = [SOC\_C_{wt\%}]*[BD_{fines,g\ cm^{-3}}]*[Fines_{vol\%}]*[Layer_{cm}] \qquad \text{[Eq. 1-1]}$$

where:

$SOC\_C_{wt\%}$ = percent soil organic carbon of the fine soil fraction (fines), less than 2mm soil particles, measured on a weight basis = $\frac{C_g}{Fines_g} * 100$;

$BD_{fines,g\ cm^{-3}}$ = bulk density of the fines = $\frac{Fines_g}{Fines_{cm^3}}$;

$Fines_{vol\%}$ = the volumetric fraction of the fines measured as percent of the total volume of excavated soil sample = $\frac{Fines_{cm^3}}{Soil_{cm^3}} * 100$;

$Layer_{cm}$ = soil layer or soil horizon thickness expressed in cm units.

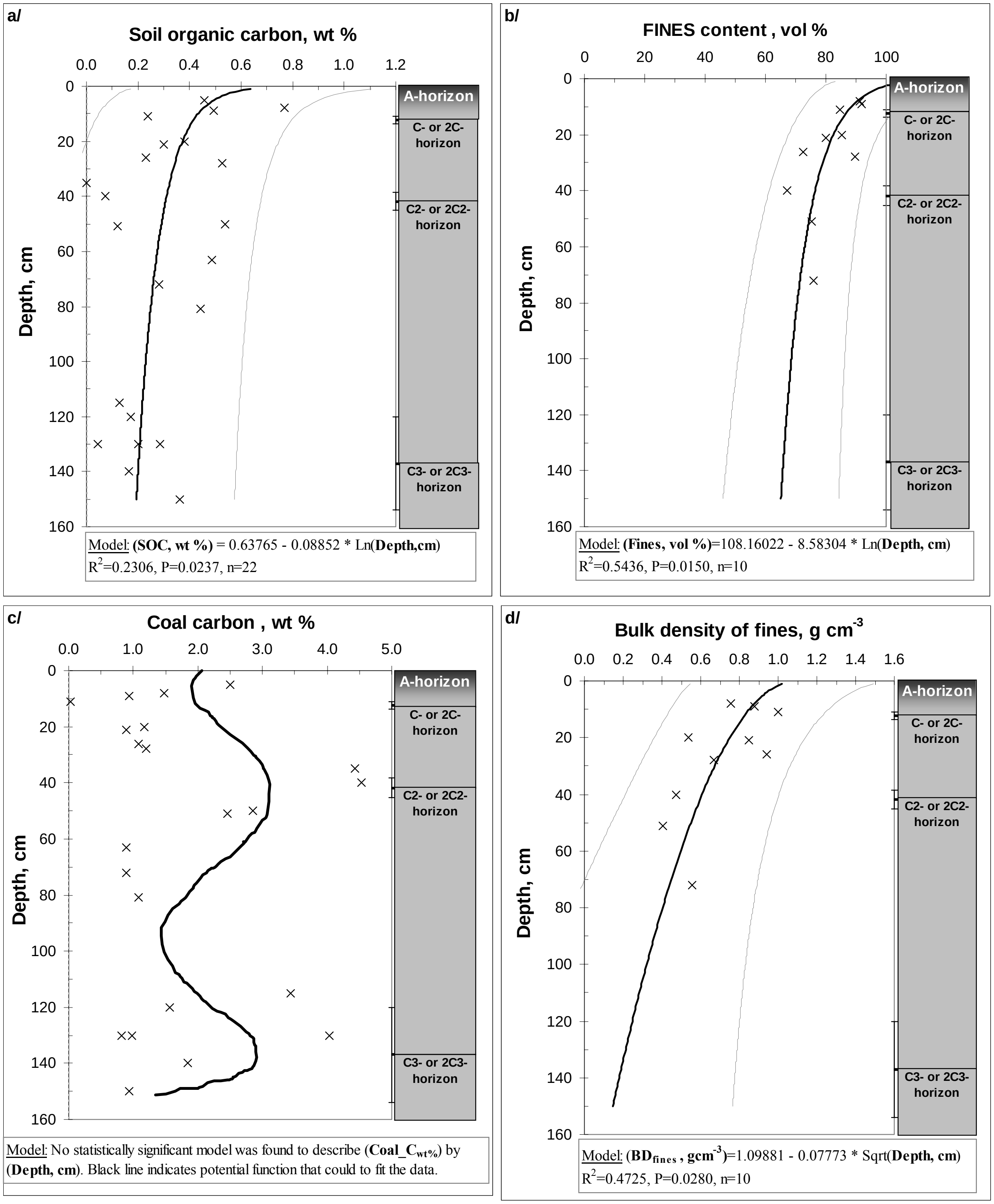
Because SOC estimates are most commonly expressed in units that represent a certain area, such as g m^{-2}, kg m^{-2} and Mg ha^{-1}, the results of any SOC quantification analysis include the combined error associated with measuring each individual component in Eq. 1-1. The rules for error propagation described in (Harris 2005) were used to produce the 95% confidence limits of individual SOC predictions estimated at 1-cm increments down the mine soil profile. The percent error for SOC $_{g\ m^{-2}}$ was estimated as the SQRT[$(\%\varepsilon SOC_{wt\%})^2 + \%\varepsilon BD_{fines,g\ cm^{-3}})^2 + \%\varepsilon Fines_{vol\%})^2$], where the %ε-term represents the percent relative uncertainty of the respective variables. Percent relative uncertainty is estimated by dividing the absolute uncertainty, expressed in the units of the variable such as standard deviation or standard error, by the magnitude of the measurement, times 100, i.e. %ε = StdErr*100/Mean.

Statistical procedures for linear regression analysis, proc REG and the C(p) model selection method (SAS, 2004), were used to create prediction models for $SOC\_C_{wt\%}$, $BD_{fines,g\ cm^{-3}}$, and $Fines_{vol\%}$ down the mine soil profile. All models presented in this paper are statistically significant at the $\alpha = 0.05$ level. In addition to model predictions of individual variables, the 95% confidence limits of prediction estimates were also reported.

Results and Discussion

From various soil horizons at lower depths ranging from 5 to 150 cm from six deep pits excavated to approximately 2 m depth, a total of 22 soil samples were taken and analyzed for their C and N content (Jones 2005). At these locations only 10 surface (A-horizon) and subsurface (C or 2C) soil horizons were analyzed for their physical properties, including soil bulk density and $CFC_{wt\%}$ (Jones 2005). The latter two variables were then used to estimate bulk density of the fines and volumetric percent content of the fines.

Results from the vertical distribution of $SOC\_C_{wt\%}$, $Fines_{vol\%}$, $Coal\_C_{wt\%}$, and $BD_{fines,\ g\ cm^{-3}}$ down the mine soil profile are depicted in Figure 1-2a-d. For three of the variables, statistically significant regression models were created which explained between 23% and 54%, respectively, of the variation of $SOC_{wt\%}$ and $Fines_{vol\%}$ down the mine soil profile. Except for one surface horizon, the results indicated that the $Coal\_C_{wt\%}$ concentration exceeded the $SOC\_C_{wt\%}$ approximately 1.2 times across all horizons at various depths down the soil profile. The $SOC\_C_{wt\%}$ concentration ranged between 0.0 and 0.767% and the $Coal\_C_{wt\%}$ concentration ranged between 0.0294 and 4.53% among all samples.



Model: **(SOC, wt %)** = 0.63765 - 0.08852 * Ln(**Depth,cm**)
R^2=0.2306, P=0.0237, n=22

Model: **(Fines, vol %)**=108.16022 - 8.58304 * Ln(**Depth, cm**)
R^2=0.5436, P=0.0150, n=10

Model: No statistically significant model was found to describe (**Coal_C$_{wt\%}$**) by (**Depth, cm**). Black line indicates potential function that could to fit the data.

Model: (**BD$_{fines}$, gcm^{-3}**)=1.09881 - 0.07773 * Sqrt(**Depth, cm**)
R^2=0.4725, P=0.0280, n=10

Figure 1-2. Vertical distribution of (a) SOC_C$_{wt\%}$, (b) Fines$_{vol\%}$, (c) Coal_C$_{wt\%}$, and (d) BD$_{fines,\ g\ cm^{-3}}$ down the mine soil profile of six deep pits excavated in Wise County, Virginia. Thicker lines indicate the fit of statistically significant prediction models to the data, marked with x's, and lighter lines show the 95% confidence limits of these predictions. The soil profile schemes to the right of each graph indicate the mean horizon boundaries and their associated standard error of the mean.

The distribution of coal-derived carbon down the profile was not found to follow any particular pattern that could be described by a mathematical model (Fig. 1-2c). This is most likely due to the fact that most coal particles are very resistant to weathering processes and can move down the soil profile, accumulating in the voids created between large rock fragments.

It is of interest to note that the highest concentration of coal-derived carbon was located at the contact zone between the observed subsurface horizons, between the C and C2 horizons and between the C2 and C3 horizons (Fig. 1-2c). A possible explanation for this phenomenon is that during the multiple stages of site reclamation and mine spoil placement, the upper boundary of the C2 and C3 horizons were heavily trafficked by machinery hauling spoil, and thus became the resting surface for a greater amount of coal particles before the next layer of overburden was placed on top.

Soil organic carbon concentration decreased exponentially down the mine soil profile, but the variation among individual $SOC\_C_{wt\%}$ measurements did not permit conclusive inferences about this soil property. The 95% confidence limits of the $SOC\_C_{wt\%}$ prediction model indicated that at the lower limit of the predictions there would not be any organic C accumulation beyond a depth of 19 cm. On the other hand, the upper limit of the predictions indicated that there will be at least 0.574% (weight percent) of soil organic carbon at a depth of 150 cm (Fig. 1-2a). The latter could be regarded as a computational error due to the fact that root growth is concentrated in the surface. Because of the excessive compaction of mine soils and type of vegetation, root growth could be restricted to the surface 1 m of the mine soil. However, it could be argued that organic carbon concentration increase in subsurface soil horizons at lower than 1-m depths could be due to the translocation of dissolved SOC down the profile and its accumulation on the surfaces of fine soil particles located in the voids between larger coarse fragments.

Depicted in Figure 1-2b, d, the results showed that down the profile the volumetric percent of fines decreased exponentially. The 95% confidence limits of the $Fines_{vol\%}$ were (51.0%, 86.2%) at 1-m depth and (46.0%, 84.0%) at 1.5-m depth. These results confirm the argument that there is a sufficient amount of fines to adsorb dissolved SOC moving from the surface to lower soil depths. Because the relative decrease of bulk density of the fines was greater than relative decrease of the volumetric content of the fines (Fig. 1-2b,d) one can conclude that a greater frequency of various size voids (free of fines and CFC) exist at lower depths. Note that bulk density of the fines was estimated from the whole soil bulk density, which is the soil mass divided by the sample volume (CFC volume + fines volume + soil air volume), after correcting for CFC content. The latter indicates that the soil air volume term was incorporated in the estimates of bulk density of the fines.

Depicted in Figure 1-3a are the predicted values for $SOC_{g\ m^{-2}}$ content estimated by multiplying the individual predictions for $SOC_{wt\%}$, $Fines_{vol\%}$, and $BD_{fines,\ g\ m^{-3}}$, from Figure 1-2, as noted in Eq. 1-1. The 95% confidence limits were estimated using the rules of error propagation, described above, and the resulting predictions were evaluated against the 10 samples for which all three parameters were measured at the same location in the profile. The R^2 of the predictions was estimated at 60.6% with the graphical representation of the prediction model resembling that of an exponential function.

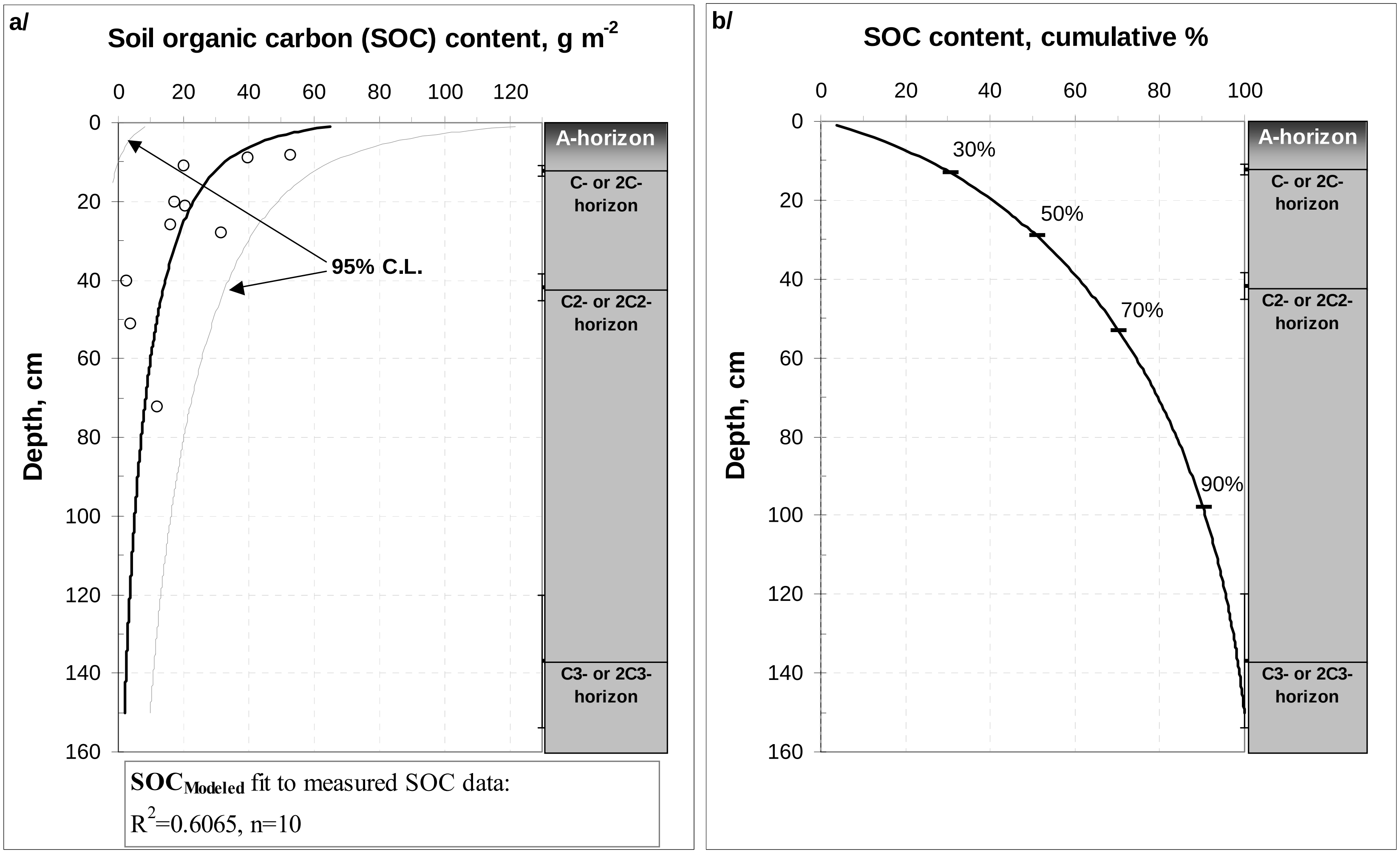


Figure 1-3. Vertical distribution of (a) SOC $_{\text{g m}^{-2}}$ (from Eq. 1-1) and (b) its cumulative distribution expressed as percent of the total SOC $_{\text{g m}^{-2}}$ sequestered down the profile within the 0-150 cm soil pedon of six deep pits excavated in Wise County, Virginia. Thicker lines indicate the fit of statistically significant prediction models to the data, marked with circles, and lighter lines show the 95% confidence limits of these predictions. The soil profile schemes to the right of each graph indicate the mean horizon boundaries and their associated standard error of the mean.

