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U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY
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Technical Progress Report

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

Quarterly Report

Report Period: April - June 2005

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July 20, 2005

Instrument No: DE-FG26-02NT41619

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ABSTRACT

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

During the reporting period we determined that by grinding the soil samples to a finer particle size of less than 250 µm (sieve No. 60), the effect of mine soil coal particle size on the extent to which these particles will be oxidized during the thermal treatment of the carbon partitioning procedure will be eliminated, thus making the procedure more accurate and precise. In the second phase of the carbon sequestration project, we focused our attention on determining the sample size required for carbon accounting on grassland mined fields in order to achieve a desired accuracy and precision of the final soil organic carbon (SOC) estimate. A mine land site quality classification scheme was developed and some field-testing of the methods of implementation was completed. The classification model has been validated for softwoods (white pine) on several reclaimed mine sites in the southern Appalachian coal region. The classification model is a viable method for classifying post-SMCRA abandoned mined lands into productivity classes for white pine. A thinning study was established as a random complete block design to evaluate the response to thinning of a 26-year-old white pine stand growing on a reclaimed surface mine in southwest Virginia. Stand parameters were projected to age 30 using a stand table projection. Site index of the stand was found to be 32.3 m at base age 50 years. Thinning rapidly increased the diameter growth of the residual trees to 0.84 cm yr^{-1} compared to 0.58 cm yr^{-1} for the unthinned treatment; however, at age 26, there was no difference in volume or value per hectare. At age 30, the unthinned treatment had a volume of 457.1 m^3 ha^{-1} but was only worth \$8807 ha^{-1}, while the thinned treatment was projected to have 465.8 m^3 ha^{-1}, which was worth \$11265 ha^{-1} due to a larger percentage of the volume being in sawtimber size classes.

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INTRODUCTION

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

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

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

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

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

EXECUTIVE SUMMARY

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

Measuring carbon on mined land has additional challenges compared to measuring it on undisturbed soils. Soil carbon analysis is complicated by coal contamination, and mine soils are highly variable. We determined that by grinding the soil samples to a finer particle size of less than 250 μm (sieve No. 60), the effect of mine soil coal particle size on the extent to which these particles will be oxidized during the thermal treatment of the carbon partitioning procedure will be eliminated, thus making the procedure more accurate and precise. In the second phase of the carbon sequestration project, we focused our attention on determining the sample size required for carbon accounting on grassland mined fields in order to achieve a desired accuracy and precision of the final soil organic carbon (SOC) estimate. We performed a preliminary soil sampling on one site to estimate the $C_{\%}$ variance and using bulk density and coarse fragment content data from the study plots established in West Virginia and Virginia. The number of samples required to estimate soil organic $C_{\%}$ in mine soils was determined to be less than or equal to the number of samples required to estimate the total soil $C_{\%}$ at a desired accuracy and precision.

A mine land site quality classification scheme was developed and some field-testing of the methods of implementation was completed. The classification scheme has been produced and validated for softwoods (white pine) on several reclaimed mine sites in the southern Appalachian coal region. The classification model is a viable method for classifying post-SMCRA abandoned mined lands into productivity classes for white pine.

Little information exists on the productive potential of forests growing on reclaimed mined land and the response of these forests to intermediate stand treatments such as thinning. A thinning study was established as a random complete block design to evaluate the response to thinning of a 26-year-old white pine stand growing on a reclaimed surface mine in southwest Virginia. Stand parameters were projected to age 30 using a stand table projection. Site index of the stand was found to be 32.3 m at base age 50 years. Thinning rapidly increased the diameter growth of the residual trees to 0.84 cm yr^{-1} compared to 0.58 cm yr^{-1} for the unthinned treatment; however, at age 26, there was no difference in volume or value per hectare. At age 30, the unthinned treatment had a volume of 457.1 m^3 ha^{-1} but was only worth \$8807 ha^{-1}, while the thinned treatment was projected to have 465.8 m^3 ha^{-1}, which was worth \$11265 ha^{-1} due to a larger percentage of the volume being in sawtimber size classes. These results indicate that commercial forestry is a viable alternative for reclamation of surface mined lands, and that stands growing on reclaimed mined land can respond well to intermediate stand treatments.

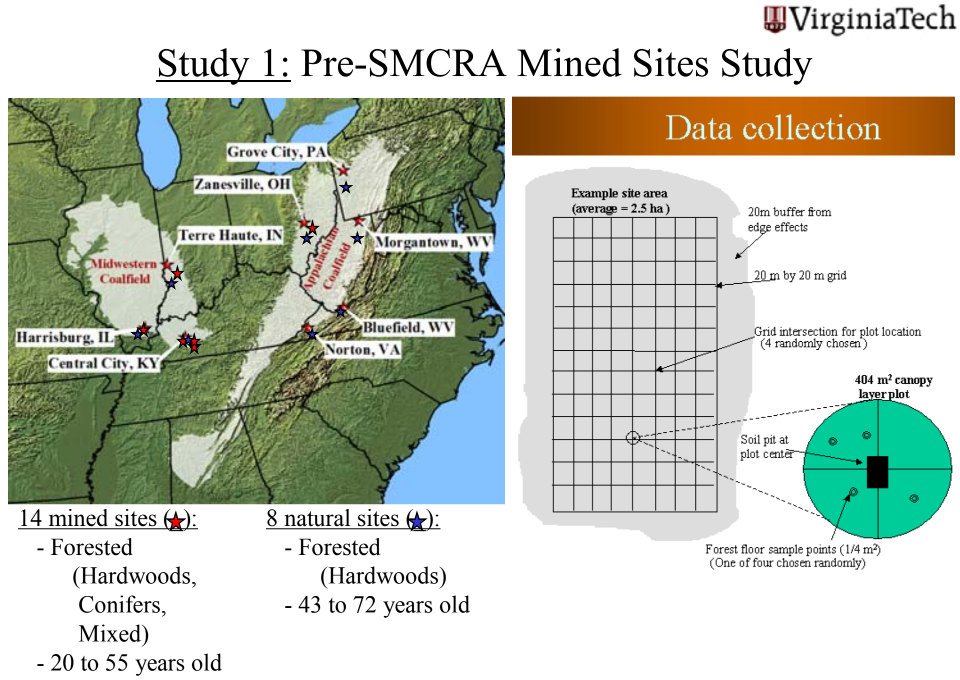


Figure 1. Location and layout of experimental sites for Study 1 across a seven-state region.

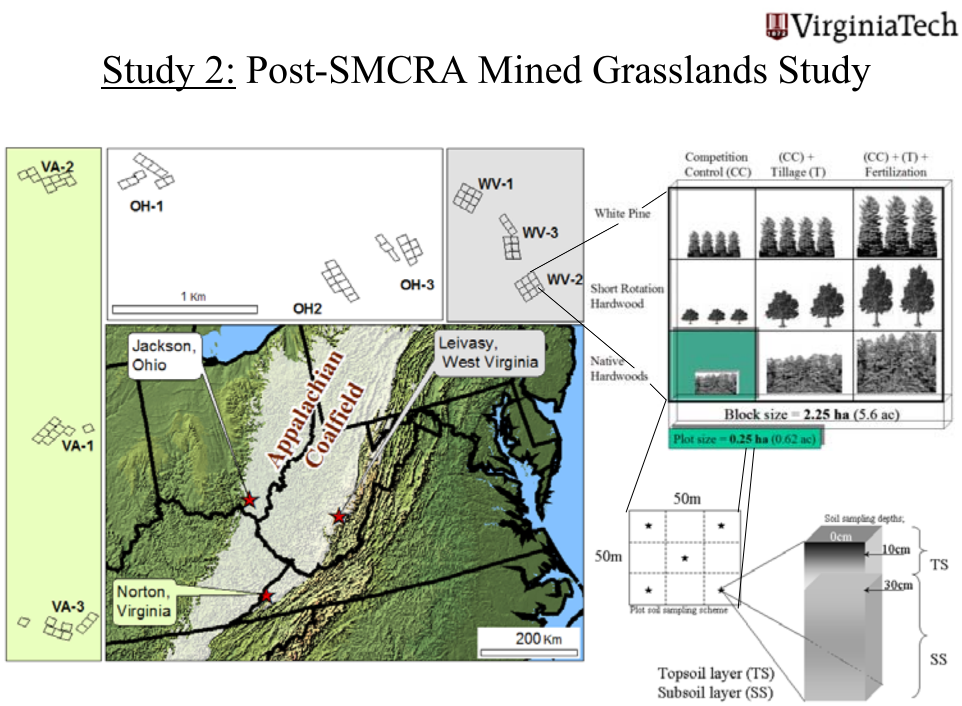


Figure 2. Location and layout of experimental sites for Study 2 in Ohio, West Virginia, and Virginia.

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

Executive Summary

We determined that by grinding the soil samples to a finer particle size of less than 250 μm (sieve No. 60), the effect of mine soil coal particle size on the extent to which these particles will be oxidized during the thermal treatment of the carbon partitioning procedure will be eliminated, thus making the procedure more accurate and precise. In the second phase of the carbon sequestration project established on the Flint Gap mined site in Russell County, Virginia, we focused our attention on determining the sample size required for carbon accounting on grassland mined fields in order to achieve a desired accuracy and precision of the final soil organic carbon (SOC) estimate. We performed a preliminary soil sampling on the Flint Gap site to estimate the $C_{\%}$ variance, and we used BD and CFC data from the study plots for this project established in the West Virginia and Virginia research sites to estimate the variance of BD and CFC. The number of samples required to estimate soil organic $C_{\%}$ in minesoils was determined to be less than or equal to the number of samples required to estimate to the total soil $C_{\%}$ at desired accuracy and precision levels. At the Flint Gap site we allocated an additional 20% and 45% of the minimum number of sampling locations required to achieve 20% accuracy of the total soil C at the 90% precision level for mapping units of site quality class one (SQC I) and site quality classes greater than one (SQC II, III, and IV). Due to the noticeably lower variation in BD compared to that of the total soil $C_{\%}$, the sample size for BD was found to be 60 and 64 times lower, respectively, than that required for C% measurement for SQC II and SQC III mapping units on the Flint Gap mine site.

Experimental

Subtask 1.1

We made progress toward establishing the experiment to evaluate the accuracy and precision of the newly proposed carbon partitioning technique that was described in our last report. We determined that by grinding the soil samples to a finer particle size of less than 250 μm (sieve No. 60), the effect of coal particle size in the mine soil sample on the extent to which these particles will be oxidized during the thermal treatment of the carbon partitioning procedure will be eliminated, thus making the procedure more accurate and precise. In addition, by grinding the soil samples, the surface area of the carbonates present in the soil sample, as well as that of coal particles and organic matter, will increase, which will allow for a quicker and more complete carbonates removal by the acid fumigation method (Harris et al. 2001).

Some of the questions we intend to resolve with this experiment are to determine (i) the effect of different levels of the ratio of soil organic matter to amount of coal particles 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 from our previously reported total soil carbon estimates for the three study sites established for this project in Ohio, West Virginia, and Virginia. The carbon partitioning procedure will also be used to determine the soil organic carbon for the Flint Gap carbon sequestration project, for which we provided information in our previous quarterly report.

Subtask 1.2

In the second phase of the carbon sequestration project established on the Flint Gap mined site in Russell County, Virginia, we focused our attention on determining the sample size required for carbon accounting on grassland mined fields in order to achieve a desired accuracy and precision of the final soil organic carbon (SOC) estimate. We determined that a more effective approach, as well as a more economically attractive one, is to sample the mined field at various levels of intensity that would best suit the different variation levels of the three soil properties required for carbon content estimation – soil carbon concentration ($C_{\%}$), bulk density (BD), and coarse fragment content (CFC). The direct relationship between project site SOC content (Mg ha^{-1}) and these mine soil variables is depicted by the following equation:

$$SOC_{Mg\ ha^{-1}} = [C_{\%}]*[BD_{g\ cm^{-3}}]*[(100–CFC)_{\%}]*[Horizon\ depth_{cm}]*[100^{-1}] \qquad (1\text{-}1)$$

where: $C_{\%}$ = soil organic carbon concentration = $\frac{C_g}{Soil_g}*100$;

$BD_{g\ cm^{-3}}$ = bulk density, <2mm soil fraction;

$(100–CFC)_{\%}$ = percent fine soil fraction (<2mm)= $\frac{Fines_{cm^3}}{Soil_{cm^3}}*100$;

$CFC_{\%}$ = percent coarse fragment content (>2mm soil fraction)= $\frac{CFC_{cm^3}}{Soil_{cm^3}}*100$;

100^{-1} = unit conversion factor.

Because the Flint Gap site is a young mined site (age 10) and the mine spoil is a at a very early stage of soil genesis and soil horizons have not yet formed, we decided that the soil will be sampled to a constant depth across the entire site, eliminating the requirement to delineate soil horizons and determine the uncertainty associated with this delineation during soil sampling. We intend to sample only the surface 0-20 cm soil layer at this early stage of mine soil development on the Flint Gap site.

We assume that the surface 0-20 cm soil layer is where the active soil organic matter pool is expected to be found and where the majority of the SOC can be measured at relatively low costs of sample collection compared to measurement costs of the soil carbon content accumulated at lower soil depths (McKenzie et al. 2000). We intend to determine the ratio of the SOC contained within the surface 0-20 cm soil layer, and at lower soil depths, to the time and costs associated with measuring the SOC content at a desired accuracy and precision in order to better define the optimal sampling depth on grassland mine fields.

In order to determine the sample size for $C_{\%}$, BD, and CFC, we performed a preliminary soil sampling on the Flint Gap site to estimate the $C_{\%}$ variance, and we used BD and CFC data from the study plots for this project established in the West Virginia and Virginia research sites to estimate the variance of BD and CFC.

The sample size *n* for baseline C estimation on Flint Gap was based on the range of total $C_{\%}$ from preliminary soil samples collected from the site on May 30-June 1. Using a systematic soil sampling design, we collected a total of 162 surface soil samples (0-10 cm) on two randomly located 0.5-acre square plots (45 m x 45 m). The only criterion for choosing the random sampling plots on Flint Gap was that a minimum number of sampling plots should include at least three of the four site quality classes mapped on the site. Plot 282 was located on a SCQ class I mapping unit and plot 184 was split between two mapping units of classes II and IV (Fig. 1-1). The sample size for SQC III was computed as the average for SQC II and SQC IV. Employing the site productivity mapping method used to map the Flint Gap site (see Task 3 report), we determined that the study plots in West Virginia were of site quality class III (SQC III), the Ohio plots were of SQC II, and the majority of plots in Virginia were of SQC II. We used BD and CFC data collected from the Virginia and West Virginia study plots to estimate the sample size required for BD and CFC measurement at desired precision and accuracy levels (Table 1-1).

Table 1-1. Bulk density of the fine soil fraction (BD_{Fines}), < 2mm particle size, and CFC of mine spoil material excavated from 2.83 x 10^{-2} mt^3 (0.30 x 0.30 x 0.30 m) soil pit from study plots established in West Virginia and Virginia research sites.

Site (0-10 cm depth)	BDFines			CFC		
	g cm^{-3}	StdDev	N	%	StdDev	N
VA-SQC II	1.36	0.138	8	56.59	3.621	8
WV-SQC III	1.14	0.229	27	51.92	5.661	27

Because the variation of CFC was lower than that of BD, and because both of these parameters can be measured using the same excavated soil sample, we did not specify sample size for CFC measurement, but instead determined the accuracy of the CFC measurement at a chosen sample size for BD, assuming that for each excavated soil pit both BD and CFC will be measured. The following formula was used to estimate the required sample size for soil $C_{\%}$ and BD:

$$n = \frac{t^2 s^2}{D^2}$$ (Crepin and Johnson, 1993)

where: t = a number from the *Student's t* table for a chosen level of precision;

s^2 = the variance which is known beforehand (from preliminary data sampling) or estimated by $s^2 = (R/4)^2$, where R is the estimated range likely to be encountered in sampling (Freese, 1962);

D = the accepted variability in mean estimation (in units of the mean).

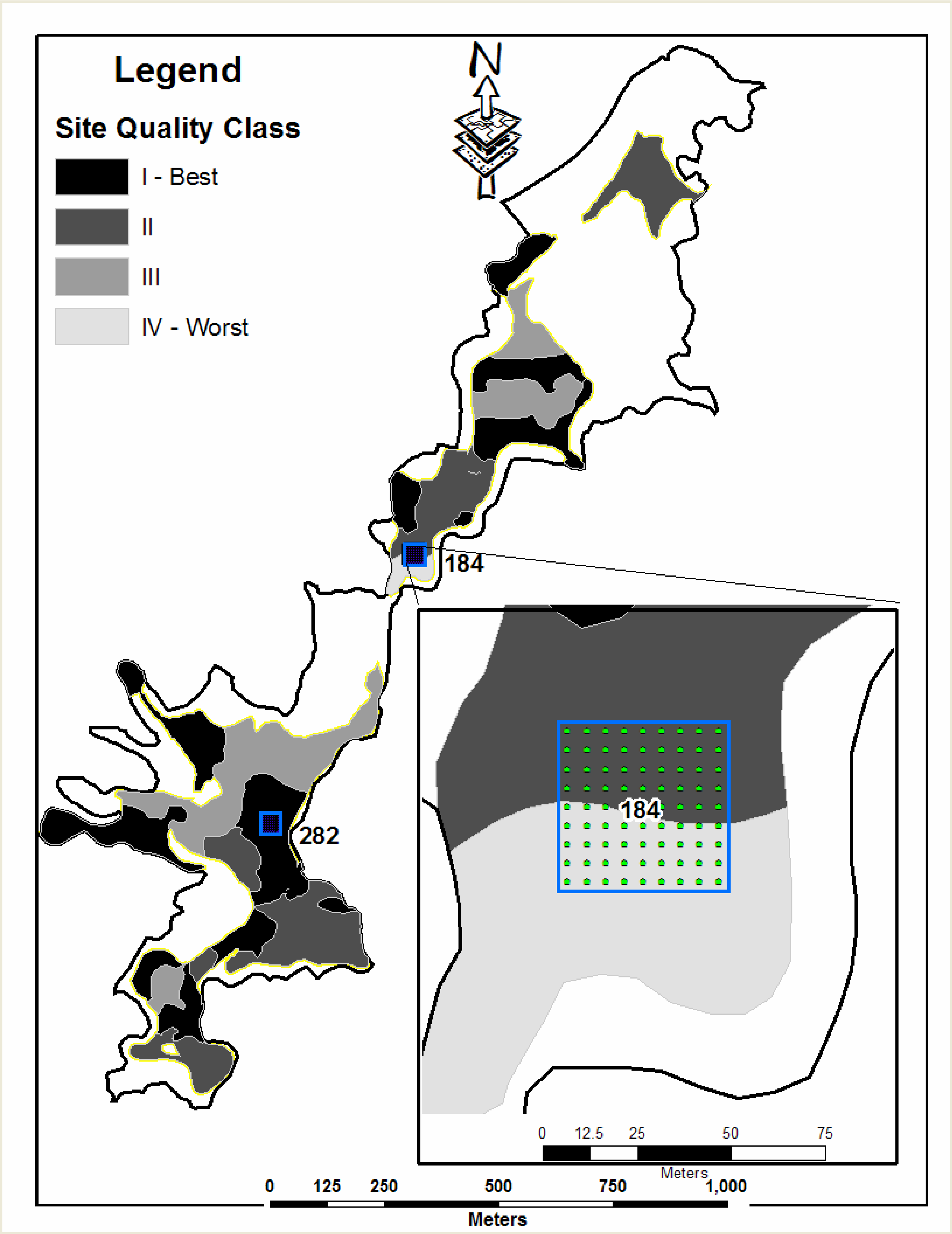


Figure 1-1. Flint Gap mined site quality class map and sampling scheme to determine $C_{\%}$ variance. The larger-scale map shows in detail the sampling locations for one of the preliminary sampling plots.

