NETL AAD DOCUMENT CONTROL BLDG. 921
U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY
P. O. BOX 10940
PITTSBURGH, PA 15236-0940

Technical Progress Report

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

Quarterly Report

Report Period: January - March 2005

Principal Author: James A. Burger

Principal Investigators: J. Burger, J. Galbraith, T. Fox, G. Amacher, J. Sullivan, and C. Zipper

June 8, 2005

Instrument No: DE-FG26-02NT41619

Department of Forestry (0324)
228 Cheatham Hall
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

DISCLAIMER

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 VA, WV, KY, OH, and PA 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, Ohio (Figure 1), West Virginia (Figure 2), and Virginia (Figure 3). 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. During the reporting period we compiled and evaluated all soil properties measured on the study sites. Statistical analysis of the properties was conducted, and first year survival and growth of white pine, hybrid poplars, and native hardwoods was assessed. Hardwood species survived better at all sites than white pine or hybrid poplar. Hardwood survival across treatments was 80%, 85%, and 50% for sites in Virginia, West Virginia, and Ohio, respectively, while white pine survival was 27%, 41%, and 58%, and hybrid poplar survival was 37%, 41%, and 72% for the same sites, respectively. Hybrid poplar height and diameter growth were superior to those of the other species tested, with the height growth of this species reaching 126.6cm after one year in the most intensive treatment at the site in Virginia. To determine carbon in soils on these sites, we developed a cost-effective method for partitioning total soil carbon to pedogenic carbon and geogenic carbon in mine soils. We are in the process of evaluating the accuracy and precision of the proposed carbon partitioning technique for which we are designing an experiment with carefully constructed mine soil samples. In a second effort, as part of a mined land reforestation project for carbon sequestration in southwestern Virginia we implemented the first phase of the carbon monitoring protocol that was recently delivered to DOE.

TABLE OF CONTENTS

LIST OF GRAPHICAL MATERIALS

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) (Figure 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 (Figure 1), West Virginia (Figure 2), and Virginia (Study 2) (Figure 2). For study 1, 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. During the reporting period we compiled and evaluated all soil properties measured on the study sites. Statistical analysis of the properties was conducted, and first year survival and growth of white pine, hybrid poplars, and native hardwoods was assessed. Hardwood species survived better at all sites than white pine or hybrid poplar. Hardwood survival across treatments was 80%, 85%, and 50% for sites in Virginia, West Virginia, and Ohio, respectively, while white pine survival was 27%, 41%, and 58%, and hybrid poplar survival was 37%, 41%, and 72% for the same sites, respectively. Hybrid poplar height and diameter growth were superior to those of the other species tested, with the height growth of this species reaching 126.6cm after one year in the most intensive treatment at the site in Virginia. To determine carbon in soils on these sites, we developed a cost-effective method for partitioning total soil carbon to pedogenic carbon and geogenic carbon in mine soils. We are in the process of evaluating the accuracy and precision of the proposed carbon partitioning technique for which we are designing an experiment with carefully constructed mine soil samples. In a second effort, as part of a mined land reforestation project for carbon sequestration in southwestern Virginia we implemented the first phase of the carbon monitoring protocol that was recently delivered to DOE. In earlier work we examined an annual carbon payment based on the amount of carbon held on site in that year (see Third Quarter '04 report). In other words, the landowner would receive a payment for carbon found on the site (i.e., above ground and root carbon) each year, regardless of when that carbon was sequestered. An alternative payment scheme has been devised and examined that envisages a payment based on the amount of carbon accumulated in a given year, rather than the amount stored. Based upon our alternative payment scheme, carbon payments that make reforestation financially viable would fall in the range of $8.66 to $71.88 per ton of carbon stored in hardwoods and $0 to $83.29 per ton of carbon stored in pines.

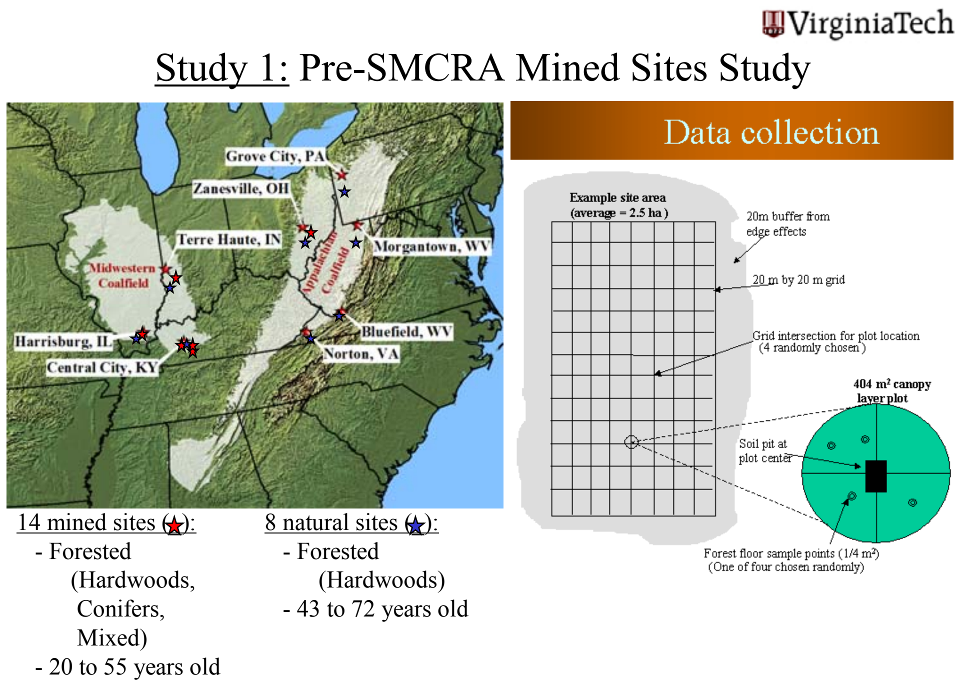


Figure 1. Location and layout of experimental sites for Study 1 across a seven-state region.

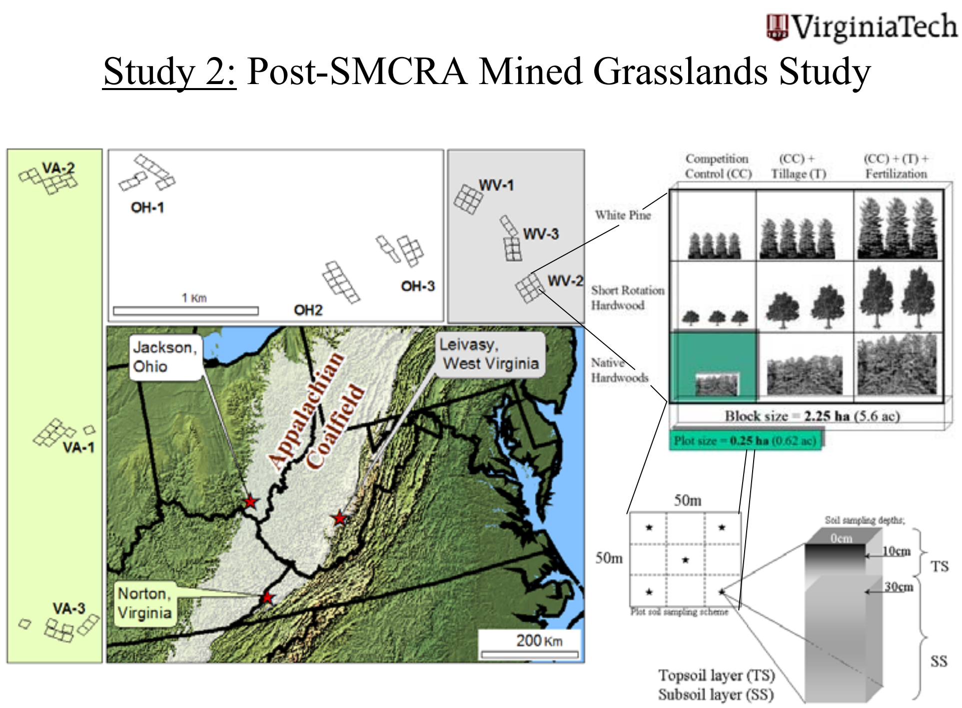


Figure 2. Location and layout of experimental sites for Study 2 in Ohio, West Virginia, and Virginia.

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

Executive Summary

We developed a cost-effective method for partitioning total soil carbon to pedogenic carbon and geogenic carbon in mine soils. We are in the process of evaluating the accuracy and precision of the proposed carbon partitioning technique for which we are designing an experiment with carefully constructed mine soil samples. In a second effort, as part of a mined land reforestation project for carbon sequestration in southwestern Virginia we implemented the first phase of the carbon monitoring protocol that was recently delivered to DOE; we mapped the Flint Gap mined site by site quality class. Following this phase permanent carbon monitoring sampling plots will be established and the baseline carbon stock will be estimated. The latter will allow us to assess the validity and practicality of the proposed carbon monitoring protocol for mined land.

Experimental

Subtask 1.1

Coal particles, infinitely small to grain size, contaminate the mine soil in most coal mined fields, it is a priority to develop a method and practical procedure for C content partitioning to C from coal and carboniferous rocks (geogenic C) and C from plants (pedogenic C). Pedogenic C can be found in the form of soil organic matter and/or plant residues. Unfortunately, there is no existing method in the literature that may be of use for such analysis. Standard laboratory organic matter analyses techniques, such as the Walkley-Black acid dichromate oxidation procedure (Walkley and Black, 1934), tend to largely overestimate the carbon content in minesoils due to interference from coal particles (Daniels and Amos, 1982) (Table 1).

Other methods for soil carbon content estimation are based on weight loss from soil organic matter following thermal oxidation of soil samples. However such methods, the loss on ignition method for example (Table 1), similar to the Walkley-Black wet oxidation procedure tend to overestimate the soil carbon content in mine soils mainly due to the limited capacity of the procedure to differentiate between weight loss from organic matter oxidation and weight loss from coal fragments oxidation, as well as weight loss from structural water loss when significant amounts of clay minerals are present in the soil.

Previously we tested the potential of a modern technique using Scanning Electron Microscopy analysis to determine the volume ratio between coal- and plant-derived particles emitted from the mine soil sample during a thermal oxidation procedure (Table 1). This procedure was briefly discussed in one of our previous reports. The main assumption for using this technique as a method for carbon partitioning was that the relative ratio between coal and plant particles emitted from the sample and subsequently caught on a filter represents the ratio between the total coal and total plant carbon in the soil sample. Because of the complexity and the high costs associated with the evaluation of this methodology we were unable to fully assess the potential and the accuracy of this technique for carbon partitioning in mine soils.

Table 1. Standard and experimental methods for soil carbon analysis used for measuring C sequestered by plants in mine soils.

	Methods of Analysis		Pedogenic C: Soil organic matter (SOM) oxidizeable	Pedogenic C: Soil organic matter (SOM) resistant	Geogenic C: CO_3 (Inorganic C)	Geogenic C: Coal	Soil organic carbon (SOC) Assumptions \ Pretreatments
			Fraction removed				
1	Walkley-Black acid dichromate oxidation procedure[5]: C content equals SOM*[correction factor, CF]	--- STANDARD ---	all	----	----	***Unknown fraction*** is oxidized, particle size and coal quality dependent[1].	***SOC={Oxidizeable SOM}*CF*** . Assumes (1) no oxidation of coal, (2) no interference from Cl^-, MnO_2, and Fe^{2+}, and (3) {oxidizeable SOM} is ~77% of total SOM.
2	Loss on ignition (375°C, 12hrs): C content estimated from sample weight difference.	--- STANDARD ---	all	all	----	***Unknown fraction*** can be combusted to CO_2, coal quality dependent.	***SOC={SOM}*CF*** . Assumes (1) no oxidation of coal and (2) no structural water loss from soil minerals.
3	C [%] elemental analysis (Vario MAX CNS analyzer, elementar, Hanau, Germany).	--- STANDARD ---	all	all	all	all	***Total C [%].*** Represents the absolute total C [%] in the soil.
4	Thermal oxidation procedure[4] (375°C, 24 hrs): C content equals the C [% weight] difference before and after procedure.	--- EXPERIMENTAL ---	all	all	----	***Unknown fraction*** can be combusted to CO_2, coal quality dependent.	***C_{coal} [%];*** Then *SOC=Total C[%] - C_{coal} [%].* Carbonates removal pretreatment. Requires correction for oxidized coal.
5	Scanning Electron Microscopy (SEM) analysis[2,3] after thermal oxidation: C content inferred from partitioning of ***Total C*** .	--- EXPERIMENTAL ---	all	***Unknown [x]***	----	***Unknown [y]***	***[SOM:Coal] volume ratio*** . Assumes that *[1-x]:[1-y]* ratio of captured airborne particles on filter is equal to the *[SOM]:[coal]* ratio in sample. Requires grinding, sieving through 270um sieve, and carbonates removal pretreatments.

[1]Daniels and Amos (1982); [2]Karls and Christensen (1998); [3]Kralovec et al. (2002) ; [4]Schmidt et al. (2001); [5]Walkley and Black (1934).

Nonetheless, we realized that thermal oxidation pretreatment of mine soils can be used to fully eliminate all pedogenic carbon matter as well as the easily oxidizeable geogenic carbon matter present in mine soils which leaves only the most resistant organic compounds in the sample unoxidized. We assumed these highly resistant organic compounds to be highly condensed carbon particles, i.e. coal, which can be measured by C elemental analysis with carbon-nitrogen auto-analyzer (Vario MAX CNS analyzer, elementar, Hanau, Germany).

There is a good potential for developing a new inexpensive and practical method based on the work by Schmidt et al. (2001) and Kuhlbusch (1995) using a combination of thermal oxidation pretreatment of mine soil samples followed by C elemental analysis. This method is presented in Table 1 and an outline of the laboratory procedure is depicted in Figure 3.

The most significant modification that we propose to the method used by Schmidt et al. (2001) is that our methodology provides a correction factor for carbon loss from the more volatile constituents of coal fragments present in mine soils. The correction factor is based on coal carbon content loss determined during a parallel thermal oxidation analysis of pure coal fragments as described in Figure 3 obtained from the same mined site as the soil samples. Based on the wide availability of coal fragments scattered on majority of mined sites as well as the simplicity of this method (Figure 3) along with its low costs of implementation we believe that this technique will serve the accuracy and precision required for a cost-effective carbon sequestration accounting method for mine soils.

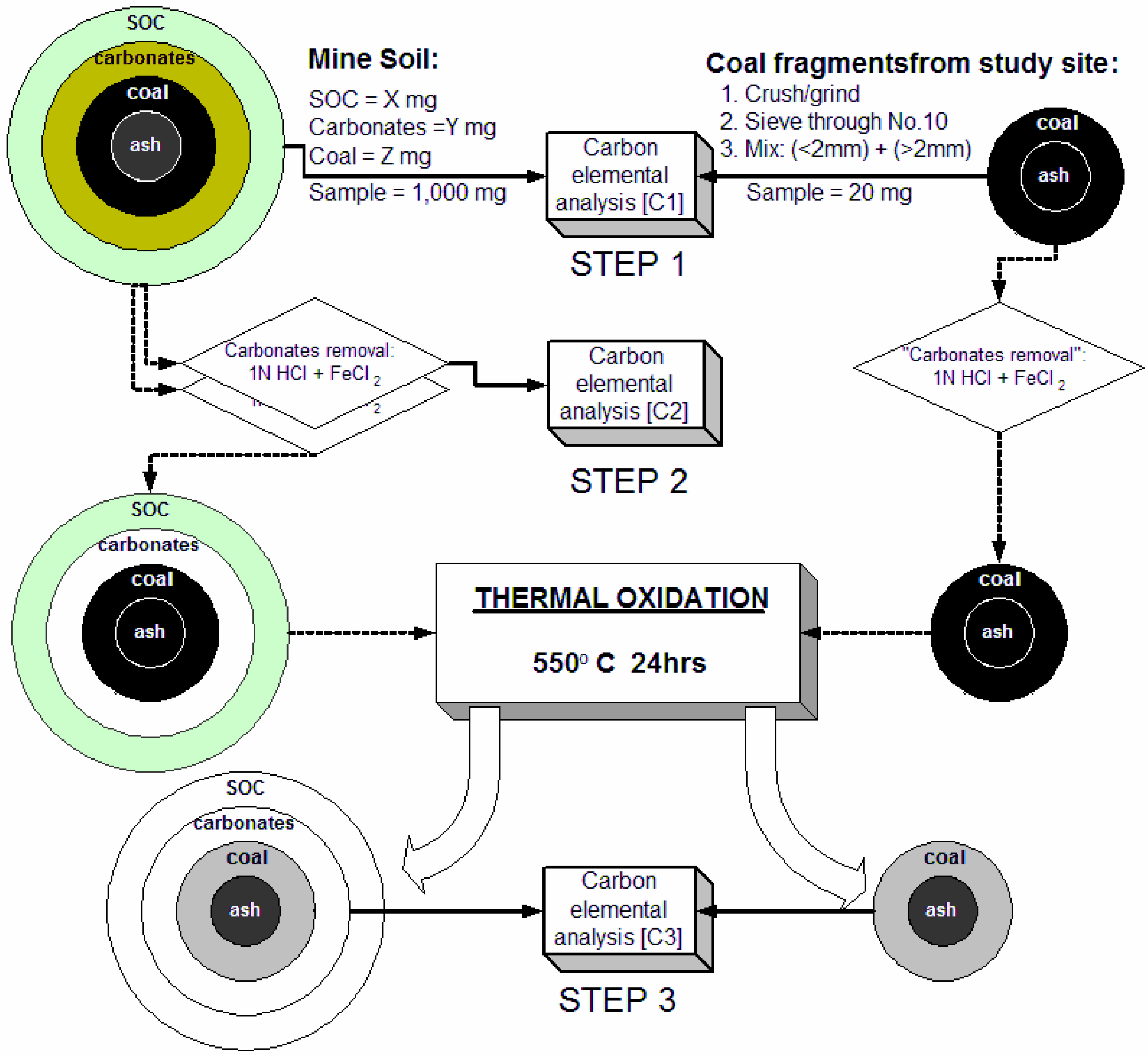
Currently we are in the process of designing an experiment to evaluate the accuracy and precision of the newly proposed carbon partitioning technique. Some of the questions that we intend to resolve with this experiment are to determine (i) the effect of coal particle size range and distribution in mine soil samples and (ii) the effect of extent (temperature) and duration (time) of thermal oxidation on the accuracy and precision of carbon partitioning of total soil carbon. All experimental measurements will be done on carefully constructed mine soil samples. As we achieve acceptable results for the accuracy and precision of the proposed carbon partitioning method we will proceed with estimating the amount of sequestered carbon in grassland mined sites for the three study sites established for this project in Ohio, West Virginia, and Virginia, from the previously reported total soil carbon estimates.

<u>Subtask 1.2</u>

The Nature Conservancy (TNC), the Virginia Department of Mines, Minerals, and Energy (DMME) and the Department of Forestry at Virginia Tech (DOFVT) intend to establish a carbon sequestration project on reclaimed coal mine fields located in the Clinch and the Powell river valleys of southwestern Virginia. An appropriate mix of native hardwood tree species will be used to restore the forests that once grew on these lands.