A more useful graphical representation of the SOC content results from Figure 1-3a is depicted in Figure 1-3b. The cumulative SOC content is presented as percent of the total SOC contained with the 0-150 cm soil pedon (Fig. 1-3b). The cumulative SOC content down the soil profile could be used to determine the most cost-effective depth for SOC inventory on mined lands.

The results indicated that one-third of the total SOC on mined lands was found in the surface 0-13 cm soil layer and more than two-thirds of it was located in the 0-53 cm soil profile. Evidently, any SOC located in lower depth would be of lesser value due to the higher cost of sample collection, especially in compacted and rocky mine soils.

In an attempt to determine the optimal sampling depth for mined land, one should know not only the variation of SOC down the profile but also the variation across the mined landscape. Assume the following scenario: the cost for excavating, sampling and analysis of a single pit 5 cm-thick soil layer is \$40; the cost of sequestered C is \$60 per ton of elemental C; and that project area is so homogeneous that only three samples per ha are necessary to estimate the sequestered SOC in Mg ha^{-1}. Upon further analysis, one could estimate that for this scenario the cost of SOC inventorying for each 1 cm soil layer is \$24 (equal to \$40/5cm*3pits). Therefore, in order for an SOC inventorying event to be feasible, the cost for SOC content estimation must be lower than the cost of the estimated SOC content; i.e., the ratio $\$(SOC_{inventory})/\$(C_{credit})$ must be greater than 1 (Fig. 1-4).

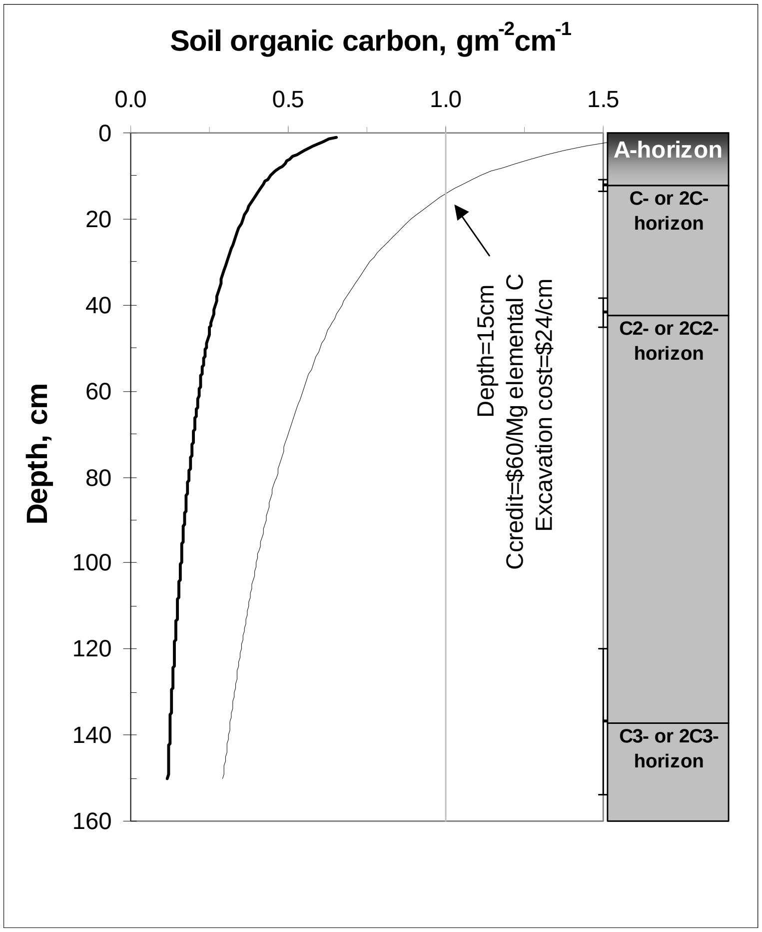


Figure 1-4. Maximum cost-effective depth for soil carbon content inventory for a hypothetical price scenario of C price equal to \$60 per 1 Mg of elemental C, and cost of SOC analysis equal to \$24 per 1 cm of mine spoil.

The results for the assumed scenario indicated that at assumed value amounts for costs of SOC content analysis down the soil profile ($24/cm) and for price of the estimated SOC content ($60/Mg C), the maximum cost-effective sampling depth is 15 cm. This is to say that although two-thirds of the total sequestered C is located below 15 cm depth (Fig. 1-3b), one will be losing money if SOC is measured to lower depths.

Conclusions

Regression models of chemical and physical soil properties were created in order to estimate the SOC content down the soil profile. Soil organic carbon concentration and volumetric percent of the fines decreased exponentially down the soil profile. The results indicated that one-third of the total SOC content on mined lands was found in the surface 0-13 cm soil layer and more than two-thirds of it was located in the 0-53 cm soil profile.

The results for a hypothetical scenario indicated that at assumed value for costs of SOC content analysis down the soil profile equal to $24 per 1 cm thick spoil layer per 1 m^2 area and for price of the estimated SOC content equal to $60 per Mg C, the maximum cost-effective sampling depth was 15 cm. For this scenario we assumed that the site was homogenous and that only three excavation pits were necessary to account for the soil variation across space. However, this assumption may be invalid due to the man-made nature of mine soils where soil variation can be significant across space.

Conant and Paustian (2002) and Conant et al. (2003) showed that soil C changes can be detected in grassland and cultivated land using current technology and sampling methods for various scales of analysis, ranging from farm-level to the entire nation. However, for systems of higher spatial variability, such as some forested sites in Washington consisting of low C content sandy soils with irregularly distributed pockets of organic C in buried logs, Conant et al. (2003) reported increased minimum detectable differences of 4.9 Mg C ha^{-1} and 31.4 Mg C ha^{-1}, respectively, for second growth and old-growth forest sites, compared to a minimum detectable difference of 2 Mg C ha^{-1} for cultivated areas, over four years following changes in management or land use.

Likewise, due to the their man-made origin and in particular the mining and reclamation methods, the spatial heterogeneity of mine soils could potentially exceed that of natural systems (Sencindiver and Ammons 2000) leading to potentially unachievable minimum detectable differences in soil organic C over a certain period of time (5-10 years) of the life of a carbon sequestration project. Therefore, additional work is needed to determine the magnitude of MDD and the relative expenses associated with the process of minimum detectable difference determination for reforestation projects on mined lands.

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TASK 2: Develop classification and inventory criteria and procedures for mined land. (Galbraith et al.)

Executive Summary

The field methods of assessing bulk density into five general classes of compaction are presented in the attached study. While this method is qualitative, it shows that with some simple analysis and tools, a person can determine which soils need remediation before being reforested. These results, when coupled with the other results of the entire study, are useful for determining site quality classes for reforestation on reclaimed mine lands.

High fine-earth bulk density (D_b) is the primary limitation for vegetation success on mine soils in the Appalachian coalfield region (Daniels and Amos, 1981). Compaction from repeated passes of heavy equipment often occurs when returning mined land to “approximate original contour” (AOC), which is required by the Surface Mining Control and Reclamation Act (SMCRA) of 1977. Compaction results in high fine earth D_b, along with reduced macroporosity, increased soil strength, impeded infiltration and drainage, reduced aeration, and other factors that are detrimental to tree survival and root growth (Ruark et al., 1982).

Measuring D_b in the field can be time-consuming and inaccurate in mine soils due to the high rock fragment (RF, particles > 2 mm) content. Conventional coring tools cannot be used because they are impeded by too many RFs. Andrews et al. (1998) used an excavation method and found D_b ranging from 0.64 to 1.94 g cm^{-3} with an average of 1.02 g cm^{-3}, and in general found no roots in horizons with a D_b >1.7 g cm^{-3}. They concluded that the D_b values were inaccurate due to the high RF content (up to 88%). An attempt by Thompson et al. (1987) to correlate penetrometer resistance with D_b in the surface of mine soils was unsuccessful. Torbert et al. (1988b) used a penetrometer in an attempt to determine total soil depth, but found it to have no value in mine soils due to the large number of RFs. Pedersen et al. (1980) determined D_b using an excavation method, direct transmission gamma probe, and soil clods. No significant differences ($\alpha = 0.05$) were found in the D_b measurements among the three methods, and they are all too time-consuming for field classifications. The excavation method of measuring D_b on mine soils is the most common but is too time-consuming for field classifications of large land areas. Pedersen et al. (1980) suggests that when using the excavation method on rocky mine soils, an excavation size of at least 1 m^3 is needed for accurate D_b estimation, which further disproves this method for efficient field classifications due to large equipment needed and time-consuming procedures.

This study was conducted in an attempt to identify new tools and methods of assessing D_b of mine soils in the field. Three tests were conducted to correlate indicator tools with D_b measured by a small pit excavation and displacement method following that of Blake and Hartage (1986). The indicator tools included a sharpshooter shovel, a screw auger, and a slide hammer device with a tapered tip.

Experimental

The study was conducted at sites in Lawrence County, Ohio (OH), Nicholas County, West Virginia (WV), and Wise County, Virginia (VA). A 3 x 3 plot matrix was replicated three times at each site and a D_b measurement was taken in each plot, giving 81 measurements, using the excavation procedure described by Blake and Hartage (1986), with an excavation surface area of approximately 900 cm^2 and a depth of 10 cm. The hole was lined with thin plastic, lightly pressed into the corners, and then filled with lead BBs as the displacement media to the original surface level. The volume of the BBs was measured in a graduated cylinder and recorded. The RFs were removed by sieving the whole sample through a 2-mm sieve and their weight was subtracted from the total sample weight to obtain RF content (%) on a weight basis. All RFs were assumed to have a specific gravity of 2.65 g cm^{-3}. The soil was corrected for moisture content in order to obtain fine earth D_b values in g cm^{-3} on an oven-dry soil basis. D_b and RF measurements were assumed to be constant throughout the thickness of the surface layer down to an abruptly different spoil layer. Particle-size distribution was determined by the pipet method (Gee and Bauder 1986). ANOVA was also used to analyze the soil properties of RFs and D_b for site and sample differences as a 3 x 2 random complete block design with three sites and two sample depths. Only the topsoil sample data is reported in this study. The three test tools were used at each plot where the D_b was measured by the excavation method described above.

A standard 14-cm wide sharpshooter (tapered shovel with rounded tip) with a 40-cm long blade was placed on the surface and stepped on using a steady force from the weight of a 70-kg person. The depth of penetration (cm) into the soil was recorded to the nearest centimeter. Three to five replications near the sample point were averaged for a final measurement.

A screw auger (round tip screw head 16 cm long and 5 cm wide with 3 complete turns and on a 97-cm long shaft) was twisted into the soil for 3 and 6 half-turns, or until a different layer of spoil was encountered. The depth of penetration (cm) that was reached at each interval was recorded, and the cm penetration per half-turn value was calculated. The depth to a different soil layer was determined by a dramatic change in color or apparent density of spoil material in shallow pit excavations. If solid rock was encountered and prevented further penetration, the process was repeated in a nearby location.

An AMS slide hammer (AMS Inc., American Falls, ID) was used with a tapered tip (constructed by the sharpening of a carriage bolt) and the depth of penetration (cm) was recorded for 5 and 10 drops, or to an abrupt change in spoil type. The cm penetration per drop was calculated for each pre-determined drop interval. If a solid rock was encountered and prevented further penetration, the process was repeated in a nearby location.

Results and Discussion

The OH site had a significantly lower ($p < 0.05$) RF content than the other two sites, likely due to topsoil (surface horizon down to bedrock) being stockpiled and replaced after mining (Table 2-1). The VA and WV sites had topsoil substitutes on the surface that were significantly higher ($p < 0.05$) in RF weight percent than OH. The D_b measured by the excavation method was not significant across all sites (Table 2-1). However, the D_b at OH may be root limiting because of its finer textures (Brady and Weil 1999). Grading of the low RF, fine texture soils increases the detrimental affects of compaction on the fine earth material and observed roots were widely spaced at the OH site. Air gaps (open pockets within the soil profile that contain no fine soil material) may result when spoil with high RFs is graded and fine earth D_b by the excavation method may be skewed, indicating lower D_b than the actual fine earth D_b. Ashby et al. (1984) indicated that increased porosity, water infiltration, water availability, and rooting depth are found on stony mine soils. These properties can lead to increased weathering rates and may ameliorate some compaction over time. The shallow measurement zone that was subject to intense soil-forming processes such as freeze-thaw and shrink-swell and biological activity also explains the relatively lower than expected D_b values at all sites. Furthermore, extremely cemented, large RFs may support the weight of heavy equipment enough to decrease its force and prevent an increase in fine earth D_b, or may overlap and protect the fine earth from some compaction.

Table 2-1. Rock fragment content (weight percent) and fine earth bulk density measured using the excavation method at each study site.

	Rock Fragments		Fine Earth Bulk Density	
Site	Mean†	Std. Dev.	Mean†	Std. Dev.
	----------- % -----------		--------- g cm^{-3} ---------	
OH	14 b	6	1.4 a	0.1
VA	49 a	14	1.2 a	0.2
WV	55 a	10	1.1 a	0.2

† Means followed by different letters are significantly different at $\alpha = 0.05$ as determined by Fisher's LSD mean separation procedure.

None of the three tools or methods was found to accurately predict D_b as measured by the excavation method that is used most commonly used for mine soils. Sharpshooter penetration depth did not correlate with measured D_b at any of the sites, with an R^2 of 0.085 at OH, 0.053 at VA, and 0.083 at WV (Fig. 2-1). We hypothesized that sharpshooter depth would decrease as D_b increased. The penetration depths were greater at the OH sites than all but four samples at VA because they had the fewest RFs ($p < 0.05$) (Table 2-1). Furthermore, the soils were moist during testing and had finer field-estimated textures than the other two sites, allowing for easier sharpshooter penetration (Table 2-2). The OH soils had a higher D_b than the other soils (Table 2-1), and the same penetration test conducted during a drier period might have produced different results. The penetration depths at VA and WV were lower than those at OH because they had a higher content of large, hard RFs ($p < 0.05$).

The screw auger cm penetration per 3 and 6 half-turns did not correlate with measured D_b, with an R^2 of 0.06 and 0.09, respectively. The cm penetration per half-turn was greater at OH than at VA and WV, and the increased soil contact and high soil moisture may have helped the screw auger pull itself down through the soil (Table 2-1). Rock fragment content affected the depth and path of the screw auger as well and influenced the measurement, but most rocks were eventually bypassed with a few extra turns. The quantitative measure of cm per half-turn was insignificant in determining D_b, but the resistance to turning is likely a good relative indicator of soil density and may resemble the resistance that tree roots encounter. Furthermore, total refusal (not from RF) to turning the screw auger may be used as a measure of total rooting depth.