Results and Discussion

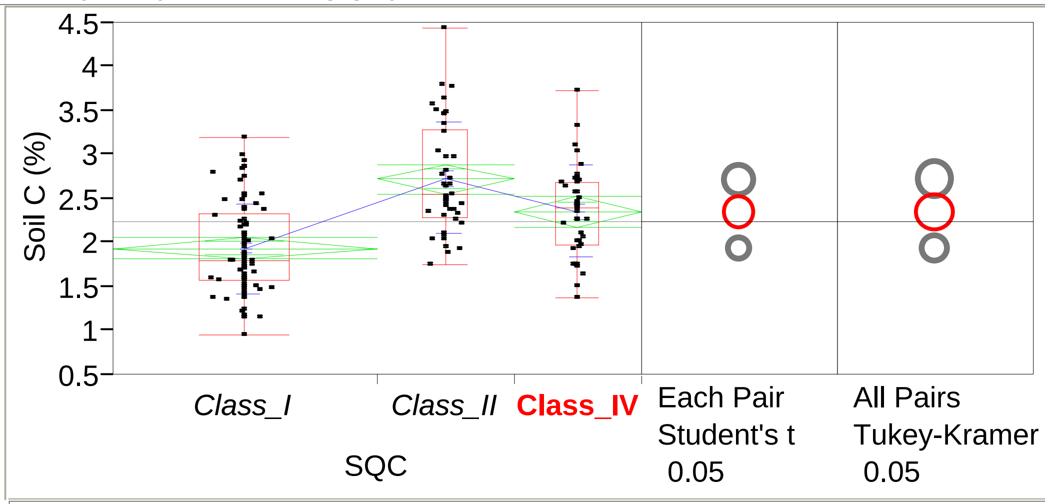
Subtask 1.1

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.

Subtask 1.2

The results from the ANOVA analysis of total $C_{\%}$ from the preliminary soil samples collected on the Flint Gap site are presented below in a print-out form available in the JUMPIN® Version 4.0.4 statistical analysis software (SAS Institute, Inc.). As expected, the results show that the means for total $C_{\%}$ for the three site quality classes sampled on Flint Gap are significantly different at the $\alpha = 0.05$ level. The latter suggests that there should be different sample sizes used for sampling mapping units of different site quality classes (Fig. 1-1).

Oneway Analysis of Soil C (%) By SQC



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
Class_I	0.950436	1.355605	1.572886	1.80583	2.340447	2.750032	3.198719
Class_II	1.754898	1.982986	2.296914	2.551695	3.288723	3.618803	4.451145
Class_IV	1.368011	1.730024	1.97144	2.406941	2.688132	3.042902	3.727906

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Class_I	81	1.94253	0.512074	0.05690	1.8293	2.0558
Class_II	42	2.72875	0.628266	0.09694	2.5330	2.9245
Class_IV	39	2.35563	0.506519	0.08111	2.1914	2.5198

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
SQC	2	17.716517	8.85826	30.0246	<.0001
Error	159	46.910359	0.29503		
C. Total	161	64.626876			

Means Comparisons

Dif=Mean[i]-Mean[j]

	Class_II	Class_IV	Class_I
Class_II	0.00000	0.37313	0.78623
Class_IV	-0.37313	0.00000	0.41310
Class_I	-0.78623	-0.41310	0.00000

Alpha= 0.05

Comparisons for each pair using Student's t

t
1.97500

Abs(Dif)-LSD

	Class_II	Class_IV	Class_I
Class_II	-0.23410	0.13457	0.58225
Class_IV	0.13457	-0.24293	0.20401
Class_I	0.58225	0.20401	-0.16857

Positive values show pairs of means that are significantly different.

Comparisons for all pairs using Tukey-Kramer HSD

q*
2.36591

Abs(Dif)-LSD

	Class_II	Class_IV	Class_I
Class_II	-0.28043	0.08736	0.54187
Class_IV	0.08736	-0.29102	0.16263
Class_I	0.54187	0.16263	-0.20193

Positive values show pairs of means that are significantly different.

To date, there is not any available procedure that can be used to accurately measure soil organic carbon on mined lands due to the specific characteristics of the mine soil, including the presence of coal particles and carbonates. However, we are able to use the variation of the total soil carbon to estimate the minimum sample size required to achieve the desired accuracy and precision of the final SOC estimate as opposed to using the variation of the soil organic. The following paragraph describes the relationship between the variance that we are currently able to measure with great accuracy and precision, which is the variance of the total carbon concentration in the soil, and the variance of the organic component in the mine soil.

In most mine soils, the total soil carbon concentration (C_{Total}) is the sum of the concentrations of the soil organic carbon (C_{Org}), the C present as coal particles (C_{Coal}), and carbonates (C_{CO3}), $C_{Total}=C_{Org}+C_{Coal}+C_{CO3}$. Each of these carbon forms could potentially be measured in the soil, and one will be able to evaluate the uncertainty associated with each component's measurement.

Commonly used measure of uncertainty is the standard deviation (StDev) of a given number of measurements for a given parameter (Harris 2005). The variance of the above arithmetic summation for C_{Total}, according to the rules of propagation of uncertainty (Harris 2005), is estimated as:

$$StDev_{Total} = \sqrt{(StDev_{Org})^2 + (StDev_{Coal})^2 + (StDev_{CO3})^2}$$

where $StDev_{Total}$, $StDev_{Org}$, $StDev_{Coal}$, and $StDev_{CO3}$ are the standard deviations of the total soil $C_{\%}$, soil organic $C_{\%}$, coal $C_{\%}$, and carbonates $C_{\%}$, respectively. With simple mathematical operations, it is evident that the standard deviation of the total soil $C_{\%}$ is larger than that of any of the three constituents.

Therefore, if the mined site is sampled at a sampling intensity *n,* allowing to estimate the total soil carbon concentration within 20% of the true C_{Total} mean (accuracy) 90% of the time (precision), which could also be depicted by a confidence interval of the type $\mu=\bar{x} \pm t_{0.90} * StDev_{Total} / \sqrt{n}$, then the confidence interval for the organic carbon component in the mine soil, C_{Org}, will be narrower at the chosen sampling intensity *n*, because the term $\pm t_{0.90} * StDev_{Org} / \sqrt{n}$ is smaller than the term $\pm t_{0.90} * StDev_{Total} / \sqrt{n}$. This is to say that for a sampling intensity *n* ,based on the variation of total soil $C_{\%}$, the number of samples required to estimate soil organic $C_{\%}$ in minesoils will be less than or equal to the number of samples required to estimate the total soil $C_{\%}$ at desired accuracy and precision levels.

Assuming that in most cases the coal C and carbonates C are present as insignificant amounts in the mine soil, then the variation of the total soil $C_{\%}$ will be equal to that of the soil organic $C_{\%}$. In order to assure sufficient numbers of samples for future mine soil carbon inventory events, we determined that additional numbers of sampling locations, depending on the underlying variation of each mapping unit, be allocated as reserve sampling locations, which will be sampled as non-reserve sampling locations are compromised for one reason or another.

At the Flint Gap site, we allocated an additional 20% and 45% of the minimum and number of sampling locations *n* required to achieve 20% accuracy of the total soil C at the 90% precision level for mapping units of SQC I and site quality classes greater than I (SQCs II, III, and IV), respectively (Table 1-2). Prior to each inventory event, a random set of *n* sampling locations will be selected from all marked locations, *Total n, (Total n = n + reserve)* (Table 1-2), and only they will be sampled during the current year. However, if any of the selected sampling locations are compromised due to natural or human-induced events, then substitute sampling locations from the reserve set within the given mapping unit will be sampled.

Based on the sample size results for C% and BD, we determined that the most cost-effective accuracy and precision levels for SOC amount estimation on the Flint Gap mine site are 20% and 90%, respectively. The latter sample size values are indicated in bold script in Figures 1-2 and 1-3. It is worth noting that due to the noticeably lower variation in BD compared to that of the total soil $C_{\%}$, the sample size for BD is 60 and 64 times lower, respectively, than that required for C% measurement for SQC II and SQC III mapping units on the Flint Gap mine site (Figs. 1-2 and 1-3, Table 1-2).

For example, for a 20-acre mapping unit of SQC II, 300 and 5 samples, respectively, will be collected for C% and BD measurements in order to produce C% and BD estimates that are within 20% of the true mean 90% of the time. For the same mapping unit, the CFC estimate will be within 12% of the true mean 90% of the time, assuming that CFC is measured for each of the five samples collected for BD estimation (Fig. 1-3). Because of the low variation of BD and CFC on mined land of SQCs II and III, we decided to apply the same sampling intensity on all SQC classes for the entire Flint Gap project area, 0.25/acre (5 samples per 20-ac site) (Table 1-2).

Table 1-2. Sample sizes for C%, BD, and CFC measurements on the Flint Gap project site for the 20% accuracy and 90% precision levels of analysis.

Site Quality Class	Variable Area (ac)	C (%)			BD (g cm^3) and CFC (%)		
		n	Reserve (% of n)	Total n	n	Reserve (% of n)	Total n
		per 1 acre					
I	32.87	11	20	13	0.25	20	0.30
II	25.75	15	45	22	0.25	20	0.30
III	21.66	16	45	23	0.25	20	0.30
IV	1.28	16	45	23	0.25	20	0.30

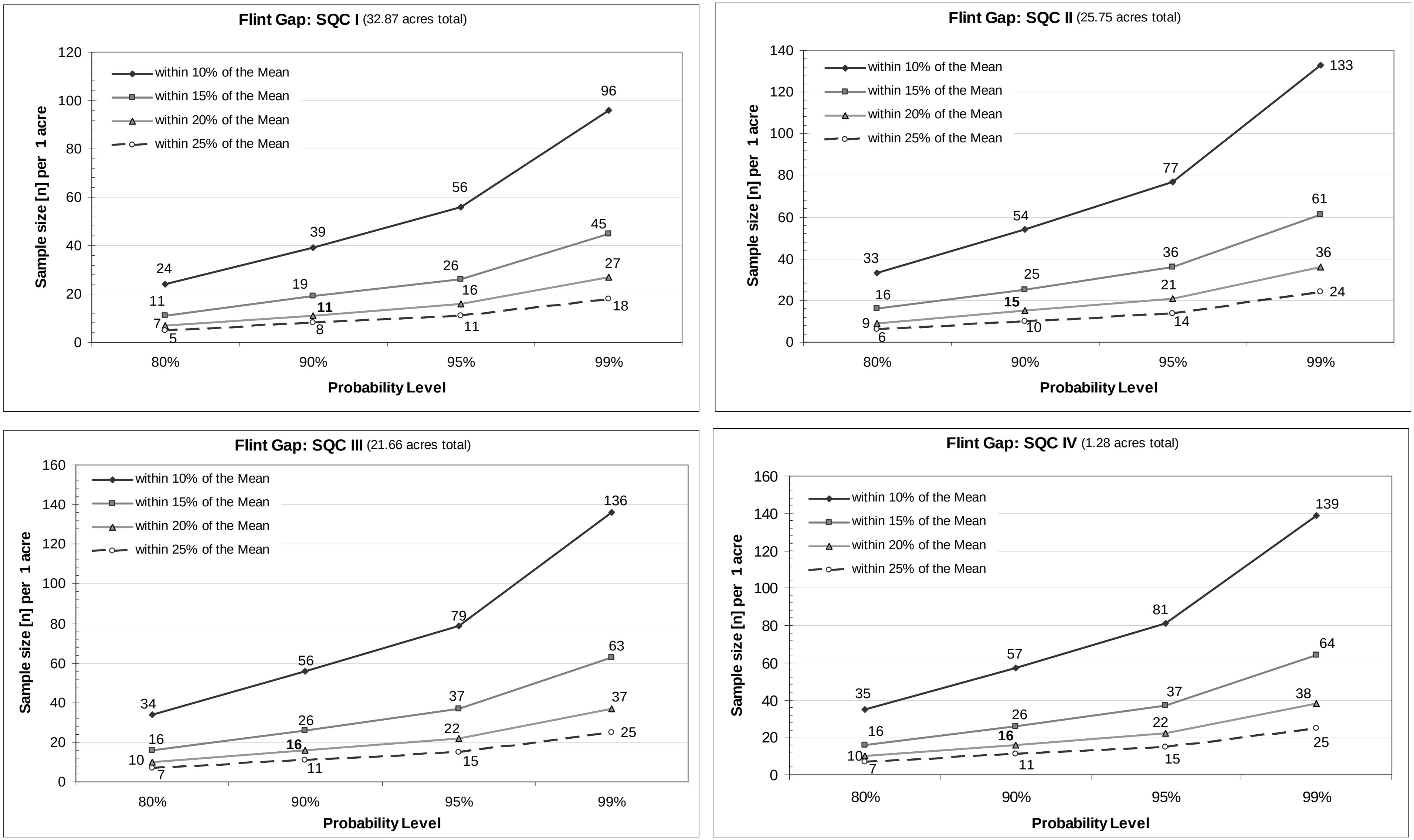


Figure 1-2. Sample size (*n*) estimates required to obtain a certain accuracy (10, 15, 20, and 25%) of the mean estimate for $C_{\%}$ with a certain probability (80, 90, 95, and 99%) of this occurring for four site quality classes on the Flint Gap mined site.

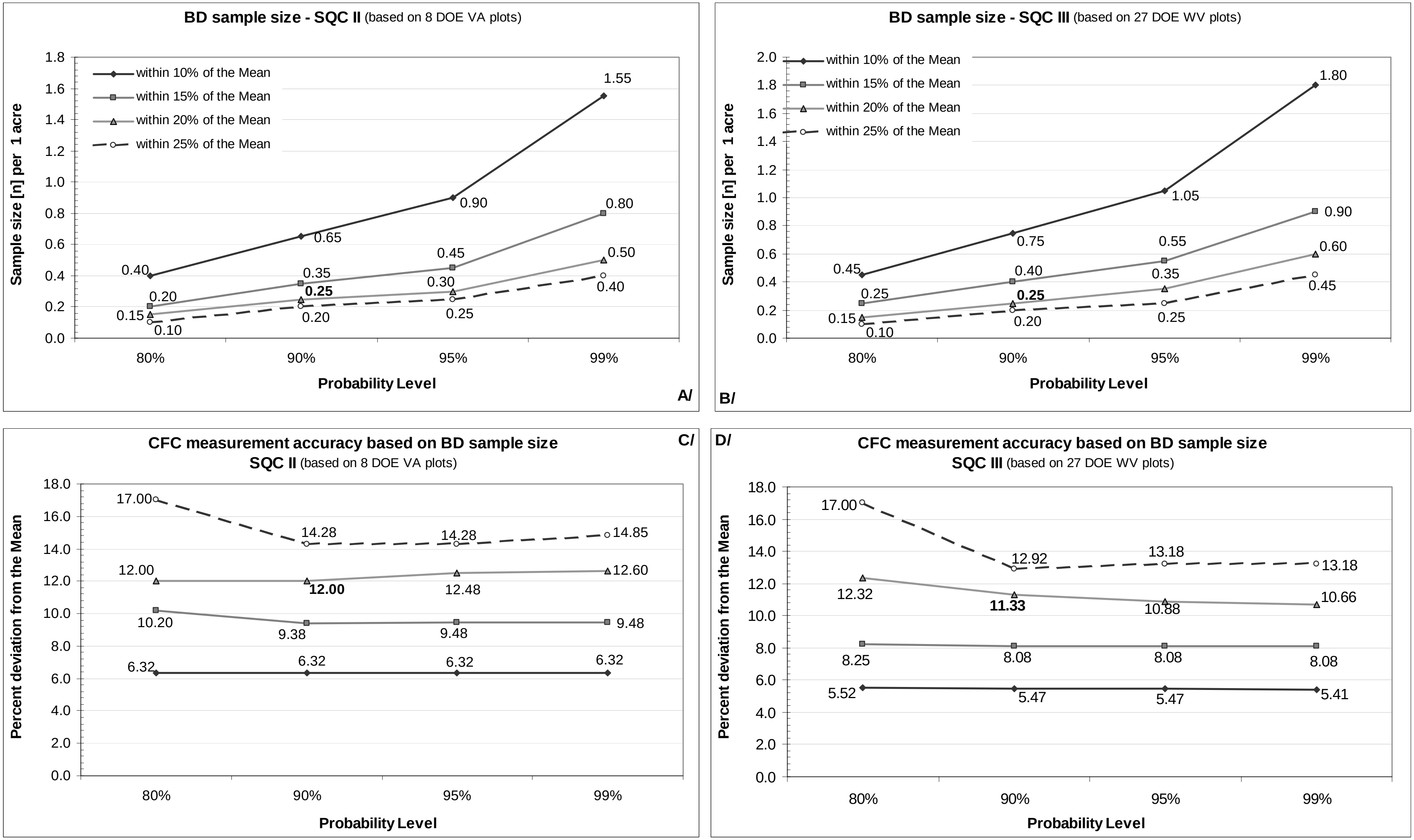


Figure 1-3. Sample size estimates (*n*) required to obtain a certain accuracy (10, 15, 20, and 25%) of the mean estimate for BD (graphs A and B) and accuracy levels of the CFC measurement for each BD sample size indicated by the same line patterns (graphs C and D), with a certain probability (80, 90, 95, and 99%) of this occurring for four site quality classes on the Flint Gap mined site.

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

Executive Summary

During the reporting period (April-June, 2005), we completed lab analysis on field samples collected in earlier reporting periods. A classification scheme has been developed and some field-testing of the methods of implementation was completed. A validation study on white pine (*Pinus strobus* L.) was completed as well.

Experimental

General Productivity Index Model Development and Validation

Previous research demonstrates known relationships between tree growth and a number of measurable site and soil properties. Agronomic researchers have successfully combined soil properties in models to estimate crop production potential (Neill 1979, Kiniry 1983, Pierce et al. 1983):

$$PI = \sum_{i=1}^{r} (A \times B \times C \times D \times WF)_i \qquad \textbf{(2-1)}$$

where PI is a productivity index scaled from 0 to 1; A, B, C, and D are sufficiency levels (scaled from 0 to 1) of soil properties known to influence crop production; and WF is a weighting factor that adjusts the relative importance of different soil layers through the profile. The product was summed over *r*, the number of soil layers within the total rooting depth.

Foresters have modified this model to estimate tree species production potential on forest land (Gale 1987, Henderson et al. 1990):

$$PI = \sum_{i=1}^{r} (A \times B \times C \times D)^{1/4} \times WF)_i \times (S \times Cl)^{1/2} \qquad \textbf{(2-2)}$$

where the first part of the equation is the same as Equation 2-1 except that the geometric mean (1/4 in the exponent) of the product is taken to assure equal weighting of the four soil properties; the product is summed over r, the number of soil layers (as in Eq. 2-1); and S and Cl are sufficiency levels for slope and climate site factors, and the geometric mean (1/2 in the exponent) of the product is taken to assure equal weighting of those two site properties.

The underlying concept of PI models is that the overall productivity of a plant is proportional to root growth (Henderson et al. 1990). Therefore, a tree whose root growth is not restricted is expected to grow at its genetic potential for a given climatic region. These soils would have a PI value of 1.0. A soil where root growth is completely prevented would receive a PI value of 0.0 and a tree would not survive.

A PI model that incorporates key soil properties most influencing forest growth on mine soils might be used by reclamation personnel to identify optimum soil and site conditions for production of specific forest trees. Foresters and reclamation managers can use important soil and site properties to classify mine soils into a set of forest site quality class (FSQC) for predicting site index by tree species. The FSQC can be used to make silvicultural recommendations such as whether a site should be planted to trees, species selection if planted, and necessary remediation or management for mine land that is to be managed for optimal forest production. The objectives were to: (1) develop a general soil-based PI model for predicting site index and FSQC for specified tree species on reclaimed surface mined land in the Appalachian coalfield region; (2) improve the accuracy of the PI model for white pine by measuring growth and soil and site properties on previously established stands; and (3) demonstrate the practicality of using the model by mapping a selected site.

Based on previous research, nine soil and site properties were selected for inclusion in a general forest PI model. Sufficiency curves defining the relationship between tree or root growth and levels of the soil and site properties were developed based on past and current research. The general PI model was developed based on the mathematical format of Equation 2-2, except that only one soil layer (0-20 cm) was analyzed, different properties were measured, and site properties were included together with soil layer properties.