We initiated the implementation of a large scale reforestation carbon sequestration project on mined sites previously reclaimed to grassland on a mined site located in Russell County, Virginia. Among the many objectives of this carbon sequestration project one main goal is to evaluate and to implement the carbon monitoring protocol that was developed for and was delivered to the Department of Energy earlier this year and may be referred to as the 2nd QTR FY05 project milestone.

Mine Soils: Soil Organic Carbon Measurement Procedure



Calculations:

NOTE: The Carbon elemental analyses 1, 2, and 3 are performed using the Vario MAX CNS analyzer and should be set to report mine soil carbon content as percent by weight based on the *initial* sample weight (1,000mg) as opposed to the sample weight after treatments.

1. At STEP [2] the C content from carbonates (inorganic C) in the mine soil sample is $[CO_3]\% = C\%_{[C1]} - C\%_{[C2]}$

2. At STEP [3] the C content loss of coal fragments due to pretreatments is computed as $C\%_{coal\_start} / C\%_{coal\_end}$ ratio and the mine soil sample carbon content (% by weight) present as resistant coal particles is measured as $C\%_{soil\_coal}$

(i) For example, if $C\%_{coal\_start} = 50\%$ (i.e.10mg) and $C\%_{coal\_end} = 20\%$ (i.e. 4mg),

then $C\%_{coal\_start} / C\%_{coal\_end} = 50/20$, also termed $Coal_{C\%\_ratio}$

(ii) Carbon content in the mine soil sample from resistant coal particles is $C\%_{soil\_coal} = C\%_{[C3]}$

3. Finally, soil organic carbon (SOC) content in the mine soil sample is estimated as percent by weight as follow:

$$C\%_{SOC} = C\%_{[C1]} - [CO_3]\% - \{C\%_{soil\_coal} * Coal_{C\%\_ratio}\}$$

Figure 3. Proposed methodology for partitioning total soil carbon to pedogenic carbon and geogenic carbon fractions for mine soils.

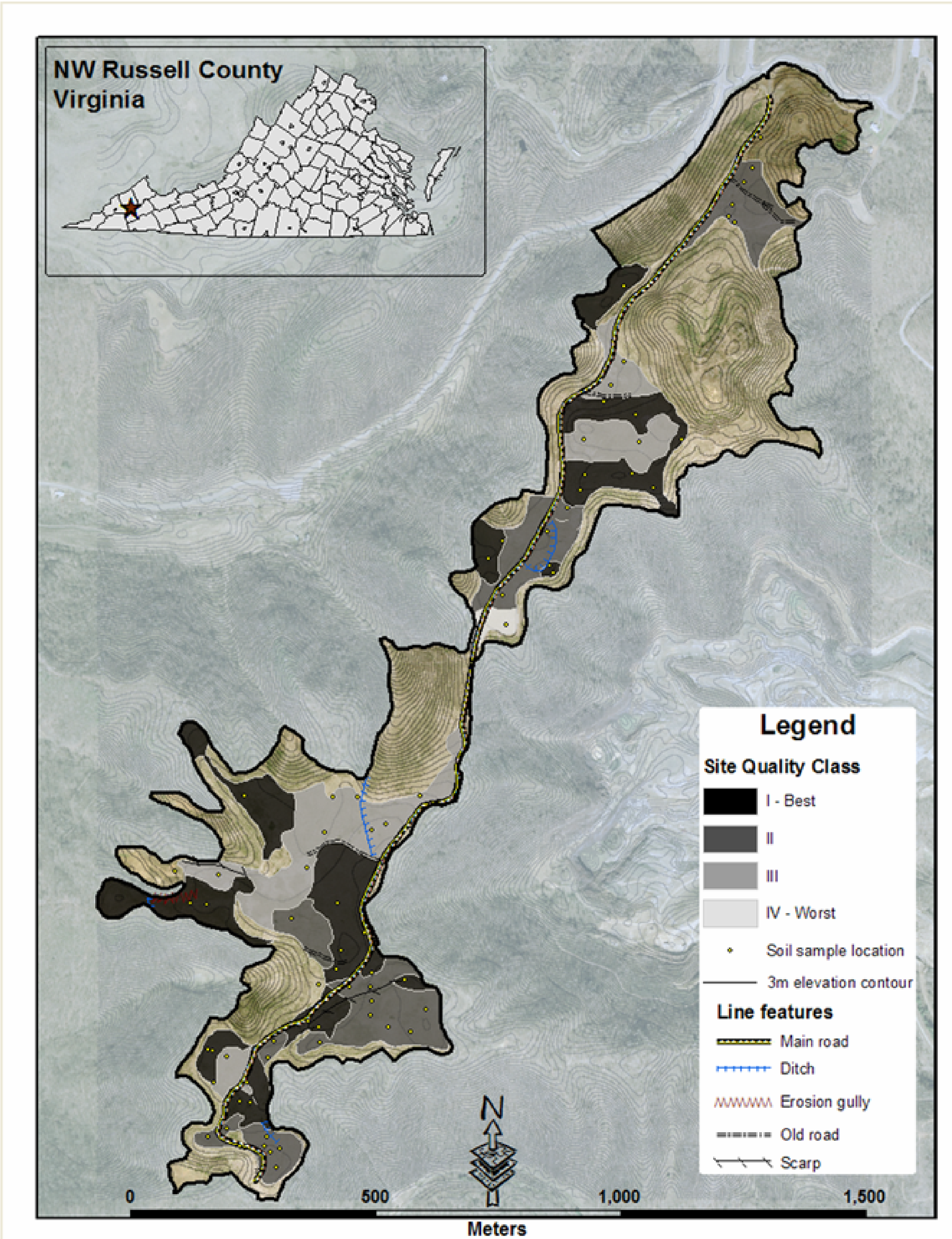


Figure 4. Site quality map of the Flint Gap mined site in Russell County, Virginia.

The Flint Gap mined site (latitude 36°59’21.47”N; longitude 80°15’17.71”W) was mapped by mine site quality class (Figure 4) as part of the initial phase of the carbon monitoring protocol. The next two phases include establishing permanent carbon monitoring sampling plots and estimating the baseline carbon stock, which will be completed before implementing any site preparation treatments on the site and before planting trees.

Results and Discussion

<u>Subtask 1.1</u>

No results are available at the present time. We are in the process of evaluating the accuracy and precision of the proposed C partitioning technique for mine soils (Figure 1).

<u>Subtask1.2</u>

The mine site quality class map depicted in Figure 2 was generated using the mapping criteria developed and tested by Galbraith and Jones (Task 3). More information about the mine soil properties used to determine site quality classes for the Flint Gap mined site and for the study sites in Ohio, West Virginia, and Virginia refer to the section for Task 3 in this report.

References

Daniels, W.L. and D.F. Amos. 1982. Chemical characteristics of some Southwest Virginia mine soils. In Proceedings of Symposium on Surface Mining Hydrology, Sedimentology and Reclamation. Lexington, KY, December 5-10, 1982)

Karls, J.F. and E.R. Christensen. 1998. Carbon particles in dated sediments from Lake Michigan, Green Bay, and tributaries. Environmental Science and Technology 32(2):225-231

Kralovec, A.C., E.R. Christensen, and R.P. Van Camp. 2002. Fossil Fuel and wood combustion as recorded by carbon particles in Lake Erie sediments 1850-1998. Environmental Science and Technology 36(7):1405-1413

Kuhlbusch, T.A.J. 1995. Method for determining black carbon in residues of vegetation fires. Environmental Science & Technology, 29:2695-2702

Schmidt, M.W., J. O. Skjemstad, C. I. Czimczik, B. Glaser, K.M. Prentice, Y. Gelinas, T.A. Kuhlbusch. 2001. Comparative analysis of black carbon in soils. Global Biogeochemical Cycles, Vol. 15, No. 1, pp. 163-167

Walkley, A., and I.A. Black. 1934. An examination of the Deggareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37:29-38.

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

Executive Summary

During the reporting period we have compiled and evaluated all soil properties measured on the study sites. Statistical analysis of the properties was conducted, and first-year survival and growth of white pine, hybrid poplars, and native hardwoods was assessed. Soil pits were excavated and evaluated at each site to further characterize the mine soil.

Experimental

<u>Study Areas and Design</u>

Research sites were chosen in Lawrence County, Ohio (OH); Nicholas County, West Virginia (WV); and Wise County, Virginia (VA) (Figure 5). The experiment was replicated three times to represent a range of pH values and rock type. The design was replicated with three blocks at each of the three study sites with nine 0.25-ha plots in each block. The study used a 3x3 factorial combination of treatments across the three sites in a randomized complete block design (Figure 6). The three treatments were weed control only, weed control plus tillage, and weed control plus tillage plus fertilization. The three species used were hybrid poplar, white pine, and native hardwoods. Areas with a slope of greater than 15% were avoided if possible in order to reduce slope and aspect effects on site quality. A 20 m x 20 m measurement plot was established in the center of each 0.25-ha treatment plot, within which all trees were assessed for survival and height growth.

The OH site was approximately 12 years past reclamation, the WV site was approximately 15 years past reclamation, and the VA site was less than 5 years past reclamation. All blocks except for VA3 had a thick cover of herbaceous vegetation. VA3 was less than one year old when soil samples were taken and trees were planted, and very little vegetation had been established. The WV site had been grazed by cattle for several years and managed as pastureland.

<u>Data Analysis</u>

Analysis of variance (ANOVA) was used with a 0.05 level of significance for survival and height growth as a 3x3 random complete block design with three sites and three species (Table 2). Only the weed control only plots were used to obtain survival and height growth of the three species. If the species by site interaction was significant, then the ANOVA was done by site and species separately to perform mean separation procedures. Tree survival was expressed as a percentage of the trees planted and these data were transformed using the arcsine transformation.

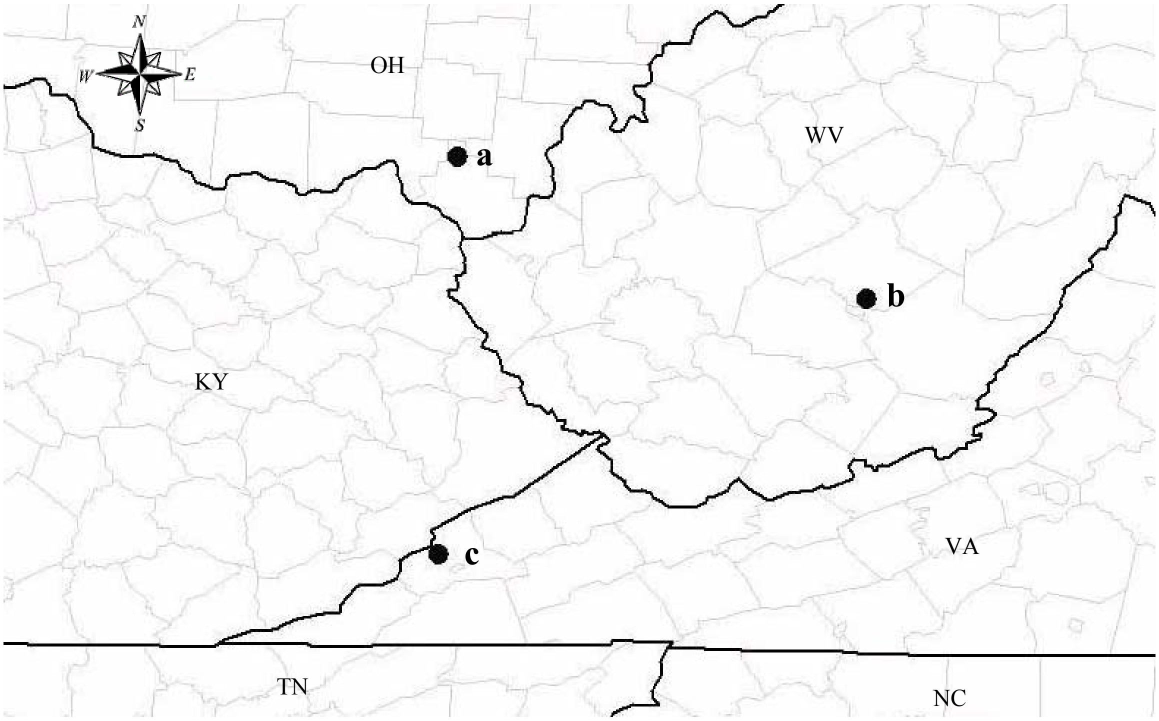


Figure 5. Research sites located in (a) Lawrence County, Ohio (OH); (b) Nicolas County, West Virginia (WV); and (c) Wise County, Virginia (VA).

Table 2. ANOVA summary for first-year survival and height growth of three species (hybrid poplar, white pine, hardwoods) and sites (Lawrence County, OH; Wise County, VA; Nicholas County, WV).

	Degree of Freedom	Variable (Pr>F) Survival	Variable (Pr>F) Height Growth
Block	2	0.3425	0.0266
Site	2	0.011	0.0053
Species	2	0.0045	<0.0001
Site x Species	4	0.1658	0.0222
Model	10	0.0095	<0.0001
Error	16		
Total	26		

ANOVA was also used to analyze soil properties for site and sample differences as a split-plot design with three blocks, three sites, and two sample depths (Tables 3, 4, 5, and 6). If the site by sample interaction term was significant, then site and sample were analyzed separately to perform mean separation procedures. All values recorded in percent were arcsine transformed.

Means were separated using Fisher's LSD with a significance level of $P < 0.05$. If interaction terms were not significant, only main effect means were compared. All statistical analysis was done using SAS 9.1 (2003).

Table 3. ANOVA summary for pH, electrical conductivity (EC), sand, silt, clay, rock fragments (RF), and sandstone (SS) content for three sites (Lawrence County, OH; Wise County, VA; Nicholas County, WV) and two samples (topsoil and subsoil).

	Degrees of Freedom	Variable (Pr>F)						
		pH	EC	Sand	Silt	Clay	CF	SS
Block	2	0.7766	0.0742	0.0130	0.0271	0.0146	0.4509	0.0815
Site	2	0.6581	0.0905	0.0007	0.0025	0.0014	0.0023	0.0320
Block x Site	4	0.1915	0.3950	0.0508	0.0884	0.0097	0.0768	0.0379
Sample	1	0.0089	0.0499	0.0132	0.0237	0.0115	0.0017	0.6645
Site x Sample	2	0.4635	0.0020	0.0006	0.0012	0.0023	0.2651	0.8314
Model	11	0.1371	0.0158	<0.0001	0.0002	<0.0001	0.0002	0.0038
Error	6							
Total	17							

Table 4. ANOVA summary for magnesium (Mg), potassium (K), calcium (Ca), manganese (Mn), nitrogen (N), cation exchanged capacity (CEC), and base saturation (BS) for three sites (Lawrence County, OH; Wise County, Va; Nicholas County, WV) and two samples (topsoil and subsoil).

	Degrees of Freedom	Variable (Pr>F)						
		Mg	K	Ca	Mn	N	CEC	BS
Block	2	0.1765	0.5361	0.2528	0.5292	0.3353	0.0603	0.5497
Site	2	0.0047	0.0115	0.0049	0.7083	0.0008	0.0051	0.8538
Block x Site	4	0.2974	0.1325	0.1437	0.4576	0.0205	0.0230	0.2711
Sample	1	0.0476	<0.0001	0.0037	0.0191	<0.0001	0.0032	0.0418
Site x Sample	2	0.0100	0.0017	0.0009	0.9912	<0.0001	<0.0001	0.4525
Model	11	0.0038	0.0005	0.0007	0.3212	<0.0001	<0.0001	0.3057
Error	6							
Total	17							

Table 5. ANOVA summary for aluminum (Al) and phosphorus (P) for three sites (Lawrence County, OH; Wise County, VA; Nicholas County, WV) and two samples (topsoil and subsoil).

	Degrees of Freedom	Variable (Pr>F)	
		Al	P
Block	2	0.2835	0.0670
Site	2	0.4091	0.0299
Block x Site	4	0.4522	0.0078
Sample	1	0.0720	<0.0001
Site x Sample	2	0.4553	0.0002
Model	11	0.3698	<0.0001
Error	5		
Total	16		

Table 6. ANOVA summary for topsoil depth and bulk density (D_b) for three sites (Lawrence County, OH; Wise County, VA; Nicholas County, WV).

	Degrees of Freedom	Variable (Pr>F)	
		Topsoil Depth	D_b
Block	2	0.4982	0.8507
Site	2	0.1489	0.0615
Model	4	0.258	0.1484
Error	4		
Total	8		

Geology and Soils

Modern USDA Soil Surveys have been produced for Lawrence County, OH (1998), and Nicholas County, WV (1992). No recent survey has been published for Wise County, VA.

Pennsylvanian aged bedrock underlies all of the sites. In OH the Pottsville, Allegheny, and Conemaugh formations underlies a majority of Lawrence County. Pre-mine soils surrounding the study area were predominantly Lily loam on the ridge tops, and Shelocta-Latham association on the sideslopes. Soils on nearby mined lands were all identified as Bethesda channery silty clay loam. Full descriptions of all established soil series are found at (http://soils.usda.gov/). Native soils near the WV site consist of Buchanan channery fine sandy loam, very stony; Fenwick silt loam; and Gilpin silt loam, stony. The New River and Pocahontas formations from the Pottsville group dominate this coal-producing area. The soils on the mined site were identified as Kaymine channery loam. The Wise formation underlies the study area in VA and consists of approximately 70% sandstone, 20% siltstone, and 10% shale (Howard, 1979). The dominant native soils in this area are the Jefferson and Dekalb series. Mined areas nearby the sites have been previously mapped as Sewell and Fiveblock series (Haering et al. 2005).

Sampling Procedures

Soils in each of nine plots were sampled in five different locations (Figure 6). Oxidized and unoxidized spoil layers were sampled separately, depending upon thickness of each layer. The plots were sampled approximately 11-m diagonally inside each corner and in the plot center. Exclusion criteria were developed prior to the sampling of plots, as follows: The sampling point will be moved to an adjacent site if any of the following occur at the sampling point:

1. A boulder is encountered that is large enough to prevent the pit from being dug in the correct location or to the proper depth,
2. severely eroded land, determined by ditches or gullies, is present directly within the sampling location,
3. disturbed areas such as roads, rock piles, etc. are directly within the sampling location, or
4. poor drainage areas that occupy less than 1 % (25 m^2) of the total plot area. Poor drainage was indicated by standing water, dominance of hydrophytic vegetation, or lack of vegetation due to ponding.

A shallow pit was dug to approximately 50 cm at each accepted sample site. There was often an abrupt boundary between the oxidized topsoil and a much greyer, unoxidized subsoil material at the VA and OH sites. A composite sample was taken from the 0- to 10-cm depth. Composite samples were also taken of all layers between the 10- to 30-cm depth unless the unoxidized subsoil was observed within 50 cm. The different materials were never mixed for laboratory analysis because they were suspected to have dramatically different chemical properties. If the unoxidized subsoil occurred at less than 50 cm, a composite sample of all layers within the subsoil was taken to the 50-cm depth. Three of the five shallow pits per plot were randomly chosen and described in order to characterize the soil variability at the site.