Drop hammer cm penetration per 5 and 10 drops did not correlate with a measured D_b, with an R^2 of 0.03 and 0.07, respectively. The cm penetration per drop results was similar to those of the sharpshooter penetration depth data. The OH site had the highest measured D_b, along with the lowest RF weight percents that allowed the drop hammer to penetrate deeper into the soil, and consequently resulted in inaccurate data.

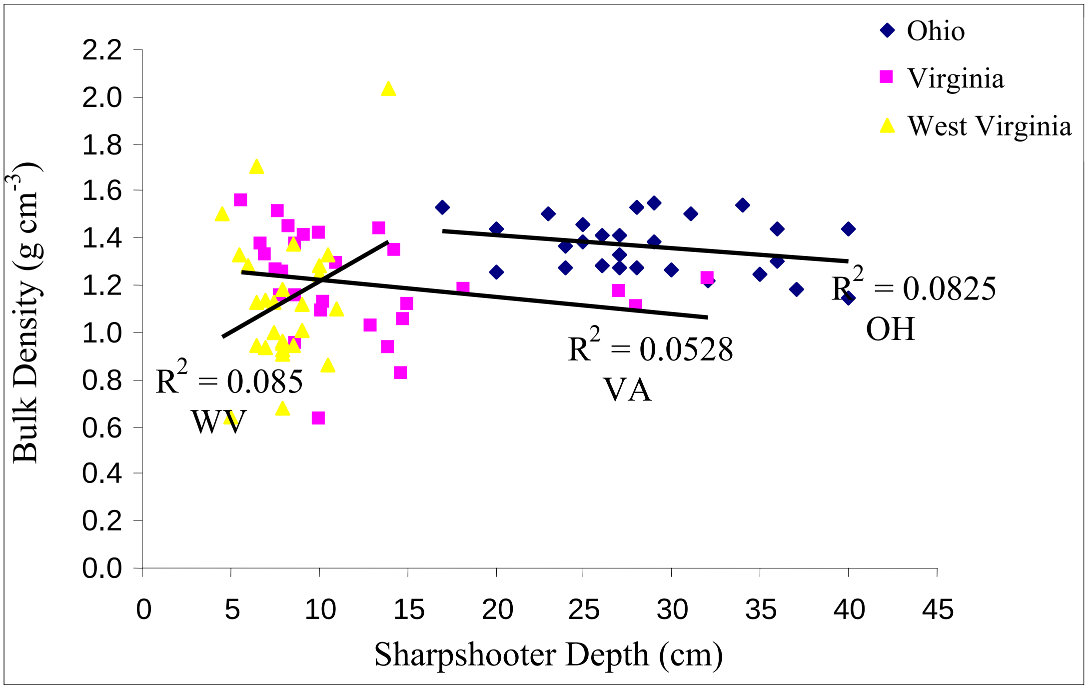

Figure 2-1. The relationship between fine earth bulk density determined by the excavation method and sharpshooter penetration depth at each study site.

No completely quantitative method was found to accurately predict mine soil D_b because of the high volume of RFs. Conventional D_b measurements using the excavation method require laboratory calculations of RF volume and moisture content, and are too time consuming for field practical measurements. Therefore, the "density class" of the upper 20 cm may be estimated based on the average penetration depth of the sharpshooter along with observations of soil rupture resistance and RF type and volume. The depth and ease with which the sharpshooter penetrated the soil was noted, along with the associated soil properties listed above. The following guides can be used to estimate five general density classes: If the sharpshooter penetrates easily to 25 cm or more, then a density class of "very low" is assigned; if penetration is 16 to 25 cm with slight resistance, then a density class of "low" is assigned; if penetration is less than 15 cm with moderate resistance, then a density class of "moderate" is assigned; if penetration is less than 5 cm with strong resistance, then a density class of "high" is assigned; and if penetration is less than 2 cm, then a density class of "very high" is assigned. The density class is decreased one class in soils with an estimated RF content greater than 50%, provided that the moist rupture resistance (a.k.a. moist consistence class) at the depth of maximum sharpshooter penetration is not very firm or extremely firm (Soil Survey Division Staff, 1993) as confirmed by shallow pit excavations. In moist soils with low RF content and textures finer than sandy loam, the density is increased one class because those soil conditions allow sharpshooter penetration into soil that has moist rupture resistance of very firm or extremely firm as confirmed by shallow pit excavations. In extremely dry soils, no adjustment was made. Along with the rupture resistance, fine root growth widely spaced or matted between aggregates and large aggregate size are used to confirm that the soil is dense.

Table 2-2. **Whole and fine soil bulk density (D_b), rock fragment (RF) weight percent, moisture content, sand, silt, and clay determined for the 0-10 cm depth in nine plots within three blocks at three sites (Lawrence County, Ohio (OH); Wise County, Virginia (VA); and Nicholas County, West Virginia (WV)).**

Block	Plot	Whole Soil D_b	Fine Soil D_b	RF	Moisture Content	Sand	Silt	Clay
		--------- g cm^{-3}	---------	----------------------	------- %	-------	-------	-------
OH1	1	1.6	1.6	6	18	30	40	30
OH1	2	1.5	1.4	17	23	35	38	27
OH1	3	1.6	1.5	16	22	31	42	27
OH1	4	1.3	1.3	4	30	26	46	28
OH1	5	1.6	1.5	14	26	34	41	25
OH1	6	1.5	1.5	6	24	27	47	26
OH1	7	1.5	1.4	10	23	31	46	23
OH1	8	1.6	1.4	18	23	29	46	24
OH1	9	1.6	1.5	11	24	24	47	29
OH2	1	1.5	1.5	6	22	42	39	19
OH2	2	1.4	1.4	8	22	47	35	17
OH2	3	1.5	1.4	13	24	36	41	23
OH2	4	1.4	1.2	23	29	36	41	23
OH2	5	1.3	1.1	17	25	39	42	19
OH2	6	1.3	1.3	6	19	54	33	13
OH2	7	1.5	1.4	3	26	33	46	21
OH2	8	1.5	1.4	7	22	40	38	22
OH2	9	1.5	1.5	2	22	42	38	20
OH3	1	1.4	1.3	15	25	31	45	24
OH3	2	1.4	1.2	18	28	38	41	22
OH3	3	1.3	1.2	17	26	39	40	21
OH3	4	1.4	1.3	18	23	33	43	24
OH3	5	1.5	1.3	21	17	35	43	22
OH3	6	1.5	1.3	24	19	33	42	25
OH3	7	1.4	1.3	16	20	30	43	27
OH3	8	1.3	1.3	9	21	30	41	29
OH3	9	1.5	1.4	15	22	35	42	23
VA1	1	1.3	1.1	24	18	46	40	14
VA1	2	1.2	0.8	43	29	62	28	10
VA1	3	1.4	0.9	50	25	56	32	11
VA1	4	1.4	1.1	38	22	49	38	13
VA1	5	1.7	1.3	40	11	51	36	12
VA1	6	1.5	1.3	30	15	45	44	11
VA1	7	1.8	1.2	61	18	57	33	11
VA1	8	1.5	1.2	41	16	49	38	13
VA1	9	1.5	1.0	53	18	56	32	12
VA2	1	1.9	1.6	45	10	52	33	15
VA2	2	2.0	1.4	63	11	49	37	14
VA2	3	2.0	1.2	73	12	58	31	11

Table 2-2 (cont.)

Block	Plot	Whole Soil D_b	Fine Soil D_b	RF	Moisture Content	Sand	Silt	Clay
		--------- g cm^{-3} ---------		---------------------- % ----------------------				
VA2	4	1.8	1.2	65	16	44	43	13
VA2	5	2.0	1.3	72	14	47	39	14
VA2	6	1.8	1.4	49	9	45	42	13
VA2	7	1.9	0.6	88	13	50	37	13
VA2	8	1.6	1.1	54	14	54	34	11
VA2	9	1.8	1.1	66	14	42	42	16
VA3	1	1.8	1.3	51	13	58	30	11
VA3	2	1.8	1.0	71	16	57	30	13
VA3	3	1.4	1.1	35	15	49	39	13
VA3	4	1.6	1.2	50	12	55	33	12
VA3	5	2.0	1.4	62	11	51	37	12
VA3	6	1.8	1.4	45	11	47	37	15
VA3	7	2.0	1.5	55	10	52	34	14
VA3	8	1.8	1.3	56	13	54	33	13
VA3	9	1.8	1.4	48	15	47	44	10
WV1	1	1.5	1.1	47	5	58	35	7
WV1	2	1.5	0.9	62	10	63	30	7
WV1	3	1.7	1.3	49	14	56	36	8
WV1	4	1.7	1.3	48	10	64	29	6
WV1	5	1.7	1.7	0	11	58	35	7
WV1	6	1.7	1.1	61	12	54	39	7
WV1	7	1.6	0.9	63	15	56	35	9
WV1	8	1.8	1.0	71	14	59	34	7
WV1	9	1.6	1.0	65	15	63	29	8
WV2	1	1.7	0.6	81	7	63	28	9
WV2	2	1.7	0.9	67	8	60	33	7
WV2	3	2.0	2.0	0	12	60	32	8
WV2	4	1.6	0.9	66	10	63	28	9
WV2	5	1.7	1.3	47	12	66	25	8
WV2	6	1.8	1.2	65	12	65	25	10
WV2	7	1.7	1.1	56	10	66	27	7
WV2	8	1.6	0.7	76	8	66	29	5
WV2	9	1.7	0.9	67	10	61	31	8
WV3	1	1.9	1.1	69	9	58	32	10
WV3	2	1.9	1.5	52	11	62	30	7
WV3	3	1.5	0.9	60	13	62	30	8
WV3	4	1.6	1.0	64	19	56	34	10
WV3	5	1.5	1.0	54	11	59	31	10
WV3	6	1.7	1.4	43	14	63	29	8
WV3	7	1.7	1.3	43	10	59	35	6
WV3	8	1.8	1.3	52	11	54	35	11
WV3	9	1.5	1.1	42	20	58	35	8

Summary and Conclusions

Fine earth D_b is often high enough in mine soils to restrict root growth and alter hydrologic properties, but measuring this limitation has proven to be very difficult in mine soils. Common measures of soil density and soil strength have been found to be inaccurate and inefficient in field studies, and the need for better measurement methods exist. None of the three tools tested in this study represent a good measure of D_b. Even though sharpshooter penetration depths do not appear to be a reliable estimate for D_b in mine soils, they may have use as an indicator of a relative soil density class. The resistance and refusal of the screw auger may indicate root limitations in mine soils, but no quantitative measurement of D_b is useful. The drop hammer was not useful for D_b estimation. A relative estimate of soil density may be best in mine soil mapping since actual D_b values are often inaccurate and difficult to obtain, and the knowledge and experience of a field scientist is invaluable in making such a qualitative assessment. Further research is needed to develop a rapid, simple, on-site measurement or estimate of D_b in high RF mine soils in the Appalachian region.

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TASK 3: Develop reforestation methods and procedures for mined land. (Fox et al.)

Executive Summary

All surface mining activities conducted after August 3, 1977, are subject to the provisions of Public Law 95-87, the Surface Mining Control and Reclamation Act of 1977 (SMCRA). This law mandated that reclamation be carried out on all surface mined lands, and set forth criteria for mine operators to follow in carrying out reclamation practices. Unfortunately, many of these criteria have created adverse conditions for reclamation with trees, and consequently reforestation of surface mined lands has decreased since the passage of SMCRA (Ashby 1991). These adverse conditions include: (1) excessive competing vegetation; (2) soil compaction; and (3) unfavorable soil chemical properties.

Competing vegetation is a direct result of ground covers sown to prevent soil erosion on newly reclaimed surfaces. The most commonly used ground covers include tall fescue, clover species, and other grasses and legumes. These dense grasses and legumes compete with tree seedlings for light, water and nutrients (Ashby 1991). On a surface mine in Indiana, Andersen and coworkers (1989) found that black walnut (*Juglans nigra*) and northern red oak (*Quercus rubra*) survival after seven growing seasons increased from 4% and 1%, respectively, when planted into an existing dense ground cover to 66% and 48%, respectively, when planted after ground cover was controlled. Adequate stocking of trees required to meet the specifications of SMCRA (1110 trees ha^{-1}) was only attained when the ground cover was controlled with herbicide. Height growth was significantly better on the mine site where weeds were controlled. Twelve-year results of this study again showed that height growth was enhanced by weed control (Chaney et al. 1995).

Soil compaction on post-SMCRA mined lands is also widespread. Soil compaction in mine soils is usually caused by the passage of large equipment over the soil in an effort to stabilize the soil when returning it to its approximate original contour as required by SMCRA. Soil compaction inhibits root growth of seedlings by increasing bulk density and consequently increasing soil strength, decreasing aeration porosity, and inhibiting the ability of the soil to drain once saturated (Omi 1985). Tillage treatments can ameliorate the detrimental effects of compaction. Ashby (1997) found that the mean height of 16 different tree species was significantly greater five years after ripping a mine soil to a depth of 1.2 m. Another study found that after 12 years, ripping to a depth of 85 cm significantly increased the survival, height, and diameter growth of both red oak and black walnut in southern Illinois (Ashby 1996). Black walnut seedlings growing on a surface mine in southern Illinois were found to have taproot lengths which were 92% and 75% greater in their first and second years of growth, respectively, in ripped versus unripped plots (Philo et al. 1982). This same study found overall rooting depth to be 81% and 58% greater in their first and second years in the ripped versus the unripped plots. For the second year only, radial root growth was found to be 89% greater in the ripped plots.

Chemical properties of mine soils are related to the overburden rock type from which these soils were created. In a study of the effect of overburden rock type on survival and growth of pitch x loblolly hybrids (*Pinus rigida* x *taeda*), an inverse relationship between soil pH and tree volume was found (Torbert et al. 1990). The rock types evaluated in this study consisted of pure sandstone and pure siltstone as well as mixtures of various amounts of these types. It is noteworthy that pH increased consistently as the proportion of sandstone decreased and as the proportion of siltstone increased. Plant available N and P are low on mine soils. Howard and coworkers (1988) found that mine soils in southwest Virginia had large quantities of P and K, but they suggest that P will likely be deficient even after fertilization due to the high P-fixing capacity of these soils. Another study in southwest Virginia found that compared to native forest soils, mine soils had less total N, and that the forms of N in the mine soils was largely unavailable to plants (Li and Daniels 1994).

Numerous species of trees have been studied for use in post-SMCRA reclamation and all with varying degrees of success, depending on the site conditions such as those previously described. White pine (*Pinus strobus* L.) has likely been the most extensively used species in reclamation. This species success in reclamation has ranged from good for a study in southwestern Virginia where the species averaged 58% survival and 3.8 m of height growth after 11 years (Torbert et al. 2000) to poor for a study in southeastern Ohio where no pines survived after three years (Larson et al. 1995).

Several hardwood species have also been tested for use in reclaiming post-SMCRA mined lands. Gorman and Skousen (2003) found excellent survival (90 to 100%) of several commercially valuable hardwoods on a reclaimed mountaintop removal mine in West Virginia when weed control and tillage were employed. A study in southwestern Virginia found 57%, 54%, and 91% survival for chestnut oak (*Quercus prinus* L.), yellow poplar (*Liriodendron tulipifera* L.), and white ash (*Fraxinus americana* L.), respectively, in plots where weeds were controlled chemically (Torbert et al. 1985).