Nine soil and site properties were measured or estimated to validate the general PI model for white pine growth on post-SMCRA reclaimed mine lands. Fifty-two white pine stands ranging from 10 to 18 years old were sampled at sites in Wise County, Virginia, and Nicholas, Mercer, and Wyoming Counties, West Virginia, for soil and site variables and for site index (SI = dominant tree height at age 50) of white pine, as explained below.

Field-Measured Soil and Site Properties

The pH, EC, texture, color, sandstone %, RF volume percent, soil density class, potential rooting depth, slope, and aspect were estimated at several (three to five) locations in a sample area and averaged for a representative result due to the extreme heterogeneity of mine soils. The color data was not included in the model but was used as ancillary data. The sample area varied from 9 to 36 m^2 depending on tree and stand diversity and the uniformity of soil types.

The dominant soil material in the upper 20 cm was evaluated at each sample site. The pH and EC were measured with a Hanna HI 9812 field meter (Hanna Instruments Inc., Woonsocket, RI) in pH units and $\mu S\ cm^{-1}$, respectively. The soil hue, value, and chroma were recorded using Munsell Color Charts. On sites where an A horizon had formed on the surface, the Munsell color was read below the zone of apparent organic matter (OM) accumulation. Soil texture class was estimated by rubbing moistened soil. Sandstone % was estimated as the proportion of sandstone fragments compared to the total volume of all rock fragments (the RF volume) in the sample area.

No completely quantitative method was found to accurately predict mine soil D_b because of the high volume of RFs. Conventional D_b measurements require laboratory calculations of RF volume and moisture content, and are too time-consuming for field practical measurements. Therefore, the "density class" of the upper 20 cm was estimated based on the average penetration depth of a sharpshooter (tapered shovel with rounded tip blade 14 cm wide and 40 cm long) along with observations of soil rupture resistance and RF type and volume. The sharpshooter was stepped on using a steady force from the weight of a 70-kg person, and the depth and ease in which it penetrated the soil was noted along with the associated soil properties listed above. The following guides were used to estimate five general density classes: If the sharpshooter penetrated easily to 25 cm or more, a density class of "very low" was assigned; if penetration was 16 to 25 cm with slight resistance, a density class of "low" was assigned; if penetration was less than 15 cm with moderate resistance, a density class of "moderate" was assigned; if penetration was less than 5 cm with strong resistance, a density class of "high" was assigned; and if penetration was less than 2 cm, a density class of “very high” was assigned. The density class was decreased one class in soils with an estimated RF content greater than 50%, provided that the moist rupture resistance (a.k.a. moist consistence class) at the depth of maximum sharpshooter penetration was not very firm or extremely firm (Soil Survey Division Staff 1993) as confirmed by shallow pit excavations. In moist soils with low RF content and textures finer than sandy loam, the density was increased one class because those soil conditions allow sharpshooter penetration into soil that has moist rupture resistance of very firm or extremely firm as confirmed by shallow pit excavations. In extremely dry soils, no adjustment was made. Along with the rupture resistance, fine root growth widely-spaced or matted between aggregates and large aggregate size were used to confirm that the soil was dense.

The potential rooting depth (cm) was determined by using a screw auger (round tip screw head 16 cm long and 5 cm wide with 3 complete turns and on a 97 cm-long shaft) and turning it into the ground until significant resistance (more than upper body strength was required) was felt or complete refusal was reached. Layers with “bridging voids” (large air gaps between rocks), greater than 90% rock fragments, and essentially no soil were considered root limiting, along with dense, compacted layers.

Site factors were measured at each sample location. Percent slope was measured using a standard clinometer. Aspect was measured as an azimuth on slopes greater than 15% using a standard compass.

At each sample point, the nearest two to four trees were measured using the growth intercept model developed by Beck (1971), in which the length of the first five internodes (distance between whorls of branches) beginning at breast height (1.4 m) is measured and converted to a site index (Eq. 2-3). Waiting until the tree reaches breast height minimizes the effects of strong competition by ground cover on tree seedlings.

$$SI = 26 + 6.6\ (\text{5-year intercept length}) \qquad \textbf{[2-3]}$$

where: SI = white pine site index (predicted tree height in feet at age 50); 26 and 6.6 are coefficients; and 5-year intercept = total length in feet of the first five internodes beginning at breast height.

Statistical Analysis

Multiple linear regression techniques were used in SAS 9.1 (2003) to identify the soil and site properties from the soil and site variables at each sample site that were the most significantly related to white pine SI calculated in Equation 2-3. Transformations of the independent variables were used to linearize the data based on known relationships. Multi-collinearity assessments were made using variance inflation factors (VIF’s) (Montgomery et al. 2001). Data points with large influence or leverage on the model were identified using various influence statistics (Montgomery et al. 2001). Distributions, normality, and homogeneity of variance of the data were all analyzed using residual plots, stem-leaf plots, and normal probability plots (SAS 9.1, 2003). Mallows’ C(p) statistic was used as a selection procedure to derive a list of the best models (Montgomery et al. 2001). Importance factors (IF) for each variable were calculated using the absolute value of standardized coefficients (Montgomery et al. 2001), and normalizing the values from 0 to 1. The PI model was developed and modified from Gale (1987), and regressed with SI using Microsoft Excel.

Sufficiency curves were developed for nine soil and site properties that were reported in the literature to have had significant effects on tree growth, and that could be analyzed in the field. Many of these curves have previously been adapted for use on mine soils and for tree growth as opposed to agricultural crops. Sufficiency curves for pH, EC, D_b, rooting depth, and slope have been previously established for white pine productivity measurements of mine soils in the study region (Andrews 1992, Torbert et al. 1994). Sufficiency curves for RF, texture, aspect, and sandstone % were developed based on previous research.

Mapping

A mountaintop removal mine was selected as a mapping demonstration area to test the practicality of the classification system developed. It was located in Dickenson County, Virginia, and is known as the Flint Gap site. This site was reclaimed in 1994, and herbaceous vegetation along with some planted white pine and Virginia pine (*Pinus virginiana* Mill.) dominated the site. Some volunteer seedlings had become established as well, but very little growth was evident.

Data were collected in selected locations using standard soil mapping techniques, and the model developed was used to delineate polygons that represented different FSQC. Ordination symbols of p, r, t, and c were designated to map units if one of the selected properties of pH, RF, texture, or density respectively had a sufficiency value of 0.6 or less. A rooting depth of less than 50 cm was given the ordination symbol of d. Spot symbols were used to indicate wet spots on the landscape.

Results and Discussion

General Productivity Index Model Assessment

A sufficiency curve was developed for pH (Fig. 2-1), similar to the one used by Andrews (1992), and was adjusted using research results from Gale et al. (1991) and Torbert et al. (1990). A pH between 4.5 and 5.8 was considered optimal for white pine and was assigned a sufficiency level of 1.0, while a linear decline on each side of the optimal plateau resulted in a pH of 3.0 and 8.0, having a sufficiency level of 0.2. High pH values (>7) may be enough to reduce the availability of boron (B), copper (Cu), zinc (Zn), iron (Fe), and manganese (Mn) (Brady and Weil 1999). A lower pH negatively affects the growth of herbaceous ground cover seeded during reclamation, reducing the competition with trees.

A sufficiency curve for EC developed by Andrews (1992) was used in this study (Fig. 2-2). An EC value less than 0.5 dS m^{-1} was not suspected to have an effect on white pine productivity, and the curve declines linearly to an EC of 2 dS m^{-1} and a sufficiency level of 0.2. Andrews et al. (1998) found that total soluble salts ranged from 0.02 and 1.97 dS m^{-1} across 78 mined sites. When values exceeded 1.00 dS m^{-1}, total salts became one of the most important chemical properties affecting white pine growth on mine soils.

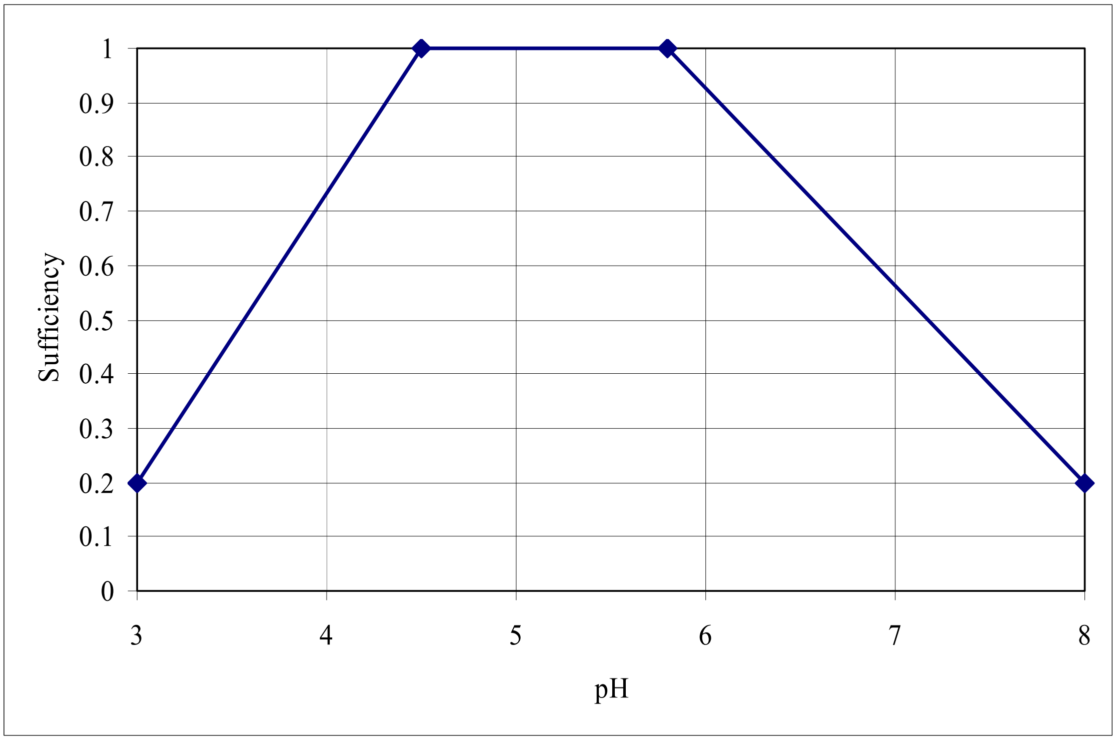

Figure 2-1. Sufficiency curve for pH based on research by Andrews (1992), Gale et al. (1991), and Torbert et al. (1990).

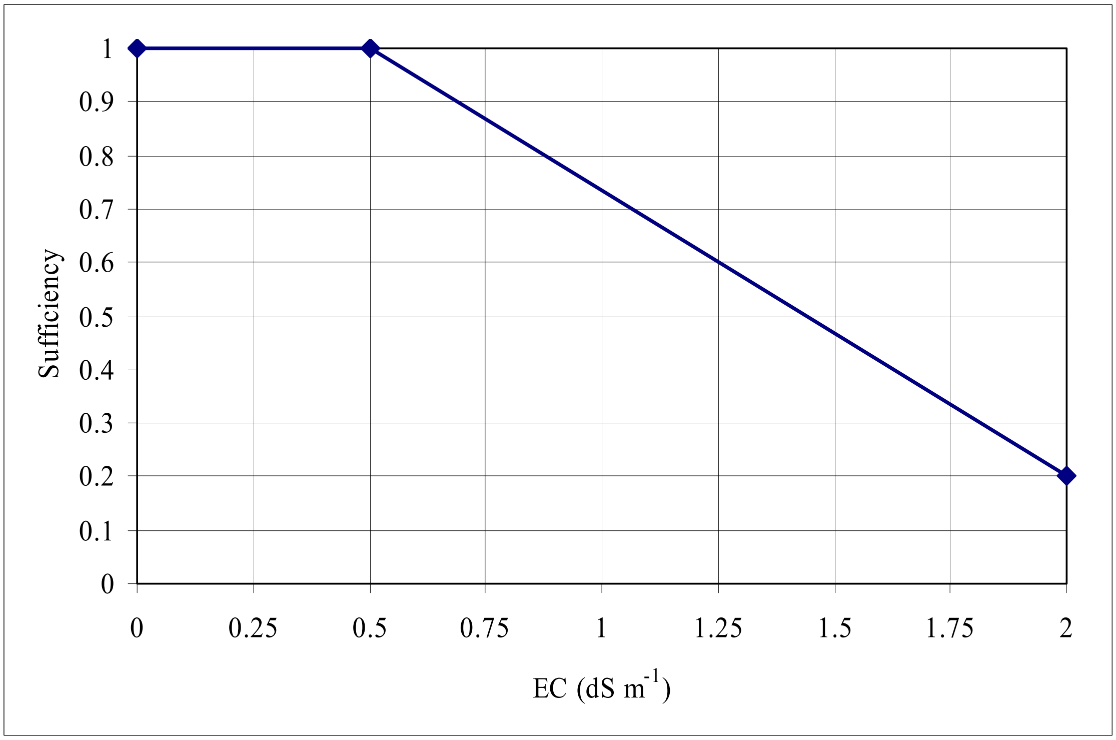

Figure 2-2. Sufficiency curve for electrical conductivity (EC) on mine soils in the Appalachian region (reproduced from Andrews 1992).

Neill (1979) and Andrews (1992) produced sufficiency curves for D_b, both of which decline in sufficiency level above a critical D_b. The sufficiency curve developed in this study follows the same pattern but is shifted slightly to the left to correlate it with our sharpshooter penetration method of soil density class assessment (Fig. 2-3). A point along the soil density continuum is chosen to determine a sufficiency value. Mine soils typically have less structure and porosity and fewer interconnected pores than native soils, which leads to lower soil moisture availability and aeration. The densities that were considered limiting were adjusted downward based on our own D_b measurements. This adjustment also accounted for inherently lower porosity in mine soils than in native soils. The D_b sufficiency curve was modified by Andrews (1992) using data from Pierce et al. (1983) to account for three different general particle size classes. Our method for determining soil density class in the field accounts for soil texture and allows the use of only one sufficiency curve.

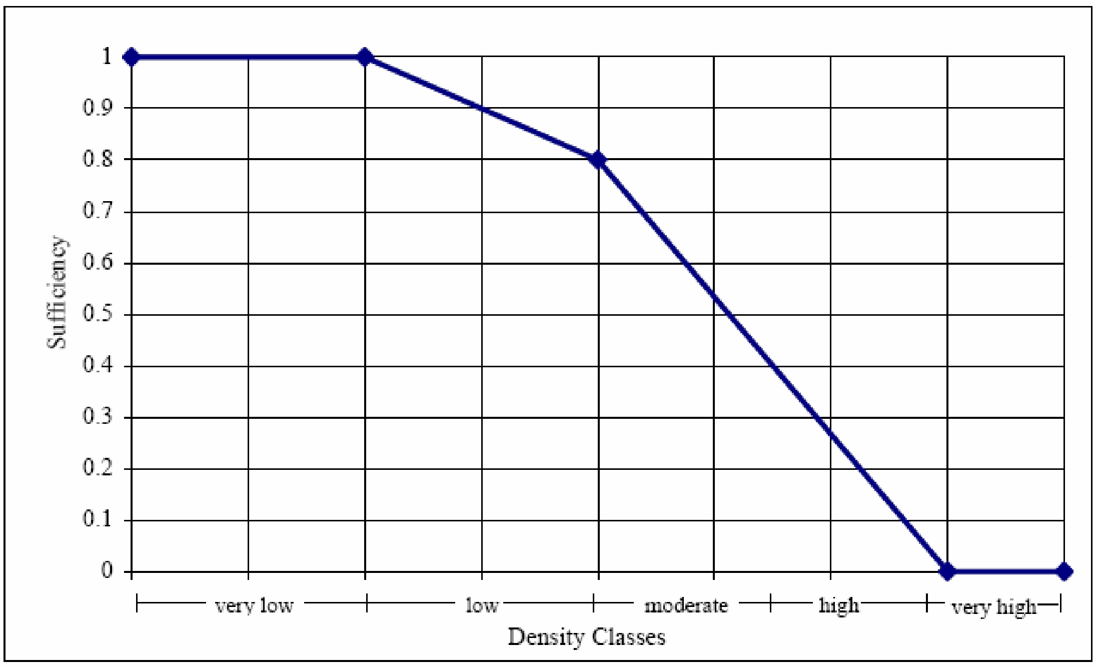

Figure 2-3. Bulk density sufficiency curve developed by Andrews (1992) and Neill (1979) and modified to accommodate the sharpshooter penetration density classes adjusted for porosity differences in mine soils compared to native soils.

With the requirement of returning the land to AOC, reclaimed mine spoil is graded with large equipment. Slopes >25 % are difficult to traverse with large equipment, and the soils on steep slopes are consequently less compacted and have a deeper rooting depth than soils on flat areas (Andrews et al. 1998). Therefore, the slope of a site may be used as a surrogate for the degree of compaction. The sufficiency curve for slope developed by Andrews (1992) assigns a sufficiency of 1.0 to all slopes greater than 35% (Fig. 2-4).

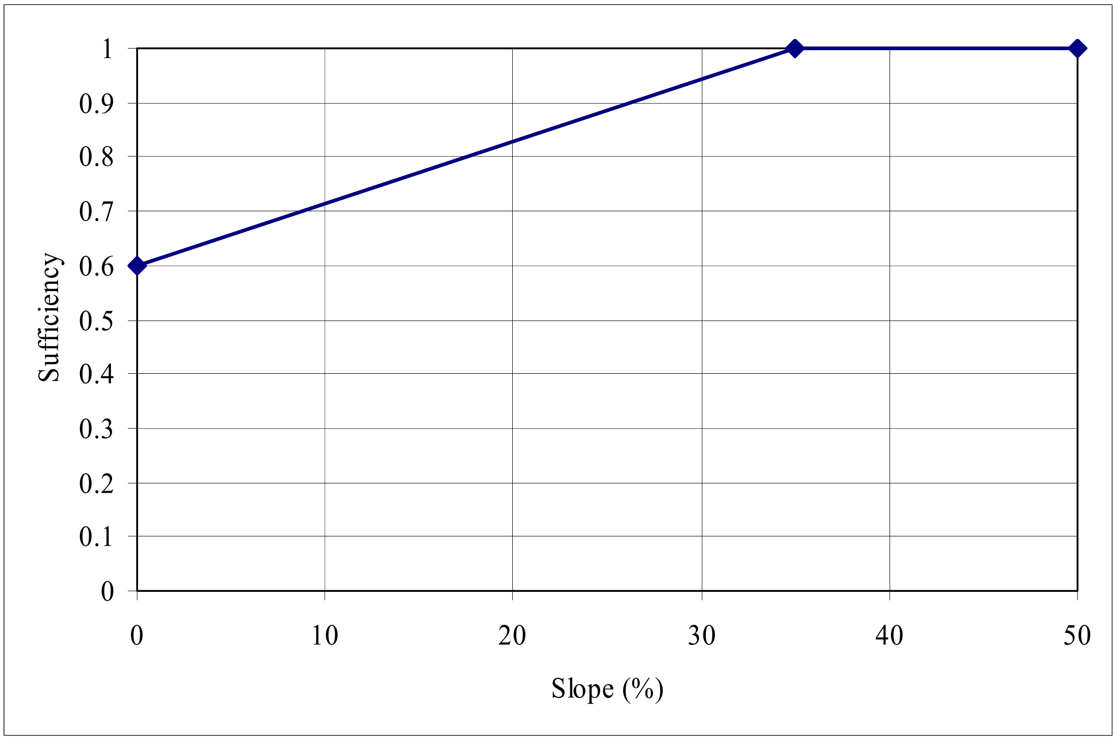

Figure 2-4. Sufficiency curve for slope on mine soils in the Appalachian region (reproduced from Andrews 1992).

No sufficiency curves for soil texture have been published. A first approximation of a soil texture sufficiency curve (Fig. 2-5) was based on mine soil research by Burger and Zipper (2002), and on white pine growth on native soils by Lancaster and Leak (1978). High clay soils are known to be unproductive for white pines, and extremely sandy soils have low water holding capacity. Sandy loam textures are optimal for pine growth (Burger and Zipper 2002); this textural class falls within the range of silt + clay % that has a sufficiency of 1.0. Silt + clay % overlap texture class boundaries. Some growth is expected at 0 and 100 % silt + clay. Silty soils and soils with high clay content are also more easily compacted and less aerated than soils dominated by sand-sized particles. Poor aeration and drainage are chief causes of poor tree survival and growth.