Multiple deep pits were excavated with a backhoe to approximately 2-m in representative locations at each site. Each horizon was described and sampled. Three to five bulk density (D_b) 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 driven vertically into the soil and then extracted. The soil within the cylinder and any loose pieces in the hole were placed in labeled sample bags. The hole was lined with thin plastic, lightly pressed into the corners, and then filled with lead BB's to the original surface level. The volume of the BB's was measured in a graduated cylinder and recorded. The extracted soil was air dried and weighed, and the weights were corrected for rock fragment (RF) percent by dry sieving through a 2-mm sieve and corrected for moisture content in order to report the fine earth D_b in g cm^{-3} on an oven-dry soil basis. All RFs >2 mm were assumed to have a specific gravity of 2.65 g cm^{-3}.

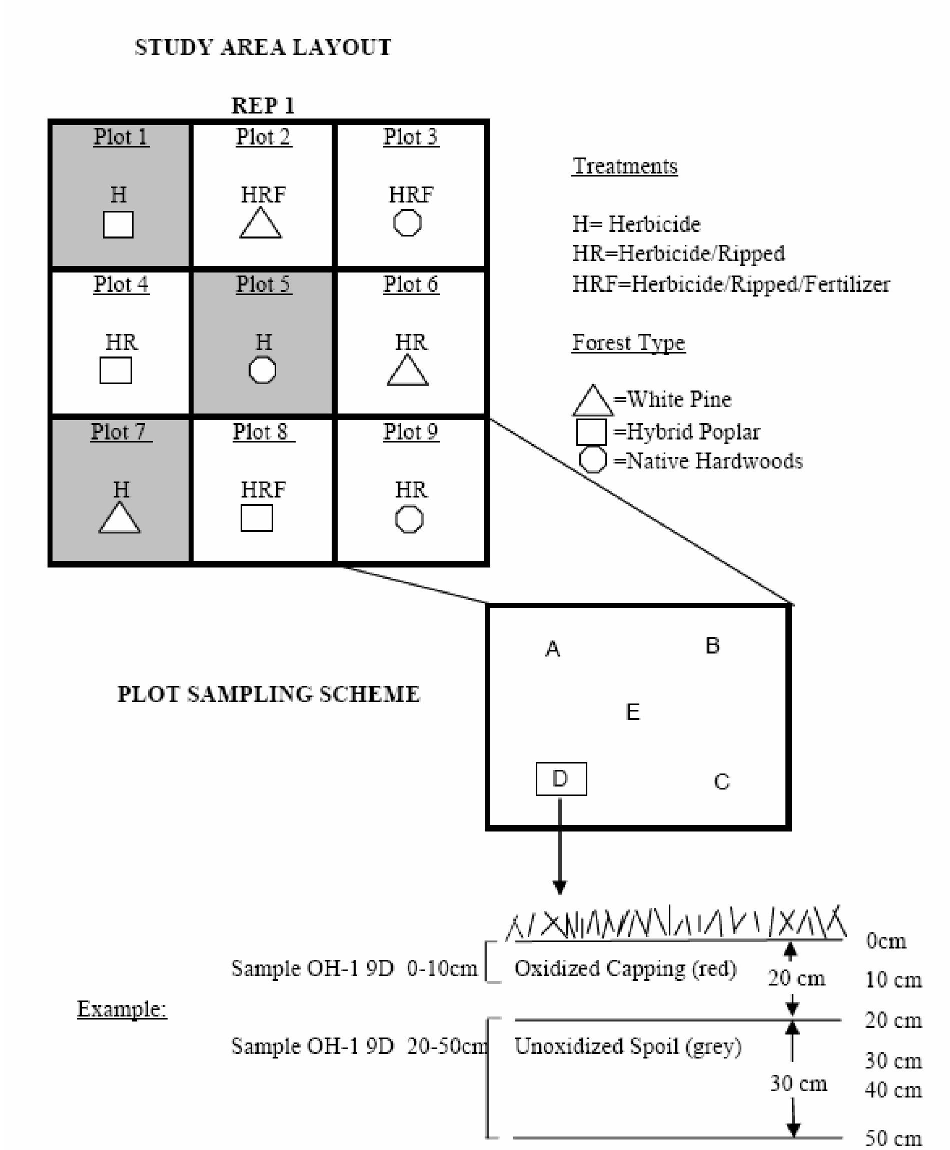


Figure 6. Schematic of one treatment block with nine plots. One plot is expanded to show the distribution of sample locations. An example of the sampling depths is shown at one sample location.

<u>Sample Preparation</u>

Bulk samples from the deep pits were air-dried, while samples from the shallow pits were dried in a room heated at 50ºC for one week. The heated room was used in order to speed drying time and space requirements for the large number of shallow pit samples (> 1000). Bulk samples (deep pits and shallow pits) were weighed and sieved through a 2-mm sieve. The fine earth was saved for laboratory analysis.

Measurements of pH, electrical conductivity (EC), carbon (C), and nitrogen (N) were taken on all samples. Equal subsamples from the 0- to 10-cm samples from all five shallow pits in each plot were then combined to save time and cost of analysis. The same was true for the 10- to 30-cm depth, and subsoil samples if they occurred.

RF type and volume were visually estimated in each field descriptions. The RFs of the bulk samples were washed in order to remove all soil material and then dried in the 50ºC drying room. RF percentage was then determined on a weight difference basis and proportions of each rock type visually estimated.

D_b of the topsoil and subsoil (if within 30 cm) was also taken within each plot. The excavation hole size was approximately 900 cm^2 and 10 cm deep. Otherwise, the same procedure with a plastic lining and lead BB's as outlined above was used. Porosity was calculated using these D_b measurements and assuming a particle density of 2.65 g cm^{-3}.

Lab Analysis

Samples were analyzed for pH and EC using an AGRI-METER (MYRON L Company) on a 20 g soil:40 g water mixture. The mixture equilibrated for 1 hr before readings were taken. Particle-size distribution was determined by the pipet method (Gee and Bauder, 1986). Surface samples were treated with H_2O_2 and heated in order to destroy organic matter present. Exchangeable cations (potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), and manganese (Mn)) were extracted with a 1M NH_4OAc (ammonium acetate) solution buffered at pH 7 (USDA, 1996). A modification of the exchangeable cation procedure was made in that only 100 ml of NH_4OAc leachate was used. Even though Ca and Mg are reported as exchangeable cations, carbonate cements that are often present in unweathered mine soils may be soluble in the NH_4OAc extract and consequently release cations that may not be truly exchangeable (Roberts et al., 1988a). Phosphorus was extracted with 0.5M $NaHCO_3$ (sodium bicarbonate) (Olsen and Sommers, 1982) as recommended for mine soils (Daniels and Amos, 1982). A modification was made from Olsen and Sommers (1982) in that only 1 g of soil and 20 ml of $NaHCO_3$ were used. Also, "Reagent B" was not added to the bicarbonate extract because the measurements were made with the Inductively Coupled Plasma Spectrometry (ICP) instrument (SpectroFlame Modula Tabletop ICP with autosampler; Type: FTMOA85D; Spectro Analytical Instruments, Inc.). The resulting data includes both organic and inorganic phosphorus (P) (Kuo, 1996). All cations were measured with the ICP instrument. Total C (%) and N (%) were measured by combustion with a carbon-nitrogen auto-analyzer (Vario Max CNS analyzer, Elementar, Hanau, Germany). Exchangeable Aluminum (Al) was extracted with a 1N KCl solution and quantified by titration (McLean, 1965). The effective cation exchange capacity (CEC) of the samples was calculated by summing the NH_4OAc-extracted K, Ca, Mg, and Na and the KCl-extracted Al (Sumner and Miller, 1996). Base saturation (BS) values were calculated by dividing the sum of K, Ca, Mg, and Na by the CEC and converting to a percentage. Mehlich I-extracted zinc (Zn), copper (Cu), iron (Fe), and boron (B) was performed by the Virginia Tech Soil Testing Laboratory (Donohue and Heckendorn, 1996) and measured by ICP.

Results and Discussion

Pit Descriptions

West Virginia

The shallow pit descriptions for all WV blocks indicated that A horizons had developed but were only approximately 5 cm thick. A 10YR 3/2 color was the most common surface color, and loam was the most common texture. Particle size analysis indicated that most of the textures described as loams in the field were actually sandy loams. C horizons were described directly below the A horizon and separated mainly on a color change, lack of structure, and decreased root growth. Colors of the C horizon were most commonly 10YR 4/2 or 4/1, and there was no structure present. Moist consistence was usually friable, but may not resemble the true soil density condition due to high RF contents that caused most extracted clods to easily rupture. Shale was the dominant rock type, and gravel and channers were the most common rock sizes.

Deep pits indicated that a Bw horizon was present in all pits down to 15-cm as determined by weak, coarse subangular blocky structure. This was likely overlooked in the shallow pits because of less viewing area of the pit face and more destructive excavation techniques. Fragmental layers with ≥ 90% RF and bridging voids were present in all three pits, and began at a depth of 60- to 125-cm. This will likely cause reductions in forest productivity because of less rooting volume and excessively-rapid drainage of soil water.

Virginia

All VA blocks were young and genetic processes were just beginning to transform the spoil material. No A horizon was described at VA1 because no darkening by organic matter was present. However, Haering et al. (1993) describe spoil loosening and aggregation for A horizons on two-year-old mine soils in the same region. These conditions were present at VA1, suggesting that a thin A horizon should have been described. The depth of the topsoil material was identified as A horizon material in the deep pits. Any organic matter translocation into the soil was likely masked by the red colors (10YR 5/6, 5/4, and 5/3). The subsoil at VA1 was most commonly a 2.5Y 4/1 color, was structureless, had a higher RF content, and was often firm in consistence. Both deep pits at VA1 had densic layers within 35 cm of the surface and confirm that the subsoil was significantly compacted and impedes root growth. Although densic layers were not described in the shallow pits, it is likely that they were overlooked due to small pit size.

The VA2 block had 5- to 10-cm thick A horizons as determined by weak subangular blocky structure. The surface color was most commonly 2.5Y 4/2 or 4/3 and the surface soil extended deeper than all other blocks. No dense layers were described in the shallow pit or deep pit descriptions and the moist consistence was most often friable. The subsoil color was usually 2.5Y 3/1, and sandy loam and loam textures were found throughout the profile.

Thin A horizons were described for VA3 due to loosening of the spoil material on the surface. Colors were widely variable due to mixed rock types, and some dense horizons were described close to the surface. Moist consistence was often firm directly below the A horizon. No obviously different spoil type was found in the subsurface layers.

Ohio

All OH blocks consisted of lower RF contents and finer textures than all other blocks. A 1- to 4-cm-thick A horizon was recognized on all blocks and often had a color of 10YR 3/2 or 2/2.

The structureless appearance and finer textures prevent much translocation of organic matter deep into the soil profile. However, weak structure was beginning to develop below the A horizon and Bw horizons had formed at all blocks. Thomas and Jansen (1985) also found weak genetic structure below the A horizon in all but the youngest site (5 years old) on pre-SMCRA mines, but no structure development was observed below 35 cm. Haering et al. (1993) describe transitional AC horizons in mine soils instead of Bw horizons. Colors of the topsoil were commonly 10YR 5/4 and 5/6, except for OH3, where topsoil colors were more commonly 2.5Y 5/3 and 5/4. Subsoil colors were usually of the 2.5Y or 5Y hue with values of 4 or 5 and chromas of 1 or 2. Loams and clay loams were the most common texture classes described, but lab data suggests that silt loams and silty clay loams were also prevalent. Moist consistence was most often friable, but may have been skewed due to high moisture contents, weak structure, and fine textures that allowed most soil clods to easily be deformed. Some dense horizons were described in the deep pits at OH2 and OH3, but both were below 50 cm. The dense layers are expected to be present at shallower depths in certain locations and should probably be described more often in the mini-pit descriptions. The ponding of water on the surface, especially at OH2, confirms suspicion that dense layers underlie the topsoil. D_b measurements for the deep pit horizons suggests that the Bw and BC horizons are often the densest and will restrict root growth and aeration in fine textured soils (Brady and Weil, 1999).

Lab Results

Physical Properties

The WV site did not have any oxidized topsoil substitute replaced on the surface. However, the topsoil depth was insignificant across all three sites likely due to the large variation within the other sites (Table 7). VA1 and VA2 had oxidized topsoil substitutes spread on the surface, while VA3 had no obvious pattern of topsoil deposition. There was oxidized topsoil at all OH blocks.

Significant differences only of total estimated volume percentages of sandstone were determined (Table 7). The WV blocks were all dominated by a dark-colored shale rock type. The OH blocks had a more oxidized spoil type on the surface and were dominated by siltstone rock types. The VA blocks had a mixture of spoil types on the surface. Sandstone content was significantly higher at VA than the other two sites and there were no significant differences of sandstone content between WV and OH (Table 7). The Wise formation underlying the VA site consists of 70% sandstone and is expected to dominate spoil types in the surrounding region (Howard 1979). No significant differences of sandstone content by sample was found.

Table 7. Physical property means by site (Lawrence County, Ohio (OH); Wise County, Virginia (VA); Nicholas County, West Virginia (WV)) and sample (0 = topsoil, 2 = subsoil) for topsoil depth; total sandstone (SS); sand, silt, and clay; rock fragments (RF); and bulk density (D_b).

Physical Property	Sample	OH	VA	WV	Sample Means
	0	21 a†	20 a	0 a	**13**
Topsoil Depth (cm)	2	.	.	.	.
	site means	.	.	.	
	0	23	61	9	**31** A
SS (%)	2	16	58	10	**28** A
	site means	**20** b	**60** a	**9** b	
	0	8	42	52	**34** B
RF (%)	2	20	57	58	**45** A
	site means	**14** b	**49** a	**55** a	
	0	35 c A‡	51 b A	61 a A	**49**
Sand (%)	2	24 b B	58 a A	54 a A	**45**
	site means	**29**	**55**	**57**	
	0	42 a B	36 b A	31 b B	**36**
Silt (%)	2	48 a A	32 b A	36 b A	**38**
	site means	**45**	**34**	**34**	
	0	23 a A	13 b A	8 b B	**15**
Dlay (%)	2	28 a A	10 b A	11 b A	**16**
	site means	**26**	**11**	**9**	
	0	1.4 a	1.2 a	1.1 a	**1.2**
D_b (g cm^{-3})	2	.	.	.	.
	site means	.	.	.	

† Across rows, means that are significantly different determined by Fischer's LSD at α = 0.05 are followed by different lower case letters.

‡ Within columns, means that are significantly different determined by Fischer's LSD at α = 0.05 are followed by different upper case letters.

Total RF content was significantly higher in the subsoil samples than in the topsoil samples (Table 7), likely due to increased weathering at the surface. Unoxidized subsoil layers have not been pre-weathered like the oxidized topsoil substitutes at the VA and WV sites, and are expected to have higher RF contents and require more time to weather into soil fines. The OH site had significantly less RFs than the WV or VA sites.

The topsoil and subsoil material at the OH site had significantly higher clay percentage than the VA or WV sites (Table 7). The spoil material used in reclamation was dominated by siltstone rock types and native soils that had higher clay contents, and is likely responsible for the high clay contents in the mine soils. The WV site was the only site in which significantly higher clay content was found in the subsoil than in the topsoil. The topsoil and subsoil material at WV was the same spoil type, and the clay increase may indicate some translocation of clay down through the mine soil profile. Thomas and Jansen (1985) found no translocation of clay in their study of 5-64 year old mine soils in southern Illinois, and Haering et al. (1993) found similar results in 8-year-old Appalachian mine soils. Sand percentages in the topsoil were significantly higher at the WV site (Table 7), but this is likely due to sand-sized shale particles and not resistant quartz sand as observed in sieved soil samples. The OH site had significantly lower sand content in both the topsoil and subsoil samples (Table 7). The OH site had significantly higher silt content than WV and VA (Table 7), most likely due to the high siltstone content. Higher silt and clay content at the OH site confirms our theory that aeration will likely limit tree growth.

No significant differences in D_b were observed across sites (Table 7). However, the D_b value for OH has been noted as being root-restricting for fine-textured soils (Brady and Weil 1999; Zisa et al. 1980).

Chemical Properties

The pH values were similar to ranges found in previous studies by Torbert et al. (1990), and Plass and Vogel (1973) (Table 8). There were no significant differences for sites, but the subsoil sample was significantly higher than the topsoil. The differences in degree of oxidation and weathering of the subsoil material at VA and OH is likely responsible for this increase. The pH of VA is expected to decrease over time due to rapid leaching of carbonates and basic cations associated with young mine soils (Roberts et al. 1988a).

Exchangeable Al was not significantly different for sites or samples (Table 8). The pH values are not low enough to expect conversion of Al to its soluble form (Al^{3+}) that is toxic to plants and Haering et al. (1993) reported that decades of weathering may be necessary before Al occupies a significant portion of the mine soil exchange complex. The EC levels at OH were significantly lower in the topsoil and significantly higher in the subsoil than the other two sites (Table 8). The higher EC in the topsoil at VA is likely due to those sites being the youngest and having little time to leach the salts that are released from the rapid weathering of newly-exposed, crushed bedrock. The WV site was previously in a managed pasture land use and the application of inorganic fertilizers and cattle manure are likely responsible for higher EC levels. Fine textures such as those found in the OH subsoils have been reported to have higher EC levels than coarse textures (Rodrigue and Burger 2004), and the same pattern is observed in this study. However, no EC levels were higher than the value of 0.5 dS m^{-1} that Andrews (1992) reports to have a negative effect on tree growth (Table 8).

All BS values were high and are not expected to be limiting to tree survival or growth at such high levels (Rodrique and Burger 2004). No significant differences between sites were found but the subsoil was significantly higher than the topsoil (Table 8). All CEC values were less than 14 $cmol_c$ kg^{-1} (Table 8), which agrees with reports by Evangelou (1995). No significant differences across sites were found in the topsoil samples, and the OH site was significantly higher than VA or WV for the subsoil samples (Table 8). This may be due to higher clay contents or a different clay mineralogy (not studied) in the OH subsoils compared to the other sites. The OH subsoil was also significantly higher than the OH topsoil and may be due to the same reasons described for site differences. However, Roberts et al. (1988a) reported CEC to be higher in the surface of mine soils than in the subsurface of mine soils due to the higher organic matter in the surface. The WV site follows this pattern, likely due to the same reasons.

Andrews et al. (1998) reported that height growth of white pine generally declined when exchangeable Mn levels exceeded 20 mg kg^{-1}. No Mn levels exceeded that critical limit in this study but the topsoils of VA and WV were very close (Table 8). There were no significant differences between sites, but the topsoil was significantly higher than the subsoil sample (Table 8). Mn deficiency is most often observed in saline, alkaline, calcareous, and coarse textured soils (McBride, 1994). In this study the significantly lower Mn levels were found in the subsoils, which had pH > 6.0 and may inhibit tree production once roots enter that layer.