The purpose of this study was to evaluate the survival and growth performance of three species assemblages under three levels of silvicultural input intended to alleviate the adverse conditions for tree survival and growth on post-SMCRA mined land. Additionally, selected physiological responses of hybrid poplar seedlings to these silvicultural treatments were assessed at one study site.

Experimental

Study Design

The study used a 3 x 3 factorial combination of treatments across three sites in a randomized complete block design to investigate the effects of silvicultural treatment, species assemblage, and site conditions on seedling survival and growth. This design was replicated with three blocks at each of the three study sites. The three levels of silvicultural treatment were:

1. Low intensity – weed control only (WC);
2. Medium intensity – weed control plus tillage to alleviate soil compaction (WC+T); and
3. High intensity – weed control and tillage plus fertilization to amend soil chemical properties (WC+T+F).

Species assemblages used were:

1. White pine (WP);
2. Hybrid poplar (*Populus trichocarpa* L. (Torr. & Gray ex Hook.) x *Populus deltoides* (Bartr. ex Marsh.) hybrid 52-225) (HP), and;
3. Native hardwood mix (HW).

Tree spacing was fixed for all species at 2.4 m x 3.0 m, giving a final planting density of 1,345 trees/ha. White pine and hybrid poplar were planted in pure stands, while the hardwood species mix varied at each site in order to approximate a pre-mining forest condition found in adjacent undisturbed forest (Table 3-1). In addition to the commercial hardwood, a combination of three nurse tree species was planted to provide early wildlife habitat and to more closely resemble the native hardwood mixture (Burger and Zipper 2002).

Table 3-1. Species composition and percentage of each species for the mixed hardwood plots at the three study sites.

Ohio		West Virginia		Virginia	
Species	**%**	**Species**	**%**	**Species**	**%**
Common Hardwoods (HW1):					
northern red oak	9.6	northern red oak	15.3	northern red oak	10.9
tulip poplar	9.6	tulip poplar	15.3	tulip poplar	10.9
sugar maple	9.6	sugar maple	15.3	sugar maple	10.9
Site-Specific Hardwoods (HW2):					
black oak	9.6	red maple	15.3	pignut hickory	10.9
chestnut oak	19.2	white ash	15.3	white oak	21.9
hickory	9.6				
scarlet oak	9.6				
Shrubs:					
redbud	7.7	redbud	7.8	redbud	7.8
flowering dogwood	7.7	flowering dogwood	7.8	flowering dogwood	7.8
Wash. hawthorn	7.7	Wash. hawthorn	7.8	Wash. hawthorn	7.8

Study sites were located in Lawrence County, Ohio, Nicholas County, West Virginia, and Wise County, Virginia, on land surface mined for coal and subsequently reclaimed according to SMCRA regulations (Fig. 3-1). The post-mining land use at all sites was hayland pasture, and the sites supported a dense vegetative cover composed of grasses and legumes prior to study establishment.

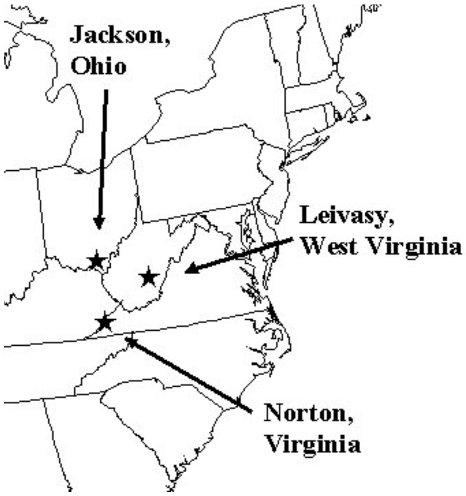

Figure 3-1. Location of study sites.

The site in Lawrence County, Ohio, had topsoil replaced to varying depths across the site. Both the surface soil and the subsurface soil had fine textures and low coarse fragment percentages compared to the other two sites (Tables 3-2 and 3-3). The oxidized surface soil had a much lower pH than the unoxidized subsurface material that was derived from siltstone material. The site has been reclaimed for at least 10 years and had a dense cover of predominantly tall fescue and sericea lespedeza (*Lespedeza cuneata*).

The Nicholas County, West Virginia, site did not have topsoil replaced and the material at this site was shale-derived throughout the profile. The site had coarse soil textures and high coarse fragment contents (50-60%) throughout the profile (Tables 3-2 and 3-3). The site was used for grazing prior to study establishment with the dominant grass species being tall fescue and had been reclaimed for at least 10 years.

The site in Wise County, Virginia, was derived from sandstone rocks, and soil textures ranged from loam to sandy loam. This site had an oxidized topsoil material returned to the surface throughout the plots. This site also had high coarse fragment percentages; however, the subsurface typically had more than the surface layer (Tables 3-2 and 3-3). The blocks at this site had been reclaimed for less than five years, with one block having been reclaimed the spring before study establishment. The newly reclaimed block was seeded to foxtail millet, while the other two sites were dominated by tall fescue and sweet clover.

Plots were blocked within each site based on soil properties (Tables 3-2 and 3-3). Nine 0.25-ha plots were established in each of the three blocks at each site. Plots were laid out to be as contiguous as possible within each block, while still maintaining uniform soil properties. Slopes in all plots were less than 15%.

The weed control treatment used herbicide to reduce existing herbaceous vegetation. In August 2003 a broadcast treatment of glyphosate herbicide was applied at a rate of 9.35 l ha^{-1}. Following the glyphosate treatment, a pre-emergent herbicide containing pendimethalin was applied after tree planting in April 2004 at a rate of 4.92 l ha^{-1} to control germinating grasses. Spot applications of glyphosate were applied around each seedling in July 2004 to control competition at all study blocks, except for one block at the Virginia site where no competition was present. Seedlings were shielded from herbicide drift during application.

The tillage treatment employed was ripping. The tillage treatments varied by site depending on local equipment availability; however, the same equipment was used within individual blocks. Variations in the tillage treatment included single shank only, single shank with coulters creating beds, and multiple shanks resulting in tillage of the entire plot. The rips were spaced approximately 3 m apart and the depth of ripping was set between 61 and 91 cm. The plots were treated prior to planting in April 2004.

Fertilizer was applied to the designated plots in late May 2004. A banded application of 272 kg ha^{-1} of diammonium phosphate added 49.0 kg ha^{-1} N and 55.1 kg ha^{-1} P. Muriate of potash and the micronutrient mix were applied around the base of each seedling at the following rates: 91 kg ha^{-1} of muriate of potash added 46.8 kg ha^{-1} K; and 20 kg ha^{-1} of a micronutrient mix added 1.8 kg ha^{-1} S, 0.2 kg ha^{-1} B, 0.2 kg ha^{-1} Cu, 0.8 kg ha^{-1} Mn, and 4.0 kg ha^{-1} Zn.

Table 3-2. Soil properties for 0-10 cm depth of study blocks at research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA.

Site	Block	pH	Electrical Conductivity (dS m^{-1})	CEC (cmol$_c$ kg$^{-1}_{soil}$)	$NaHCO_3$ Extractable P (mg kg^{-1})	Total N (%)	Coarse Fragments (%)	Sand-stone (%)	Silt-stone (%)	Shale (%)	Texture	Bulk Density (g cm^{-3})
OH[†]	1	4.89	0.06	9.26	10.3	0.125	6.4	14.44	85.56	0.00	L[*]	1.53
OH[†]	2	5.19	0.11	7.69	7.69	0.114	6.96	27.22	61.67	0.00	L	1.44
OH[†]	3	6.05	0.13	9.05	5.38	0.106	9.86	27.22	72.78	0.00	L	1.4
Mean:		**5.38**	**0.10**	**8.67**	**7.79**	**0.115**	**7.74**	**22.96**	**73.34**	**0.00**	**L**	**1.46**
VA[†]	1	4.75	0.18	5.46	9.98	0.058	32.36	72.78	15.00	0.00	L	1.48
VA[†]	2	6.3	0.28	6.57	10.07	0.091	41.06	46.67	31.11	0.00	L	1.87
VA[†]	3	6.43	0.38	5.21	13.75	0.053	51.65	65.00	35.00	0.00	L/SL	1.76
Mean:		**5.83**	**0.28**	**5.75**	**11.27**	**0.067**	**41.69**	**61.48**	**27.04**	**0.00**	**L**	**1.70**
WV[††]	1	5.91	0.21	8.81	20.13	0.278	54.29	9.44	13.89	76.67	SL	1.66
WV[††]	2	5.72	0.22	8.37	20.81	0.258	55.26	7.22	11.67	81.11	SL	1.71
WV[††]	3	5.52	0.21	7.85	18.03	0.281	46.21	10.56	15.00	73.33	SL	1.67
Mean:		**5.72**	**0.21**	**8.34**	**19.66**	**0.272**	**51.92**	**9.07**	**13.52**	**77.04**	**SL**	**1.68**

[†] Topsoils in OH and VA were comprised of oxidized material replaced specifically as topsoil or topsoil substitute.

[††] Topsoil in WV was the upper 10cm of soil is unoxidized and is the same material that comprises the subsoil layer.

[*] L = loam; SL = sandy loam

Table 3-3. Soil properties for subsurface samples of study blocks at research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA.

Site	Block	pH	Electrical Conductivity (dSm^{-1})	CEC ($cmol_c\ kg^{-1}{}_{soil}$)	$NaHCO_3$ Extractable P ($mgkg^{-1}$)	Total N (%)	Coarse Fragments (%)	Sand-stone (%)	Silt-stone (%)	Shale (%)	Texture	Bulk Density ($g\ cm^{-3}$)
OH†	1	6.86	0.26	16.21	0	0.048	25.41	18.89	80	1.11	SiCL	1.7
OH†	2	6.15	0.61	13.12	0.84	0.052	18.01	21.67	73.89	0	L	1.73
OH†	3	6.91	0.53	14.08	0.32	0.043	16.36	8.89	91.11	0	SiCL	1.66
Mean:		**6.64**	**0.47**	**14.47**	**0.39**	**0.048**	**19.93**	**16.48**	**81.67**	**0.37**	**SiCL**	**1.70**
VA†	1	6.77	0.21	6.02	3.38	0.060	50.27	81.43	18.57	0	SL	1.74
VA†	2	7.55	0.28	7.46	2.94	0.087	63.25	20	68.89	0	SL	-
VA†	3	6.37	0.26	4.35	2.78	0.065	56.57	66.25	33.75	0	SL	-
Mean:		**6.90**	**0.25**	**5.94**	**3.03**	**0.071**	**56.70**	**55.89**	**40.40**	**0.00**	**SL**	**1.74**
WV††	1	6.72	0.1	6.62	7.13	0.120	59.21	10.56	10	67.22	SL	-
WV††	2	6.03	0.12	5.89	5.94	0.101	61.56	6.67	12.22	73.11	SL	-
WV††	3	5.87	0.1	5.85	3.68	0.100	53	12.22	17.78	59	L/SL	-
Mean:		**6.21**	**0.11**	**6.12**	**5.58**	**0.107**	**57.92**	**9.82**	**13.33**	**66.44**	**SL**	**-**

† Subsurface samples in OH and VA were collected from spoil material located directly below the oxidized material at the surface that was of variable thickness.

†† Subsurface samples in WV were collected from 10 to 30 cm of depth as this layer was the same material that comprised the topsoil layer.

* L = loam; SiCL = silty clay loam; SL = sandy loam

Survival and Growth Data Collection

A 20 x 20 m measurement plot was established in the center of each treatment plot, within which all trees were assessed for survival, height growth, and groundline diameter growth. Initial height and groundline diameter were assessed in May 2004, shortly after bud break. First-year survival and growth was determined following measurement in late August of 2004.

Hybrid Poplar Biomass Measurements

Detailed destructive sampling to determine above- and below-ground biomass allocation was conducted in the hybrid poplar plots at the site in Nicholas County, West Virginia. Three randomly selected trees from each plot were harvested in mid-September for plant biomass determinations. Harvested trees were located outside the measurement plots used to assess survival and growth. Trees were cut off at the groundline and leaves were separated from the stems. The entire root system of each tree was carefully excavated from the soil and washed gently with water to remove soil adhering to the roots. Roots were stored at 4^{o}C in sealed plastic bags with a moist paper towel for a period of up to four weeks, during which time the roots were separated into coarse (>0.5 mm) and fine (<0.5 mm) root fractions. All tissue samples were dried at 65°C for a minimum of 72 hours and weighed. A subsample was then ground using a Wiley mill to pass a 1-mm screen. In some instances when samples were small, a coffee grinder was used to grind all the foliage collected.

Hybrid Poplar Tissue Analysis

Tissue samples from the harvested trees in each plot were composited by the following tissue types for nutrient analysis: (1) foliage, (2) stem, and (3) roots. Total C and N were determined using an Elementar varioMAX CNS analyzer (Mt. Laurel, NJ). After dry ashing and digesting with 6*N* HCl, the tissue samples were analyzed using a SpectroFlame Modula Tabletop inductively coupled plasma spectrophotometer to determine elemental concentrations of P, Mg, Ca, and K for all tissue samples and S, B, Cu, Mn, and Zn for foliage samples only.

Hybrid Poplar Moisture Stress Measurements

Seedling water potential was measured using a pressure chamber (PMS Instrument Co. Model 1000 Corvallis, OR) for four consecutive rain-free days (August 16-19, 2004), with the initial measurement having been made the day after a significant rain event. Three trees from each hybrid poplar plot were measured to obtain average water potential for that plot. Measurements were timed so as to measure the water potential of all trees within a plot at the same time during the afternoon (2:30 to 6:30 p.m.) over the course of the four-day period. Water potential readings were taken immediately after the leaf was excised from the tree.

Soil samples of the surface 30 cm were collected each day from three random locations in each plot. Soil samples were stored in a sealed plastic bag and returned to the lab for determination of gravimetric soil moisture content. Soil sampling preceded water potential sampling and was confined to a time period between 12:30 and 2:00 p.m. Individual plots were sampled at the same time each of the three days.

Data Analysis

Analysis of variance was used to analyze survival and growth data for differences in survival percentage, height growth, total height, diameter growth, total diameter, volume growth, and total volume as a 3 x 3 x 3 factor random complete block design having three species assemblages, three sites, and three treatments. Tree volume was calculated as diameter squared multiplied by tree height. Analysis of variance was done by site if interaction terms containing site were significant. Additionally, if the species x treatment interaction was significant after analyzing by site, analysis of variance was done by species and by treatment to perform mean separation procedures. For all survival and growth data, survival percentages for seedlings were transformed using the arcsine transformation and any of the growth measures that showed non-normality or heteroscedasticity were transformed using the natural log function prior to analysis of variance and subsequent mean separation procedures (Gomez and Gomez 1984).

Subsequent to the overall analysis, hardwood species were divided into three groups (Table 3-2) for further investigation of differences between the species used. The HW1 and shrub groups were found at each site, and the HW2 group varied by site. These data were analyzed in the same manner as the overall analysis, except that the three groups of hardwoods replaced the three species assemblages used in the overall study.