The RF sufficiency curve is based on research by Rodrigue and Burger (2004). A linear relationship with increasing RF contents and decreasing sufficiency levels is expected at RF content greater than 35 % (Fig. 2-6). Bramble (1952) reported that at least 20% of soil-sized particles must be present for trees to survive. Others have recognized 90% rock fragments as being totally root-limiting (J. Sencindiver 2005, pers. comm.).

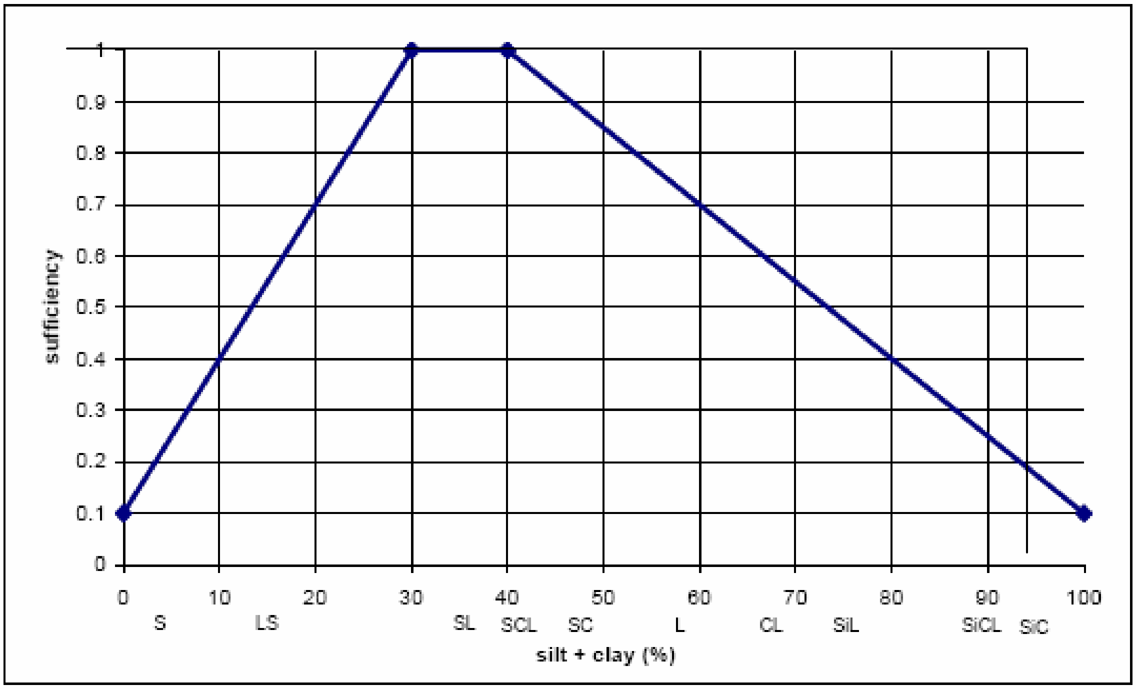

Figure 2-5. Sufficiency curve for texture and its influence on white pine growth on mine soils in the Appalachian region based on research from Burger and Zipper (2002) and Lancaster and Leak (1978). Silt + clay % overlap texture class boundaries.

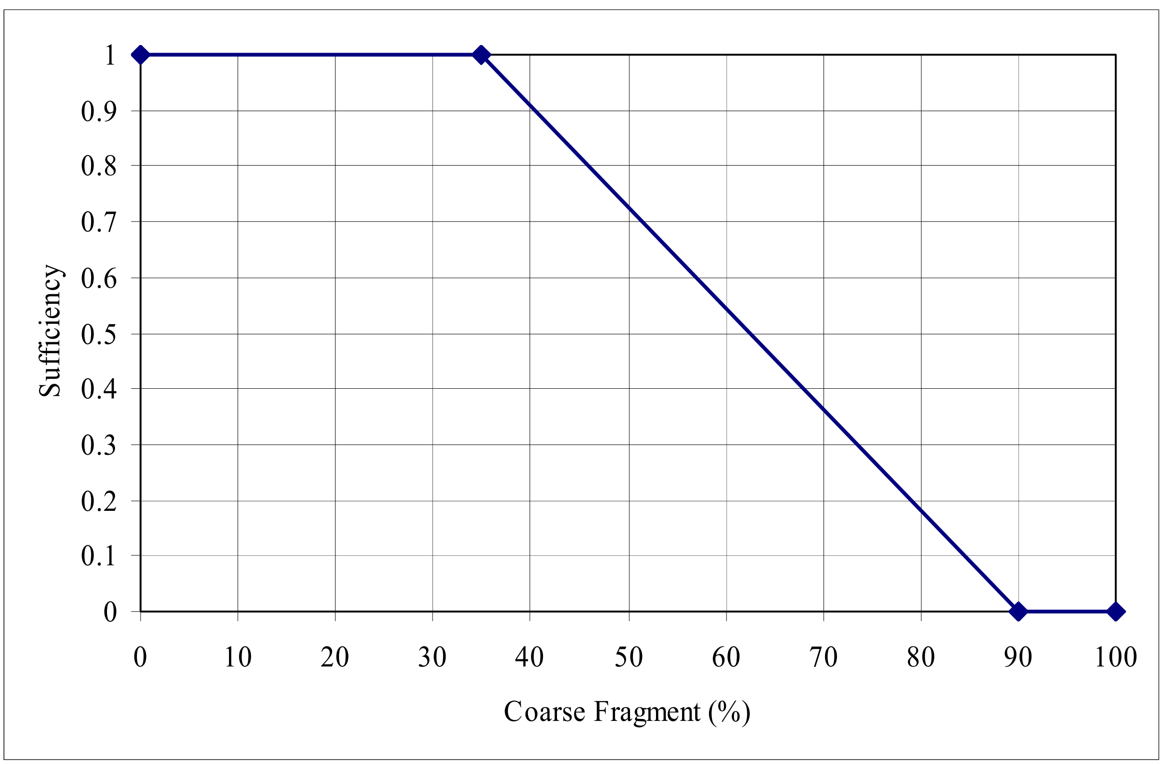

Figure 2-6. Rock fragment sufficiency as a function of rock fragment volume.

The sufficiency of potential rooting depth was defined by Equation 2-4 (Gale, 1987):

$$Y = 1 - \beta^{d} \qquad \textbf{[2-4]}$$

where Y = cumulative root fraction from the soil surface to soil depth ^{d} (cm), and β = 0.96, an estimated parameter used by Torbert et al. (1994) for white pine.

The sufficiency curve for rooting depth attributes greatest importance to the thickness of the surface soil layer, with the relative importance of rooting in subsoil layers decreasing exponentially with depth (Fig. 2-7) (Gale 1987). Torbert et al. (1988b) found that the rooting volume index (RVI = rooting depth x percent fraction <2 mm) accounted for almost 50% of the variation in tree height for eight-year-old white pines.

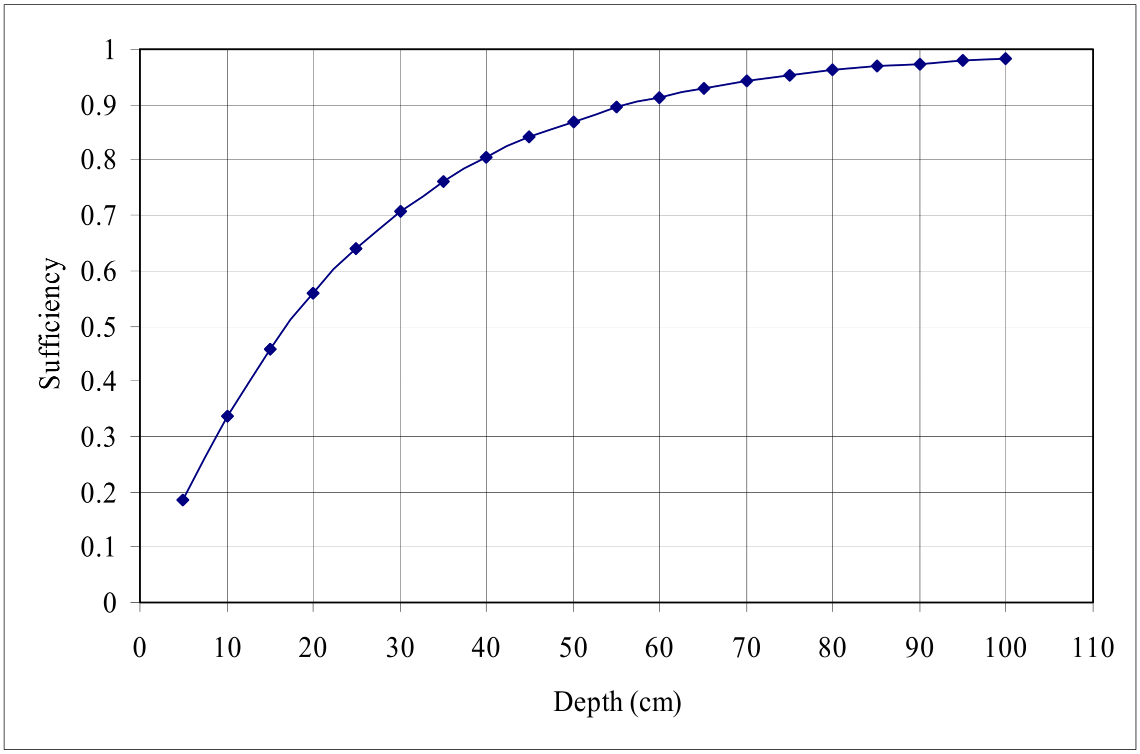

Figure 2-7. Sufficiency of rooting depth potential declines exponentially with decreasing depth (Gale 1987).

No sufficiency curves have been previously developed for sandstone %, so a linear sufficiency curve was developed based on research from Torbert et al. (1990) (Figure 2-8). A sufficiency of 0.4 is given for 0% sandstone because lack of sandstone is not expected to totally limit tree growth. Siltstone and shale weather into finer particles and are generally more susceptible to compaction, have fewer macropores, a higher pH, and higher levels of soluble salts than most sandstone spoils. In a study by Torbert et al. (1988a) of hybrid pine growth on different rock mixtures, four-year-old trees had an average height, diameter, and volume of 146.2 cm, 40.4 mm, and 685 cm^3, respectively, on oxidized sandstone spoil. On siltstone spoil, the respective values reported were 84.8 cm, 21.8 mm, and 123 cm^3. After five years, Torbert et al. (1990) concluded that overall survival was not significantly affected by rock type, but tree volume was. About 1.2 m of uncompacted sandstone material is needed to produce a mine soil of high quality and productivity for native trees (Burger and Zipper 2002).

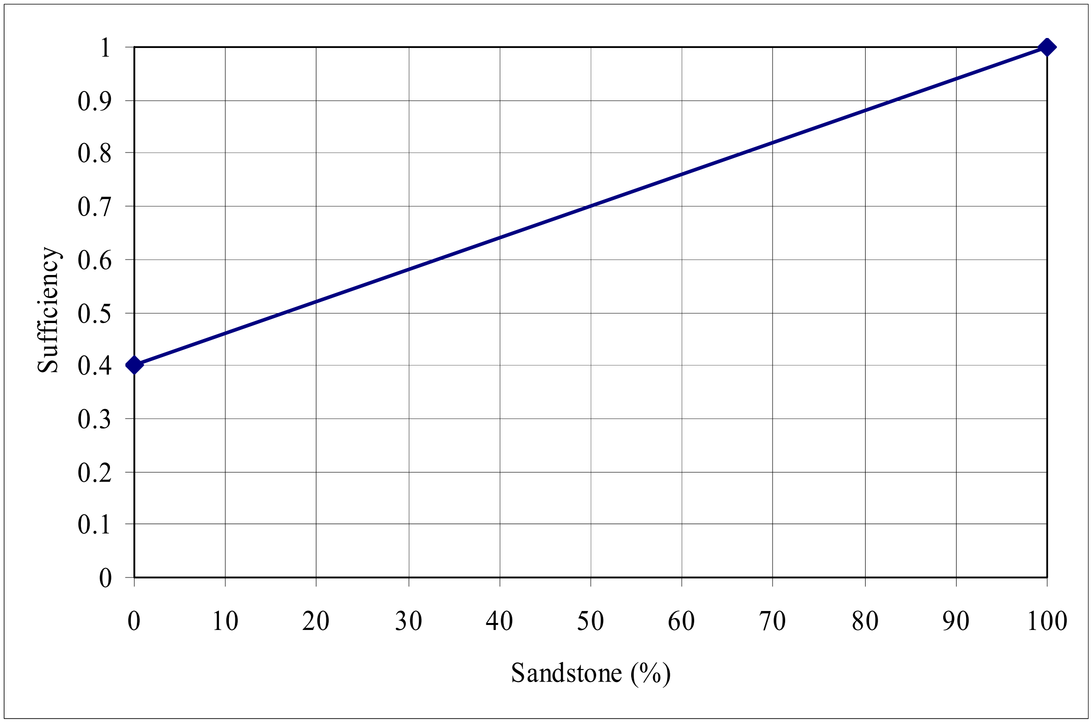

Figure 2-8. Sufficiency curve for sandstone % used on mine soils in the Appalachian region, developed based on research from Torbert et al. (1990).

A sufficiency curve was developed indicating northeast aspects being the best and southwest aspects being the worst sites for tree growth (Figure 2-9), based on research by Hicks and Frank (1984) and Burger et al. (2002). The sufficiency levels may not be true on high-elevation mine sites, where sunlight may become limiting on steep northeast-facing aspects (Miller et al. 2004, Whittaker 1966).

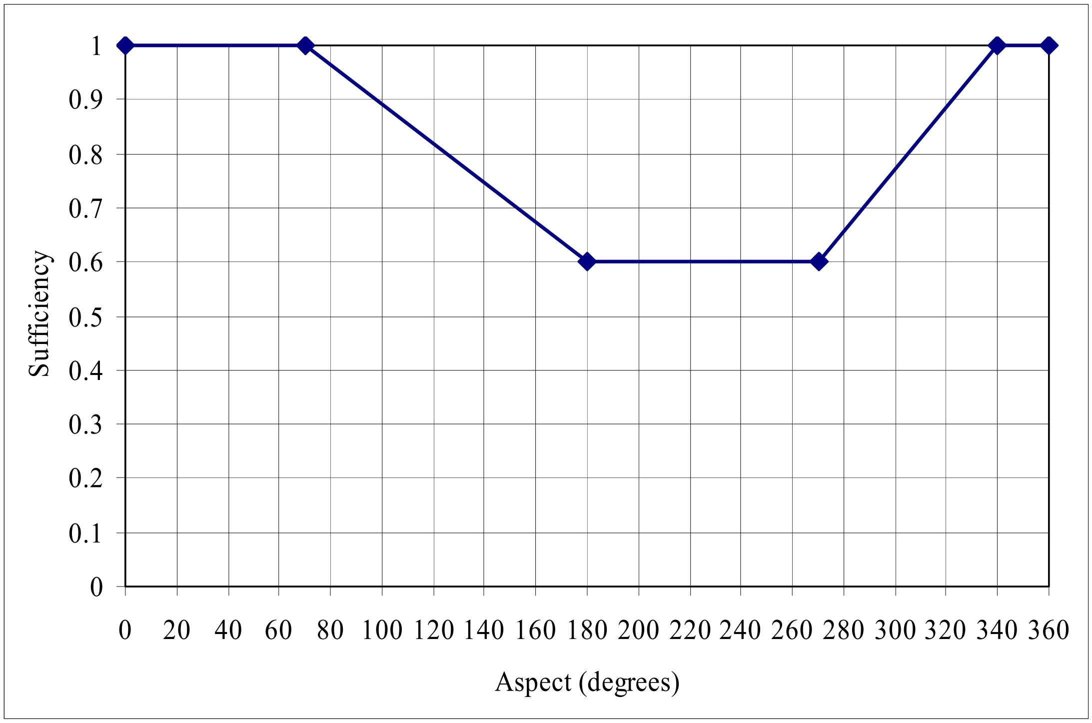

Figure 2-9. Sufficiency curve for aspect used on mine soils in the Appalachian region, based on research by Hicks and Frank (1984) and Burger et al. (2002).

The general PI model incorporating the soil and site properties that affect forest productivity on mine soils is:

$$PI = (pH \times EC \times density \times slope \times texture \times RF \times sandstone\ \% \times aspect)^{1/8} \times depth \quad \textbf{[2-5]}$$

where PI = productivity index; pH = sufficiency of pH; EC = sufficiency of electrical conductivity; density = sufficiency of density class; slope = sufficiency of slope; texture = sufficiency of texture determined by silt + clay %; RF = sufficiency of rock fragment volume; sandstone % = sufficiency of sandstone %; aspect = sufficiency of aspect; depth = sufficiency of potential rooting depth (equivalent to the WF variable in Equation 2-2).

PI was calculated for each of the 52 white pine sites using Equation 2-5. PI values were regressed with white pine SI to determine the extent to which the general PI model correlated with SI. The fit of the general PI model to SI of the validation sites resulted in an R^2 value of 0.61 (Figure 2-10). This shows that the general soil-based PI model could be used in lieu of SI to estimate the productivity of white pine on post-SMCRA mined land.

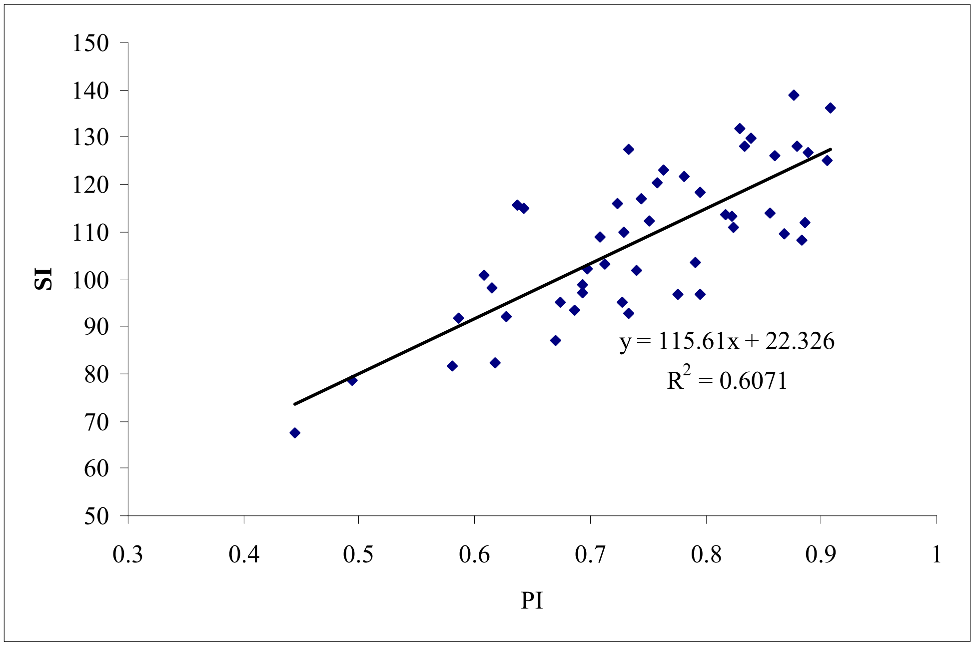

Figure 2-10. The general productivity index (PI = x) regressed with site index (SI = y, tree height at age 50) of white pine growing on mine soils in the Appalachian region.

White Pine-Specific Productivity Index Model

The general PI model (Eq. 5-5) calculated a geometric mean for all soil property sufficiency levels, assuming that each had the same level of importance on the PI. Soil and site properties have varying influence on productivity dependent upon the tree species. The general PI model could be improved if each property was weighted based on the extent to which it influenced growth of a particular tree species. A white pine-specific PI model was developed using regression relationships between white pine SI and soil and site properties found on the 52 measured sites.