Phosphorus was significantly higher for the topsoil at the WV site than at VA and OH (Table 8). This is possibly due to fertilization used for the managed pasture land use and possibly from supplemental feed and manure. Only the OH site tested below 9 mg kg^{-1} P in the topsoil, which is considered the critical level for tree response (Andrews 1992). The P levels at VA and WV significantly decreased from the topsoil to subsoil samples (Table 8). The pasture fertilization at WV, residual fertilization from hydro-seeding the young VA sites, and the immobility of P are likely responsible for the higher topsoil levels. The P levels in this study were similar to those found by Andrews et al. (1998), but were slightly higher than reported by Roberts et al. (1988a), and Daniels and Amos (1982). The N content was also significantly higher at WV (Table 8), again possibly due to previous fertilization with the past land use and through the addition of cattle manure. The VA site had the lowest N content. The age factor and less time for herbaceous legumes to fix N in the soil are likely reasons, along with higher sandstone percent that has been shown to be associated with lower total N (Roberts et al., 1988a). A significant decrease in N content from the topsoil to subsoil at the OH and WV blocks (Table 8) is likely due to the shallow rooting of legumes that fix N in the topsoil but do not reach the subsoil. The younger VA site does not yet demonstrate this pattern.

There were no significant differences for Ca in the topsoils across all sites (Table 8). The subsoil at the OH site was significantly higher than the other subsoils and higher than the OH topsoil. The Conemaugh formation that underlies this site contains more limestone bedrock layers than the geologic formations that are found at the other sites and a limestone quarry was nearby. Furthermore, some limestone rock fragments were observed in pit descriptions and are likely responsible for the high Ca levels. These high levels may be responsible for forming insoluble P compounds as well. Mg and K were significantly higher in the topsoil at the WV site than VA and OH (Table 8). WV was the only site with dominantly unoxidized topsoil substitutes present on the surface, and that may explain the higher amount of exchangeable cations (Haering et al., 1993). The Mg, K, and Ca values at all sites were similar to those reported by Roberts et al. (1988a), and Torbert et al., (1990) who studied similar mine soils.

Table 8. Chemical property means by site (Lawrence County, Ohio (OH); Wise County, Virginia (VA); Nicholas County, West Virginia (WV)) and sample (0 = topsoil, 2 = subsoil) for pH, exchangeable aluminum (Al), electrical conductivity (EC), base saturation (BS), cation exchange capacity (CEC), exchangeable manganese (Mn), extractable phosphorus (P), nitrogen (N), exchangeable calcium (Ca), magnesium (Mg), and potassium (K) by block and site.

Chemical Property	Sample	OH	VA	WV	Sample Means
pH	0	5.4	5.8	5.7	**5.6** B
	2	6.6	6.9	6.2	**6.6** A
	site means	**6.0** a†	**6.4** a	**6.0** a	
Al ($cmol_c\ kg^{-1}$)	0	0.6	0.3	0.2	**0.4** A
	2	0.1	0.0	0.1	**0.1** A
	site means	**0.3** a	**0.2** a	**0.1** a	
EC ($dS\ m^{-1}$)	0	0.1 b A‡	0.3 a A	0.2 a A	**0.2**
	2	0.5 a A	0.3 b A	0.1 b B	**0.3**
	site means	**0.3**	**0.3**	**0.2**	
BS (%)	0	94	95	98	**95** B
	2	100	100	99	**99** A
	site means	**97** a	**97** a	**98** a	
CEC ($cmol_c\ kg^{-1}$)	0	9 a B	6 a A	8 a A	**8**
	2	14 a A	6 b A	6 b B	**9**
	site means	**12**	**6**	**7**	
Mn ($mg\ kg^{-1}$)	0	15	19	19	**18** A
	2	4	6	7	**6** B
	site means	**9** a	**13** a	**13** a	
P ($mg\ kg^{-1}$)	0	8 b A	11 b A	20 a A	**13**
	2	3 a A	5 a B	6 a B	**5**
	site means	**6**	**8**	**13**	
N ($mg\ kg^{-1}$)	0	1196 b A	752 c A	2719 a A	**1556**
	2	482 b B	643 b A	1082 a B	**735**
	site means	**839**	**698**	**1900**	
Mg ($mg\ kg^{-1}$)	0	237 b A	243 b A	383 a A	**288**
	2	278 a A	203 a A	301 b B	**261**
	site means	**258**	**223**	**342**	
K ($mg\ kg^{-1}$)	0	131 b A	84 c A	162 a A	**126**
	2	97 a B	70 a A	82 a B	**83**
	site means	**114**	**77**	**122**	
Ca ($mg\ kg^{-1}$)	0	1169 a B	646 a A	925 a A	**913**
	2	2385 a A	811 b A	673 b B	**1290**
	site means	**1777**	**729**	**799**	

† Across rows, means that are significantly different determined by Fischer's LSD at α = 0.05 are followed by different lower case letters.

‡ Within columns, means that are significantly different determined by Fischer's LSD at α = 0.05 are followed by different upper case letters.

Seedling Survival and Growth

Seedling survival across all species was significantly higher at VA than at WV and OH (Table 9). This is most likely explained by the significantly higher sandstone content at VA (Table 7), which has been recognized as the best medium for tree survival and growth (Hearing et al., 1993; Torbert et al. 1990). The sandstone content influences soil properties that positively affect water and aeration relations and may out-weigh chemical property differences in this study. The N content in the topsoil at VA is significantly lower than the other two sites (Table 8) and may actually have a positive affect on seedling survival, in that the herbaceous vegetation is not stimulated at VA as much as at the other sites. The young age of the VA site as compared to the others has not allowed the seed pool of competing vegetation to become as well established and the weed control treatment was more effective. The survival rate of hardwoods was significantly higher than white pine or hybrid poplar across all sites (Table 9). The hardwoods planted are adapted to a wider range of soil properties than the white pine or hybrid poplars as shown by survival rates.

Table 9. First-year survival rates (%) by site (Lawrence County, Ohio (OH); Wise County, Virginia (VA); Nicholas County, West Virginia (WV)) and species type (HP = hybrid poplar; WP = white pine; HW = hardwoods).

Species Type	OH	VA	WV	Species Means
HP	49	79	32	53 B‡
WP	45	54	41	47 B
HW	60	81	78	73 A
Site Means	51 b†	71 a	50 b	

† Across rows, means that are significantly different determined by Fischer's LSD at $\alpha = 0.05$ are followed by different lower case letters.

‡ Within columns, means that are significantly different determined by Fischer's LSD at $\alpha = 0.05$ are followed by different upper case letters.

First-year height growth of hybrid poplar was significantly higher than white pine and hardwoods across all sites (Table 10). Only at WV were hardwoods significantly different (lower) than white pine. Hybrid poplar growth was the highest at VA and was significantly higher than WV (Table 10). There were no significant differences of hybrid poplar height growth between OH and the other two sites. Again, the high sandstone content at VA and the fact that an oxidized material was on the surface at VA and OH explain the higher growth rates at these two sites. The WV site had a high RF content and low silt and clay contents that likely resulted in lower available water and decreased growth of the hybrid poplars. Hardwood height growth was significantly higher at VA than at WV and OH (Table 10). The high sandstone content at VA continues to create a growing medium for tree roots with a proper balance of air and water, and it affects height growth as well. Available water is likely to be limiting at WV and aeration is likely to be limiting at OH. No significant differences across sites were found for height growth of white pine (Table 10). White pine seedlings have a very slow early growth stage for two to three years before more rapid growth begins (Wendel and Smith, 1990). The effects of soil properties on white pine growth will not likely be observed until the initial stage of slow early growth is surpassed.

Table 10. First-year height growth (cm) by site (Lawrence County, Ohio (OH); Wise County, Virginia (VA); Nicholas County, West Virginia (WV)) and species type (HP = hybrid poplar; WP = white pine; HW = hardwoods).

Species Type	OH	VA	WV
HP	36 ab[†]A[‡]	41 aA	22 bA
WP	5 aB	6 aB	6 aB
HW	-1 bB	4 aB	-1 bC

† Across rows, means that are significantly different determined by Fischer's LSD at $\alpha = 0.05$ are followed by different lower case letters.

‡ Within columns, means that are significantly different determined by Fischer's LSD at $\alpha = 0.05$ are followed by different upper case letters.

Conclusions

Mine soil properties are highly variable throughout the Appalachian region due to differences in site geology and reclamation activities. The topsoil substitute will likely change in soil composition the quickest through pedo-genesis at the soil surface. Horizon formation in mine soil profiles became more pronounced with increased weathering time, and soil properties will likely change as weathering, leaching and biological activity continues. The three sites were dominated by different rock types that affected the physical and chemical soil properties. Only the WV site did not have an oxidized topsoil substitute replaced on the surface.

The OH site was dominated by siltstone rock types, WV was dominated by shale, and VA was dominated by sandstone. Finer textures and fewer rock fragments were found at the OH site compared to VA and WV. The soil at OH likely presents aeration problems for optimal tree growth due to reduced macroporosity associated with fine textures and the destruction of natural soil structure. The soil at WV has a high rock fragment content and bridging voids are present lower in the profile, which may increase drainage rates and create a droughty soil with low water-holding capacity. The VA site allowed for a good balance of water and air in the soil due to the high sandstone content, and will likely create fewer limitations for tree growth.

Mine soil properties were used to explain tree seedling survival and growth differences for site and species. The VA site had the best survival rates likely due to the soil properties created from weathering the sandstone based topsoil substitute. Hybrid poplars and hardwoods had the greatest height growth at VA, and white pine growth was statistically the same across all sites due to its slow initial growth habit. The sandstone content continues to be the overwhelming soil property affecting tree growth on Appalachian mine soils. Future growth measurements may indicate other physical and chemical soil properties as significant to overall forest productivity.

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

Executive Summary

Surface mined lands in the Appalachian coal-producing region reclaimed after the passage of the Surface Mining Control and Reclamation Act of 1977 (SMCRA) have often been found to have dense ground covers, compacted soil materials, and unfavorable soil chemical properties associated with them. To address these concerns, three study sites which had been reclaimed post-SMCRA were located in Lawrence County, Ohio, Nicholas County, West Virginia, and Wise County, Virginia. At each site, three species assemblages were planted, including hybrid poplar, white pine, and a native hardwood mix. Each species assemblage was treated with a gradient of silvicultural treatments to alleviate the previously mentioned problems associated with post-SMCRA mined land. Treatments included weed control only, weed control plus tillage, and weed control and tillage plus fertilization. Response to treatment in terms of first-year survival and growth was variable by site, with the site in Virginia having the best survival and greatest growth of the three. Hardwood species survived better at all sites than white pine or hybrid poplar. Hardwood survival across treatments was 80%, 85%, and 50% for sites in Virginia, West Virginia, and Ohio, respectively, while white pine survival was 27%, 41%, and 58%, and hybrid poplar survival was 37%, 41%, and 72% for the same sites, respectively. Hybrid poplar height and diameter growth were superior to those of the other species tested, with the height growth of this species reaching 126.6 cm after one year in the most intensive treatment at the site in Virginia. In comparison, the greatest height growths of white pine and hardwood were 8.9 cm and 7.9 cm, respectively. Hybrid poplar biomass increased from 15.7 g to 104.5 g from the least intensive to the most intensive silvicultural treatment for the site in Nicholas County, West Virginia. Additionally, the highest level of intensity improved the foliar nutrition of hybrid poplars and appeared to result in more favorable water relations than were found in the intermediate treatment. Hybrid poplar's excellent response to silvicultural treatment and adequate survival, especially at the site in Virginia, may give this species an advantage over the others tested in this experiment for reforesting post-SMCRA reclaimed mined lands previously reclaimed to grasses.

Introduction

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 mandates that all surface mined lands be reclaimed after mining and sets forth criteria for mine operators to follow in carrying out reclamation practices. Unfortunately, many of these criteria can create 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 (*Festuca arundinacea* Schreb.), clover species (*Trifolium* spp.), 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* L.) and northern red oak (*Quercus rubra* L.) 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 also 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 reclaimed 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 1986). Tillage treatments can ameliorate the detrimental effects of compaction. Cleveland and Kjelgren (1994) found that deep tillage (70 cm) through ripping doubled the cross-sectional area of low-impedance soil (<1.4 MPa of resistance). Ashby (1997) found that the mean height of 16 different tree species was significantly greater five years after ripping the 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 1996a). 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, respectively, in the ripped versus the unripped plots. Radial root growth was found to be 89% greater in the ripped plots in the second year.

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* P. Mill. X *Pinus taeda* L.), an inverse relationship between soil pH and tree growth 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 was 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 were largely unavailable to plants (Li and Daniels 1994).

Numerous species of trees have been studied for use in reclamation with varying degrees of success, depending on the site conditions. White pine (*Pinus strobus* L.) has been used extensively to reclaim mined land in the east, although with variable success. For example, one study in southwestern Virginia found good survival (58%) and height growth after (3.8m) after 11 years (Torbert et al. 2000), whereas in a study in southeastern Ohio no white pines survived after three years (Larson et al. 1995). White pine is appealing for use in reclamation due to its ability to grow well on soils of low fertility, which are frequently encountered on reclaimed surface mines.

Several hardwood species have also been tested for use in reclaiming surface mined lands. Gorman and Skousen (2003) found excellent survival (90-100%) of several commercially valuable hardwoods, including red oak, black walnut, black cherry (*Prunus serotina* Ehrh.), yellow-poplar (*Liriodendron tulipifera* L.), and white ash (*Fraxinus americana* L.) on a reclaimed mountaintop removal mine in West Virginia when weed control and tillage were employed. A study in southwestern Virginia reported survival rates of 57% for chestnut oak (*Quercus prinus* L.), 54% for yellow-poplar, and 91% for white ash in plots where weeds were controlled chemically (Torbert et al. 1985). The use of hardwoods in reclamation of surface mined land is logical for restoring native vegetation, as surface mined lands in the Appalachian coalfields are primarily forested prior to mining.

Hybrids of the genus *Populus* have been found to grow well on reclaimed surface mines (McGill et al. 2004, Czapowskyj 1978). These fast-growing species have the potential to provide revenue from timber harvest in as few as 16 years (Davidson 1979), shade out competing vegetation common to reclaimed surface mines due to rapid canopy growth (Ashby 1995), and improve soil quality through organic matter cycling and rapid root growth (Ashby and McCarthy 1990). Additionally, the wood properties of hybrid poplars have been found to exceed industry standards for oriented strand board (Peters et al. 2002), a product that is produced throughout the Appalachian coalfields. Despite these potential benefits, there is a lack of information regarding the response to silvicultural treatment and soil properties on reclaimed surface mined lands.

The purpose of this study was to evaluate the impact of silvicultural treatments designed to ameliorate growth-limiting conditions on survival and growth of a variety of tree species planted on post-SMCRA reclaimed mined land in the Appalachian coal- producing region of the eastern United States.

Methods and Materials

Site Descriptions

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 (Figure 7). The post-mining land use at all sites was hayland pasture, and a dense vegetative cover composed of grasses and legumes existed prior to study establishment.

The site in Lawrence County, Ohio, had topsoil replaced to varying depths, which ranged from 5 to 51 cm across the site. Both the topsoil and the spoil had fine textures and low coarse fragment percentages (Tables 11 and 12). The topsoil had a lower pH and lower electrical conductivity than the spoil, which 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* (Dum.-Cours.) G.Don).

The Nicholas County, West Virginia, site did not have topsoil replaced, and the spoil at this site was derived from shale material throughout the profile. The site had coarse soil textures and high coarse fragment contents (50-60%) throughout the profile (Tables 11 and 12). 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 topsoil returned to the surface throughout the plots, with topsoil thicknesses from 0 to 47 cm. This site also had high coarse fragment percentages; however, the spoil typically had more than the topsoil (Tables 11 and 12). 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 an annual ground cover, while the other two sites were dominated by tall fescue and sweet clover.

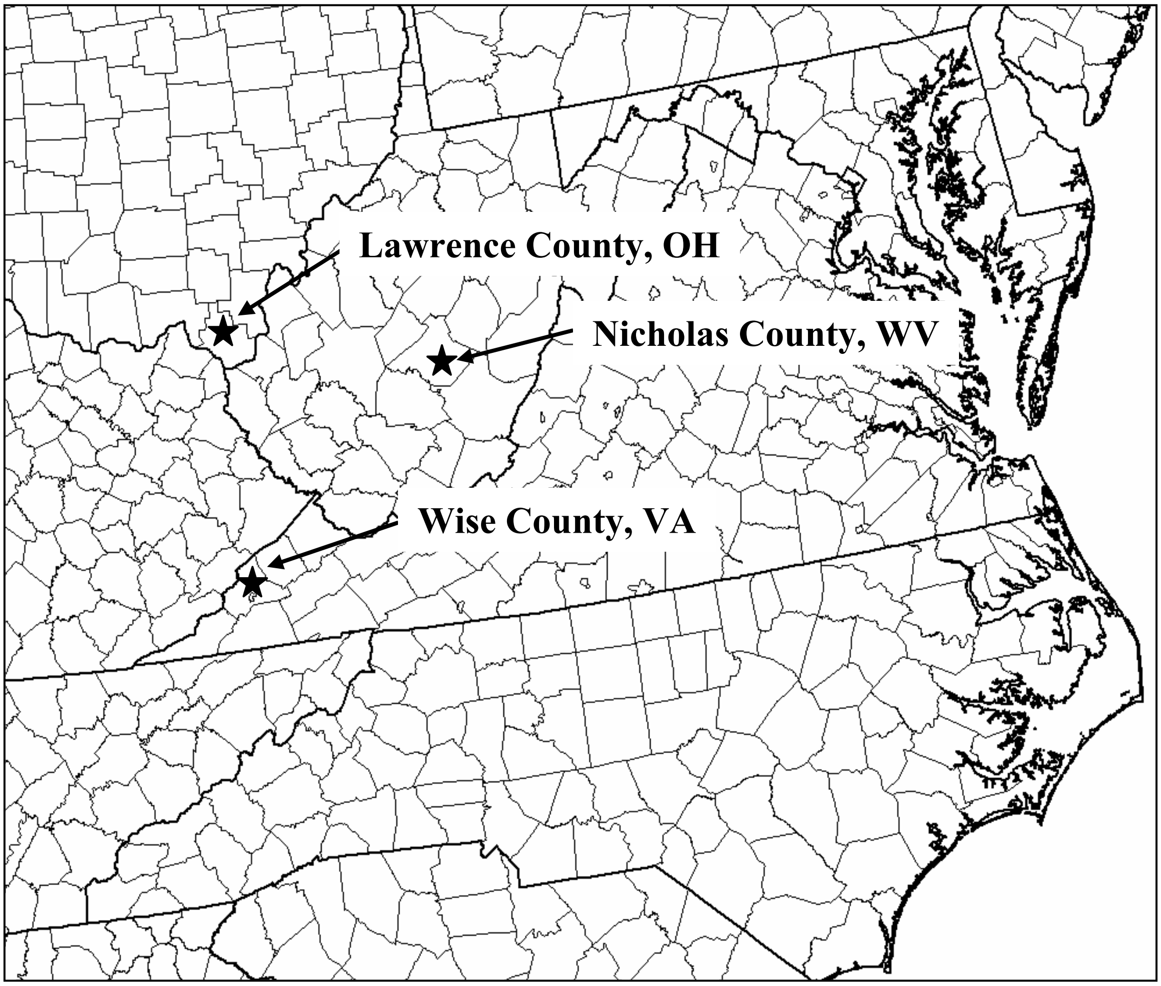


Figure 7. Geographic location of study sites in the Appalachian coalfield region of the eastern United States.