Hybrid poplar biomass data were analyzed for differences between biomass measures by treatment. Arcsine transformation was used to transform percentage data prior to analysis of variance, and any non-normal or heteroscedastic data were transformed using either the inverse or natural logarithm transformation (Gomez and Gomez 1984). Similarly, data from tissue samples were analyzed for differences between nutrient concentrations by tissue type, and non-normal and heteroscedastic data were transformed using the inverse function prior to analysis of variance. Moisture stress data was analyzed as a split-plot design with treatment as the whole plot and date as the split plots for differences between dates and treatments for soil moisture as well as plant water potential.

Mean separation was done using Tukey's HSD with significance set at $P < 0.05$ for all comparisons. If interaction terms were not significant, only main effect means were compared. SAS version 8.2 (SAS Institute Inc., Cary, NC 2001) was used for all statistical analyses.

Results

Survival

Site, species, and treatment effects, as well as both two-way interactions involving site, were all statistically significant for survival (Table 3-4). Treatment effects by site show that in Ohio (OH), weed control plus tillage plus fertilization (WC+T+F) significantly decreased survival to 14% compared to weed control plus tillage (WC+T) and weed control only (WC) at 49% and 51%, respectively (Table 3-5). At the West Virginia (WV) site, WC+T resulted in significantly higher survival than in either of the other treatments. The treatments had no effect on survival in Virginia (VA). The mean survival across species was notably higher in VA than at the other sites, though site means were not separated.

In terms of species effects, hardwood (HW) species had the highest mean survival at all sites (Table 3-5). This difference was significantly higher than all other species means at all other sites with the exception of hybrid poplar (HP) in OH. White pine (WP) had very low survival in OH and WV across treatments (27% and 41% respectively). Survival for HP was also low in OH and WV at 37 and 41% respectively whereas VA again had notably higher mean survivals for all species across treatments (Table 3-5).

Table 3-4. Analysis of variance results for survival and growth parameters for research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA.

Source	Degrees of Freedom	Variable (Pr>F)						
		Survival	Height Growth	Diameter Growth	Volume Growth	Total Height	Total Diameter	Total Volume
Block	2	0.0057	0.0076	0.0812	0.8254	0.0231	0.1650	0.0270
Site	2	<0.0001	<0.0001	0.0004	<0.0001	0.0005	0.0001	0.0001
Treatment	2	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Site*Treatment	4	0.0097	0.0003	0.0036	<0.0001	0.0535	0.0031	0.0143
Species	2	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Site*Species	4	0.0332	<0.0001	0.0009	<0.0001	0.0021	0.0049	0.0179
Treatment*Species	4	0.3567	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Site*Treatment*Species	8	0.3367	<0.0001	0.1146	<0.0001	0.1214	0.0678	0.3442
Model	28	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Error*	**51(52)**							
Total*	**79(80)**							

* Degrees of freedom in parentheses are for survival only. Zero survival in one study block caused the loss of one degree of freedom from all growth variables.

Table 3-5. Survival percentage for research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA by treatment and species group.

Site and Treatment	Species Group			Treatment Mean
	HW	HP	WP	
Ohio:				
WC	60	49	45	51 x**
WC+T	72	45	29	49 x
WC+T+F	18	17	6	14 y
Species Mean	**50 a***	**37 ab**	**27 b**	**38**
West Virginia:				
WC	78	32	41	51 x
WC+T	94	62	50	69 y
WC+T+F	68	27	33	43 x
Species Mean	**80 a**	**41 b**	**41 b**	**54**
Virginia:				
WC	81	79	53	71 x
WC+T	90	70	70	77 x
WC+T+F	84	67	50	67 x
Species Mean	**85 a**	**72 b**	**58 b**	**72**

* a, b, c – For each site, values within rows with the same letter are not significantly different at $P < 0.05$.

** x, y, z – For each site, values within columns with the same letter are not significantly different at $P < 0.05$.

Height Growth

All model terms, including the three-way interaction among site, species, and treatment, were significant for height growth (Table 3-4). Analysis by site revealed that the species by treatment interaction was not significant in OH and that there were no treatment effects at this site (Table 3-6). Species by treatment interaction was still significant in WV and VA when analyzed by site. Significant treatment effects in WV included higher mean height growth for HW in WC+T+F than in WC as well as lower mean height growth for HP in WC (22.4 cm) compared to both of the other treatments (60.2 cm for WC+T and 57.6 cm for WC+T+F). In VA, both HW and HP had significantly more height growth as a result of WC+T+F than in either of the other treatments, with this difference being pronounced for HP (126.6 cm in WC+T+F versus 40.9 and 65.4 cm for WC and WC+T, respectively) (Table 3-6).

Considering species effects, HP grew significantly more than HW and WP across treatments in OH (45.6cm versus –2.3cm and 6.0cm respectively) and HW had negative height growth means for all treatments at this site (Table 3-6). In WV, HP grew significantly more that HW and WP in all treatments. In the WC treatment, WP also had significantly more height growth than HW (5.5cm versus –1.4cm). At the VA site, HP grew significantly more than HW and WP (Table 3-6).

Table 3-6. Average height growth (cm) for research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA, by treatment and species group.

Site and Treatment	Species Group			Treatment Mean
	HW	HP	WP	
Ohio:				
WC	-1.0	35.8	5.2	13.3 x[**]
WC+T	-3.7	50.3	5.4	17.4 x
WC+T+F	-2.3	50.8	7.9	20.2 x
Species Mean	**-2.3 a**[*]	**45.6 b**	**6.0 a**	**16.8**
West Virginia:				
WC	-1.4 a x	22.4 b x	5.5 a x	8.8
WC+T	3.2 a xy	60.2 b y	8.9 a x	24.1
WC+T+F	7.7 a y	57.6 b y	5.8 a x	23.7
Species Mean	**3.2**	**46.7**	**6.7**	**18.9**
Virginia:				
WC	3.7 a x	40.9 b x	6.0 a x	16.9
WC+T	3.9 a x	65.4 b x	5.9 a x	25.1
WC+T+F	7.9 a y	126.6 b y	5.5 a x	46.7
Species Mean	**5.2**	**77.6**	**5.8**	**29.5**

[*] a, b, c – For each site, values within rows with the same letter are not significantly different at $P < 0.05$.

[**] x, y, z – For each site, values within columns with the same letter are not significantly different at $P < 0.05$.

Total Height

All model terms except the three-way interaction among site, species, and treatment and the site by treatment interaction were significant for total height after one growing season (Table 3-4). Analysis by site revealed that the species by treatment interaction was not significant in OH and that there were no treatment effects at this site (Table 3-7). In WV and VA, species interacted significantly with treatment. Treatment effects by species in WV included larger final heights for HP in WC+T and WC+T+F compared to WC and more total height for WP in WC+T compared to the other treatments. In VA, the only significant treatment response was a higher final height for HP in WC+T+F than the other two treatments (Table 3-7).

As expected, species effects for total height were somewhat different than those for height growth. In OH, mean HW height across treatments was 30.1 cm, which was not significantly different from HP or WP at 45.6 and 23.3 cm, respectively. HP and WP total heights were significantly different from each other at this site (Table 3-7). In WV, all three species were significantly different at each level of treatment with the species by treatment interaction occurring in the WC treatment where HP was found to have the shortest total height as opposed to the other two treatments where HP had the tallest total height (Table 3-7). In VA, HW species were not significantly different from WP or HP, which were significantly different from each other for WC. In WC+T and WC+T+F at this site, all species were significantly different. Mean WP heights were the shortest and HP heights the tallest for all treatments at this site (Table 3-7).

Table 3-7. Total tree height (cm) for research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA, by treatment and species group.

Site and Treatment	Species Group			Treatment Mean
	HW	**HP**	**WP**	
Ohio:				
WC	30.8	35.8	22.4	29.7 x[**]
WC+T	25.0	50.3	24.7	33.4 x
WC+T+F	34.4	50.8	22.6	37.6 x
Species Mean	**30.1 ab**[*]	**45.6 a**	**23.3 b**	**33.4**
West Virginia:				
WC	32.4 a x	22.4 b x	25.2 c x	26.6
WC+T	38.6 a x	60.2 b y	28.2 c y	42.3
WC+T+F	36.5 a x	57.6 b y	22.9 c x	39.0
Species Mean	**35.8**	**46.7**	**25.4**	**36.0**
Virginia:				
WC	33.1 ab x	40.9 a x	23.5 b x	32.5
WC+T	37.0 a x	65.4 b x	25.0 c x	42.4
WC+T+F	40.6 a x	126.6 b y	22.6 c x	63.3
Species Mean	**36.9**	**77.6**	**23.7**	**46.1**

[*] a, b, c – For each site, values within rows with the same letter are not significantly different at $P < 0.05$.

[**] x, y, z – For each site, values within columns with the same letter are not significantly different at $P < 0.05$.

Diameter Growth

All model terms were significant for diameter growth with the exception of the three-way interaction among site, species, and treatment (Table 3-4). Analysis by site eliminated the species by treatment interaction at the site in OH and showed that there were no treatment effects at this site on diameter growth. The species by treatment interaction in WV was likely due to the significant diameter growth response to WC+T (7.0mm) and WC+T+F (7.5 mm) compared to WC (3.1 mm) when no other species had a significant response to treatment at this site (Table 3-8). Similarly, species by treatment interaction in VA was likely due to the significant response for HP in WC+T+F (13.9 mm) compared to WC+T (7.0 mm) and WC (4.9 mm). There were no other treatment differences at this site.

Species effects show that HP had significantly more diameter growth than any other species at any level of treatment at all three sites (Table 3-8). In WV, where species by treatment interaction was significant, in addition to the HP response HW grew significantly more in diameter than WP. There were no other differences in species in VA other than the HP response.

Table 3-8. Average diameter growth (mm) for research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA, by treatment and species group.

Site and Treatment	Species Group			Treatment Mean
	HW	HP	WP	
Ohio:				
WC	0.9	4.1	0.9	2.0 x[**]
WC+T	0.8	5.5	0.5	2.3 x
WC+T+F	0.3	7.4	0.7	3.1 x
Species Mean	**0.7 a**[*]	**5.7 b**	**0.7 a**	**2.4**
West Virginia:				
WC	0.9 a x	3.1 b x	0.5 c x	1.5
WC+T	1.4 a x	7.0 b y	0.7 a x	3.0
WC+T+F	1.8 a x	7.5 b y	0.9 a x	3.4
Species Mean	**1.4**	**5.9**	**0.7**	**2.6**
Virginia:				
WC	0.8 a x	4.9 b x	0.6 a x	2.1
WC+T	1.4 a x	7.0 b x	0.6 a x	3.0
WC+T+F	2.1 a x	13.9 b y	0.7 a x	5.6
Species Mean	**1.4**	**8.6**	**0.6**	**3.6**

[*] a, b, c – For each site, values within rows with the same letter are not significantly different at $P < 0.05$.

[**] x, y, z – For each site, values within columns with the same letter are not significantly different at $P < 0.05$.

Total Diameter

As with diameter growth, all model terms were significant for total diameter with the exception of the three-way interaction between site, species, and treatment (Table 3-4). Analysis by site eliminated the species by treatment interaction at the site in OH and showed that there were no treatment effects at this site on total diameter (Table 3-9). In WV and VA, species and treatment interacted significantly. There were no significant treatment effects in WV for any species, while in VA; the only significant treatment response was for HP, where the WC+T+F total diameter (13.6 mm) compared to the WC+T (7.0 mm) and WC (4.9 mm).

There were no significant differences among species in OH across all treatments (Table 3-9). The significant interaction between species and treatment in WV was attributable to HP in WC being significantly less than HW and WP, whereas HP is no different than HW in WC+T and significantly higher than WP in WC+T and HW and WP in WC+T+F. There were no species differences in WC at the site in VA (Table 3-9), where species by treatment interaction was significant. For WC+T, HP was significantly greater than WP, and for WC+T+F, HP was significantly greater than both WP and HW.

Table 3-9. Total tree diameter (mm) for research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA, by treatment and species group.

Site and Treatment	**Species Group**			**Treatment Mean**
	HW	**HP**	**WP**	
Ohio:				
WC	5.3	4.1	4.6	4.7 x[**]
WC+T	4.5	5.5	4.3	4.8 x
WC+T+F	4.9	7.4	3.8	5.6 x
Species Mean	**4.9 a**[*]	**5.7 a**	**4.3 a**	**5.0**
West Virginia:				
WC	5.2 a x	3.1 b x	4.5 a x	4.3
WC+T	5.6 ab x	7.0 a x	5.1 b x	5.9
WC+T+F	5.7 a x	7.5 a x	4.3 a x	5.8
Species Mean	**5.5**	**5.9**	**4.7**	**5.3**
Virginia:				
WC	4.9 a x	4.9 a x	5.0 a x	4.9
WC+T	5.6 ab x	7.0 a x	4.9 b x	5.8
WC+T+F	6.5 a x	13.9 b y	4.8 a x	8.4
Species Mean	**5.7**	**8.6**	**4.9**	**6.4**

[*] a, b, c – For each site, values within rows with the same letter are not significantly different at $P < 0.05$.

[**] x, y, z – For each site, values within columns with the same letter are not significantly different at $P < 0.05$.

Volume Growth

For volume growth, all model terms, including the three-way interaction among site, species, and treatment, were significant (Table 3-4). Analysis by site eliminated the species by treatment interaction in OH and showed no differences among treatments for volume growth at this site (Table 3-10). Species by treatment interaction was significant for WV and VA when analyzed by site. The interaction in WV was found to be the significant volume growth response in WC+T (4.2 cm^3) for WP compared to WC (2.3 cm^3), though neither treatment was significantly different from WC+T+F (2.8 cm^3). There was also a notable response for HP to WC+T (43.3 cm^3) and WC+T+F (51.7 cm^3) compared to WC (2.8 cm^3). In VA, the interaction is explained by the positive response to WC+T+F for HW and HP, while WP was unresponsive. The response was significant compared to WC and WC+T for HP and compared only to WC for HW (Table 3-10).

Looking at species effects in OH, HP had significantly more volume growth than HW or WP across treatments (Table 3-10). The species differences in WV occurred in WC+T, where HP had significantly more volume growth than HW or WP, and in WC+T+F, where HP volume growth was significantly higher than that for WP. In VA, HP volume growth was significantly higher than HW and WP for all treatments (Table 3-10).

Table 3-10. Average volume growth (cm^3) for research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA, by treatment and species group.

Site and Treatment	Species Group			Treatment Mean
	HW	**HP**	**WP**	
Ohio:				
WC	4.1	11.3	2.8	6.1 x[**]
WC+T	2.0	26.2	1.9	10.0 x
WC+T+F	0.2	54.5	2.1	21.0 x
Species Mean	**2.1 a**[*]	**30.7 b**	**2.3 a**	**12.4**
West Virginia:				
WC	2.3 a x	2.8 a x	2.3 a x	2.4
WC+T	7.3 a x	43.3 b y	4.2 a y	18.2
WC+T+F	10.4 ab x	51.7 a y	2.8 b xy	21.6
Species Mean	**6.6**	**32.6**	**3.1**	**14.1**
Virginia:				
WC	4.0 a x	15.6 b x	2.8 a x	7.5
WC+T	8.2 a xy	54.1 b x	2.7 a x	21.7
WC+T+F	16.5 a y	312.1 b y	2.7 a x	110.4
Species Mean	**9.5**	**127.3**	**2.8**	**46.5**

[*] a, b, c – For each site, values within rows with the same letter are not significantly different at $P < 0.05$.