Data from three of the original 52 sampling points were discarded because the SI values were extreme outliers or had large influence and leverage on the model determined by influence statistics. Site index was regressed with all soil and site properties after the raw soil and site data were transformed to linearize them and reduce the variability. The pH variable was squared, an arcsine transformation was used on all data that was recorded in percent, and the RF and slope variables were log transformed.

The C(p) selection procedure indicated that the best white pine PI model included only the variables of texture, density, and rooting depth ($R^2 = 0.695$ and adjusted $R^2 = 0.675$). The VIF's indicated that no significant multi-collinearity problems existed.

Soil density was the most significant variable ($p < 0.0001$) affecting tree growth (Table 2-1), as predicted by the work of Daniels and Amos (1981) and Torbert and Burger (1990). A regression of SI and soil density class alone resulted in a R^2 of 0.53, with higher densities having lower SI values. Rooting depth was the second most influential significant variable ($p = 0.0002$), which agrees with the results reported by Andrews et al. (1998) and Torbert et al. (1988b).

Rooting depth is not expected to be as important in seedling survival and early growth when the root system is not yet fully developed. Sandy loam and loam were the only textures recorded across all of the validation sites. This may have led to a biased evaluation of the texture variable, but the variable was significant ($p = 0.0051$) (Table 2-1) and has been reported as an influential property by Burger and Zipper (2002).

Table 2-1. Standardized coefficients, importance factors, and significance values for the independent variables used in the final model (Eq. 2-6).

Variable	Standardized Coefficient	Importance Factor	*p*-value
Density	-0.54219	0.47	<0.0001
Rooting Depth	0.36684	0.32	0.0002
Texture	-0.24362	0.21	0.0051

The pH variable was insignificant ($p > 0.10$). The soil reaction ranged from pH 4.3 to 8.0 with the distribution of values skewed to values lower than the median value (Table 2-2). Most native trees in the Appalachian Mountains grow where pH is approximately 5.5 (Skousen et al. 1994), but some species can also grow well at more neutral pH values. A more diverse range of observed pH values would likely have increased the importance of pH on the model.

Table 2-2. Ranges of measured values and sufficiency values for pH, electrical conductivity (EC), aspect, texture, rock fragment (RF) content, sandstone (SS) content, slope, soil density, and soil depth at 52 sites in southern West Virginia and southwest Virginia.

Property	pH	EC (dS m^{-1})	Aspect (degrees)	Texture (USDA class)	RF	SS	Slope	Density	Depth (cm)
					----------------%----------------				
Range of values	4.3-8.0	0.01-0.25	1-355	SL, L, SiL	10-43	10-90	1-50	very low - high	28-100
Range of sufficiencies	0.2-1.0	1.0-1.0	0.6-1.0	0.55-1.0	0.86-1.0	0.45-0.94	0.6-1.0	0.2-1.0	0.68-0.98

RF volume ranged from 10 to 43% (Table 2-2). These values were lower than initially expected due to the increased age and weathering time of the white pine validation sites. RF volume % was negatively correlated with SI and was an insignificant variable ($p > 0.10$). Rodrigue and Burger (2004) found RF volume % to be negatively correlated with SI of white oak, and the same was expected in this study. However, the low levels of RF volume % in this study may not be in the range in which limitations to growth occur, but they do affect water holding capacity and total rooting volume, both of which are extremely important to forest productivity (Aydelott 1978). RF volume % may be more important on younger sites for seedling survival when trees have not yet developed an extensive root system, available soil moisture is limiting, and most RFs have not undergone physical weathering into finer soil material (Haering et al. 1993).

EC was not significantly ($p > 0.10$) correlated with white pine in the white pine PI model, contrary to the results of Andrews et al. (1998) and Rodrigue and Burger (2004). In a study on 10-year-old white pines by Torbert et al. (1988b), the highest EC level recorded was 1.7 dS m^{-1} and it corresponded to a tree size of only 1.18 m. This suggests that a critical value of 1 dS m^{-1} is associated with white pine productivity and all EC values in this study were lower than 1 dS m^{-1} (Table 2-2). All textures were sandy loam, loam, and silt loam (Table 2-2), which have been reported to have low EC values, while finer textures are more commonly associated with higher EC levels (Rodrigue and Burger 2004). The ages of the sites were all between 10 and 18 years, allowing any initially high salt levels to leach over time. However, the use of the EC variable for younger sites (< 5 years) may be beneficial for predicting tree survival.

In this study slope was insignificant ($p > 0.10$), but it could serve as an indicator of probable soil density, as flatter slopes tend to be more compacted on post-SMCRA mine lands (Andrews et al. 1998). Aspect was also insignificant ($p > 0.10$) in this model. Aspect becomes more important as slope angle increases, and steep, southwest-facing slopes should be the driest and thus have the lowest SI values for white pine. However, soil density decreases as slope angle increases, and therefore the lack of compaction and increased rooting depth may offset the effect of aspect on steep, post-SMCRA reclaimed mine soil slopes. The proportion of sandstone was not significant ($p > 0.10$) in this PI model. However, the proportion of different rock types in the topsoil substitute affect SI to some degree because they control the mine soil color, texture, and pH properties that occur after years of exposure and weathering.

A relative IF was calculated for each soil property in the regression model. IFs were calculated by normalizing the standardized coefficients from 0 to 1. Density was the most important soil property that affected white pine growth in this data set, followed by rooting depth and soil texture (Table 2-1). The sufficiency level of each soil property was weighted by its relative importance (IF) as shown in the following additive PI model:

$$PI_{wp} = (texture*IF_{txt}) + (density*IF_{Db}) + (depth*IF_{d}) \quad \textbf{[2-6]}$$

where PI_{wp} = white pine-specific productivity index; texture = sufficiency of texture; density = sufficiency of soil density class or D_b; depth = sufficiency of rooting depth; and IF = importance factor for each soil property (Table 2-1).

A regression of PI_{wp} with SI (Figure 2-11) shows that weighting the sufficiency values based on the relative importance of each soil property improved the mine soil productivity estimation. The R^2 of the PI_{wp} versus SI relationship was 0.68, better than the R^2 of 0.61 for the general PI model (Figure 2-10).

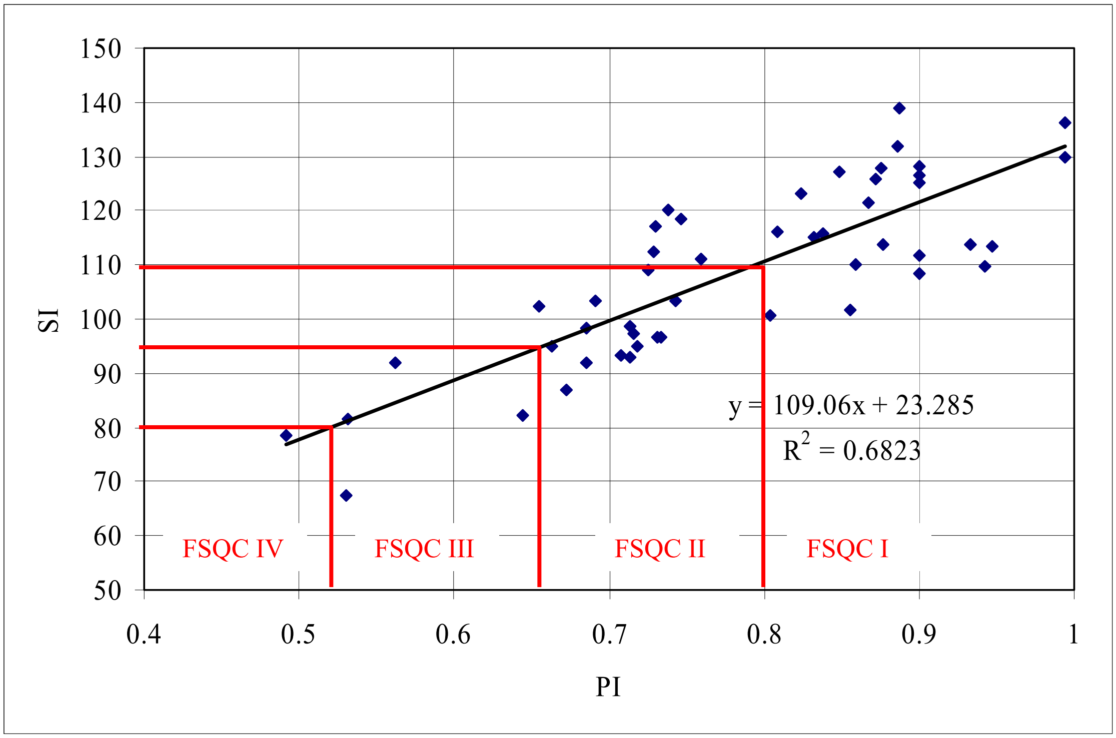

Figure 2-11. A regression of the white pine-specific productivity index (PI_{wp} = x) with site index (SI = y, tree height at age 50) of white pine.

Forest Site Quality Class Development

For management purposes, foresters commonly divide the site quality gradient found across the landscape into site quality classes. The PI_{wp} was used to separate five categories of FSQC for white pine, with FSQC (I) being the most productive and FSQC (V) being the least productive (Table 2-3). No white pines were found in this study that survived in soil-site conditions of FSQC (V). The SI breakpoints for white pine were based on the research of Doolittle (1958), who found the average SI for white pine on natural soils in the southern Appalachians to be 24 m (80 ft). His study showed an SI range from 20-30 m (66-98 ft).

Table 2-3. Productivity index (PI) associated with forest site quality classes (FSQC) and predicted site index (SI, tree height at age 50) for white pine growing on mine soils in the Appalachian coalfield region.

PI	FSQC	SI (ft)	SI (m)
≤0.38	V	< 65	< 20
0.39-0.52	IV	65-79	20-24
0.53-0.66	III	80-94	24.4-28.7
0.67-0.80	II	95-110	29-33.5
>0.80	I	> 110	>33.5

The following example data can be used to demonstrate the use of the FSQC to predict white pine SI: silt + clay % = 60 %, density level = midrange moderate, and rooting depth = 57 cm. SI_{wp} = (0.7*0.21) + (0.5*0.47) + (0.9*0.32) = 0.67. According to Table 2-3, this value falls on the high end of the range for FSQC III, and white pines growing on this site will likely have a SI in the high end of the 80- to 94-ft range.

Hardwood Productivity Index Model Development

The PI_{wp} model appears to be a good estimator of FSQC for white pine on older surface mines. However, some reclamationists may want to plant trees immediately following final reclamation grading or before bond release. We believe that the addition of the RF volume %, EC, sandstone %, and color variables would be beneficial for sites less than five years old. Sites older than this have already been through the initial weathering stages during which salts are leached and easily weathered rocks have broken down into soil fines, and the PI model similar to that discussed above may be more appropriate.

Native hardwood tree species may be preferred on some reclaimed mined sites. Hardwood species may respond differently to mine soil properties compared to white pine (Burns and Honkala 1990). Therefore, it would be important to calibrate sufficiency curves for hardwoods, to the extent possible, based on published species/mine soil relationships. Hardwoods have only recently been used for post-SMCRA reforestation in the Appalachian region, and very few sites exist for model validation. However, based on the success of this initial FSQC model developed for white pine, it appears that an adequate general model could be developed for hardwoods as well. Furthermore, hardwood SI can be estimated with site index comparison curves developed for several Appalachian species (Doolittle 1958).

Hypothesized sufficiency curves have been developed for hardwood species based on known silvicultural characteristics of species native to the Appalachian region (Burns and Honkala, 1990). The EC, density class, slope, and rooting depth sufficiency curves developed for white pine are considered adequate for hardwoods. The pH curve is shifted toward higher pH values since most hardwoods are not as acid-loving as white pine and other conifers (Fig. 2-12). The texture curve shifts toward higher silt + clay % and has a wider optimal range (Fig. 2-13). Hardwoods are not adversely affected by heavy clay soils (Lancaster and Leak 1978), but structureless mine soils will likely continue to present aeration problems when sand percent is very low. The RF curve indicates that RF volume % will become a limiting factor for hardwood productivity at lower levels than for white pine (Fig. 2-14). White pine is more tolerable of stony, droughty soils and can be productive on sites where moisture limits optimal hardwood growth (Lancaster and Leak 1978). Sandstone rock types are more acidic, weather into sandy loam soil textures, and have higher nutrient levels than siltstone rock types (Torbert et al. 1990, Burger and Zipper 2002, Haering et al. 1993). Due to a higher acceptable pH range and increased tolerance of fine-textured soils, the hardwood sufficiency curve for sandstone % indicates that optimal sandstone percents may be lower than for white pine (Fig. 2-15). The hardwood sufficiency curve for aspect designates a lower sufficiency rating for southwest aspect in order to capture differences in drought tolerance from white pine (Fig. 2-16).

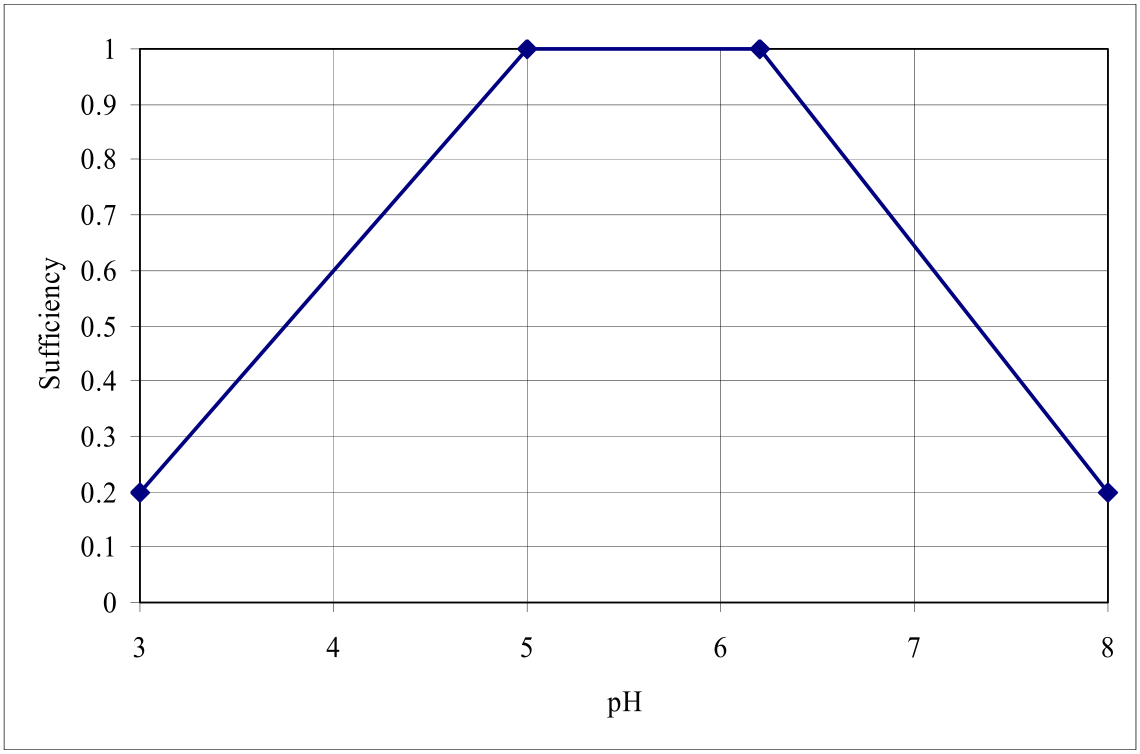

Figure 2-12. Sufficiency curve for pH used for hardwoods on mine soils in the Appalachian region.

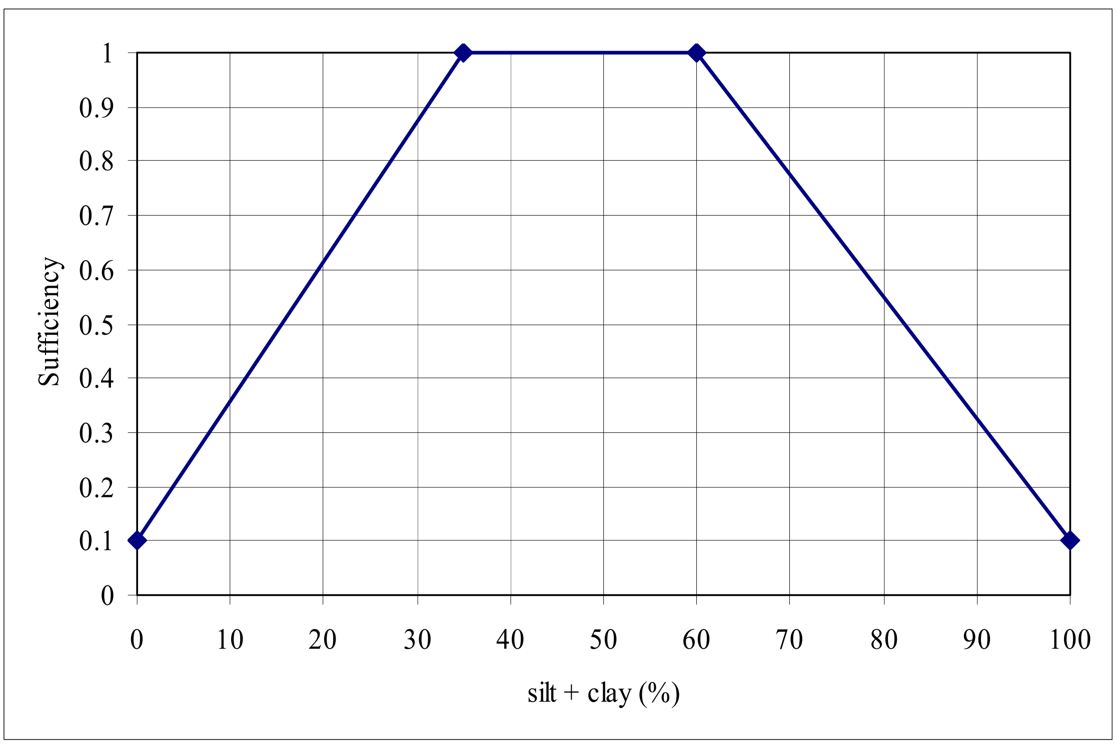

Figure 2-13. Sufficiency curve for texture used for hardwoods on mine soils in the Appalachian region.

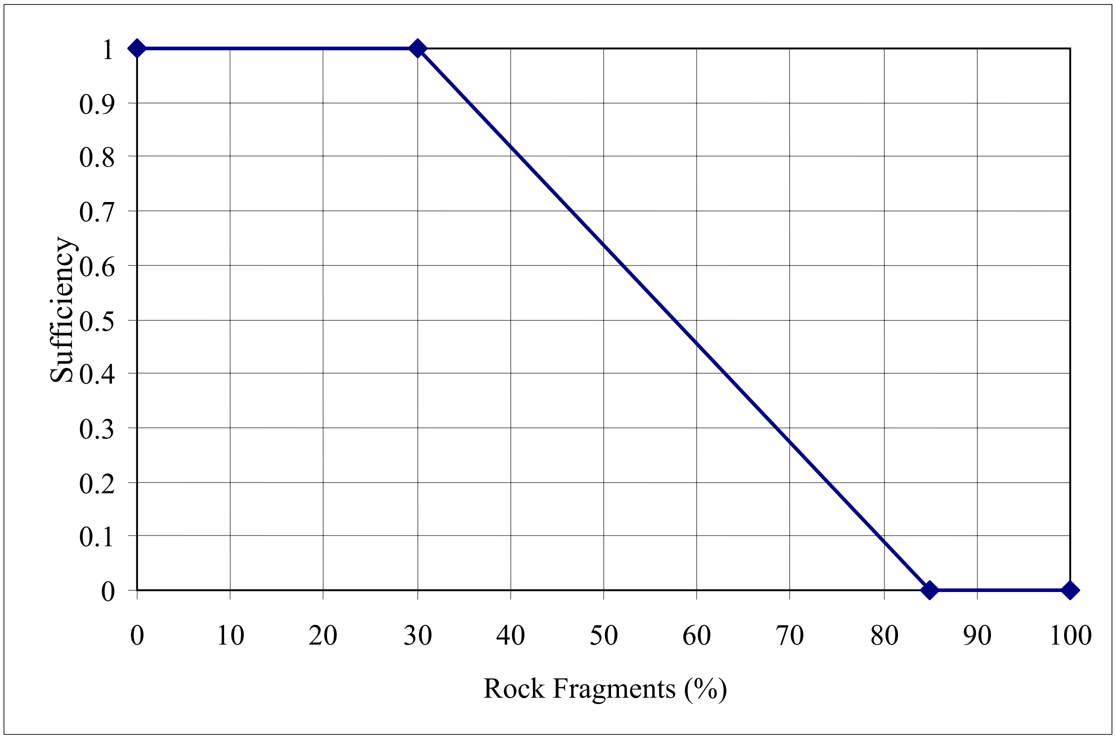

Figure 2-14. Sufficiency curve for rock fragments used for hardwoods on mine soils in the Appalachian region.