Table 11. **Chemical and physical properties for 0-10 cm depth of the topsoil of study blocks at research sites in Lawrence County, Ohio, and Wise County, Virginia, and of the spoil material in Nicholas County, West Virginia.**

Site	Block	pH	Electrical Conductivity (dSm^{-1})	CEC ($cmol_c$ kg^{-1})	$NaHCO_3$ Extractable P (mg kg^{-1})	Total N (g kg^{-1})	Coarse Fragments (%)				Texture	Bulk Density (g cm^{-3})
							Total	Sandstone	Siltstone	Shale		
OH†	1	4.89	0.06	9.26	10.3	1.25	6.4	14.44	85.56	0.00	L*	1.53
OH†	2	5.19	0.11	7.69	7.69	1.14	6.96	27.22	61.67	0.00	L	1.44
OH†	3	6.05	0.13	9.05	5.38	1.06	9.86	27.22	72.78	0.00	L	1.40
Mean		5.38	0.10	8.67	7.79	1.15	7.74	22.96	73.34	0.00	L	1.46
VA†	1	4.75	0.18	5.46	9.98	0.58	32.36	72.78	15.00	0.00	L	1.48
VA†	2	6.3	0.28	6.57	10.07	0.91	41.06	46.67	31.11	0.00	L	1.87
VA†	3	6.43	0.38	5.21	13.75	0.53	51.65	65.00	35.00	0.00	L/SL	1.76
Mean		5.83	0.28	5.75	11.27	0.67	41.69	61.48	27.04	0.00	L	1.70
WV††	1	5.91	0.21	8.81	20.13	2.78	54.29	9.44	13.89	76.67	SL	1.66
WV††	2	5.72	0.22	8.37	20.81	2.58	55.26	7.22	11.67	81.11	SL	1.71
WV††	3	5.52	0.21	7.85	18.03	2.81	46.21	10.56	15.00	73.33	SL	1.67
Mean		5.72	0.21	8.34	19.66	2.72	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 12. Chemical and physical properties for spoil materials underlying the topsoil of study blocks at research sites in Lawrence County, Ohio, and Wise County, Virginia, and of the 10-30 cm sampling depth of the spoil material in Nicholas County, West Virginia.

Site	Block	pH	Electrical Conductivity (dSm^{-1})	CEC ($cmol_c$ kg^{-1})	$NaHCO_3$ Extractable P ($mg\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Coarse Fragments (%)				Texture	Bulk Density ($g\ cm^{-3}$)**
							Total	Sandstone	Siltstone	Shale		
OH†	1	6.86	0.26	16.21	0	0.48	25.41	18.89	80	1.11	SiCL	1.70
OH†	2	6.15	0.61	13.12	0.84	0.52	18.01	21.67	73.89	0	L	1.73
OH†	3	6.91	0.53	14.08	0.32	0.43	16.36	8.89	91.11	0	SiCL	1.66
Mean		6.64	0.47	14.47	0.39	0.48	19.93	16.48	81.67	0.37	SiCL	1.70
VA†	1	6.77	0.21	6.02	3.38	0.60	50.27	81.43	18.57	0	SL	1.74
VA†	2	7.55	0.28	7.46	2.94	0.87	63.25	20	68.89	0	SL	-
VA†	3	6.37	0.26	4.35	2.78	0.65	56.57	66.25	33.75	0	SL	-
Mean		6.90	0.25	5.94	3.03	0.71	56.70	55.89	40.40	0.00	SL	1.74
WV††	1	6.72	0.1	6.62	7.13	1.20	59.21	10.56	10	67.22	SL	-
WV††	2	6.03	0.12	5.89	5.94	1.01	61.56	6.67	12.22	73.11	SL	-
WV††	3	5.87	0.1	5.85	3.68	1.00	53	12.22	17.78	59	L/SL	-
Mean		6.21	0.11	6.12	5.58	1.07	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 30cm of depth, as this layer was the same material that comprised the topsoil layer.

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

** Spoil bulk densities were not measured in all blocks in VA, and in WV were assumed to be the same as the 0-10cm depths.

Study Design

The study used a 3x3 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 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).

The tree species assemblages used were:

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

All trees were planted at a 2.4 x 3.0 m spacing, giving a final planting density of 1,345 trees ha^{-1}. White pine and hybrid poplar were planted in pure stands, while the mixture of hardwood species varied by site in order to approximate the pre-mining forest condition found in adjacent undisturbed forest (Table 13). In addition to commercial hardwood species, a combination of three nurse tree species were planted to provide early wildlife habitat and to more closely resemble the species diversity found in the native hardwood mixture (Burger and Zipper 2002).

Plots were blocked within each site based on soil properties (Tables III.1 and III.2). 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 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 this application.

Table 13. Species composition and percentage of each species for the mixed hardwood plots at the three study sites.

Species	Percentage		
	Ohio	West Virginia	Virginia
Commercial Hardwoods:			
Northern red oak (*Quercus rubra* L.)	9.6	15.3	10.9
Tulip-poplar (*Liriodendron tulipifera* L.)	9.6	15.3	10.9
Sugar maple (*Acer saccharum* L.)	9.6	15.3	10.9
Black oak (*Q. velutina* Lam.)	9.6	---	---
Chestnut oak (*Q. prinus* L.)	19.2	---	---
Bitternut hickory (*Carya cordiformis* [Wengenh.] K.Koch)	9.6	---	10.9
Scarlet oak (*Q. coccinea* Muenchh.)	9.6	---	---
Red maple (*A. rubrum* L.)	---	15.3	---
White ash (*Fraxinus americana* L.)	---	15.3	10.9
White oak (*Q. alba* L.)	---	---	21.9
Shrub Species:			
Redbud (*Cercis canadensis* L.)	7.7	7.8	7.8
Flowering dogwood (*Cornus florida* L.)	7.7	7.8	7.8
Wash. Hawthorn (*Cretaegus phaenopyrum*)	7.7	7.8	7.8

The tillage treatment employed was ripping. The equipment used to install 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 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 a micronutrient mix were applied around the base of each seedling at the following rates: 91 kg ha^{-1} of muriate of potash that added 46.8 kg ha^{-1} K; and 20 kg ha^{-1} of a micronutrient mix that 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.

Soil Sampling and Analysis

Soil samples were collected from all plots prior to installing any of the silvicultural treatments. Five samples were systematically collected from each plot, four of which were collected at 11 m from each plot corner in the direction of the plot center, and the fifth at the center of each plot. Surface soil samples (0-10 cm depth) were collected at all plots. If topsoil was present as a cap overlying spoil material, an additional sample of the spoil material underneath the topsoil was collected. If there was no difference in the topsoil material present, the 10-30 cm depth was sampled in addition to the surface soil sample. Bulk density of the surface soil was measured at each plot using the excavation method (Blake and Hartge, 1986). Bulk density of the spoil material was measured when it was within 30cm of the soil surface.

All samples were returned to the lab, dried at 50°C for one week, weighed, and sieved to pass a 2mm screen to separate coarse fragments. Coarse fragments were washed with water to remove any fine soil particles, dried, and weighed to determine coarse fragment percentage by weight. Additionally, the percentages of sandstone, siltstone, and shale rock types of each sample were visually estimated as a percentage of the total coarse fragment content.

Soil pH and electrical conductivity were measured on all samples using an AGRI-METER (MYRON L Company) and a 1:2 soil:water mixture. Total soil C and N were determined using an Elementar varioMAX CNS analyzer (Mt. Laurel, NJ). All other laboratory analyses were made on a composite sample of all five samples collected in each plot. All exchangeable cations were extracted with a 1M NH_4OAc solution (USDA, 1996). To determine cation exchange capacity (CEC), exchangeable Al was extracted with 1N KCl and determined titrimetrically (McLean, 1965). The effective CEC was calculated as the sum of NH_4Oac extractable Ca, Mg, K, and NA, and KCl extractable Al (Sumner and Miller, 1996). Particle size analysis was determined using the pipet method (Gee and Bauer, 1986).

Survival and Growth Data Collection

A 20 x 20m measurement plot was established in the center of each 0.25-ha treatment plot, within which all trees were assessed for survival, height growth, and ground line diameter growth. Initial height and ground line diameter were assessed in May 2004 shortly after bud break. First-year survival and growth were determined following measurement in late August of 2004.

Hybrid Poplar Biomass Measurements. Destructive sampling was used to determine above- and belowground biomass allocation in the hybrid poplar plots at the site in Nicholas County, West Virginia. Three randomly selected trees located outside the interior measurement plot were harvested in each plot in mid-September for plant biomass determinations. Trees were cut off at the ground line 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 1^{o} to 2°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 1mm 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). Samples were dry ashed at 500°C for 24 hours and digested with 6*N* HCl. A SpectroFlame Modula Tabletop inductively coupled plasma spectrophotometer was used 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. Water potential of the hybrid poplar seedlings at the site in Nicholas County, West Virginia, was measured using a pressure chamber (PMS Instrument Co. Model 1000 Corvallis, OR) for four consecutive rain-free days (August 16-19, 2004). The initial measurement was made the day after approximately 0.46cm of rain fell in the previous 24 hours and 1.85cm had fallen in the previous 96 hours in nearby Beckley, West Virginia. 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.

On the same day on which the plant water stress was measured, soil samples of the surface 30 cm were collected 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 (August 17-19, 2004).

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 3x3x3 factorial random complete block design having three species assemblages, three sites, and three silvicultural treatments (Table 14). Tree volume was calculated as diameter squared multiplied by tree height. Results for total diameter and total height are presented in Appendix A.

A separate analysis of variance was done for each site if interaction terms containing site were significant in the overall model. Likewise, if the species by treatment interaction was significant after analyzing by site, analysis of variance was done by species and by treatment to perform mean separation procedures. Seedling survival was expressed as a percentage of the trees planted, and these data were transformed using the arcsine transformation. The growth measures that showed non-normality or heteroscedasticity and failed to meet the assumptions of the analysis of variance were transformed using the natural log function prior to analysis of variance and subsequent mean separation procedures (Gomez and Gomez 1984).

Following the overall analysis, separate analyses were performed on each of the groups of hardwoods that were planted (Table 13). The same species were included in the HW1 and shrub groups at each site, while the species in 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 and are presented in Appendix B.

Table 14. Analysis of variance results for survival and growth parameters for research sites in Lawrence County, Ohio, Nicholas County, West Virginia, and Wise County, Virginia.

Site and Source	Degrees of Freedom	Variable (Pr > F)				
		Survival	Total Height	Height Growth	Diameter Growth	Volume Growth
All Sites:						
Block	2	0.0057	0.0231	0.0076	0.0812	0.8254
Site	2	<0.0001	0.0005	<0.0001	0.0004	<0.0001
Treatment	2	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Site*Treatment	4	0.0097	0.0535	0.0003	0.0036	<0.0001
Species	2	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Site*Species	4	0.0332	0.0021	<0.0001	0.0009	<0.0001
Treatment*Species	4	0.3567	<0.0001	<0.0001	<0.0001	<0.0001
Site*Treatment*Species	8	0.3367	0.1214	<0.0001	0.1146	<0.0001
Model	28	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Error*	52(51)					
Total*	80(79)					
Ohio:						
Block	2	0.1730	0.0432	0.0354	0.1340	0.0881
Treatment	2	0.0005	0.7589	0.5026	0.6628	0.3674
Species	2	0.0197	0.0116	<0.0001	<0.0001	0.0036
Treatment*Species	4	0.3072	0.7321	0.6724	0.1790	0.3126
Model	10	0.0038	0.0640	<0.0001	<0.0001	0.0238
Error*	16 (15)					
Total*	26 (25)					
West Virginia:						
Block	2	0.4873	0.0614	0.0180	0.0713	0.0723
Treatment	2	<0.0001	<0.0001	<0.0001	<0.0001	0.0007
Species	2	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Treatment*Species	4	0.1384	<0.0001	<0.0001	0.0003	0.0026
Model	10	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Error*	16					
Total*	26					
Virginia:						
Block	2	0.0164	0.5926	0.6402	0.9342	0.8400
Treatment	2	0.3422	<0.0001	<0.0001	<0.0001	<0.0001
Species	2	0.0006	<0.0001	<0.0001	<0.0001	<0.0001
Treatment*Species	4	0.4849	<0.0001	<0.0001	<0.0001	<0.0001
Model	10	0.0060	<0.0001	<0.0001	<0.0001	<0.0001
Error*	16					
Total*	26					

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

Hybrid poplar biomass data were analyzed for differences among the silvicultural treatments. 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 prior to analysis (Gomez and Gomez 1984). Similarly, nutrient concentration data from tissue samples were analyzed for differences among silvicultural treatments by tissue type. Non-normal and heteroscedastic data were transformed using the inverse function prior to analysis of variance. Data on soil moisture content and plant water potential were analyzed as a split-plot design with silvicultural treatment as the whole plot and date as the split plots (Gomez and Gomez 1984).

Mean separation was conducted 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

The site by treatment and site by species group interaction terms were significant for all response variables measured, with the exception of the site by treatment interaction for total height, which had a p-value of 0.0535 (Table 14). Therefore, because each site was established as a random complete block experiment with three replications, the results will be presented separately for each location. This enables us to focus on the interaction between species group and silvicultural treatment at each of the three study locations, which we felt were the more important aspects of the results.

<u>Survival</u>

The species by treatment interaction was not significant for any site (Table 14). Treatment main effects in Ohio (OH) show that 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), which had similar survival rates at 49% and 51%, respectively (Table 15). At the West Virginia (WV) site, survival in WC+T was significantly higher than in either of the other treatments. Silvicultural treatments had no effect on survival in Virginia (VA). The mean survival across species and silvicultural treatments was notably higher in VA than at the other sites, though site means were not separated.

The hardwood species group had the highest mean survival at all sites (Table 15) and the rate was significantly higher than that of all other species at all three sites except for hybrid poplar in OH. White pine generally had the lowest survival at all three locations, ranging from 27% to 58%. Survival of hybrid poplar was low in OH and WV, at 37 and 41%, respectively, but as with the other species groups, was higher in VA, averaging 72% (Table 15).

Table 15. Survival percentage for three species groups planted on post-SMCRA reclaimed surface mined lands in Lawrence County, Ohio, Nicholas County, West Virginia, and Wise County, Virginia, as affected by silvicultural treatments.

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 $P<0.05$.

<u>Total Height</u>

At the site in OH, there were no significant differences among species or treatments, as shown by the insignificant model term for this site (Table 14). Total height ranged from 29.7 cm in WC to 33.4 cm in WC+T to 37.6 cm in WC+T+F (Table 16). Total heights of hybrid poplar, white pine, and hardwoods were 45.6 cm, 23.3 cm, and 30.1 cm for these species, respectively.

In WV, there was a significant interaction between species groups and silvicultural treatments for total height (Table 14). Hybrid poplar was the shortest (22.4 cm) in WC compared to hardwood (32.4 cm) and white pine (25.2 cm). In contrast, hybrid poplar was taller in both WC+T (60.2 cm) and WC+T+F (57.6 cm) compared to hardwood and white pine in comparable treatments, where total heights ranged from 36.5 cm to 38.6 cm for hardwood and from 22.9 cm to 28.2 cm for white pine.

There was also a significant interaction between species groups and silvicultural treatment in VA (Table 14). There was no difference among the silvicultural treatments for hardwood or white pine, where total height ranged from 22.6 cm to 25.0 cm for white pine and from 33.1 cm to 40.6 cm for hardwood. However, hybrid poplar was significantly taller in WC+T (65.4 cm) and WC+T+F (126.6 cm) than both hardwood and white pine. Hybrid poplar was significantly taller than white pine in WC, with average total heights of 40.9 cm versus 23.5 cm, respectively, but it was not taller than hardwood (33.1cm).

Table 16. Total tree height (cm) for three species groups planted on post-SMCRA reclaimed surface mined lands in Lawrence County, Ohio, Nicholas County, West Virginia, and Wise County, Virginia, as affected by silvicultural treatments.

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 A*	45.6 A	23.3 A	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 $P<0.05$.

Height Growth

Analysis by site revealed that the species by treatment interaction was not significant in OH (Table 14) and that there were no treatment effects at this site (Table 17). Height growth of hybrid poplar was several times higher than hardwood and white pine in OH (45.6 cm versus -2.3 cm and 6.0 cm, respectively). Seedlings in the hardwood group had died back; thus, they were shorter at the end of the growing season than at the start; hence, negative height growth was observed for all treatments at this site for the hardwood group (Table 17).

In WV, the species by silvicultural treatment interaction was significant (Table 14), and height growth for hardwood was greater in WC+T+F than in WC (Table 17). Height growth of hybrid poplar in WC (22.4 cm) was significantly less than in both of the other treatments (60.2 cm for WC+T and 57.6 cm for WC+T+F). Hybrid poplar at this site grew significantly more than hardwood and white pine in all treatments. In the WC treatment, white pine also had significantly more height growth than hardwood (5.5 cm versus -1.4 cm).

In VA, there was also significant treatment by species interaction (Table 14). Height growth was greater in WC+T+F than in the other treatments for both hardwood and hybrid poplar (Table 17). The differences in height growth were more pronounced for hybrid poplar (126.6 cm in WC+T+F versus 40.9 cm and 65.4 cm for WC and WC+T, respectively) (Table 17).

Table 17. Average height growth (cm) for three species groups planted on post-SMCRA reclaimed surface mined lands in Lawrence County, Ohio, Nicholas County, West Virginia, and Wise County, Virginia, as affected by silvicultural treatments.

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 Ay	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 $P<0.05$.

Diameter Growth

There was no interaction between species and silvicultural treatment (Table 14), nor were there any silvicultural treatment effects on diameter growth at the OH site (Table 18). However, diameter growth of hybrid poplar (5.7 mm) was significantly greater than diameter growth of hardwood or white pine, which both averaged 0.7 mm.

Table 18. Average diameter growth (mm) for three species groups planted on post-SMCRA reclaimed surface mined lands in Lawrence County, Ohio, Nicholas County, West Virginia, and Wise County, Virginia, as affected by silvicultural treatments.

Site and Treatment	Species Group HW	HP	WP	Treatment Mean
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.

A significant interaction between species group and silvicultural treatment occurred in WV (Table 14). At this site, diameter growth of hybrid poplar was greater than diameter growth of either the hardwood or white pine species groups in all silvicultural treatments (Table 18). Diameter growth of hybrid poplar also responded to silvicultural treatment, increasing from 3.1 mm in WC to 7.0 mm in WC+T to 7.5 mm in WC+T+F. In contrast, diameter growth of both hardwood and white pine did not respond to silvicultural treatment. Diameter growth of hardwood was 0.9 mm in WC and only 1.8 mm in WC+T+F, while diameter growth of white pine was only 0.5 mm and 0.9 mm in these two treatments respectively.

A similar pattern among species and treatments occurred for diameter growth in VA (Table 18), which also had a significant species by silvicultural treatment interaction (Table 14). Diameter growth of hybrid poplar was greater than the diameter growth of both hardwood and white pine in all treatments. As in WV, diameter growth of hardwood and white pine was not affected by silvicultural treatment, ranging only from 0.8 mm to 2.1 mm and from 0.6 mm to 0.7 mm in the two species, respectively. Diameter growth of the hybrid poplar was significantly affected by silvicultural treatment increasing from 4.9 mm in WC to 7.0 mm in WC+T to 13.9 mm in WC+T+F.