[**] x, y, z – For each site, values within columns with the same letter are not significantly different at $P < 0.05$.

Total Volume

All model terms with the exception of the three-way interaction among site, species, and treatment were significant for total volume (Table 3-4). Analysis by site eliminated the species by treatment interaction for OH, where no treatment effects were evident (Table 3-11). Species by treatment interaction was significant for WV and VA. The only treatment effect in WV was a significantly higher total volume in WC+T and WC+T+F compared to WC only for HP. In VA, HW had significantly more volume in WC+T+F than WC, while for HP, WC+T+F had significantly more volume (312.1 $cm^{3)}$ than both WC+T and WC (54.1 and 15.6 cm^3, respectively) (Table 3-11).

In terms of species differences, HP had significantly more final volume than WP in OH. In WV, HP volume was the lowest and HW the highest in WC, where all three species were significantly different (Table 3-11). HP was significantly higher than all other species in WC+T and WP was significantly lower than the other species in WC+T+F in WV. In VA, there were no differences in volume among species in WC. In WC+T, HP had significantly more volume than HW or WP, and in WC+T+F, all three species were significantly different, with HP having the highest volume (312.1 cm^3) followed by HW (25.9 cm^3) and WP (6.2 cm^3).

Table 3-11. Total tree volume (cm^3) for research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA, by treatment and species group.

Site and Treatment	Species Group			Treatment Mean
	HW	**HP**	**WP**	
Ohio:				
WC	13.9	11.3	5.6	10.3 x[**]
WC+T	7.4	26.2	5.6	13.1 x
WC+T+F	14.7	54.5	3.9	26.9 x
Species Mean	**12.0 ab**[*]	**30.7 a**	**5.2 b**	**16.4**
West Virginia:				
WC	11.7 a x	2.8 b x	6.2 c x	6.9
WC+T	17.6 a x	43.3 b y	9.0 a x	23.3
WC+T+F	16.4 a x	51.7 a y	5.2 b x	24.4
Species Mean	**15.2**	**32.6**	**6.8**	**18.2**
Virginia:				
WC	11.4 a x	15.6 a x	6.9 a x	11.3
WC+T	17.6 a xy	54.1 b x	7.0 a x	26.3
WC+T+F	25.9 a y	312.1 b y	6.2 c x	114.7
Species Mean	**18.3**	**127.3**	**6.7**	**50.8**

[*] a, b, c – For each site, values within rows with the same letter are not significantly different at $P < 0.05$.

[**] x, y, z – For each site, values within columns with the same letter are not significantly different at $P < 0.05$.

Hardwood Species Differences

Survival

For hardwood survival percentage, site, treatment, species group, and the site by treatment interaction terms were significant in the model (Table 3-12). Analysis of treatment effects by site revealed that WC+T+F significantly decreased survival across species in OH to 16% compared to WC and WC+T, which had survival percentages of 60% and 71%, respectively (Table 3-13). In WV, WC+T+F decreased survival (63%) significantly compared to WC+T (94%). There were no differences in survival among treatments in VA.

The survival of the site-specific hardwood species (HW2) (Table 3-1) was significantly higher than either the HW1 group consisting of red oak, sugar maple (*Acer saccharum* Marsh.), and tulip poplar, or the shrub group (Table 3-13).

Table 3-12. Analysis of variance results for survival and growth parameters for hardwood groups at research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA.

		Variable (Pr>F)		
Source	**Degrees of Freedom**	**Survival**	**Height Growth**	**Total Height**
Block	2	<0.0001	0.0045	0.0682
Site	2	<0.0001	<0.0001	0.0001
Treatment	2	<0.0001	<0.0001	0.2632
Site*Treatment	4	0.0105	0.0429	0.1458
Species	2	0.0005	<0.0001	<0.0001
Site*Species	4	0.9222	0.0087	0.1914
Treatment*Species	4	0.8364	0.1485	0.1996
Site*Treatment*Species	7	0.5439	0.3193	0.9807
Model	27(28)	<0.0001	<0.0001	0.0003
Error*	50(51)			
Total*	77(79)			

* Degrees of freedom in parentheses are for survival only. Zero survival for shrubs in three study blocks caused the loss of one degree of freedom from all growth variables.

Table 3-13. Survival percentage of hardwood species groups for research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA, by treatment and species group.

Site and Treatment	Species Group			Treatment Mean
	HW1	HW2	Shrub	
Ohio:				
WC	66	67	49	60 x[**]
WC+T	64	82	65	71 x
WC+T+F	15	27	0	16 y
Species Mean	**48 a**[*]	**59 b**	**43 a**	**50**
West Virginia:				
WC	71	87	81	80 xy
WC+T	92	96	93	94 x
WC+T+F	68	86	35	63 y
Species Mean	**77 a**	**90 b**	**69 a**	**79**
Virginia:				
WC	82	92	69	81 x
WC+T	86	96	89	90 x
WC+T+F	79	89	79	82 x
Species Mean	**82 a**	**92 b**	**79 a**	**85**

[*] a, b, c – For each site, values within rows with the same letter are not significantly different at $P < 0.05$.

[**] x, y, z – For each site, values within columns with the same letter are not significantly different at $P < 0.05$.

Height Growth

Site, species group, treatment, and the site by treatment and site by species interactions were significant terms in the model for height growth of hardwoods (Table 3-12). Analysis by site revealed that there were no treatment effects in OH across species groups, and all treatment means were negative (Table 3-14). In WV, both WC+T and WC+T+F were significantly higher than WC (3.6 cm and 7.4 cm, respectively, versus –1.2 cm). In VA, WC+T+F had a mean height growth of 9.8 cm, which was significantly higher than the 4.0 cm resulting from WC and the 4.4 cm resulting from WC+T.

The HW1 species had the lowest mean height growth at all sites (Table 3-14). In OH, the height growth of -6.3 cm was significantly less than the mean height growth for shrubs of 1.5 cm. Height growth of HW1 species was significantly less than both HW2 and shrub groups in WV, and this mean value was negative (-1.1 cm), whereas the other two groups had positive mean height growth values (6.9 and 4.1 cm, respectively). HW1 species in VA were no different from HW2 species, which both had positive mean height growth at this site. Both of these groups had significantly less height growth than the shrub group in VA (Table 3-14).

Table 3-14. Height growth (cm) of hardwood species groups for research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA, by treatment and species group.

Site and Treatment	Species Group			Treatment Mean
	HW1	HW2	Shrub	
Ohio:				
WC	-1.9	-1.0	0.5	-0.8 x**
WC+T	-13.5	-3.2	2.5	-4.7 x
WC+T+F	-3.6	-2.1	---	-2.9 x
Species Mean	**-6.3 a***	**-2.1 ab**	**1.5 b**	**-2.8**
West Virginia:				
WC	-5.9	3.0	-0.8	-1.2 x
WC+T	0.0	6.9	4.0	3.6 y
WC+T+F	2.5	10.8	9.1	7.4 y
Species Mean	**-1.1 a**	**6.9 b**	**4.1 b**	**3.3**
Virginia:				
WC	1.5	2.7	7.9	4.0 x
WC+T	0.2	3.8	9.2	4.4 x
WC+T+F	2.3	7.4	19.7	9.8 y
Species Mean	**1.3 a**	**4.6 a**	**12.2 b**	**6.1**

* a, b, c – For each site, values within rows with the same letter are not significantly different at $P < 0.05$.

** x, y, z – For each site, values within columns with the same letter are not significantly different at $P < 0.05$.

Total Height

Site and species were the only significant terms in the model for total height (Table 3-12). There were no treatment effects for any site or species (Table 3-15). Examining species differences in total height across sites and treatments revealed that HW2 species were significantly shorter than HW1 or shrub species. Lack of interaction in this analysis facilitated the comparison of site main effects, where WV and VA were found to have significantly greater total heights than OH (Table 3-15).

Table 3-15. Total tree height (cm) of hardwood species groups for research sites in Lawrence County, OH, Nicholas County, WV, and Wise County, VA, by treatment and species group.

Site and Treatment	Species Group			Treatment Mean
	HW1	HW2	Shrub	
Ohio:				
WC	39.1	24.3	28.8	30.7 x[**]
WC+T	27.1	20.8	31.0	26.3 x
WC+T+F	42.2	25.3	---	33.7 x
Species Mean	**36.1 a**[*]	**23.5 b**	**29.9 a**	**29.8 m**[†]
West Virginia:				
WC	34.2	30.3	32.6	32.4 x
WC+T	40.2	32.3	45.1	39.2 x
WC+T+F	38.7	34.7	34.9	36.1 x
Species Mean	**37.7 a**	**32.4 b**	**37.5 a**	**35.9 n**
Virginia:				
WC	38.5	27.9	36.4	34.3 x
WC+T	37.5	27.2	52.8	39.2 x
WC+T+F	45.7	33.0	53.2	44.0 x
Species Mean	**40.5 a**	**29.4 b**	**47.5 a**	**39.1 n**

[*] a, b, c – For each site, values within rows with the same letter are not significantly different at $P < 0.05$.

[**] x, y, z – For each site, values within columns with the same letter are not significantly different at $P < 0.05$.

[†] m, n – For overall site means, values with the same letter are not significantly different at $P < 0.05$.

Hybrid Poplar Biomass

Total plant biomass differences increased significantly with the intensity of silvicultural input. Root, stem, and foliage biomass also increased significantly with the level of silvicultural intensity (Figure 3-2). The percentage of fine roots (<0.5 mm) was the same for the WC+T+F and WC+T treatments (23%), while the WC plots had a much higher fine root percentage (54%), which was significantly different from the other two treatments. Additionally, the root-to-shoot ratios were not significantly different between WC+T and WC+T+F (0.31 and 0.37, respectively), but both were significantly higher than that of the WC treatment (0.08).

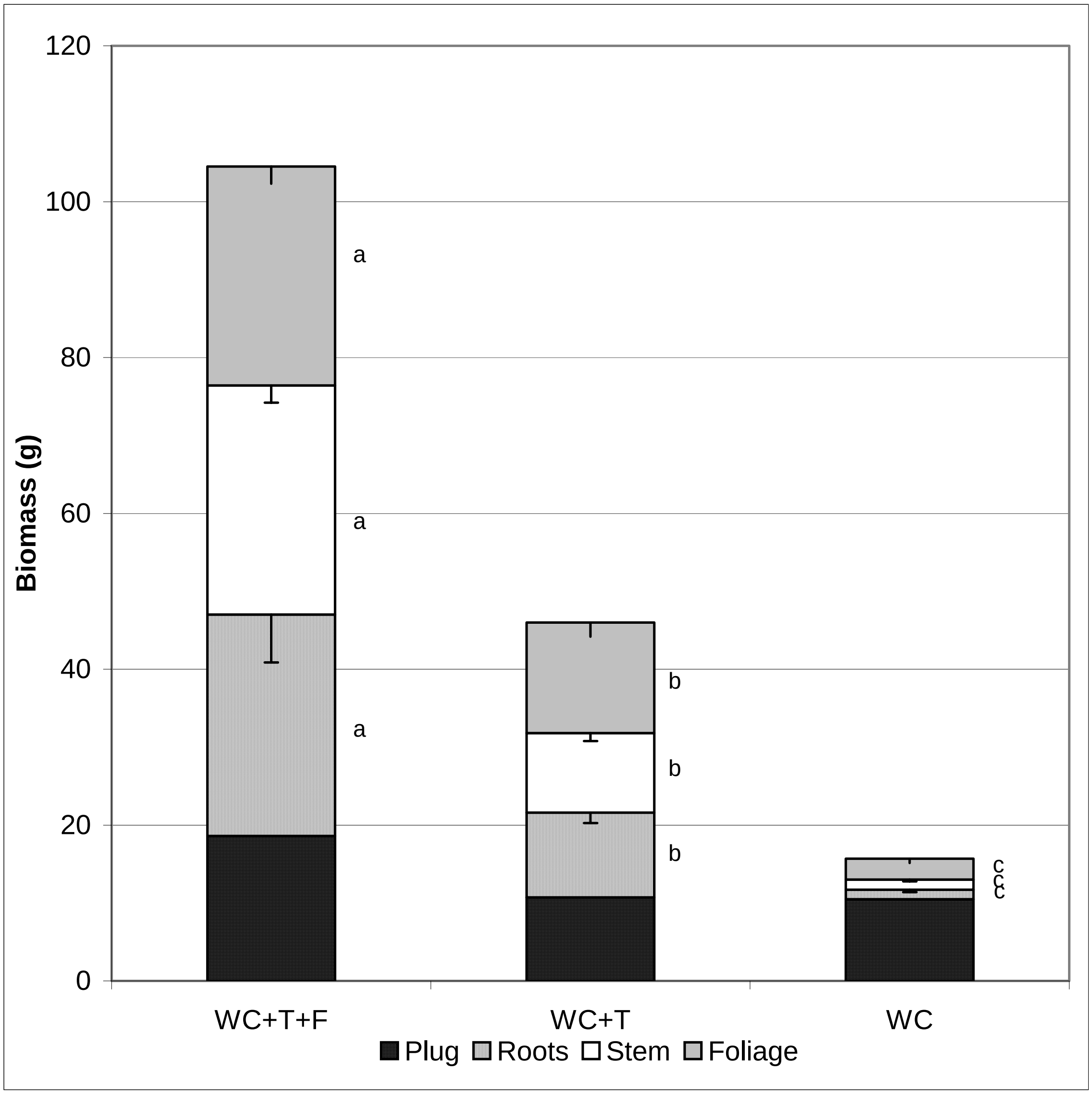

Figure 3-2. Hybrid poplar biomass by plant part and treatment for study site in Nicholas County, WV. Letters beside segments indicate significant differences at the $P < 0.05$ level among treatments for that particular segment.

Hybrid Poplar Tissue Analysis

Foliar nutrient concentrations were significantly higher for N, P, and Mn in the WC+T+F treatment compared to the other two treatments (Table 3-16). Foliar K in the WC+T+F treatment was only significantly higher than in the WC+T treatment. There were no differences between treatments for any other nutrients.

For stem tissue, N was the only added nutrient that had a higher mean concentration in the WC+T+F treatment and this mean was only significantly different from the WC treatment (Table 3-16). The concentration of N in the root tissue was significantly higher for the WC+T+F treatment compared to the WC+T treatment, but was not significantly different from the WC treatment.

Table 3-16. Macro- and micronutrient concentrations by tissue type and treatment for hybrid poplar growing at the research site in Nicholas County, WV.

Tissue Type and Treatment	Macronutrients ($g\ kg^{-1}$)					Micronutrients ($mg\ kg^{-1}$)				
	N	P	K	Mg	Ca	S	Zn	B	Cu	Mn
Foliage:										
WC	24.16 x*	1.98 x	14.19 x	4.60 x	12.14 x	3.92 x	84.30 x	30.04 x	8.95 x	161.17 x
WC+T	26.09 x	1.93 x	15.89 xy	4.86 x	12.26 x	4.82 x	92.21 x	26.61 x	9.71 x	134.44 x
WC+T+F	32.58 y	2.32 y	17.28 y	5.11 x	11.95 x	4.42 x	84.94 x	46.98 x	10.92 x	309.97 y
Stem:										
WC	7.16 x	0.37 x	2.76 x	0.51 x	1.37 x					
WC+T	7.40 xy	0.24 x	2.14 x	0.51 x	1.25 x					
WC+T+F	8.33 y	0.25 x	1.71 x	0.41 x	0.98 x					
Root:										
WC	9.38 xy	1.06 x	8.68 x	1.80 x	6.30 x					
WC+T	7.88 x	0.95 x	10.65 x	1.79 x	7.28 x					
WC+T+F	11.26 y	1.21 x	10.63 x	2.01 x	7.55 x					

* For a given plant part, different letters within a column indicate significant differences at $P < 0.05$.