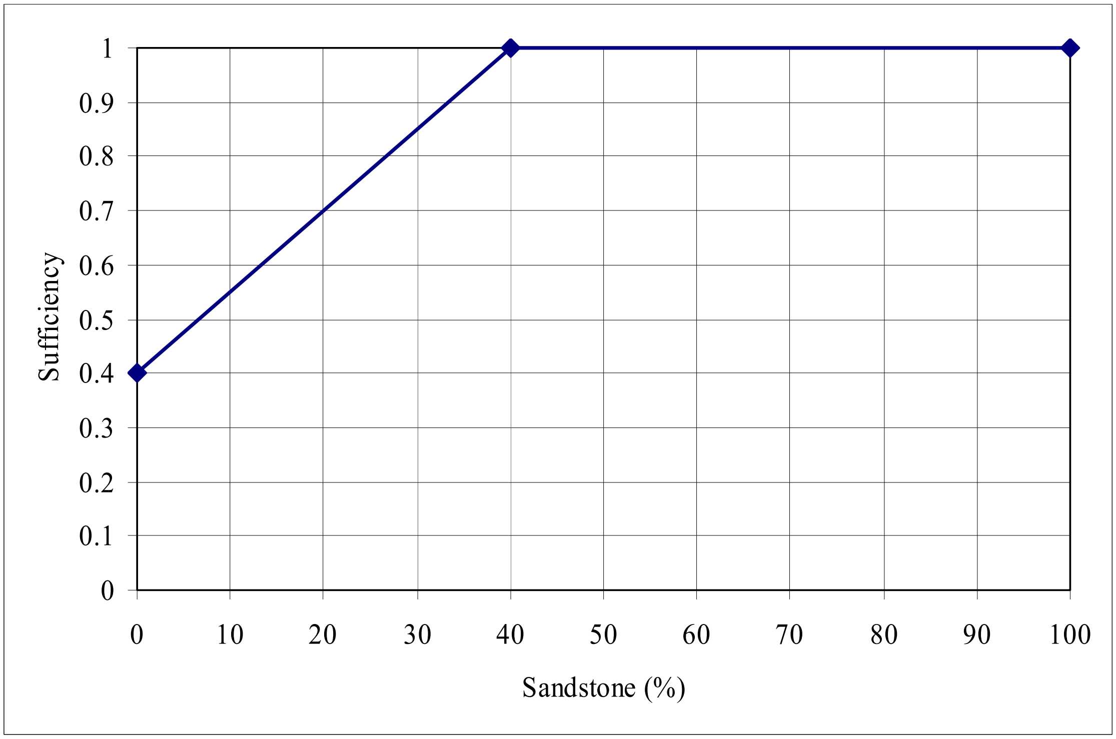

Figure 2-15. Sufficiency curve for sandstone % used for hardwoods on mine soils in the Appalachian region.

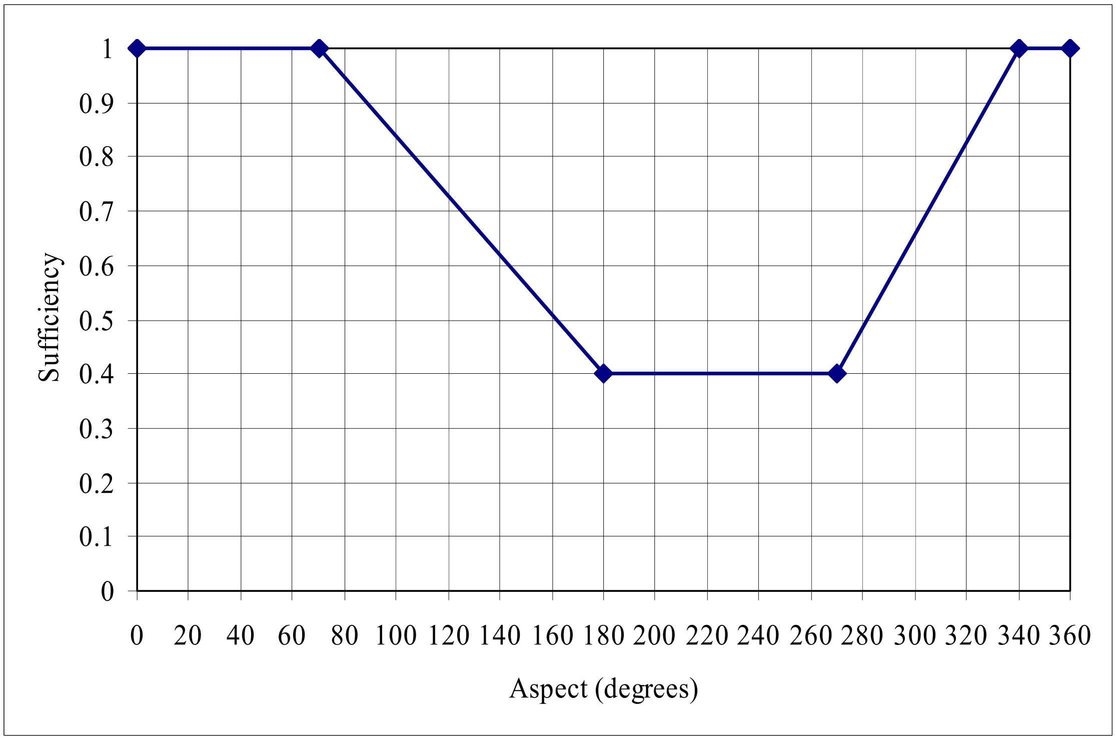

Figure 2-16. Sufficiency curve for aspect used for hardwoods on mine soils in the Appalachian region.

Rapoca Study Site

In order to assess the influence of mine soil properties on different hardwood species, a selected site in Buchanan County, Virginia, known as "Rapoca" was evaluated for the original nine soil and site properties used in the general PI model and the soil color variable. The 10 properties were correlated with height growth of planted hardwood species in their third growing season (Table 2-4). Multiple linear regressions were performed with the properties with the highest correlation coefficients and used to select the most influential independent variables, and recognize any multi-colinearity problems. All results are interpreted with caution due to the juvenility of the tree seedlings, competition from herbaceous ground covers during the first two growing seasons, and the differences that may occur in later growth.

Chestnut oak (*Quercus prinus* L.), red oak (*Q. rubra* L.), and white oak (*Q. alba* L.) are all desirable species for mast production and sawtimber production on reclaimed mines in the Appalachian region. A loam texture appears to be better than sandy loam for height growth of these species, confirming that the increased water retention of the heavier soils is likely beneficial for hardwood production. A higher pH is also correlated with red oak height growth and represents the need for better nutrient availability with this species as compared to others. Density was the only variable with any correlation to white oak height growth.

Density was the common variable found to be influential in the height and diameter growth of all other species (red maple, sugar maple, white ash, sycamore). This confirms that increased soil density continues to be the major limitation and most influential soil property on tree productivity on mined lands in the Appalachian region.

Table 2-4. Correlation coefficients for height growth of selected hardwood species correlated with pH, electrical conductivity (EC), rock fragments (RF), color, sandstone (SS), density, slope, aspect, and rooting depth.

	pH	EC	Texture	RF	Color	SS	Density	Slope	Aspect	Rooting Depth
Red Oak	0.40655	-0.28236	0.42348	0.53704	-0.13406	-0.1112	-0.54789	0.41411	-0.3186	-0.62112†
	0.2775	0.4616	0.256	0.136	0.731	0.7758	0.1267	0.2678	0.6013	0.0742‡
	9	9	9	9	9	9	9	9	5	9§
White Oak	-0.00739	-0.25754	0.19592	0.32633	-0.30309	0.25952	-0.52352	0.24346	-0.51659	-0.50097
	0.9849	0.5035	0.6134	0.3914	0.4279	0.5001	0.148	0.5279	0.3728	0.1695
	9	9	9	9	9	9	9	9	5	9
Chestnut Oak	0.24977	0.10518	0.40077	-0.16447	0.14514	-0.29733	0.1139	-0.12344	0.2861	0.27942
	0.5169	0.7877	0.2851	0.6724	0.7095	0.4372	0.7705	0.7517	0.6408	0.4665
	9	9	9	9	9	9	9	9	5	9
Sugar Maple	0.27775	-0.34992	-0.38906	0.22541	0.38705	0.40901	-0.48467	0.60187	-0.78635	0.04976
	0.5054	0.3955	0.3408	0.5915	0.3435	0.3143	0.2235	0.1144	0.1147	0.9069
	8	8	8	8	8	8	8	8	5	8
Red Maple	0.19192	-0.22954	0.15438	0.49422	-0.36728	-0.32169	-0.84423	0.763	-0.5919	0.23102
	0.6489	0.5845	0.7151	0.2132	0.3708	0.4372	0.0084	0.0276	0.293	0.582
	8	8	8	8	8	8	8	8	5	8
White Ash	0.45624	-0.27841	-0.08335	0.14753	0.52744	0.14847	-0.32749	0.48932	-0.16258	-0.21862
	0.2171	0.4682	0.8312	0.7049	0.1445	0.703	0.3896	0.1813	0.7939	0.572
	9	9	9	9	9	9	9	9	5	9
Sycamore	0.00166	-0.25819	0.01858	0.68024	-0.13859	0.1898	-0.84826	0.78623	-0.72763	-0.22918
	0.9966	0.5024	0.9622	0.0438	0.7221	0.6248	0.0039	0.012	0.1635	0.5531
	9	9	9	9	9	9	9	9	5	9

† Correlation coefficient.
‡ Probability |>|r.
§ Number of observations.

An approximate PI model for hardwood productivity in the Appalachian region follows the same form as Equation 2-5. A more specific model is not able to be produced due to the lack of data, but a first approximation is found in Equation 2-7:

$$PI_{HW} = (\text{density x texture x RF x aspect})^{1/4} \text{ x depth} \qquad \textbf{[2-7]}$$

where PI_{HW} = the hardwood seedling productivity index; the geometric mean is taken of the product of the sufficiency of density class or D_b, texture, RF volume %, and aspect; and then multiplied by the sufficiency of depth. Soil density is expected to be the most important factor. With further research and location of more mature stands of hardwoods to measure, IF's should improve the hardwood model and develop it into a PI specific to a particular hardwood species.

Mapping Project Demonstration Area

The mapping of the Flint Gap site proved the usability of the developed classification system. The system appears to adequately delineate map units based on forest productivity potential, and improves on inaccuracies associated with mine soil mapping using the current USDA soil series. Approximately 78 acres were mapped, with a majority of the map units being a FSQC II or III, and rooting depth along with soil density were the most commonly recognized limitations (Table 2-5). This site was a post-SMCRA mountaintop removal site, was not reclaimed to original contours, and was predominantly flat. Soil density levels were low to moderate, with only very few areas having very low or high levels. RF volume % and pH were highly variable, and the texture was most often loam or sandy loam.

The use of established vegetation on the site proved to be invaluable for determining map unit boundaries (Figs. 2-17 and 2-18). This follows patterns of previous research in which vegetation was found to be a good indicator of soil properties and site quality (Daubenmire 1976, Jones 1991). Absence of vegetation or scattered broadleaf weeds often indicated extreme acidity, while thick, pure stands of fescue, orchard grass, and/or sweet clover indicated high pH values. Stunted, chlorotic vegetation was visible in compacted areas. A site's natural vegetation distribution begins to become naturalized and more representative of soil properties after about five years. Before this amount of time, the use of vegetation as soil indicators should be done with caution.

There were areas of ponded water scattered throughout the site (Figs. 2-17 and 2-18). The ponded water usually indicates high density, impermeable mine soil at some depth, and was not always associated with footslopes and depressional areas. Landscape position commonly used to delineate soil map unit boundaries on native soils did not work on this site and is not suspected to work on other reclaimed mined lands due to different mine reclamation strategies and drastically altered hydrology.

Table 2-5. Sample point data from the Flint Gap mountain top removal site in Dickenson County, Virginia. pH, electrical conductivity (EC), aspect, slope, texture, color, rock fragments (RF), sandstone (SS), density, and rooting depth were recorded and selected properties were used to calculate a white pine productivity index (PI_{wp}) and forest site quality class (FSQC) to delineate map units. Ordination symbols are used to indicate the most limiting properties.

Point #	pH	EC (dS m^{-1})	Aspect (degrees)	Slope (%)	Texture	Color	RF (%)	SS (%)	Density	Rooting Depth (cm)	PI_{wp}†	FSQC	Symbol‡
1	5.6	0.09	flat	§	SiL	2.5Y 4/2	20	10	low	45	0.75	II	t,d
2	7.2	0.08	flat	§	SiL	2.5Y 4/2	36	10	low	46	0.75	II	p+,t,d
3	5.5	0.08	22	18	SiL	2.5Y 4/2	30	10	low	63	0.78	II	t
4	4.9	0.08	flat	§	L	10YR 4/2	25	10	moderate	>90	0.71	II	c
5	5.4	0.06	flat	8	L	10YR 4/3	20	10	low	68	0.82	I	
6	4.5	0.03	flat	§	L	10YR 4/3	20	10	low	>75	0.85	I	
7	4.6	0.01	flat	5	L	10YR 4/4	15	10	low	>75	0.85	I	
8	6.3	0.07	flat	§	L	10YR 4/2	40	10	moderate	37	0.65	III	c,d
9	6.0	0.03	flat	§	SL	10YR 4/4	36	50	low	33	0.81	I	d
10	6.9	0.06	flat	9	L	2.5Y 4/3	30	10	low	45	0.79	II	p+,d
11	6.7	0.03	flat	2	SL	10YR 4/4	30	22	low	60	0.87	I	
12	5.1	0.06	flat	2	L	10YR 4/2	20	10	low	40	0.79	II	d
13	4.9	0.02	flat	§	L	10YR 4/6	10	10	very low	>75	0.95	I	
14	4.9	0.02	flat	§	L	10YR 4/6	10	10	low	40	0.79	II	d
15	5.0	0.02	flat	3	L	10YR 5/6	10	25	low	45	0.79	II	d
16	5.5	0.02	flat	2	L	10YR 4/4	20	10	low	72	0.82	I	
17	6.0	0.03	flat	§	SL	10YR 4/4	34	50	moderate	50	0.73	II	c
18	5.4	0.02	flat	3	SL	10YR 5/6	25	75	moderate	32	0.67	II	c,d
19	6.0	0.03	flat	5	SL	10YR 4/4	34	50	moderate	52	0.73	II	c
20	6.0	0.03	flat	7	SL	10YR 4/3	34	50	low	90	0.91	I	
21	5.3	0.02	flat	6	L	10YR 4/4	25	10	low	68	0.82	I	
22	5.1	0.03	flat	§	L	10YR 4/3	25	15	low	52	0.82	I	
23	5.1	0.03	flat	4	L	10YR 3/2	30	50	moderate	35	0.65	III	c,d
24	5.1	0.03	flat	8	L	10YR 4/3	30	15	low	61	0.82	I	
25	4.2	0.01	flat	4	L	10YR 4/3	30	25	moderate	36	0.65	III	c,d
26	6.2	0.07	flat	2	L	10YR 4/2	30	15	moderate	40	0.65	III	c,d
27	4.6	0.02	flat	§	L	10YR 4/4	15	15	very low	80	0.95	I	
28	5.6	0.04	flat	§	SL	10YR 4/2	40	15	low	40	0.84	I	d
29	3.6	0.01	flat	4	L	10YR 5/6	15	10	low	>100	0.85	I	p-

Table 2-5 (continued).

Point #	pH	EC (dS m^{-1})	Aspect (degrees)	Slope (%)	Texture	Color	RF (%)	SS (%)	Density	Rooting Depth (cm)	PI_{wp}†	FSQC	Symbol‡
30	4.9	0.01	flat	§	L	10YR 4/4	30	15	low	40	0.79	II	d
31	5.5	0.03	76	20	SL	10YR 4/3	30	25	low	60	0.87	I	
32	6.4	0.03	flat	§	SL	10YR 5/4	65	90	high	10	0.43	IV	r,c,d
33	6.5	0.06	flat	§	SL	10YR 4/2	40	50	moderate	45	0.70	II	c,d
34	6.5	0.04	flat	§	SL	10YR 4/2	30	25	low	>75	0.91	I	
35	4.9	0.03	flat	§	SL	10YR 4/3	15	50	low	44	0.84	I	d
36	5.9	0.04	flat	§	SL	2.5Y 4/3	30	50	moderate	41	0.70	II	c,d
37	6	0.04	flat	§	SL	2.5Y 4/3	55	85	moderate	37	0.70	II	c,d
38	4.4	0.04	210	16	SL	10YR 4/6	30	90	low	45	0.84	I	d
39	5.9	0.03	flat	§	SL	10YR 4/4	30	75	low	>100	0.91	I	
40	6.2	0.03	flat	8	SL	10YR 4/3	60	90	moderate	21	0.64	III	r,c,d
41	4.7	0.03	flat	5	SL	10YR 5/6	30	95	low	38	0.84	I	d
42	6.7	0.06	flat	8	SL	10YR 4/4	70	90	low	17	0.75	II	r,d
43	5.7	0.01	4	16	SL	10YR 5/6	45	95	low	42	0.84	I	d
44	6.1	0.03	flat	8	SL	10YR 4/3	60	95	moderate	24	0.64	III	r,c,d
45	4.4	0.04	flat	§	L	10YR 4/4	30	30	low	>100	0.85	I	
46	6.5	0.03	flat	7	SL	10YR 4/4	40	75	moderate	34	0.67	II	c,d
47	4.7	0.02	flat	§	L	10YR 5/6	25	50	low	37	0.79	II	d

† PI_{wp}= (texture x 0.21) + (rooting depth x 0.32) + (density x 0.47); sufficiency values used for soil properties.
‡ Ordination symbol given if sufficiency of soil property was ≤0.6; c=density, d=depth, p=pH, r=rock fragments, t=texture.
§ 0-1%, nearly level.