Volume Growth

The interaction between species groups and silvicultural treatments was not significant at the study site in OH for volume growth (Table 14). Volume growth of hybrid poplar (30.7 cm^3) was significantly greater than the volume growth of either hardwood (2.1 cm^3) or white pine (2.3 cm^3), which were not different from one another (Figure 8a). There were no significant effects of silvicultural treatment on volume growth in OH, although volume growth more than tripled from 6.1 cm^3 in the WC treatment to 21.0 cm^3 in the WC+T+F treatment at this site (Figure 8b).

In WV, there was an interaction between species group and silvicultural treatment (Table 14). The volume growth response was larger in hybrid poplar, which increased from 2.8 cm^3 to 43.3 cm^3, than in WP, which increased from 2.3 cm^3 to 4.2 cm^3 (Figure 8c). As a result of the large increase in the WC+T treatment, volume growth in hybrid poplar was significantly greater than volume growth in either hardwood or white pine for this treatment (Figure 6d). There was no additional increase in volume growth in WV in the WC+T+F treatment for either hybrid poplar or white pine. Silvicultural treatment had no impact on the growth of the hardwood species group in WV. Volume growth in the WC treatment was not different among the species groups, which averaged 2.3 cm^3 in both hardwood and white pine and 2.8 cm^3 in hybrid poplar (Figure 8d). Volume growth in both hybrid poplar and white pine increased as silvicultural intensity increased from WC to WC+T.

At the site in VA, there was also a significant species by silvicultural treatment interaction for volume growth (Table 14). Volume growth of hybrid poplar (15.6 cm^3) was greater than volume growth of either hardwood (4.0 cm^3) or WP (2.8 cm^3) in the WC treatment (Figure 8e). Volume growth in both hardwood and hybrid poplar increased in response to increasing silvicultural input. In the WC+T+F treatment, volume growth increased to 16.5 cm^3 for hardwood and 312.1 cm^3 for hybrid poplar (Figure 8f). In contrast, volume growth in white pine was not affected by silvicultural treatment. Volume growth of hybrid poplar remained significantly greater than volume growth of hardwood or white pine as silvicultural intensity increased.

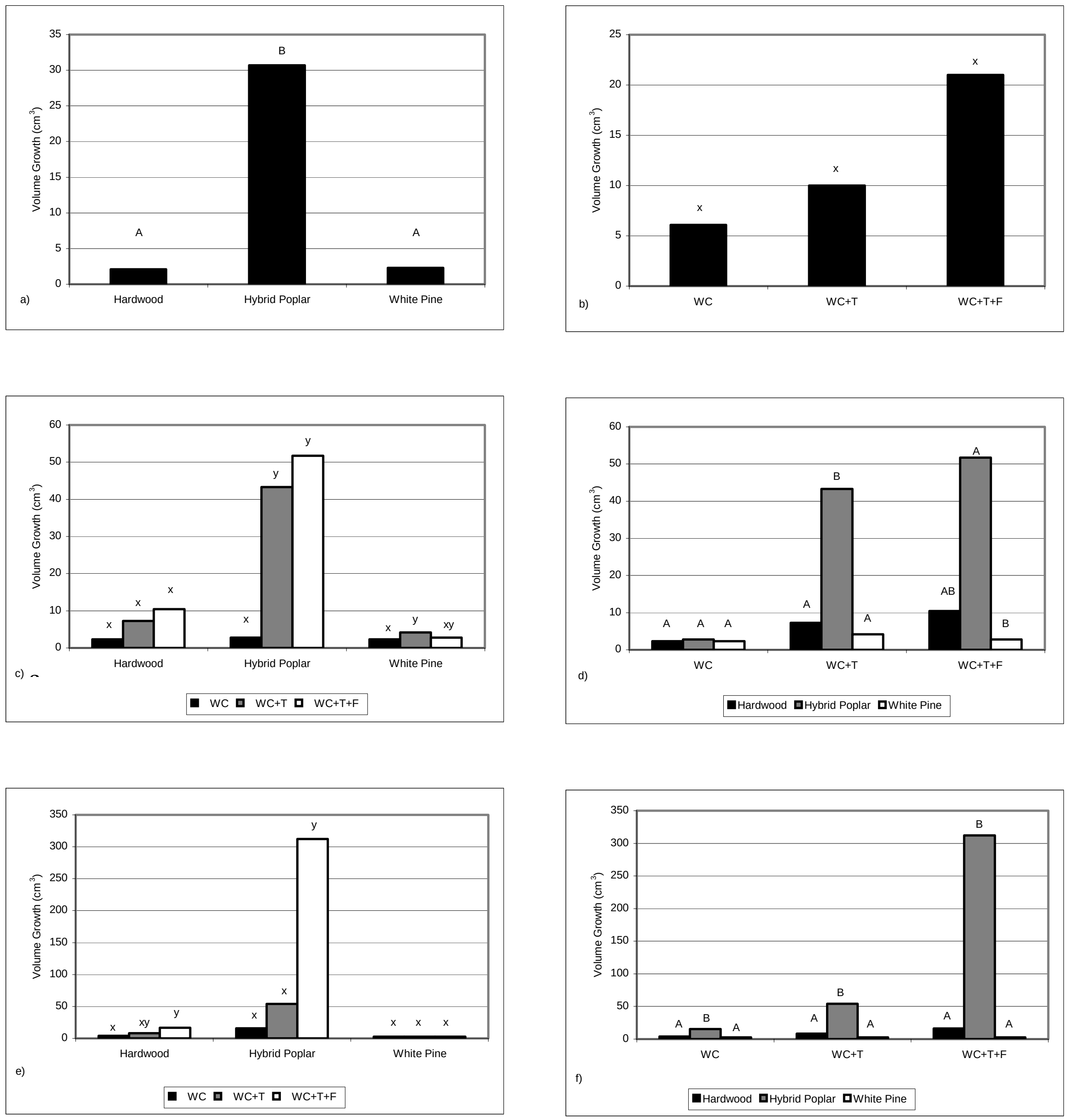


Figure 8. Average volume growth (cm^3) for three species groups planted on post-SMCRA reclaimed surface mined lands in: (a-b) Lawrence County, Ohio (main effects only), (c-d) Nicholas County, West Virginia, and (e-f) Wise County, Virginia, as affected by silvicultural treatments.

Hybrid Poplar Biomass

Total plant biomass of hybrid poplar at the site in WV increased significantly with the intensity of silvicultural input (*P* = 0.0002) (Figure 9). Total plant biomass increased from 15.7 g in WC to 45.9 g in WC+T to 104.5 g in WC+T+F. Root, stem, and foliage biomass also increased significantly with the level of silvicultural intensity (Figure 9). 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 than 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).

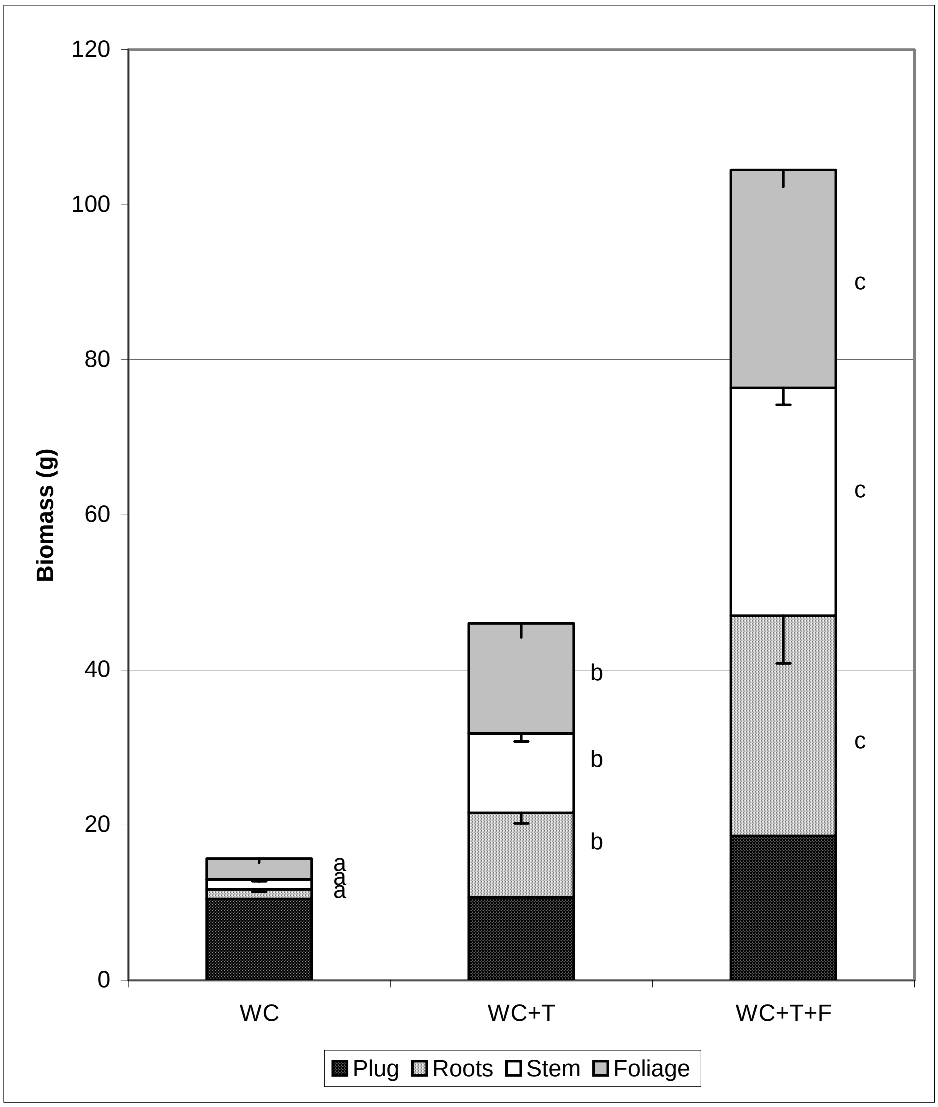


Figure 9. Hybrid poplar biomass by plant part and treatment for the study site in Nicholas County, West Virginia. Letters beside segments indicate significant differences at the P < 0.05 level among treatments for that particular segment.

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 19). Foliar N in the WC+T+F treatment was 32.58 g kg^{-1} compared to 24.16 g kg^{-1} and 26.09 g kg^{-1} in the WC and WC+T treatments, respectively. Foliar K in the WC+T+F (17.28 g kg^{-1}) treatment was only significantly higher than in the WC treatment (14.19 g kg^{-1}). There were no differences among silvicultural treatments for any other nutrients.

For stem tissue, N concentration in the WC+T+F treatment (8.33 g kg^{-1}) was significantly greater than in the WC treatment (7.16 g kg^{-1}) (Table 19). No other significant differences were found for nutrient concentrations in stem tissue. The concentration of N in the root tissue was also significantly higher for the WC+T+F treatment compared to the WC+T treatment (11.26 g kg^{-1} versus 7.88 g kg^{-1}). This was the only significant difference in root tissue nutrient concentrations.

Hybrid Poplar Moisture Stress

There was a statistically significant decrease in soil moisture over the three-day measurement period (Table 20). Soil moisture decreased from 0.15kg kg^{-1} on August 17 to 0.12 kg kg^{-1} on August 19. Soil moisture content in the WC treatment was significantly greater than moisture content in the WC+T treatment only.

There were no differences in leaf water potential among the three treatments on Aug. 16, when leaf water potentials ranged from -1.17 MPa in the WC+T+F treatment to -1.32 MPa in the WC+T treatment to -1.30 MPa in the WC treatment. Leaf water potential decreased from Aug. 16 to Aug. 17 in all three treatments, with the largest decrease occurring in the WC+T+F treatment. On Aug. 17, leaf water potential in the WC+T+F treatment declined to -1.97 MPa, which was significantly less than leaf water potential in the WC+T treatment (-1.72 MPa) or the WC treatment (-1.66 MPa). Leaf water potential stabilized in the WC+T+F treatment, but continued to decline over time in the other two treatments, dropping to -1.89 MPa in the WC treatment and -1.90 MPa in the WC+T treatment on Aug. 18. Leaf water potential increased on Aug. 19 in the WC and the WC+T+F treatments, but continued to decline rapidly in the WC+T treatment, where it reached -2.30 MPa, which was significantly different than leaf water potential in the WC treatment.

Table 19. Macro- and micronutrient concentrations by tissue type and silvicultural treatment for hybrid poplar growing at the research site in Nicholas County, West Virginia.

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					

* x,y,z - For a given plant part, values within columns with the same letter are not significantly different at $P<0.5$.

Table 20. Gravimetric soil moisture and water potential for hybrid poplar growing at the research site in Nicholas County, West Virginia, over four rain-free days by silvicultural treatment.

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<0.5.

Discussion

Site Effects

Replaced topsoil has been shown to perform better as a growth medium for trees (Larson 1995, Kost et al. 1998a) and to have more favorable soil physical and chemical properties (Schoenholtz et al. 1992) compared to cast overburden. Despite having topsoil replaced over the entire site, both survival and growth were lower in OH than at either of the other sites. Topsoil at this site had a loam texture, but was underlain by a compacted (1.70 g cm^{3}) siltstone-derived spoil, which had a silty clay loam texture and no soil structure. This combination of physical properties associated with the spoil at this site has been shown to perch water (Kozlowski 1999). Poor drainage was further evidenced by areas of standing water and hydrophytic vegetation that were frequently found across the site. The underlying spoil materials also had unfavorable chemical properties for good survival and growth. For example, both pH and electrical conductivity (EC), at levels of 6.9 and 0.47 dS m^{-1}, respectively, are within or near the ranges reported by Torbert and coworkers (1994) as negatively affecting tree growth (pH > 6.0 and EC > 0.50 dS m^{-1}).

Another explanation of the poor survival and growth of all species in OH could be that although weed control was carried out uniformly at all sites, the site in OH was observed to have the densest cover of weeds throughout the growing season, hence excessive competition for light water and nutrients could have decreased survival and growth at this site (Nyland 2002).

The site in WV did not have topsoil replaced. The shale-derived overburden at this site proved to be better than the replaced topsoil and underlying siltstone-derived spoil in OH for the treatments and species used. Although bulk density at this site (1.68 g cm^{-3}) was similar to that in OH, the WV site likely had better water relations due to sandy loam textures throughout the profile and coarse fragment percentages in excess of 50%. Compaction was evident, however, as survival increased significantly as a result of tillage, whereas in OH and VA survival was not significantly affected by tillage. Further evidence that this site was compacted is indicated by the fact that WC+T tripled the height growth and total plant biomass of hybrid poplar compared to that found in the WC treatment at this site. Another explanation of better survival and growth in WV when compared to OH would be that the inherent soil N and P levels were nearly double those found at any of the other sites. Kost and coworkers (1998a) found that improving soil N status through fertilization significantly increased the survival of silver maple and the height growth of green ash after seven years.

The oxidized sandstone spoil that was characteristic of the site in VA proved to be superior to the soils at the other sites in terms of potential for good survival and growth for the species and treatments used. Survival across species and treatments at this site averaged 72%, compared with 54% and 38% for WV and OH, respectively. Similar trends were evident for all growth measures. This oxidized sandstone material has been shown to be a superior growth medium for trees (Torbert et al. 1990, Torbert et al. 1991). Reasons cited by these authors for using this specific material include chemical properties similar to the native soils on which these trees grow in comparison to unoxidized materials such as lower pH and lower soluble salt levels. This material also has improved physical properties compared to material derived from finer textured rock types. Oxidized sandstone has also been shown to weather to soil-sized particles faster than unoxidized siltstone spoils (Hearing et al. 1993), thereby increasing water holding capacity and nutrient availability at a more rapid rate than would be found in the other materials.

Silvicultural Treatment Effects

Weed control on reclaimed surface mines has been shown by numerous researchers to be necessary for adequate establishment of forests. For example, on a surface mine in Indiana, Andersen and coworkers (1989) found that black walnut and northern red oak survival increased from 4% and 1% respectively with no ground cover control to 66% and 48% respectively with ground cover control. Torbert et al. (2000) found that after five years, average tree height growth for three pine species was 66 cm greater in plots where ground cover was controlled than in plots where it was not. The same study reported that after 11 years, the difference in average tree height increased to 158 cm, which shows that ground cover control has effects lasting for more than a few years after the trees become established.

Although weed control is necessary, this treatment alone may not provide adequate survival or growth if unfavorable soil physical or chemical properties exist. For example, compacted layers are common on surface mines (Daniels and Zipper 1997, Bussler et al. 1984) despite the fact that many of these mine soils are over 50% coarse fragments. In our study, tillage to alleviate soil compaction coupled with weed control (WC+T) generally resulted in better survival and growth compared with the WC treatment. This was especially true in WV, where compaction likely limited tree survival and growth. In VA and in OH there was no response to WC+T, and in the case of white pine in OH, WC+T decreased survival considerably, though this decrease was not significant.

Tillage in addition to weed control at the WV site significantly increased the survival of all species and nearly tripled height growth and total plant biomass of hybrid poplar. Tillage has been shown to ameliorate the poor physical properties that are common on reclaimed surface mined land. The net effect of ripping mine soil is a lower bulk density, which translates into lower soil strength, better aeration, and a better rooting environment for trees. Cleveland and Kjelgren (1994) found that deep tilling a mine soil to a depth of 0.7 m with a vibrating shank doubled the cross-sectional area of low- impedance soil from 0.29 to 0.58 m^2. Tillage has also been shown to improve survival and growth of trees on reclaimed mined land. For instance, Ashby (1997) found that the mean height of 16 different tree species combined as well as all species individually (with the exception of yellow-poplar) in all five years of the study showed significant increases in height growth as a result of ripping the soil to a depth of 1.2 m. 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.

One explanation for the failure of the tillage treatment to increase survival or growth consistently, despite the high bulk density structureless spoils in OH, could be that tillage would have brought the roots into contact with the spoil, which would have been detrimental to survival and growth in terms of the chemical properties associated with the spoil. The tillage treatment was also carried out at this site when the soils were very wet. Given that the soils at this site are fine textured, ripping them when soil moisture content was high would have simply sliced through the soil rather than shatter it (Unger and Cassel 1991). It is likely that the lack of response to tillage in OH was that it failed to reduce the bulk density and improve aeration through shattering at this site.

Fertilization in addition to weed control and tillage provided mixed results in this study. One trend that was clearly evident with this treatment was a reduction in survival. This reduction was most pronounced in WV and OH, where WC+T+F reduced survival to levels significantly below that found in WC+T in WV, and below both WC and WC+T in OH. Two hypotheses exist for decreased survival in the WC+T+F treatment: (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. In OH, a combination of these two hypotheses would be more likely, as 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. The diammonium phosphate and muriate of potash fertilizers used in this treatment pose moderate and high salt hazards, respectively (Brady and Weil 2002). In a study of aspen establishment and growth, van den Driessche and coworkers (2003) found that fertilization without irrigation led to a 17% decrease in survival compared with the control. These authors cited moisture stress due to the use of soluble fertilizers as the reason for the decrease in survival. For a detailed review of salt effects in forest trees, see Allen and coworkers (1994). Additionally, the spoils at this site, though covered with topsoil material, were still generally within the rooting zone of the trees. This would be especially true in WC+T and WC+T+F, where tillage brought this material closer to the surface. The spoils at this site were found to be near alkaline, with soluble salt levels near the range of 0.50 dS m^{-1}, which was found to be near reported ranges where tree growth was negatively affected (Torbert et al. 1994). Electrical conductivity in both the surface and subsurface layers at the sites in WV and VA had values less than this same reported range (0.50 dS m^{-1}).