Hybrid Poplar Moisture Stress

There was a statistically significant decrease with each successive day for all treatments. The WC only and WC+T treatments were significantly different over all three days of the dry down period (Table 3-17).

The treatment by date interaction was significant for water potential means. Each treatment increased or remained the same over the first three days of the dry down experiment. No means were statistically significant for the first and third days with respect to treatments. The WC+T+F treatment was significantly different from the other treatments for day 2. For the final day, however, the WC+T treatment continued to increase rapidly (Table 3-17) to -2.30 MPa, which was significantly higher than the WC treatment, which had decreased to -1.62 MPa. The WC+T+F and WC treatment means decreased on day 4, likely as a result of the cloud cover present over the site that particular day.

Table 3-17. Gravimetric soil moisture and water potential for hybrid poplar growing at the research site in Nicholas County, West Virginia.

Treatment	Aug. 16	Aug. 17	Aug. 18	Aug. 19	Treatment Average
Gravimetric Soil Moisture (kg kg^{-1})					
WC	---	0.16	0.15	0.12	0.14 x**
WC+T	---	0.14	0.13	0.12	0.13 y
WC+T+F	---	0.15	0.12	0.12	0.13 xy
Date average	---	0.15 a*	0.13 b	0.12 c	0.13
Water Potential (MPa)					
WC	-1.30 a x	-1.66 b x	-1.89 b x	-1.62 ab x	-1.62
WC+T	-1.32 a x	-1.72 ab x	-1.90 bc x	-2.30 c y	-1.81
WC+T+F	-1.17 a x	-1.97 b y	-1.97 b x	-1.78 b xy	-1.72
Date average	-1.26	-1.78	-1.92	-1.90	-1.72

* a, b, c – Values within rows with the same letter are not significantly different at $P < 0.05$.

** x, y, z – Values within columns with the same letter are not significantly different at $P < 0.05$.

Discussion

The results of this study point to the fact that there is likely no universal prescription for good establishment and first-year growth of the species used in this study, as numerous interactions existed among the sites, treatments, and species assemblages used in this study. Survival differences in this study were largely attributable to site differences, as the overall analysis of variance showed significant site by treatment and site by species interactions (Table 3-4). Overall survival was lowest in OH, with white pine having the lowest survival of the three species assemblages at this site. Larson et al. (1995) found white pine to survive and grow poorly on sites in this geographic area with the near alkaline and fine texture spoil materials common to the area. At this site, WC+T+F decreased survival below that of the WC-only treatment, which did not occur at the other two sites, though mean survival was less in WC+T+F than in WC at the other two sites. Two hypotheses exist for decreased survival in WC+T+F: (1) fertilization stimulated the competing vegetation (Ramsey et al. 2001); and/or (2) a salt effect was created by the fertilizer, leading to moisture stress in the trees such as that postulated by van den Driessche and coworkers (2003) for aspen seedlings. In OH, a combination of these two hypotheses would be more likely because, despite uniform herbicide applications at all sites, OH was observed to have much more competing vegetation by the end of the growing season than either of the other sites. Additionally, the spoils at this site, though covered with an oxidized topsoil material, were still generally within the rooting zone of the trees, especially in WC+T and WC+T+F, where tillage brought this material closer to the surface. The spoil materials at this site were found to be near alkaline and to have a much higher cation exchange capacity relative to the other sites (Tables 3-2 and 3-3). Both electrical conductivity and pH were within ranges (>0.05 dS m^{-1} and pH > 6.0, respectively) reported by Torbert and coworkers (1994) as negatively affecting white pine growth. Electrical conductivity in both surface and subsurface layers at the sites in WV and VA had values less than 0. 05dS m^{-1}. In addition to this, the loam to sandy loam textures at this site could have allowed excess salts to leach faster than what would be expected in the finer-textured structureless spoils in OH.

In addition to added weed control as a result of tillage, tillage has been shown to reduce bulk density and consequently increase survival and growth of trees on reclaimed surface mines (Ashby 1996, Torbert and Burger 1996). Tillage in this study produced mixed results in terms of providing a survival and growth response. In OH, WC+T did not produce a significant response compared to WC. The tillage treatment was carried out at this site when the soils were very wet. Given that the soils at this site are fine-textured and that it was only 20% coarse fragments, which would tend to aid in loosening the soil during ripping, it is possible that the reason for the lack of response is that the tillage failed to sufficiently loosen the soil at this site. There was a notable response to WC+T for HP in WV in terms of survival, growth, and biomass measures, indicating that soil compaction is likely a limiting factor for good growth at this site. Interestingly, the site in VA had similar soil textures and bulk densities to the WV site, but did not have a significant response to WC+T; however, mean survival and mean growth for all measures across species were higher in WC+T than in WC only.

The sites in VA and WV were both characterized by coarse textured spoils and high coarse fragment contents (Tables 3-2 and 3-3). The primary differences between these two sites were rock type, topsoil replacement, and average age since reclamation. Looking at survival differences between these two sites, it can be seen that survival in VA was better than that in WV, regardless of species or treatment. This again could be a result of better weed control on the younger spoils in VA, where the seed pool for competing vegetation may have been smaller. Additionally, soil N and P levels were much higher in the surface layer in WV than in the subsurface layer at the same site and higher than the surface or subsurface layer in VA and OH. This may be evidence that the site was fertilized to maintain the lush grass cover for the grazing animals that occupied the site prior to study establishment. This could make weed control more difficult at this site, creating conditions conducive to competition growth in plots that did not receive fertilization and in the WC+T+F plots, by adding nutrients in excess of what the trees likely needed. In WV, WC+T produced the largest response in both survival and growth of HP and WP. The lack of a significant growth response due to fertilization, especially for the site-demanding poplars, may be explained by the higher levels of N and P at this site compared to the other sites. Hybrid poplar at this site did, however, have significantly higher root, stem, foliage, and total plant biomass in the fertilized plots versus the other two treatments. Fertilized trees appeared to have improved water relations compared to WC+T. Harvey and van den Driessche (1997) found that N fertilization alone increased drought resistance of *Populus trichocarpa* Torr. & Gray, but fertilization with P alone increased drought resistance and suggest that fertilization with N and P may allow good growth without leading to poor water relations. The growth response to WC+T+F in VA is reasonable given the previously mentioned considerations, namely (1) better weed control relative to the other two sites, and (2) inherently low N and P levels in both soil layers. The response to WC+T+F was exceptional for HP in VA, where total stem volumes were 312.1 cm^3 and total heights were 126.6 cm. The next closest total height was also in VA in WC+T at 65.4 cm, followed by WC+T in WV at 60.2 cm. This species has been shown to be very responsive to fertilization with N in combination with P when soil fertility levels are low (van den Driessche 1999, Brown and van den Driessche 2005).

A study conducted on three surface mines in West Virginia using similar species and treatments found trends similar to those in our study (McGill et al. 2004). For instance, the same hybrid poplar clone averaged 1.0 m in total height after one year, and average survival for this same species across all three sites was found to be 79%. Additionally, these authors found excellent survival (>90%) for the two hardwood species used and found low survival for white pine (48%) at the one site on which this species was planted.

Conclusions

Several conclusions can be drawn from the results of this investigation, including:

1. White pine and hardwood species grew little over the course of the first growing season, which could translate into a need for continued weed control to ensure the trees do not succumb to the competing vegetation as mean heights ranged from 25 to 40 cm for hardwoods and from 20 to 30 cm for white pine.
2. Hardwood species had excellent survival in WV and VA, and better survival than the other species used in OH, while white pine had the poorest survival of all species at all sites. Survival was particularly good for the site-specific hardwoods planted at each site.
3. Weed control plus tillage may be the optimum treatment for hardwoods and white pine, as any increased growth resulting from fertilization may not offset the decreased survival that accompanied fertilization.
4. Hybrid poplar appears to have good potential for reverting post-SMCRA mined lands reclaimed to grasses back to forests, as this species had good growth with 50 to 65 cm of height growth in one year in WC+T at all sites and excellent growth in WC+T+F in VA. This good growth, coupled with survival percentages that may be adequate to ensure that without further weed control, an adequately stocked stand could develop, gives this species an advantage over the other species used in this study.
5. Considering mean survival and growth, sites with soil characteristics similar to those at the site in VA would seem to be very suitable for tree survival and growth, while those in WV appear to be less suitable with the treatments and species used, and on sites similar to OH, other treatments and/or species may be needed to ensure good establishment and growth of forest stands.
6. Though height and diameter growth were not statistically different for HP for WC+T and WC+T+F in WV, biomass responded significantly to each level of silvicultural input, with WC+T+F trees also showing improved foliar nutrition compared to WC and WC+T.

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TASK 4: Conduct economic analyses of reforestation and forest management activites for carbon sequestration and a variety of forest products and services. (Amacher and Sullivan)

Executive Summary

This quarter, emphasis of Task 4 focused on short-rotation hardwood management as an alternative to white pine and traditional hardwood management options examined earlier. As in earlier analyses, land expectation value (LEV) was considered the metric for financial viability, and LEVs were calculated for short-rotation hardwood management under a range of site classes, reforestation intensities, interest rates, and timber prices. Findings indicate that the short-rotation option is only slightly more attractive financially than earlier-examined traditional hardwood management, and that the short-rotation management is only profitable (LEV > 0) under a limited combination of circumstances, including better sites, high prices, low interest rates. In addition, an analysis of carbon payment options demonstrates that the payment required to make reforestation profitable under short-rotation hardwood management may be substantially lower than payments required under traditional hardwood management, if those payments are based on incremental carbon added to the site each year.

Experimental

Short-rotation hardwoods may provide a financially viable alternative to traditional forestry practices, as they provide earlier and more frequent income opportunities for landowners. In examining the viability of short-rotation hardwoods, we utilize the same landowner framework used in white pine and traditional hardwood options, namely land expectation value (LEV), that accounts for the opportunity cost of money invested in both the land and the forestry practices:

$$LEV = \frac{pQ_f(t)e^{-it} - c_f e^{-it}}{(1 - e^{-it})} - c_0$$

where: p is the unit price of timber, $Q_f(t)$ is the volume of timber produced from reforested land at age t (rotation length), i is the discount rate, e is the base of the natural logarithm, c_f is regular reforestation costs after timber harvest, and c_0 is initial reforestation costs incurred when converting grassland into forest. In this analysis, we consider a 10-year rotation, rather than the 40 and 60 year rotations considered in the earlier analyses.

As in earlier analyses, both low and high price assumptions are considered in the LEV calculations. Low prices are based on 2003 Timber Mart-South standing timber average prices for hardwood pulp in the mountains of Virginia and high prices are derived from the 2003 Pennsylvania Woodlands timber market report, with these two locations representing the relative extremes of the timber market in the Appalachian mine region. The 2003 prices are utilized to maintain consistency with our earlier results for white pine and traditional hardwood management. All of the timber is assumed to be sold as pulpwood, given the short rotation length considered.

In addition, scenarios are developed using 3.5%, 5%, and 7.5% as alternative rates of return (ARR) (variable i in the landowner model). A 5% discount rate is a common baseline for terrestrial carbon studies (e.g., Plantinga et al. 1999, Richards et al. 1993, Stavins 1999) and, as Stavins and Richards (2005, p. 22) note in their recent survey of carbon sequestration work, is a rate that “also represents a social discount rate that has been commonly employed in the analysis of public projects and policies." The lower and higher rates are included to provide insight into the sensitivity of results to ARR assumptions.

As in earlier analyses, we consider the carbon payments necessary to provide minimum profitability for forestry under the short rotation scenario. Payments based on both accumulating carbon and incremental carbon are examined, with the annual accumulated carbon payment being calculated by solving the following expression for s_{ca}, the annual payment per ton of accumulated carbon found on site each year:

$$R(L_f) = \frac{pQ_f(t)e^{-it} - c_f e^{-it}}{(1-e^{-it})} - c_0 + s_{ca} \int_0^{\infty} x(z)e^{-iz}dz = 0$$

where *x(z)* is the quantity of carbon accumulated on the forested site at time *z*, which could include both above-ground carbon sequestered in the timber at a given time and carbon sequestered in the soil. Incremental carbon payments, which are based upon only the amount of carbon grown in a given year were calculated by solving the following expression for s_{cg} in:

$$R(L_f) = \frac{pQ_f(t)e^{-it} - c_f e^{-it}}{(1-e^{-it})} - c_0 + s_{cg} \int_0^{\infty} \dot{x}(z)e^{-iz}dz = 0$$

Note that *x(z)*, the cumulative on-site production of carbon, is replaced by $\dot{x}(z)$, the annual carbon increment, or $\dot{x}(z) = dx/dt$. That is, the annual payment s_{cg} will be based only on the carbon grown on the site that year. This formulation is similar to the model that Englin and Callaway (1993) used to examine the effects of climate change on optimal forest management under a pre-defined set of possible carbon payments, except that we do not attempt to value harvested carbon, which would require additional assumptions about end use and carbon release rate.

Results and Discussion

Calculated LEVs indicate that short rotation hardwood management would be profitable under only a subset of conditions found at reclaimed mined sites. Only under conditions of better site classes, high prices, and low interest rates do we find positive LEVs when the landowner carries the cost burden of forest establishment (Table 4-1). These findings indicate that without outside support for reforestation, short rotation hardwood management may only be slightly more attractive to landowners than traditional hardwood management on these sites. Of course all scenarios provide positive LEVs when the mine operator pays for reforestation of the site.

Further, carbon payments that are based upon the cumulative carbon found on the reforested site each year (Table 4-2) are slightly higher than payments required under the same circumstances for traditional hardwood management. This increase in carbon payments occurs because carbon has less time to accumulate on site in the short rotation scenarios. Conversely, calculated carbon payments that are based upon incremental carbon grown each year (Table 4-3) are substantially lower in the case of short-rotation hardwoods than under traditional hardwood regimes. In this case, the incremental carbon growth is kept at a much higher rate under the short-rotation scenarios; hence, payments required to make forestry profitable do not need to be as large.

Table 4-1. Land expectation values of mixed Appalachian hardwood reforestation of reclaimed mine sites when landowner or mine operator pay establishment costs, by site class, reforestation intensity, and discount rate – 10-year rotation ($/ha).