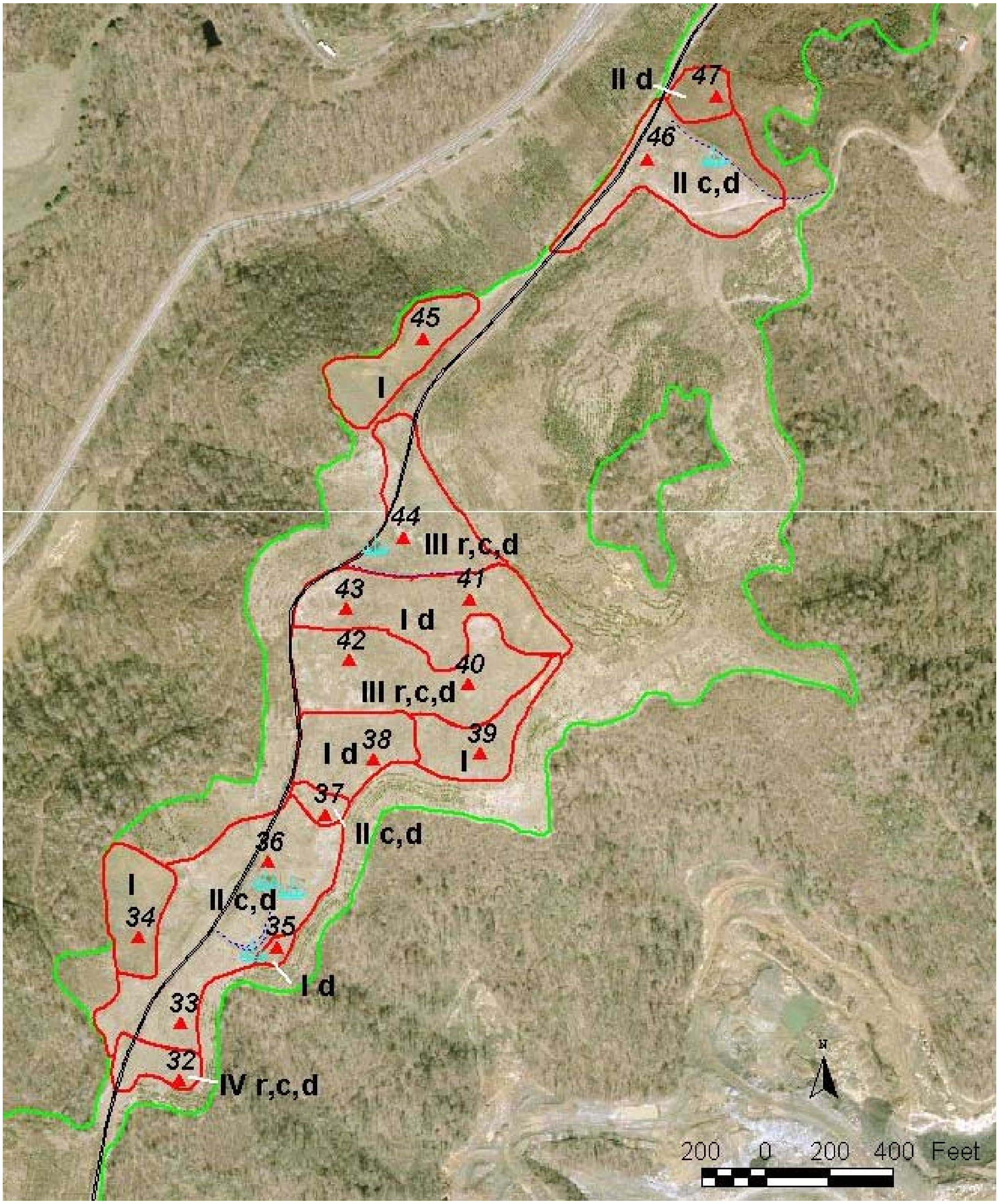

Figure 2-17. Data points taken and used along with vegetation differences to delineate map units at the north end of the Flint Gap mountaintop removal site.

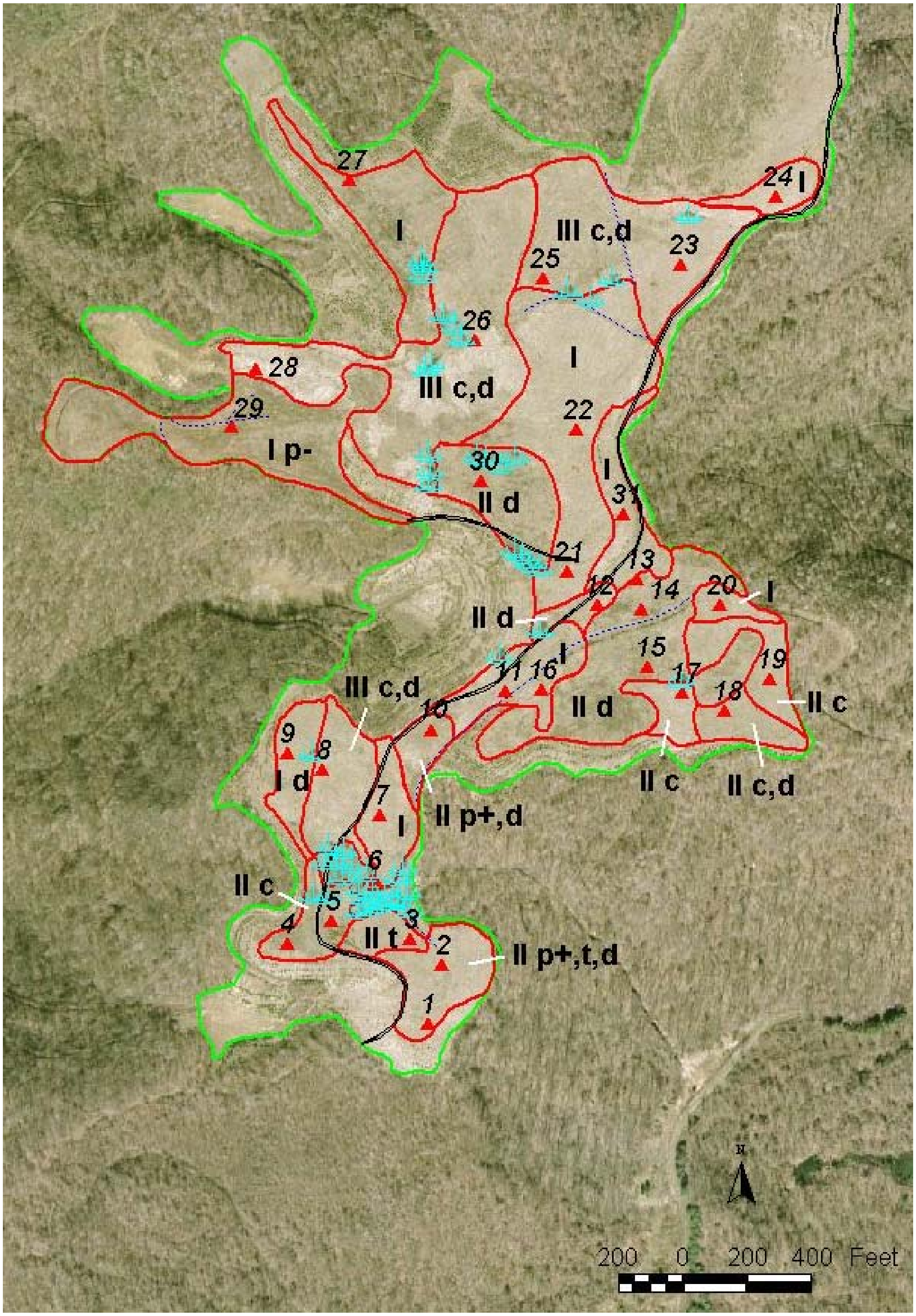

Figure 2-18. Data points taken and used along with vegetation differences to delineate map units at the south end of the Flint Gap mountaintop removal site.

The ordination symbols designated to map unit boundaries can be used for management decisions on mined land (Table 2-6). Symbols are given to a map unit if the sufficiency of the property is 0.6 or less. If the ordination symbol for density (c) is used, the land would benefit from a ripping or tillage treatment. The depth (d) symbol indicates the same, given that the ripping treatment used will reach the depth of the root-limiting layer. A high RF content is represented by the ordination symbol (r), and may influence species selection decisions. More drought-tolerant species should be planted in these map units. Ripping or tillage treatments may also improve these sites by bringing more soil fines to the surface and improving the planting bed. The ordination symbol for pH (p) is given a + or – to indicate which side of the optimal level the pH falls on. This will give experienced scientists an indication of nutrient availability in the soil, and may affect species selection for planting. The ordination symbol for texture (t) indicates that a soil is high in silt + clay content and will likely be limited by aeration. Different species are adapted to these sites and should be used in reclamation planting. An ordination symbol (s) (for sandstone) is suggested to be used on young sites for interpretations of rock type on a site. The ordination symbol (s) should be followed by a number from 1 to 5, with 1 = < 20% sandstone, 2 = 20-39% sandstone, 3 = 40-59% sandstone, 4 = 60-79% sandstone, and 5 = 80-100% sandstone. This will guide a land manager in making decisions on species selection and fertilization treatments based on known properties of different rock types and optimal soil properties for different tree species.

Table 2-6. Suggested management practices for ordination symbols associated with high soil density (c), shallow rooting depth (d), high rock fragment content (r), high pH (p+), low pH (p-), and high silt + clay contents (t) to optimize forest productivity.

Ordination Symbol	Management Practice
c	ripping and/or tillage
d	deep ripping
r	plant drought-tolerant species; ripping or tillage may improve planting bed by bringing more soil fines to the surface
p+	plant hardwoods or hybrid poplars
p-	plant acid-loving pines; liming may improve the site for hardwoods
t	plant FSQC II, III, and IV hardwoods; bedding may improve aeration for pines

A variety of species may be used in reclamation planting in the Appalachian region, and selecting the proper species may have dramatic consequences on reforestation success (Burns and Honkala 1990). The FSQC and mapping techniques can be used to determine which species should be planted in selected map units (Table 2-7). Map units with an FSQC of I and sometimes II suggest that white pine, red oak, and sugar maple (*Acer saccharum* Marsh.) may be the best species to plant. Tulip poplar (*Liriodendron tulipifera* L.) has been observed to have low survival rates on mine soils and should be planted only on the very best FSQC I sites. White oak, chestnut oak, and hickory (*Carya spp.*) are more tolerant of adverse soil conditions and should be used on FSQC II and some III. Green ash (*Fraxinus pennsyvlvanica* Marsh.), white ash (*F. americana* L.), American sycamore (*Platanus occidentalis* L.), and red maple (*A. rubrum*

L.) are species that grow on a broad range of soil types and will likely grow better on all mined sites. These may be the only species that will grow on FSQC III and IV sites. Very little, if any, tree seedling survival and growth is expected on FSQC V, and tree planting is not recommended. Any FSQC of II or higher will likely be improved with silvicultural treatments.

Table 2-7. Suggested species selection for each forest site quality class (FSQC).

FSQC				
I	II	III	IV	V
t. poplar, w. pine, r. oak, s. maple				
	w. oak, c. oak, hickory			
		r. maple, sycamore, w. ash, g. ash		
				none

Department of Energy Project: Site Quality

The FSQC for white pine was used to predict white pine productivity at each study site. These predictions will be evaluated later in the rotation and used to improve upon the FSQC. Only relationships between seedling survival percent and FSQC can be discussed at this time.

West Virginia

All three WV blocks were fairly uniform and resulted in a FSQC of III (Table 2-8). The PI values were in the lower portion of the acceptable range for FSQC III, and white pine SI will likely be near 80. However, WV3 had a white pine survival percentage of nearly twice that of WV1 and WV2 (Table 2-9). WV3 had a slightly lower pH and slightly lower RF content (Table 2-8). Lower RF volume % may have improved water availability to the young seedlings and been responsible for the increased survival rates, but RF volume % are not accounted for in the FSQC model. Slightly higher sandstone percents in WV3 may have resulted in a greater portion of the total porosity being macropores and consequently improved aeration. Hardwood survival rates were fairly uniform across all blocks and were much higher than white pine (Table 2-9). A high density level suggests that ripping and/or tillage treatments will likely improve survival for all species. Along with high density, the high RF volume % is likely to be a limiting factor to tree growth.

Virginia

The VA blocks have more variation among blocks than do the other sites. VA1 and VA2 are identified as FSQC II, and VA3 is FSQC III (Table 2-8). White pine survival percents of VA2 are much lower than those of the other two VA blocks (Table 2-9), likely due to high RF volume %, low sandstone percent, and high pH. Higher pH was advantageous to herbaceous vegetation growth and the competition likely increased mortality. VA3 also had high pH but was recently reclaimed and had little established competitive vegetation. Hardwood survival followed the same pattern as white pine with VA2 being the lowest, but overall hardwood survival was greater at all blocks, with VA1 and VA3 having 96% and 88% survival, respectively (Table 2-9). It appears that increased competition at VA2 affected survival of all species. FSQC may prove to be inaccurate for predicting forest productivity on young sites such as VA3, because most of the measured properties will quickly change within a few years of weathering.

Ohio

The OH blocks consisted of clayier textures than the other sites, and various topsoil depths. All three blocks resulted in FSQC II (Table 2-8), but OH3 had a much lower survival percent for white pine and hardwoods (Table 2-9). The high pH of this block (>6) is likely responsible for tree mortality since most native species are not adapted to this range (Skousen et al. 1994). Most competitive grasses and legumes do thrive at this pH range and cause tremendous competition that likely resulted in elevated mortality levels.

White pine can compete on most soil types except for heavy clay soils (Lancaster and Leak 1978). The OH blocks had from 20% to 27% clay in the topsoil material, which are only medium levels of clay contents for natural soils in the white pine range. However, the lack of structure in these mine soils result in reduced macroporosity and aeration, which resembles the native soils referred to by Lancaster and Leak that have higher clay contents. Hardwoods are expected to outgrow white pine on clayey soil (Lancaster and Leak 1978).

The compacted subsoils of all OH blocks will also affect white pine survival and growth, not only in physical root resistance, but in impeded drainage. Compacted subsoils are likely to perch water and temporarily raise the water table into the root zone. Subsurface drainage is difficult to predict in mine soils but is of extreme importance. The topography of OH1 is more undulating and will likely have better drainage than the other blocks, while OH2 is flat and has features indicating restricted surface drainage and slow percolation. White pine prefers well-drained soils and cannot withstand anaerobic conditions in its root zone. Some native hardwoods are more adapted to surviving under saturated conditions and may be better adapted to these sites (Burns and Honkala 1990). With no measure of subsurface drainage, FSQC may prove to be inappropriate for SI predictions of white pine on these OH blocks. Silvicultural operations such as deep ripping may improve drainage, and bedding can be used to raise seedlings above the local water table.

Table 2-8. Measured soil properties resulted in forest site quality classes (FSQC) of II and III for white pine growth at three blocks each in Nicholas County, West Virginia (WV), Lawrence County, Ohio (OH), and Wise County, Virginia (VA). pH, electrical conductivity (EC), texture; color, rock fragments (RF), sandstone (SS), density, and rooting depth were recorded and selected properties were used to calculate a white pine productivity index (PI_{wp}), and forest site quality class (FSQC). Ordination symbols are used to indicate the most limiting properties.

Block	pH	EC ($dS\ m^{-1}$)	Texture	Color	RF (weight %)	SS (%)	Density	Rooting Depth (cm)	PI_{wp}†	FSQC	Symbol‡
WV-1	5.9	0.2	SL	10YR 4/2	55	10	high	36	0.55	III	c,d
WV-2	5.7	0.2	SL	10YR 4/2	55	10	high	32	0.54	III	c,d
WV-3	5.5	0.2	SL	10YR 4/2	45	15	high	34	0.54	III	c,d
OH-1	4.8	0.07	CL	10YR 5/4	10	20	low	45	0.76	II	t,d
OH-2	5.1	0.1	L	10YR 5/6	10	25	low	48	0.78	II	d
OH-3	6.1	0.2	L	2.5Y 5/3	10	25	low	42	0.77	II	d
VA-1	4.8	0.2	SL	10YR 5/3	30	80	low	32	0.80	II	d
VA-2	6.3	0.3	L	2.5Y 4/3	55	50	moderate	60	0.70	II	c
VA-3	6.5	0.4	SL	10YR 4/2	55	65	moderate	34	0.66	III	c,d

† PI_{wp}= (texture x 0.21) + (rooting depth x 0.32) + (density x 0.47); sufficiency values used for soil properties.
‡ Ordination symbol given if sufficiency of soil property was ≤0.6; c=density, d=depth, p=pH, r=rock fragments, t=texture.

Table 2-9. 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	Survival Rate (%) 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.

Conclusions

Many chemical and physical soil properties, as well as site factors, influence tree growth and forest productivity on mined land. Successful establishment of a productive forest on reclaimed mined land can provide economic benefits through wood production, wildlife habitat, watershed protection, and carbon sequestration. The SMCRA of 1977 requires that reclaimed land be equally as or more productive than pre-mined conditions. However, since the passage of this law, few productive forests have been established due to poor mine soil conditions, lack of incentives for mine operators to plant trees, and inability to estimate mine soil quality for forests.

FSQC ratings based on field-measured soil properties can be used to predict potential forest productivity, which will aid in forest management prescriptions. Soil texture, density, and rooting depth were the most influential properties for white pine growth on post-SMCRA reclaimed surface mines, with soil density being the most important. Other factors may be more influential on younger sites or on sites for which native hardwoods are the intended forest type. Soil pH and rock fragment content are known to be important for forest productivity on mine soils but were not found to be significant in this study. The EC and sandstone content variables will likely be useful for recently reclaimed (< 5 years) mined sites. An evaluation of all soil properties in the general PI model is highly suggested.

Furthermore, the model developed is useable for mapping mined landscapes and making management decisions. Ordination symbols can be used to recognize the most limiting properties and offer suggestions of species selection and silvicultural prescriptions for land managers. Observations of vegetation type and vigor will lend much insight into determining map unit boundaries.

The PI model developed can only be validated where trees are present and therefore may not recognize soil properties that completely limit tree survival. Furthermore, Beck's growth intercept model may overestimate white pine SI, as extremely high SI estimations were observed in this study. Extrapolation of data beyond the ranges of soil properties, geographic regions, and PI values using this model may not be accurate.

Our FSQC model should aid mine operators, foresters, and landowners in determining the productive capability of mined land, in making management decisions, and in reducing the risk associated with planting trees on mined land.

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

Executive Summary

Little information exists on the productive potential of forests growing on reclaimed mined land and the response of these forests to intermediate stand treatments such as thinning. A thinning study was established as a random complete block design to evaluate the response to thinning of a 26-year-old white pine stand growing on a reclaimed surface mine in southwest Virginia. Stand parameters were projected to age 30 using a stand table projection. Site index of the stand was found to be 32.3 m at base age 50 years. Thinning rapidly increased the diameter growth of the residual trees to 0.84 cm yr^{-1}, compared to 0.58 cm yr^{-1} for the unthinned treatment; however, at age 26, there was no difference in volume or value per hectare. At age 30, the unthinned treatment had a volume of 457.1 m^3 ha^{-1} but was only worth \$8807 ha^{-1}, while the thinned treatment was projected to have 465.8 m^3 ha^{-1}, which was worth \$11265 ha^{-1} due to a larger percentage of the volume being in sawtimber size classes. These results indicate that commercial forestry is a viable alternative for reclamation of surface mined lands and that stands growing on reclaimed mined land can respond well to intermediate stand treatments.

Experimental

The study site was a white pine plantation located on a surface mine in Wise County, Virginia, reclaimed prior to the passage of the Surface Mining Control and Reclamation Act of 1977. Following surface mining of the coal, the overburden rock was simply pushed back across the site, creating a bench and highwall profile. The resulting spoil at this site was a mixture of sandstone, siltstone, and coal-derived materials. The stand was planted in 1978, and in 1996 a thinning study was installed. In 1996, at age 17, the stand contained 1438 stems ha^{-1} with 30.1 m^2 ha^{-1} of basal area. Three paired blocks of 0.02-ha plots were established in the stand prior to thinning. One plot in each block was randomly selected for thinning, and the basal area was reduced to 20.7 m^2 ha^{-1}, leaving a final stand density of 652 stems ha^{-1}. The second plot in each pair was left as a control and was not thinned. All plots were measured in 1996 for total height and diameter at breast height for all living white pines. Five randomly selected dominant or co-dominant trees from each plot were measured annually to evaluate the change in diameter increment due to thinning over time. Height and diameter of all trees in the plots were re-measured in 2004, nine years after the thinning, when the stand was 26 years old.

Site index was calculated based on the average height of trees in the upper quartile of total height to approximate dominant and co-dominant trees using site index equations for white pine in the southern Appalachians (Beck 1971). Cubic foot volumes to a 10-cm top diameter inside bark (dib) were calculated using volume equations for white pine in the southern Appalachians (Vimmerstedt 1962). Board foot volumes to a 15-cm top dib were calculated using equations for white pine plantations in southeastern Ohio (Dale et al. 1989). Minimum diameter for sawtimber was set at 30 cm. For pulpwood, cubic meter volumes were converted to cubic foot volumes and then to tons of pulpwood using a conversion factor of 35.9 ft^3 ton^{-1}. Stumpage prices for sawtimber and pulpwood (Timber Mart-South 2004) were applied to stand volume estimates to obtain stand value estimates for thinned and unthinned treatments. Stand parameters measured at age 26 were projected to age 30 using a stand table projection (Avery and Burkhart 2002). Total tree height at age 30 was predicted from site index equations (Beck 1971) based on the site index of each tree at age 26.