The growth of hardwood species in WV and both hardwood and hybrid poplar in VA increased as a result of fertilization. Some hardwood species have been shown to be more tolerant of alkaline soils with relatively high levels of soluble salts compared to white pine, and therefore would not be as affected by fertilization-induced salt effects. Kost and coworkers (1998a) found that on cast overburden with high levels of soluble salts, green ash (*Fraxinus* *pennsylvanica* Marsh.) had 91% survival after seven years, whereas white pine survival in the same material was only 1%. Looking at the hybrid poplar response, WC+T+F in VA produced the largest response to treatment of all combinations of sites, treatments, and species used in this study, as first-year height growth averaged 126.6 cm with a survival rate of 67%. As spoils from the same geologic formation have been shown to be inherently low in plant-available N (Li and Daniels, 1994) and have high P-fixing capacities (Howard et al., 1988) this response to fertilization at this site is logical. Additionally, better weed control on the younger spoils in VA, where the seed pool for competing vegetation may have been smaller, could have resulted in better survival and growth at this site due to less competition for the added soil nutrients. Similar results were found by McGill and coworkers (2004) for hybrid poplar on surface mines in central WV. In their study of plots receiving similar treatments to the WC+T+F treatment in our study, the same hybrid poplar clone averaged 1.0 m in total height after one year, and average first-year survival for this same species across all three sites was found to be 79%, compared to 72% for the WC+T+F treatment in our study.

<u>Species Effects</u>

Both hardwood and white pine grew little over the course of the first year. White pine is known for its slow growth during its initial years of establishment (Wendel and Smith 1990, Lancaster and Leak 1978). Chaney and coworkers (1995) found that red oak and black walnut grew at a rate of 10 cm yr^{-1} after 12 years on reclaimed mined land where weeds had been controlled chemically, which, despite being greater than the highest growth rate for hardwoods in this study (7.9 cm), is still slow in comparison to hybrid poplar. Hardwoods, however, had survival rates (60% to 94% in WC and WC+T) that were higher than those observed for white pine, which indicate that if weed control can be continued, an adequately stocked stand of hardwood trees has the potential to develop. The white pine survival rates observed (27% in OH, 41% in WV, and 58% in VA across treatments) are low enough that even if weed control were continued, the final stand would likely be understocked without replanting. Several cases of good hardwood survival have been reported. On a site in northern West Virginia, red oak, black cherry, black walnut, white ash, and yellow-poplar were found to have excellent survival (95% to 100% after 1 year) where treated with ground cover control through mowing and tillage through ripping (Gorman and Skousen 2003). McGill and coworkers (2004) found excellent survival (> 90%) for the two hardwood species used (white ash and black cherry), whereas low survival was found for white pine (48%) at the one site at which this species was planted.

Growth of hybrid poplar was superior to that of any other species assemblage tested at any level of silvicultural treatment at all sites. There was a large response to WC+T+F for hybrid poplar in VA, where total stem volumes averaged 312.1 cm^3 and total heights averaged 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) as was the case in VA, where spoils from the same geologic formation have been shown to be inherently low in plant-available N (Li and Daniels 1994) and have high P-fixing capacities (Howard et al. 1988).

The evaluation of hybrid poplar biomass, foliar nutrition, and water relations at the WV site revealed that this species responded well to silvicultural treatment. At this site, hybrid poplar had significantly higher root, stem, foliage, and total plant biomass as silvicultural intensity levels increased from WC to WC+T to WC+T+F. In terms of N, P, and K nutrient levels in hybrid poplar foliage, Stanturf and coworkers (2001) recommend 2% to 3% foliar N as a critical level below which fertilization should be considered and noted that growth increases are common above this range. Our results show that this level was maintained in all treatments, with the level of the WC+T+F treatment exceeding the previously mentioned range (approximately 3.3%). These same authors recommended foliar N to foliar P and foliar K ratios of 100:11 and 100:48 for these elements, respectively. Foliar P failed to meet this level in all treatments, though the concentration was significantly higher in the WC+T+F treatment compared to the other treatments, while foliar K exceeded these levels in all treatments and was highest in WC+T+F. The WC+T+F treatment appeared to improve water relations compared to WC+T near the end of the growing season as evidenced by the more favorable leaf water potential (-1.78 MPa) at the end of a four-day period without measurable precipitation compared to the WC+T treatment (-2.30 MPa). Harvey and van den Driessche (1997) found that N fertilization alone decreased drought resistance in *Populus trichocarpa* Torr. & Gray, but fertilization with P alone increased drought resistance. They suggest that fertilization with N and P, as was used in our study, may allow good growth without leading to poor water relations.

Conclusions

Successful reforestation of surface mined land that has been reclaimed to grasses involves selecting sites with suitable soil characteristics for good establishment and growth of trees. Soil conditions can be altered through silvicultural treatments to ameliorate certain conditions that will limit tree establishment and growth on these lands. The results of our investigation show the importance of recognizing the interactions among site conditions, silvicultural treatments, and tree species, as there were numerous interactions among these factors that ranged from reforestation failure to success. Several conclusions can be drawn from the results of this investigation, including:

1. Sites with sandstone-derived topsoil as a rooting medium would seem to be very suitable for tree survival and growth, while shale-derived spoils appear to be less suitable with the treatments and species used. For fine-textured topsoils in conjunction with siltstone-derived alkaline spoils, other treatments and/or species may be needed to ensure good establishment and growth of forest stands.
2. Weed control plus tillage may be the optimum treatment for establishment of hardwoods and white pine, as any increased growth resulting from the fertilization treatment applied in this study may not offset the decreased survival that accompanied the fertilization.
3. White pine and hardwood species grew little over the course of the first growing season as mean heights ranged from 25-40 cm for hardwoods and from 20-30 cm for white pine. Continued weed control will be needed to ensure the trees do not succumb to the competing vegetation.
4. 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.
5. Hybrid poplar appears to have good potential for reverting post-SMCRA reclaimed mined lands that currently support grasses back to forests, as this species had good growth with 50-65 cm of height growth in 1 year in WC+T at all sites and excellent growth in WC+T+F in VA (126.6 cm). 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.

6. Though height and diameter growth were not statistically different for hybrid poplar in 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, and improved water relations compared to the WC+T treatment.

References

Allen, J.A., J.L. Chambers, and M. Stine. 1994. Prospects for increasing the salt tolerance of forest trees: a review. *Tree Physiology*. 14:843-853.

Andersen, C.P., B.H. Bussler, W.R. Chaney, P.O. Pope, and W.R. Byrnes. 1989. Concurrent establishment of ground cover and hardwood trees on reclaimed mined land and unmined reference sites. *Forest Ecology and Management.* 28:81-99.

Andrews, J.A., Johnson, J.E., Torbert, J.L., Burger, J.A., and D.L. Kelting. 1998. Minesoil and site properties associated with the early height growth of eastern white pine. *Journal of Environmental Quality.* 27:192-199.

Ashby, W.C. 1998. Reclamation with trees pre- and post-SMCRA in southern Illinois. *International Journal of Surface Mining and Reclamation.* 12(3):117-121.

Ashby, W.C. 1997. Soil ripping and herbicides enhance tree and shrub restoration on stripmines. *Restoration Ecology.* 5(2):169-177.

Ashby, W.C. 1996a. Red oak and black walnut growth increased with minesoil ripping. *International Journal of Surface Mining and Reclamation.* 10(3):113-116.

Ashby, W.C. 1996b. Growth of hardwoods and conifers after 47 years on coal mine spoils in southern Illinois. *Tree Planter's Notes.* 47(1):24-29.

Ashby, W.C. 1995. Hybrid populus in reclamation. *International Journal of Surface Mining and Reclamation.* 9(2):69-71.

Ashby, W.C. 1991. Surface mine tree planting in the midwest pre- and post-Public Law 95-87. *In* Oaks, W., and J. Bowden (ed.) Technologies for Success. Proceedings American Society for Surface Mining and Reclamation Vol. 2., May 14-17. Durango, CO. American Society for Surface Mining and Reclamation, Lexington, KY.

Ashby, W.C. and J.R. McCarthy, J.R. 1990. Compaction mitigation using plant materials. *In* Proceedings first Midwestern Region Reclamation Conference July 18-19. Southern Illinois University, Carbondale, IL.

Atkinson, R.B., W.L. Daniels, and J. Cairns, Jr. 1996. Ontogeny of accidental wetlands and hydric soil development on surface mined landscapes. *In* Proceedings of the American Society for Mining and Reclamation, Knoxville, TN. May 1996. American Society for Surface Mining and Reclamation, Lexington, KY.

Avery, T.E. and H.E. Burkhart. *Forest Measurements*. 5th ed. McGraw-Hill, Boston. 456pp.

Beck, D.E. 1971. Polymorphic site index curves for white pine in the southern Appalachians. USDA Forest Service Research Paper SE-80. 8p.

Blake, G.R. and K.H. Hartge. 1986. Bulk Density. p. 363-375. *In* A. Klute (ed.) Methods of Soil Analysis. Part 1. Agronomy Monograph No. 9. ASA and SSSA, Madison, WI.

Bolan, N.S. 1991. A critical review on the role of mycorrhizal fungi in the uptake of phosphorus by plants. *Plant and Soil*. 134:189-207.

Brady, N.C. and R.R. Weil. 2002. *The Nature and Properties of Soils*. 13th ed. Prentice Hall, Upper Saddle River.

Brown, K.R. and R. van den Driessche. 2005. Effects of nitrogen and phosphorus fertilization on the growth and nutrition of hybrid poplars on Vancouver Island. *New Forests.* 29:89-104.

Burger, J.A. and C.E. Zipper. 2002. How to Restore Forests on Surface-Mined Land. Virginia Cooperative Extension Service Publication 460-123. Virginia Polytechnic and State University, Blacksburg. 18p.

Burgess, D., J.A. Baldock, S. Wetzell, and D.G. Brand. 1995. Scarification, fertilization and herbicide treatment effects on planted conifers and soil fertility. *Plant and Soil*. 168-169:513-522.

Bussler, B.H., W.R. Byrnes, P.E. Pope, and W.R. 1984. Chaney. Properties of minesoil reclaimed for forest land use. *Soil Science Society of America Journal*. 48:178-184.

Campbell, R.G. 1978. The Weyerhaeuser land classification system. *In* W.A. Balmer (ed.) Proceedings Soil Moisture…Site Productivity Symposium. U.S. Department of Agriculture, Forest Service, Washington, DC. 400p.

Chaney, W.R., Pope, P.E., and W.R. Byrnes. 1995. Tree survival and growth on land reclaimed in accord with Public Law 95-87. *Journal of Environmental Quality.* 24:630-634.

Cleveland, B. and R. Kjelgren. 1994. Establishment of six tree species on deep-tilled minesoil during reclamation. *Forest Ecology and Management.* 68:273-280.

Coile, T.S. 1952. Soil and the growth of forests. *Advances in Agronomy.* 4:329-398.

Czapowskyj, M.M. 1978. Hybrid poplar on two anthracite coal-mine spoils: 10-year results. USDA Forest Service. Research Note NE-267.

Dale, M.E., D.E. Lutz, and H.J. Bailey. 1989. Yield of white pine plantations in Ohio. *Northern Journal Applied Forestry*. 6:51-56.

Daniels, W.L. and D.F. Amos. 1982. Chemical characteristics of some southwest Virginia mine soils. p.277-281. *In* D. Graves (ed.). Proceedings of the Symposium on Surface Mining Hydrology, Sedimentology and Reclamation. Lexington, KY. 1982. University of KY, Lexington.

Daniels, W.L. and C.E. Zipper. 1997. Creation and management of productive mine soils. Virginia Cooperative Extension Service Publication 460-121. Virginia Polytechnic and State University, Blacksburg. 11p.

Davidson, W.H. 1979. Hybrid poplar pulpwood and lumber from a reclaimed strip-mine. USDA Forest Service. Research Note NE-282.

Davidson, W.H. 1981. Timber volumes of old Pennsylvania surface mine reclamation plantations. USDA Forest Service. Research Note NE-303.

Davidson, W.H. 1986. Predicting tree survival and growth form mine soil analysis. p. 244-246. *In* Forests, the world, and the profession: Proceedings of the 1986 Society of American Foresters National Convention, Birmingham, AL. 5-8 Oct. 1986. Society of American Foresters, Bethesda, MD.

Della-Bianca, L. 1981. Thinning eastern white pine in the southern Appalachians. *Southern Journal of Applied Forestry*. 5(2): 68-73.

Doolittle, W.T. 1958. Site index comparisons for several forest species in the southern Appalachians. *Soil Science Society of America Proceedings.* 22:450-458.

Doolittle, W.T. 1962. Southern Appalachian white pine plantations: site, volume, and yield. USDA Forest Service Station Paper SE-149.

Fisher, R.F. and D. Binkley. 2000. *Ecology and Management of Forest Soils*. 3rd ed. John Wiley & Sons, Inc. New York.

Gee, G.W. and J.W. Bauder. 1986. Particle size analysis. p.383-411. *In* A. Klute (ed.) Methods of Soil Analysis. Part 1. Agronomy Monograph No. 9. ASA and SSSA, Madison, WI.

Gillespie, A.R., and H.W. Hocker, Jr. 1986. Thinning response of immature white pine. *Northern Journal of Applied Forestry*. 3:148-150.

Greacen, E.L. and R. Sands. 1980. Compaction of forest soils. A review. *Australian Journal of Soil Research*. 18:163-189.

Gomez, K.A. and A.A. Gomez. 1984. *Statistical Procedures for Agricultural Research*. John Wiley & Sons, New York. 680pp.

Gorman, J. and Skousen, J. 2003. Second Year Survival of Commercial Hardwoods on Reclaimed Mine soils in West Virginia. p. 279-291. *In* Proceedings of the American Society for Surface Mining and Reclamation, Billings, MT. June 3-6, 2003. American Society for Surface Mining and Reclamation, Lexington, KY.

Hart, S.C., J.M. Stark, E.A. Davidson, and M.K. Firestone. 1994. p. 985-1018. Nitrogen mineralization, immobilization, and nitrification. *In* R.W. Weaver et al. (eds.). Methods of Soil Analysis, Part 2. Microbiological and Biochemical Properties. SSSA Book Series, No. 5. SSSA, Madison, WI.

Harvey, H.P. and R. van den Driessche. 1997. Nutrition, xylem cavitation and drought resistance in hybrid poplar. *Tree Physiology*. 17:647-654.

Hearing, K.C., W.L. Daniels, and J.A. Roberts. 1993. Changes in mine soil properties resulting from overburden weathering. *Journal of Environmental Quality*. 22:194-200.

Hearing, K.C., W.L. Daniels, and J.M. Galbraith. 2004. Appalachian mine soil morphology and properties: effects of weathering and mining method. *Soil Science Society of America Journal*. 68:1315-1325.

Howard, J.L., D.F. Amos, and W.L. Daniels. 1988. Phosphorous and potassium relationships in southwestern Virginia coal-mine spoils. *Journal of Environmental Quality*. 17(4):695-700.

Kost, D.A., J.P. Vimmerstedt, and J.H. Brown. 1998a. Topsoiling, ripping and fertilizing effects on tree growth and nutrition on calcareous mine soils. *Forest Ecology and Management*. 103:307-319.

Kost, D.A., J.P. Vimmerstedt, and J.H. Brown. 1998b. Site factor effects on establishment of planted and volunteer trees and shrubs on graded cast overburden and replaced topsoil. *International Journal of Surface Mining and Reclamation*. 12(2):79-86.

Kozlowski, T.T. 1999. Soil compaction and growth of woody plants. *Scandinavian Journal of Forest Research*. 14:596-619.

Kraske, C.R. and I.J. Fernandez. 1990. Conifer seedling growth response to soil type and selected nitrogen availability indices. *Soil Science Society of America Journal*. 54:246-251.

Lancaster, K.F. and W.B. Leak. 1978. A silvicultural guide for white pine in the northeast. USDA Forest Service. General Technical Report NE-41.

Larson, M.M., D.A. Kost, and J.P. Vimmerstedt. 1995. Establishment of trees on mine soils during drought and wet years. *International Journal of Surface Mining and Reclamation*. 9(3):99-103.

Li, R.S. and L. Daniels. 1994. Nitrogen accumulation and form over time in young mine soils. *Journal of Environmental Quality*. 23:166-172.

McCormick, L.H. and F.A. Amendola. 1983. Soil pH, extractable aluminum and tree growth on acid mine soils. *Pennsylvania Agricultural Experiment Station Journal Series* . 6525:249-262.

McFee, W.W., W.R. Byrnes, and J.G. Stockton. 1981. Characteristics of coal mine overburden important to plant growth. *Journal of Environmental Quality*. 10(3):300-308.

McGill, D.W., V.L. Ford, and J.F. McNeel. 2004. Early development of a species test established on surface mines thirty years post-reclamation. pp. 1227-1238. In: Proceedings, American Society for Mining and Reclamation. Morgantown, West Virginia. American Society for Surface Mining and Reclamation, Lexington, KY.

McLean, E.O. 1965. Aluminum. p. 978-998. *In* C.A. Black et al. (ed.) Methods of soil analysis, Part 2. Agron. Monogr. 9. ASA, Madison, WI

McLean, E.O. 1982. Soil pH and lime requirement. p. 199-224. *In* A.L. Page et al. (eds.). Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties, 2nd ed. Agronomy Monograph No. 9. ASA and SSSA, Madison. WI.

McNab, W.H. and B.A. Ritter. 2000. The old orchard white pine plantation at Biltmore. *Journal of Forestry*. 98(11):18-23.

Nyland, R.D. 2002. *Silviculture Concepts and Applications*. 2nd ed. McGraw Hill, Boston. 682pp.

Olsen, S.R. and L.E. Sommers. Phosphorus. *In* A.L. Page et al. (eds.). Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties, 2nd ed. Agronomy Monograph No. 9. ASA and SSSA, Madison. WI.

Omi, S.K. 1986. Soil compaction: Effects on seedling growth. USDA Forest Service GTR RM-125.

Parish, D.H. 1971. Soil conditions as they affect plant establishment, root development, and yield: Effects of soil compaction on nutrient supply in plants. *In* Compaction of Agricultural Soils. K.K. Barnes et al. (eds.) American Society of Agricultural Engineers, St. Joseph, MI.

Pederson, T.A., A.S. Rogowski, and R. Pennock, Jr. 1978. Comparison of morphological and chemical characteristics of some soils and mine soils. *Reclamation Review*. 1:143-156.

Peters, J.J., D.A. Bender, M.P. Wolcott, and J.D. Johnson. Selected properties of hybrid poplar clear wood and composite panels. *Forest Products Journal*. 52(5):45-54.

Philo, G.R., C.A. Kolar, and W.C. Ashby. 1982. Effects of ripping on minesoil compaction and black walnut establishment. Symposium on Surface Mining Hydrology, Sedimentation and Reclamation. Lexington, KY.