	Landowner Pays to Reforest			Mine Operator Pays to Reforest		
5% ARR, Low Prices:						
Site/Intensity	Low	Medium	High	Low	Medium	High
V	-951.19	-1145.52	-1537.19	654.75	756.94	875.07
IV	-849.00	-1027.39	-1400.62	756.94	875.07	1011.64
III	-730.87	-890.82	-1242.73	875.07	1011.64	1169.53
II	-608.86	-749.77	-1172.88	997.08	1152.69	1239.38
I	-453.25	-663.08	-1172.88	1152.69	1239.38	1239.38
5% ARR, High Prices:						
Site/Intensity	Low	Medium	High	Low	Medium	High
V	-331.64	-429.28	-709.17	1274.30	1473.18	1703.09
IV	-132.76	-199.37	-443.37	1473.18	1703.09	1968.89
III	97.15	66.43	-136.08	1703.09	1968.89	2276.18
II	334.61	340.94	-0.14	1940.55	2243.40	2412.12
I	637.46	509.66	-0.14	2243.40	2412.12	2412.12
3.5% ARR, Low Prices:						
Site/Intensity	Low	Medium	High	Low	Medium	High
V	-610.36	-750.36	-1085.51	1002.85	1159.36	1340.30
IV	-453.84	-569.42	-876.33	1159.36	1340.30	1549.48
III	-272.90	-360.24	-634.51	1340.30	1549.48	1791.31
II	-86.03	-144.21	-527.52	1527.17	1765.52	1898.30
I	152.31	-11.43	-527.52	1765.52	1898.30	1898.30
3.5 % ARR, High Prices:						
Site/Intensity	Low	Medium	High	Low	Medium	High
V	338.58	346.67	182.73	1951.78	2256.40	2608.55
IV	643.19	698.82	589.84	2256.40	2608.55	3015.66
III	995.34	1105.93	1060.50	2608.55	3015.66	3486.31
II	1359.04	1526.39	1268.72	2972.24	3436.12	3694.53
I	1822.91	1784.81	1268.72	3436.12	3694.53	3694.53
7.5% ARR, Low Prices:						
Site/Intensity	Low	Medium	High	Low	Medium	High
V	-1206.34	-1442.29	-1872.17	388.08	448.65	518.67
IV	-1145.77	-1372.27	-1791.22	448.65	518.67	599.62
III	-1075.75	-1291.32	-1697.64	518.67	599.62	693.20
II	-1003.44	-1207.72	-1656.24	590.99	683.22	734.60
I	-911.20	-1156.34	-1656.24	683.22	734.60	734.60
7.5% ARR, High Prices:						
Site/Intensity	Low	Medium	High	Low	Medium	High
V	-839.12	-1017.76	-1381.38	755.30	873.18	1009.46
IV	-721.24	-881.49	-1223.84	873.18	1009.46	1167.00
III	-584.97	-723.94	-1041.71	1009.46	1167.00	1349.14
II	-444.22	-561.23	-961.13	1150.20	1329.71	1429.71
I	-264.71	-461.23	-961.13	1329.71	1429.71	1429.71

Table 4-2. Annual payment required per ton of cumulative carbon stored on-site to allow minimal profitability (LEV ≥ 0) for landowner of reclaimed mine land, by site class, reforestation intensity, and discount rate ($/ton/yr).

	Mixed Hardwoods (10-year rotation)		
5% ARR, Low Prices:			
Site/Intensity	**Low**	**Medium**	**High**
V	4.84	5.10	5.99
IV	3.78	4.00	4.77
III	2.85	3.04	3.70
II	2.10	2.26	3.31
I	1.37	1.87	3.31
5% ARR, High Prices:			
Site/Intensity	**Low**	**Medium**	**High**
V	1.69	1.91	2.76
IV	0.59	0.78	1.51
III	*	*	0.41
II	*	*	0.00
I	*	*	0.00
3.5% ARR, Low Prices:			
Site/Intensity	**Low**	**Medium**	**High**
V	2.10	2.26	2.86
IV	1.37	1.50	2.02
III	0.72	0.83	1.28
II	0.20	0.29	1.01
I	*	0.02	1.01
3.5% ARR, High Prices:			
Site/Intensity	**Low**	**Medium**	**High**
V	*	*	*
IV	*	*	*
III	*	*	*
II	*	*	*
I	*	*	*
7.5% ARR, Low Prices:			
Site/Intensity	**Low**	**Medium**	**High**
V	9.76	10.22	11.60
IV	8.12	8.50	9.71
III	6.67	7.00	8.04
II	5.51	5.80	7.43
I	4.38	5.19	7.43
7.5% ARR, High Prices:			
Site/Intensity	**Low**	**Medium**	**High**
V	6.79	7.21	8.56
IV	5.11	5.46	6.63
III	3.63	3.92	4.93
II	2.44	2.69	4.31
I	1.27	2.07	4.31

* indicates LEV is positive without additional payments

Table 4-3. Payment required per ton of carbon added to the site that allows minimal profitability (LEV ≥ 0) for landowner of reclaimed mine land, by site class, reforestation intensity, and discount rate ($/ton/yr).

	Mixed Hardwoods (10-year rotation)		
5% ARR, Low Prices:			
Site/Intensity	**Low**	**Medium**	**High**
V	20.48	21.56	25.27
IV	15.98	16.89	20.11
III	12.02	12.79	15.57
II	8.86	9.53	13.92
I	5.76	7.87	13.92
5% ARR, High Prices:			
Site/Intensity	**Low**	**Medium**	**High**
V	7.14	8.08	11.66
IV	2.50	3.28	6.37
III	*	*	1.71
II	*	*	0.00
I	*	*	0.00
3.5% ARR, Low Prices:			
Site/Intensity	**Low**	**Medium**	**High**
V	9.05	9.72	12.29
IV	5.88	6.44	8.66
III	3.09	3.56	5.47
II	0.86	1.26	4.31
I	*	0.09	4.31
3.5% ARR, High Prices:			
Site/Intensity	Low	Medium	High
V	*	*	*
IV	*	*	*
III	*	*	*
II	*	*	*
I	*	*	*
7.5% ARR, Low Prices:			
Site/Intensity	Low	Medium	High
V	40.09	41.90	47.52
IV	33.29	34.83	39.71
III	27.31	28.63	32.86
II	22.55	23.69	30.36
I	17.88	21.19	30.36
7.5% ARR, High Prices:			
Site/Intensity	Low	Medium	High
V	27.89	29.57	35.06
IV	20.95	22.38	27.13
III	14.85	16.05	20.16
II	9.98	11.01	17.62
I	5.19	8.45	17.62

* indicates LEV is positive without additional payments

Conclusions

In our analysis this quarter, we have found that although short-rotation hardwood management on reclaimed surface mined lands may have higher LEVs than traditional, long-rotation hardwood management, it is only profitable in a limited set of circumstances. In addition, we have found that carbon payments required to make short-rotation hardwood management profitable may be higher or lower than those required under traditional hardwood management, depending on the structure of the payment. Where the payment is based on cumulative carbon found on the reclaimed site each year, traditional hardwood management might be more attractive (require a lower carbon payment), whereas if the payment is based on the annual carbon increment, the short-rotation hardwood option may make more sense.

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TASK 5: Determine the potential of large-scale SMCRA grassland restoration to sequester carbon and create other societal benefits. (Zipper and McGrath)

Executive Summary

During the recent quarter, we completed field sampling of 25 mine sites selected randomly from Virginia, West Virginia, Kentucky, and Ohio, and herbaceous biomass assessment plots in Virginia.

Experimental

Six mine sites were sampled in Ohio, Kentucky, and Virginia, and seven mines were sampled in West Virginia. The 25 sites yielded 225 sample locations. The soil samples were split at the topsoil-subsoil interface and will be analyzed for nutrient content (P, K, Ca, Mg, Zn, Mn, Cu, Fe, and B), organic matter, total C and N, cation exchange capacity, pH, soluble salts, bulk density, moisture content, and soil texture. Ground cover and composition, rooting depth (by methods developed by A. Jones and J. Galbraith for mine-soil application, using a screw auger to penetrate the soil until refusal), slope, and aspect were measured in the field. Herbaceous vegetation samples were also collected to measure biomass production.

Results and Discussion

Table 5-1 shows the original permit issue date, sampling date, and number of samples collected from each site. Table 5-2 shows the average rooting depth and slope by state. Figure 5-1 shows the locations of the 25 sites sampled during the study. We are currently organizing other data collected in the field and preparing to perform laboratory analysis on the sites.

Table 5-1. Date of permit issue for each mine sampled and the number of samples collected.

Site	Sample Date	Number of Samples	Permit Issue Dates*		
Kentucky:					
1	08/16/05	5	n/a		
2	08/17/05	10	n/a		
3	08/18/05	10	05/17/93		
4	08/31/05	10	02/19/85	01/06/88	
5	09/02/05	3	06/21/84		
6	09/27/05	10	08/09/89		
Ohio:					
1	07/19/05	10	08/07/84		
2	10/04/05	9	09/18/96		
3	10/06/05	10	03/25/98	08/28/97	
4	10/18/05	10	01/04/80	12/01/87	08/04/88
5	10/19/05	9	01/24/85	12/28/79	08/31/87
6	10/20/05	6	06/27/77		
Virginia:					
1	06/01/05	8	n/a		
2	06/08/05	9	n/a		
3	06/15/05	10	n/a		
4	06/22/05	10	n/a		
5	08/09/05	10	n/a		
6	09/26/05	10	12/30/83	05/17/91	
West Virginia:					
1	07/27/05	10	n/a		
2	08/03/05	9	02/11/85		
3	08/04/05	10	04/15/93		
4	09/07/05	8	06/05/78		
5	09/08/05	9	09/15/80	02/20/96	
6	09/20/05	10	n/a		
7	09/21/05	10	06/25/85		

* Note: Sampling sites with multiple dates listed include multiple permits.

n/a = data not available at present (inquiries pending).

Table 5-2. Sample site characteristics measured in the field.

State	Mean Rooting Depth	Minimum Rooting Depth	Maximum Rooting Depth	Mean Slope	Maximum Slope
	---------------------------- cm	----------------------------		------------ %	------------
Kentucky	31	23	50	22	80
Ohio	33	25	45	10	50
Virginia	37	23	78	36	105
West Virginia	30	19	37	38	165
Average	**33**	**19**	**78**	**27**	**165**

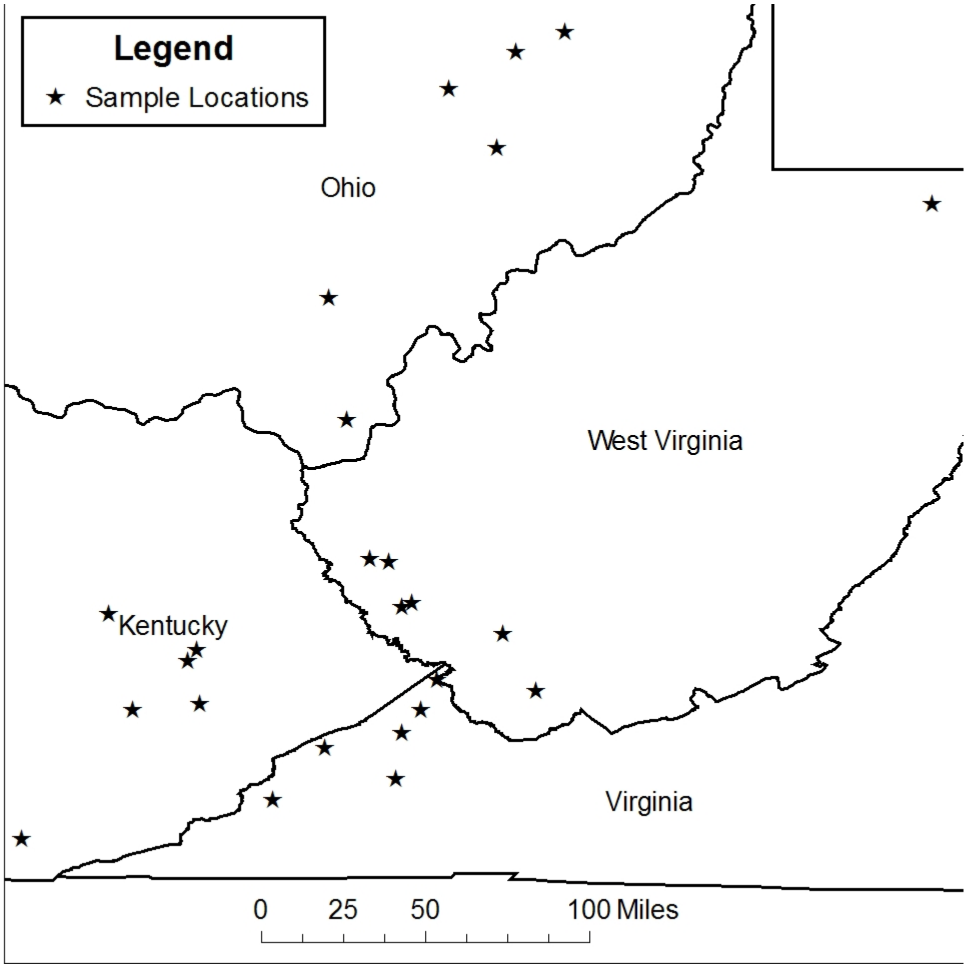

Figure 5-1. Map showing the location of 25 sites sampled in Kentucky, Ohio, Virginia, and West Virginia.

PROJECT TIMETABLE

░ Planned ▓ Completed

Year:	**2002**	**2003**				**2004**				**2005**		
Quarter:	**4th**	**1st**	**2nd**	**3rd**	**4th**	**1st**	**2nd**	**3rd**	**4th**	**1st**	**2nd**	**3rd**
Task 1												
Subtask 1.1	▓ Baseline CarbonSequestration Potential	▓	▓	▓	▓	▓						
Subtask 1.2	▓ Mine SoilProductivity	▓	▓	▓	▓	▓						
Subtask 1.3					▓ Carbon Sequestration by Forest Practice	▓	▓	▓	▓	░		
Subtask 1.4						▓ Accounting Procedures	▓	▓	▓	▓	▓	░
Task 2												
Subtask 2.1	▓ Classification Criteria	▓	▓	▓								
Subtask 2.2				▓ GIS Mapping	▓							
Subtask 2.3				▓ Test Remote Sensing	▓							
Subtask 2.4						▓ Experimental Plots	▓	▓	▓	▓	▓	
Subtask 2.5							▓ Soil Analyses	▓	▓	▓	▓	▓
Subtask 2.6											▓ Validate classification criteria	▓
Task 3												
Subtask 3.1	▓ Locate sites	▓	▓									
Subtask 3.2			▓ Establish experiment	▓	▓	▓	▓					
Subtask 3.3				▓ Silvicultural recommendations	▓	▓	▓	▓				
Subtask 3.4					▓ Reforestation costs	▓	▓	▓	▓			
Subtask 3.5						▓ Evaluate survival and growth	▓	▓	▓	▓		
Subtask 3.6						▓ Estimate growth potential	▓	▓	▓	▓		
Subtask 3.7							▓ Estimate timber & carbon value	▓	▓	▓	▓	░
Task 4												
Subtask 4.1	▓ Economic feasibility	▓	▓	▓	▓							
Subtask 4.2				▓ Evaluation	▓	▓	▓	▓	▓			
Subtask 4.3								▓ Government policies	▓	▓	▓	░
Task 5												
Subtask 5.1			▓ Identify SMCRA grassland	▓								
Subtask 5.2				▓ Use characteristics of permits	▓	▓	▓					
Subtask 5.3							▓ Soil properties by permit	▓	▓			
Subtask 5.4								▓ Est. quantity grassland	▓			
Subtask 5.5								▓ Est. C sequ. by site quality	▓	▓	░ class	
Subtask 5.6											░ Est. C sequ. by policy scenario	░