Preve, R.E., J.A. Burger, and R.E. Kreh. 1984. Influence of mine spoil type, fertilizer, and mycorrhizae on pines seeded in greenhouse trays. *Journal of Environmental Quality.* 13(3):387-391.

Ramsey, C.L., S. Jose, B.J. Brecke, and S. Merritt. 2001. Growth response of longleaf pine (*Pinus palustris* Mill.) seedlings to fertilization and herbaceous weed control in an old field in southern USA. *Forest Ecology and Management.* 172:281-289.

Rhoades, J.D. 1982. Soluble salts. p. 167-178. *In* A.L. Page et al. (eds.). Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties, 2nd ed. Agronomy Monograph No. 9. ASA and SSSA, Madison. WI.

Rodrigue, J.A., J.A. Burger, and R.G. Oderwald. 2002. Forest productivity and commercial value of pre-law reclaimed mined land in the eastern United States. *Northern Journal of Applied Forestry*. 19(3):106-114.

Rodrigue, J.A. and J.A. Burger. 2004. Forest soil productivity of mined land in the midwestern and eastern coalfield regions. *Soil Science Society of America Journal.* 68:833-844.

Ruark, G.A., D.L. Mader, and T.A. Tattar. 1982. The influence of soil compaction and aeration on the root growth and vigour of trees – a literature review. Part 1. *Arboricultural Journal.* 6:251-265.

Russell, R.S. 1977. *Plant root systems. Their function and interaction with the soil*. 298pp. McGraw – Hill, London.

SAS Institute. 2001. SAS System for Windows V8. SAS Institute Inc., Cary, NC.

Schoenholtz, S.H., J.A. Burger, and R.E. Kreh. 1992. Fertilizer and organic amendment effects on mine soil properties and revegetation success. *Soil Science Society of America Journal*. 56:1177-1184.

Shepard, R.K. Jr., G.A. Reams, and R.C. Lemin, Jr. 1991. Response of eastern white pine to nitrogen fertilization. *Northern Journal of Applied Forestry*. 8:83-85.

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., and Broderson, W.D. (editors), 2002. Field book for describing and sampling soils, Version 2.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Shukla, M.K., R. Lal, and M. Ebinger. 2004. Soil quality indicators for reclaimed mine soils in southeastern Ohio. *Soil Science*. 169:133-142.

Stanturf, J.A., C. van Oosten, D.A. Netzer, M.D. Coleman, and C.J. Portwood. 2001. Ecology and silviculture of poplar plantations. pp. 153-206. *In* Dickmann, D.I. et al. (eds.) Poplar Culture in North America. NRC Research Press, Ottawa.

Sumner, M.E. and W.P. Miller. 1996. Ch. 40 - Cation exchange capacity and exchange coefficients. *In* Methods of Soil Analysis. Part 3. Chemical Methods. D.L. Sparks et al. (ed.). SSSA Book Series No. 5. Madison, WI.

Timber Mart-South. T. Harris (ed.). 2004. Warnell School of Forest Resources, Athens, GA.

Thomas, G.W. 1982. Exchangeable cations. p. 159-164. *In* A.L. Page et al. (eds.). Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties, 2nd ed. Agronomy Monograph No. 9. ASA and SSSA, Madison. WI.

Thomas, W.R. 1999. Reclamation of surface mined lands in eastern Kentucky using native high value tree species. MS Thesis. University of Kentucky, Lexington KY. 82pp.

Torbert, J.L. and J.A. Burger. 2000. Forest land reclamation. p.371-398. In: R.I. Barnhisel et al. (eds). Reclamation of Drastically Disturbed Lands. Agronomy Monograph No. 41. ASA, CSSA, and SSSA, Madison, WI.

Torbert, J.L. and J.A. Burger. 1996. Influence of grading intensity on herbaceous ground cover, erosion, and tree establishment in the southern Appalachians. pp. 637-646. *In* Proceedings, American Society for Mining and Reclamation. Knoxville, Tennessee. American Society for Surface Mining and Reclamation, Lexington, KY.

Torbert, J.L., J.A. Burger, and W.L. Daniels. 1990. Pine growth variation associated with overburden rock type on a reclaimed surface mine in Virginia. *Journal of Environmental Quality.* 19:88-92.

Torbert, J.L., J.A. Burger, J.N. Lien, and S.H. Schoenholtz. 1985. Results of a Tree -Species Trial on a Recontoured Surface Mine in Southwestern Virginia. *Southern Journal of Applied Forestry.* 9(3):150-153.

Torbert, J.L., J.A. Burger, and T. Probert. 1991. A reforestation case study on a reclaimed Appalachian mine soil in West Virginia. p. 663-668. *In* Proceedings of the American Society for Surface Mining and Reclamation, Durango, CO. May 14-17. 1991. American Society for Surface Mining and Reclamation, Lexington, KY.

Torbert, J.L., J.A. Burger, J.E. Johnson, and J.A. Andrews. 1994. Final Report: *Indices for indirect estimates of productivity of tree crops*. OSM Cooperative Agreement GR996511. Virginia Polytechnic Institute and State University, Blacksburg, VA. 22p.

Torbert, J.L., J.A. Burger, S.H. Schoenholtz, and R.E. Kreh. 2000. Growth of three pine species after eleven years on reclaimed mine soils in Virginia. *Northern Journal of Applied Forestry.* 17(3):95-99.

Torbert, J.L., A.R. Tuladhar, J.A. Burger, and J.C. Bell. 1988. Minesoil property effects on the height of ten-year-old white pine. *Journal of Environmental Quality*. 17(2):189-192.

Trouse, A.C. 1971a. Soil conditions as they affect plant establishment, root development, and yield: Effects of soil moisture on plant activities. *In* Compaction of Agricultural Soils. K.K. Barnes et al. (eds.) American Society of Agricultural Engineers, St. Joseph, MI.

Trouse, A.C. 1971b. Soil conditions as they affect plant establishment, root development, and yield: Effects of soil aeration on plant activities. *In* Compaction of Agricultural Soils. K.K. Barnes et al. (eds.) American Society of Agricultural Engineers, St. Joseph, MI.

Unger, P.W. and D.K. Cassel. 1991. Tillage implements disturbance effects on soil properties related to soil and water conservation: a literature review. *Soil and Tillage Research*. 19:363-382.

USDA. 1996. Soil survey laboratory methods manual. Soil survey investigations report no. 42. Version 3.0.

USDI. Office of Surface Mining. 2003. *U.S. Coal Production Under the Surface Mining Law* December 30, 1978 – present [online]. Washington, D.C. [cited 19 April 2004]. Available from: <http://www.osmre.gov/coal/1978-2002coal.xls>.

Van den Burg, J. 1985. Foliar analysis for determination of tree nutrient status – A compilation of literature data. Rijksinstituut Voor Onderzoek In De Bos- En Landshapsbouw “De Dorschkamp”. Wageningen. Rapport nr. 414. 615p.

Van den Driessche, R. 1999. First-year growth response of four *Populus trichocarpa* x *Populus deltoides* clones to fertilizer placement and level. *Canadian Journal of Forest Research*. 29:554-562.

Van den Driessche, R., W. Rude, and L. Martens. 2003. Effect of fertilization and irrigation on the growth of aspen (*Populus tremuloides* Michx.) seedlings over three seasons. *Forest Ecology and Management*. 186:381-389.

Vimmerstedt, J.P. 1962. Southern Appalachian white pine plantations: site, volume, and yield. USDA Forest Service. Southeastern Forest Experiment Station. Asheville, NC. Station Paper No.149.

Wendel, G.W. and H.C. Smith. 1990. Eastern White Pine. *In* Burns, R. M., and B. H. Honkala (tech. coords.) Silvics of North America: 1. Conifers. Agriculture Handbook 654. U.S. Department of Agriculture, Forest Service, Washington, DC. vol.2, 877 p.

Zisa, R.P., H.G. Halverson, and B.B. Stout. 1980. Establishment and early growth of conifers on compact soils in urban areas. USDA Forest Service. Research Paper NE-451.

Timetable

This phase of the project has been completed.

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

Terrestrial carbon markets provide one opportunity for forestry to become a financially viable post mining land use in the Appalachian coal mining region. This quarter, emphasis of Task 4 focused on alternative carbon sequestration incentives for promoting reforestation of reclaimed mined lands. Earlier carbon-based incentives examined an annual carbon payment based on the amount of carbon held on site in that year (see Third Quarter '04 report). In other words, the landowner would receive a payment for carbon found on the site (i.e., above ground and root carbon) each year, regardless of when that carbon was sequestered. An alternative payment scheme has been devised and examined that envisages a payment based on the amount of carbon accumulated in a given year, rather than the amount stored. Based upon our alternative payment scheme, carbon payments that make reforestation financially viable would fall in the range of $8.66 to $71.88 per ton of carbon stored in hardwoods and $0 to $83.29 per ton of carbon stored in pines.

Experimental

In our original approach for determining the level of carbon payment required for a minimal level of profitability from forestry, we set the LEV of forestry plus carbon production equal to zero, and solve for s_c in:

$$r(L_f) = \frac{pQ_f(t)e^{-it} - c_f e^{-it}}{(1-e^{-it})} - c_0 + s_c \int_0^{\infty} x(z)e^{-iz}dz = 0 \qquad (4.1)$$

where p is the unit price of timber, Q_f is the volume of timber produced from reforested land at age t, c_f is regular reforestation costs after timber harvest, c_0 is initial reforestation costs incurred when converting grassland into forest, *x(z)* is the level of carbon produced on the forested site, which is a function of the volume of timber on the site at a given time plus carbon sequestered in the soil, and s_c is the annual carbon payment. This approach assumes a payment would be made for carbon each year, based upon all carbon found on the site that year. As carbon accumulates under this approach, additional payment is received for the same carbon year-after-year, as long as that carbon remains on site.

Determining the level of payment for carbon under the original formulation that would provide for a full reimbursement of reforestation costs, LEV of forestry plus carbon are set equal to the LEV of forestry without conversion costs, and s_c' was computed in:

$$r(L_f) = \frac{pQ_f(t)e^{-it} - c_f e^{-it}}{(1-e^{-it})} - c_0 + s_c^{'} \int_0^{\infty} x(z)e^{-iz}dz = \frac{pQ_f(t)e^{-it} - c_f e^{-it}}{(1-e^{-it})}$$

$$or \qquad (4.2)$$

$$s_c^{'} \int_0^{\infty} x(z)e^{-iz}dz = c_0$$

Alternatively, if carbon markets develop in which landowners receive a payment only at the time that carbon is added to the site, the problem would be slightly modified from (4.1) above:

$$r(L_f) = \frac{pQ_f(t)e^{-it} - c_f e^{-it}}{(1-e^{-it})} - c_0 + s_c \int_0^{\infty} \dot{x}(z)e^{-iz}dz = 0 \qquad (4.3)$$

where $\dot{x}(z)$ is the change (time derivative) of carbon. In this formulation, the carbon payment s_c only recognizes the carbon added to the site in a given year, and not the total carbon stored during that year.

Similarly, determining the level of carbon payment for added carbon that would provide for a full reimbursement of reforestation costs, LEV of forestry plus carbon are set equal to the LEV of forestry without conversion costs, and s_c' is computed in:

$$r(L_f) = \frac{pQ_f(t)e^{-it} - c_f e^{-it}}{(1-e^{-it})} - c_0 + s_c^{'} \int_0^{\infty} \dot{x}(z)e^{-iz}dz = \frac{pQ_f(t)e^{-it} - c_f e^{-it}}{(1-e^{-it})}$$

$$or \qquad (4.4)$$

$$s_c^{'} \int_0^{\infty} \dot{x}(z)e^{-iz}dz = c_0$$

Results and Discussion

Calculated payments that compensate only for carbon accumulated on site each year that are required for a minimal level of profitability (Table 21) range of $8.66 to $71.88 per ton of carbon stored in mixed hardwoods and $0 to $83.29 per ton of carbon stored in pines. Lowest ($0/ton) payments are needed in white pine plantations with low to moderate interest rates and moderate to high productivity levels (where LEVs already are greater than zero), while the highest payments are required for white pines in situations with a high interest rate and low productivity. On poor quality sites, required carbon payments are higher for white pines than for mixed hardwoods, whereas on higher quality sites required carbon payments to achieve minimal profitability are lower for white pine. These findings are a consequence of differing relative growth rates between pines and hardwoods (which are dependent upon site quality), and rotation length (where hardwoods carry higher volumes of timber and carbon longer before starting the next rotation).

Carbon payments required for full reimbursement of conversion costs (Table 22) are somewhat higher than those required for providing minimal profitability, ranging from under $16.50 per ton per year for mixed hardwoods on high quality sites with a low interest rate to almost $97 per ton per year for white pines grown on poor quality sites in situations with high alternative rates of return.

Table 21. 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/year).

	Mixed Hardwoods (60-year rotation)			White Pine (30-year rotation)		
5% ARR, Low Prices						
Site/Intensity	Low	Medium	High	Low	Medium	High
V	42.53	44.11	49.36	39.15	35.34	38.91
IV	36.28	37.63	42.19	25.62	22.53	25.43
III	30.81	31.97	35.93	15.41	12.86	15.25
III	25.94	26.95	33.11	*	*	*
I	21.69	24.67	33.11	*	*	*
3.5% ARR, Low Prices						
Site/Intensity	Low	Medium	High	Low	Medium	High
V	25.80	26.92	31.03	16.99	12.87	15.66
IV	20.85	21.82	25.37	6.42	3.07	5.34
III	16.52	17.34	20.42	*	*	*
III	12.03	12.74	17.56	*	*	*
I	8.66	10.94	17.56	*	*	*
7.5% ARR, Low Prices						
Site/Intensity	Low	Medium	High	Low	Medium	High
V	62.76	65.01	71.88	81.68	78.17	83.29
IV	54.51	56.45	62.42	61.81	58.96	63.11
III	47.30	48.97	54.15	46.80	44.45	47.87
III	41.41	42.87	50.98	28.74	26.76	29.64
I	35.81	39.87	50.98	18.36	16.73	24.12

* Indicates LEV is positive without additional payments.

Table 22. Payment required per ton of carbon added to the site that provides full reimbursement of forest conversion costs to landowner of reclaimed mine land, by site class, reforestation intensity, and discount rate ($/ton/year).

	Mixed Hardwoods (60-year rotation)			White Pine (30-year rotation)		
5% ARR, low prices						
Site/Intensity	Low	Medium	High	Low	Medium	High
V	48.59	50.21	55.52	55.22	54.33	57.27
IV	42.39	43.79	48.40	44.83	44.10	46.49
III	36.96	38.17	42.18	36.98	36.38	38.35
III	32.67	33.72	39.91	31.00	30.50	32.14
I	28.47	31.48	39.91	25.57	25.16	29.19
3.5% ARR, low prices						
Site/Intensity	Low	Medium	High	Low	Medium	High
V	37.87	39.10	43.30	36.16	35.55	37.54
IV	33.03	34.09	37.73	29.35	28.86	30.47
III	28.79	29.71	32.87	24.21	23.80	25.14
III	25.44	26.24	31.11	20.30	19.95	21.07
I	22.17	24.49	31.11	16.74	16.46	19.14
7.5% ARR, low prices						
Site/Intensity	Low	Medium	High	Low	Medium	High
V	64.66	66.92	73.81	93.53	92.13	96.82
IV	56.43	58.38	64.37	75.92	74.78	78.60
III	49.23	50.91	56.12	62.62	61.69	64.83
III	43.52	45.00	53.11	52.49	51.71	54.35
I	37.94	42.01	53.11	43.30	42.65	49.36

Conclusions

Carbon revenues that allow profitability (or full cost reimbursement) for reforesting reclaimed surface coal mine sites that are received only when carbon is added to the site must be substantially greater than those required when the payment is based upon total carbon stored, as earlier reported (see Quarter 3, 2004 report). Further, recent carbon prices reported by the Chicago Climate Exchange have remained below $2/ton, which is substantially lower than payments required to make reforestation of reclaimed mine sites profitable, under most circumstances. In addition, while the original payment (based on total carbon stored) provided incentive for landowners to delay harvests and keep carbon stored on site longer than would occur with the carbon revenues, this alternative scheme may have the effect of shortening rotation lengths in order to keep the site accumulation of carbon at a higher rate (which would provide a higher payment). To the extent that carbon harvested from the site remains sequestered for a long period of time in wood products, this rotation issue may not be a concern.

However, if carbon is released to the atmosphere quickly from harvested products, the alternative carbon payment scheme may be undesirable. Further analysis of the comparative statics of carbon payment form is forthcoming on the project.

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 finalized a field sampling strategy to measure site properties (soil and vegetation) associated with forest productivity and carbon sequestration. Furthermore, we randomly selected mine permits in Kentucky, Ohio, Virginia, and West Virginia for sampling using available data from state agencies.

Experimental

Using shapefiles and data made available from state agencies, we selected sample sites in a four-state region. The selection process was random, stratified by state, and based on acreage so that each acre of mined land within each state had the same probability of being selected.

Consulting with other investigators, a field-sampling protocol for soil properties and vegetation was developed. Soil properties and herbaceous vegetatation will be sampled at nine points located randomly within each mine site, and vegetative cover properties will be measured along three transects defined by these randomly located sampling points on each mine site.

Results and Discussion

Because the time required to execute the procedures described in prior reports for using Landsat data to identify and quantify mined acreages proved to be excessively time consuming as the field-sampling season approached, those procedures were temporarily abandoned and an alternative procedure was utilized to identify mine permits for field sampling.

The characteristics of mine sites within state-agency databases vary by state. For example, while Virginia's database extends back to the early 1990s, databases available from other states extend to the early 1980s or to SMCRA implementation. Kentucky's database does not include shapefile representations of permit boundaries, but data available from other states include this information. Pennsylvania mine permits have not been selected for sampling because we expect Pennsylvania mined landscapes to be more complex than those present in other states, and that experience in initiating field sampling of other states will aid the process of selecting potential sample sites for the Pennsylvania permit files.

An original 20 sites were selected within each state for potential field sampling, ordered by priority through the randomization procedure used for site selection (Table 23). We intend to sample the top 10 sites within each state that we determine to be available for sampling. Sites will be considered as unavailable if property access cannot be obtained, or if other site characteristics are found which render them unsuitable for meeting project objectives. For example, in initiating the process of site-list refinement for Virginia, we found that two of the sites are deep-mine faceups less than 5 acres in size, while another has been utilized for refuse disposal. The mean permit size of sites selected for sampling exceeds the mean permit size in all states because the sampling procedure was acreage-weighted.

Table 23. Summary statistics for randomly selected mine permits and the entire database available from each state.

State	Sample Sites				State Database			
	N	Sum	Range	Mean	N	Sum	Range	Mean
		-------------acres-------------				--------------acres--------------		
Kentucky	20	8561	45-3190	428	2515	195916	0-3190	78
Ohio	20	7284	31-1089	364	3667	330137	0-4426	90
Virginia	17	ND*	ND	ND	852	ND	ND	ND
West Virginia	20	4337	32-602	217	655	38863	0-748	59

* No data.

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	Economic feasibility											
Subtask 4.1				Evaluation								
Subtask 4.2								Government policies				
Subtask 4.3												
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	