Data from the 2005 inventory were analyzed for differences in dbh, basal area per hectare, trees per hectare, volume per hectare, volume per tree, proportion of volume in sawtimber, and value per hectare between treatments using a random complete block design with three blocks and two treatments per block. Analysis of variance was used to detect statistically significant differences between treatments. Proportion data were transformed using arcsine transformation prior to analysis of variance. The annual diameter measurements were analyzed using a repeated measures mixed model procedure to test the statistical significance of change in diameter increment with respect to thinning treatment over time. Transformation of the response variable using the natural log function was used to satisfy model assumptions. SAS version 8.2 (SAS Institute Inc., Cary, NC 2001) was used for all statistical analyses and significance was set at $P < 0.05$ for all comparisons.

Results and Discussion

Site index for the stand averaged 32.0 m at base age 50 years using equations from Beck (1971) for white pine in the southern Appalachians. This is well above the site index noted by Doolittle (1962), who found average site index for white pine in the southern Appalachians to be 24.4 m at base age 50. Dale and coworkers (1989) reported average site index of white pine in southeastern Ohio to be 23.5. The response to thinning from age 17 to age 26 is shown in Table 3-1. As expected, total height of the thinned treatment was greater than that of the unthinned treatment for both ages due to the removal of intermediate and suppressed trees from the plots treated with low thinning. Thinning increased dbh by nearly 4.5 cm over the nine years since treatment compared to the unthinned treatment (27.9 cm versus 23.4 cm for these treatments, respectively). The annual diameter increment calculated from the repeated measures data for the thinned treatment was 0.84 cm yr^{-1}, while that for the unthinned treatment was 0.58 cm yr^{-1}, and this difference was significant ($P < 0.0001$) (Fig. 3-1). Basal area was not significantly different between treatments. Gillespie and Hocker (1986), in a study of white pine thinning response in New England, found that stand basal area was not affected by thinning, but mean diameter increment was significantly greater in the thinned plots. Both treatments have accrued a large amount of basal area (15.6 m^2 ha^{-1} and 12.9 m^2 ha^{-1} for thinned and unthinned, respectively). Comparing the stand density prior to thinning (1438 stems ha^{-1}) with the stand density in the unthinned treatment, it can be seen that substantial mortality has taken place in the unthinned treatment, as there remains only 63% of the original number of trees in the unthinned plots. Low thinning has been shown to decrease competition-induced mortality for white pine in the southern Appalachians (Della-Bianca 1981). The volume per acre in the thinned treatment was not significantly different compared to the unthinned treatment. Additionally, the volume of the thinned plots is standing volume and does not account for the 94.2 m^3 ha^{-1} removed during the thinning. Individual tree volume was significantly different between treatments at age 26 (P = 0.0327), which is reasonable given the diameter growth response observed.

Table 3-1. Thinning effects at age 26, nine years after thinning, and projected thinning effects at age 30 for a white pine stand growing on a reclaimed surface mine in southwestern Virginia.

Treatment	DBH (cm)	Total Height (m)	Basal Area (m^2 ha^{-1})	Trees per Hectare	Stand Volume (m^3 ha^{-1})	Volume per Tree (m^3)	Volume in Sawtimber (%)	Value per Hectare ($)
Age 26:								
Thinned	27.9	19.3	36.3	566	289.6	0.52	62	5641
Unthinned	23.4	17.0	42.9	899	312.7	0.35	55	5481
Pr > F	0.018	0.017	0.111	0.044	0.360	0.033	0.514	0.593
Age 30:								
Thinned	33.0	22.1	49.8	566	465.6	0.84	92	11265
Unthinned	26.2	19.7	53.0	899	456.9	0.51	66	8807
Pr > F	0.007	0.018	0.415	0.044	0.796	0.015	0.015	0.008

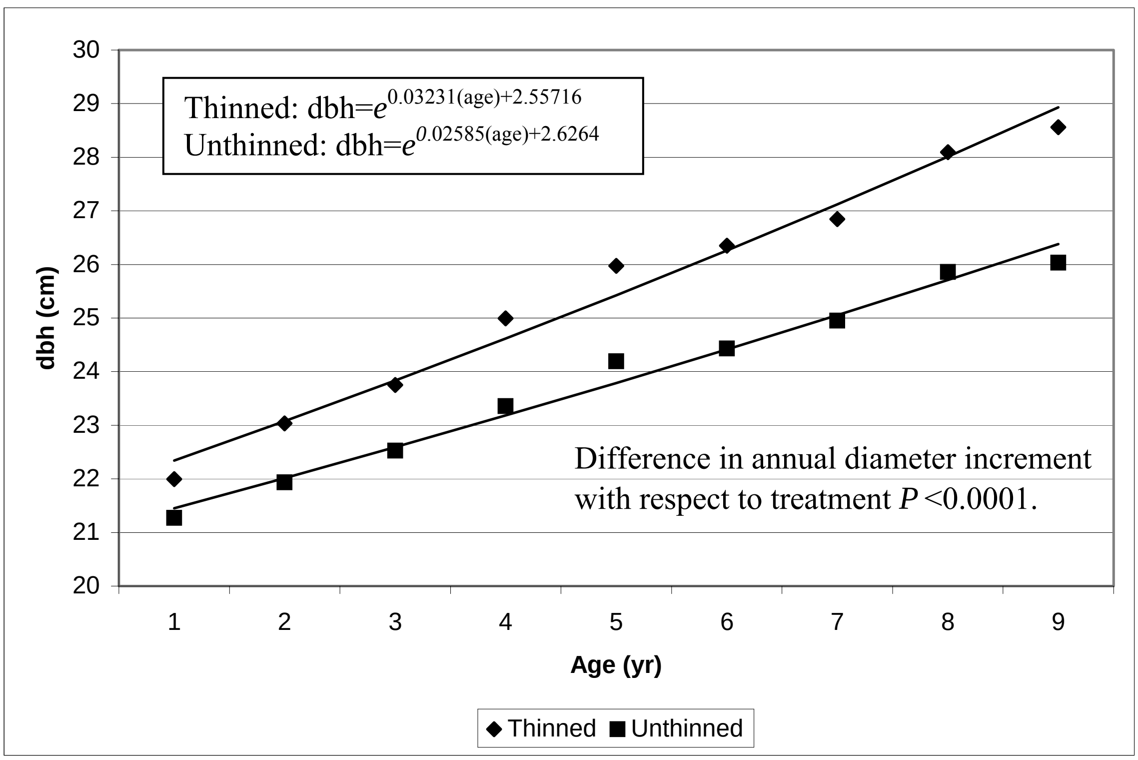

Figure 3-1. Diameter response to thinning of a 26-year-old white pine stand growing on a reclaimed surface mine site in southwestern Virginia.

At age 26, low thinning had not created a significant difference in the proportion of stand volume in the sawtimber size classes compared to the unthinned treatment, but with the continued increased diameter growth rates (Fig. 3-1), this shift would be expected in the near future. Stand table projection was used to predict the stand parameters at age 30. This projection indicated that there would be nearly a three-inch difference in dbh between the thinned and unthinned treatments, which was statistically significant (P = 0.0066) (Table 3-1).

Due to the accelerated diameter growth, stand basal area would be very similar for thinned (49.8 m^2) and unthinned (53.0 m^2) treatments.

At age 30, standing volume in thinned plots was estimated to be 465.6 m^3ha^{-1}, which would surpass the volume of the 456.9 m^3ha^{-1} in the unthinned treatment. Volume per tree was estimated to be nearly 0.34 m^3 $tree^{-1}$ more in the thinned treatment than the unthinned treatment at age 30, compared to an approximate 0.17 m^3 $tree^{-1}$ difference between the same treatments, respectively, at age 26. It is estimated that at current diameter growth rates, 92% of the volume in the thinned treatment would be sawtimber compared to 66% for the unthinned treatment, and this difference would be statistically significant ($P = 0.0154$). Results of a white pine thinning study in the southern Appalachians found that at both 80 and 100 years, thinning had shifted the diameter distributions to larger size classes, but failed to increase cumulative yield compared to an unthinned control (Della-Bianca 1981, McNab and Ritter 2000). McNab and Ritter (2000) did note that site quality, as measured by site index, was higher in the unthinned control, indicating that if site qualities were equal, it might be possible for thinned plots to produce more cumulative yield. Due to higher stumpage values for sawtimber, the higher proportion of sawtimber in the thinned treatment would translate into a significantly higher value per acre for the thinned treatment ($P = 0.0079$), whereas at age 26, both treatments had similar standing volume and proportion of volume in sawtimber, and consequently there was no significant difference in value per acre at age 26. The magnitude of the shift into the sawtimber class for both treatments at ages 26 and 30 can be seen in Figure 3-2. The result of this shift is an approximate 200% increase in value for the thinned treatment from age 26 to age 30 ($5641 and $11265 ha^{-1} for ages 26 and 30, respectively) and an approximate 160% increase in value for the unthinned treatment ($5481 and $8807 ha^{-1} for ages 26 and 30, respectively).

To examine the economic feasibility of establishing stands with this level of productivity on surface mined lands, it is important to understand that several factors have been found to limit tree productivity on post-SMCRA reclaimed surface mined land. The two major limitations are soil compaction and competing vegetation (Ashby, 1991) that result from SMCRA's requirement to return the land to approximate original contour and to stabilize the reclaimed landscape from erosion. Burger and Zipper (2002) have outlined procedures for restoring forests on surface mined lands. Part of their prescription includes the establishment of a tree-compatible ground cover, which is intended to minimize the need for competition control treatments when forestry is chosen as the post-mining land use; however, these treatments may still be required if other more aggressive herbaceous species become established on the site. As such, using the stand value information from this study, net present values (NPV) and internal rates of return (IRR) were calculated for four different management scenarios that are likely to face landowners who wish to establish forests on post-SMCRA mined lands. The NPV allows for comparison of the different scenarios while accounting for the opportunity costs associated with each investment scenario. Important assumptions include having a tree-compatible ground cover established by the mining company, having appropriate spoil materials for tree growth (Torbert and Burger 2000), and having these materials returned to the surface in an uncompacted state. It was also assumed that the harvested volume resulting from thinning would cover the cost of the thinning operation at no net benefit or cost (harvestable volume would have generated $667 ha^{-1} based on pulpwood prices and the cubic foot volume removed during thinning).

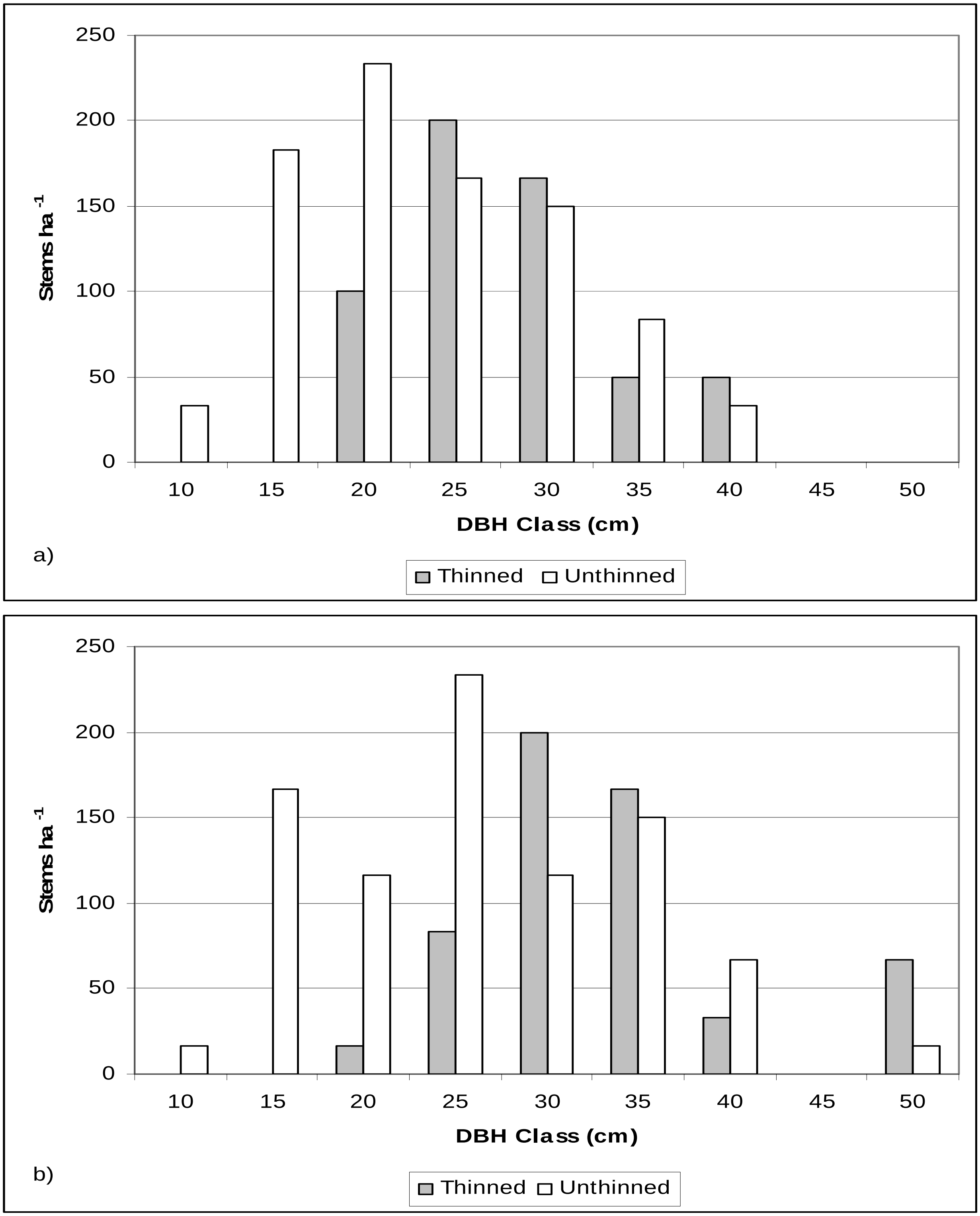

Figure 3-2. Diameter distributions for (a) stand at age 26 and (b) stand projected to age 30 for a 26-year-old white pine stand growing on a reclaimed surface mine in southwestern Virginia.

A 6% discount rate was used in calculating NPV. The scenarios evaluated differ only with respect to costs incurred over the rotation and include:

Scenario 1. Establishment costs only of \$618 ha^{-1} (Burger and Zipper 2002)

Scenario 2. \$618 ha^{-1} establishment cost and \$173 ha^{-1} herbicide cost (based on author estimates) in first year

Scenario 3. \$618 ha^{-1} establishment cost and \$173 ha^{-1} herbicide cost in years 1 and 2

Scenario 4. \$618 ha^{-1} establishment cost and \$173 ha^{-1} herbicide cost in years 1, 2, and 3

Scenario 5. All establishment and herbicide costs borne by mining company up to year 5 to obtain bond release.

Cash flows for each scenario are depicted in Figures 3-3 and 3-4. The results of this simulation show that at age 26, the IRR's and NPV's are virtually the same between thinned and unthinned treatments for Scenarios 1 through 4 and ranged from approximately 9% when management inputs include only establishment costs to approximately 6.5% using the most intensive scenario (Table 3-2). Using projected values at age 30, the IRR's for Scenarios 1 through 4 differed by approximately 1% between the treatments, with the IRR of the thinned treatment being higher. For the thinned treatment, IRR's range from 10.2% to 8.1% from the least intensive to the most intensive scenarios respectively. For the unthinned treatment, the range is 9.3% to 7.2%, respectively. When commercial forestry is specified as the post-mining land use, mining companies are required by law to establish a minimum stocking of crop trees per hectare within a fixed time period to obtain bond release. In Virginia, 988 crop trees ha^{-1} are required (Burger and Zipper 2002). It is important to understand that Scenario 5 is not typical for forestry business enterprises and represents a situation in which all harvest revenues are purely profit to the landowner as there are no establishment costs to be considered. This resulted in NPV values that were approximately \$600 ha^{-1} greater under Scenario 5 when compared to Scenario 1, with this difference increasing as additional herbicide costs are incurred. Calculation of IRR for Scenario 5 was not possible given that revenues were generated, but no cost were incurred, meaning that regardless of the interest rate, NPV could not be set equal to zero.

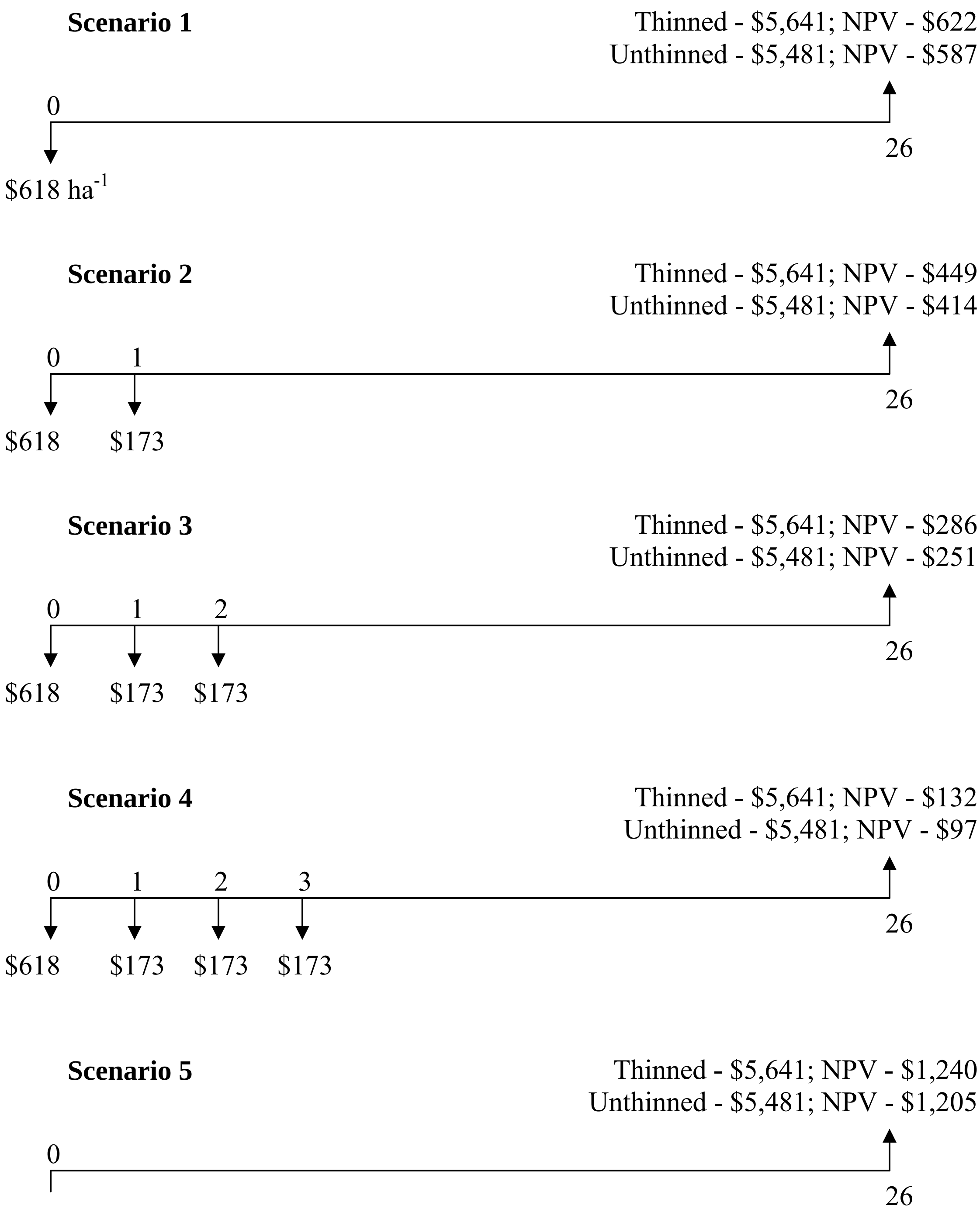

Figure 3-3. Cash flow diagrams for thinned and unthinned treatments under Scenarios 1-5 at age 26 for a white pine stand growing on a reclaimed surface mine in southwestern Virginia.

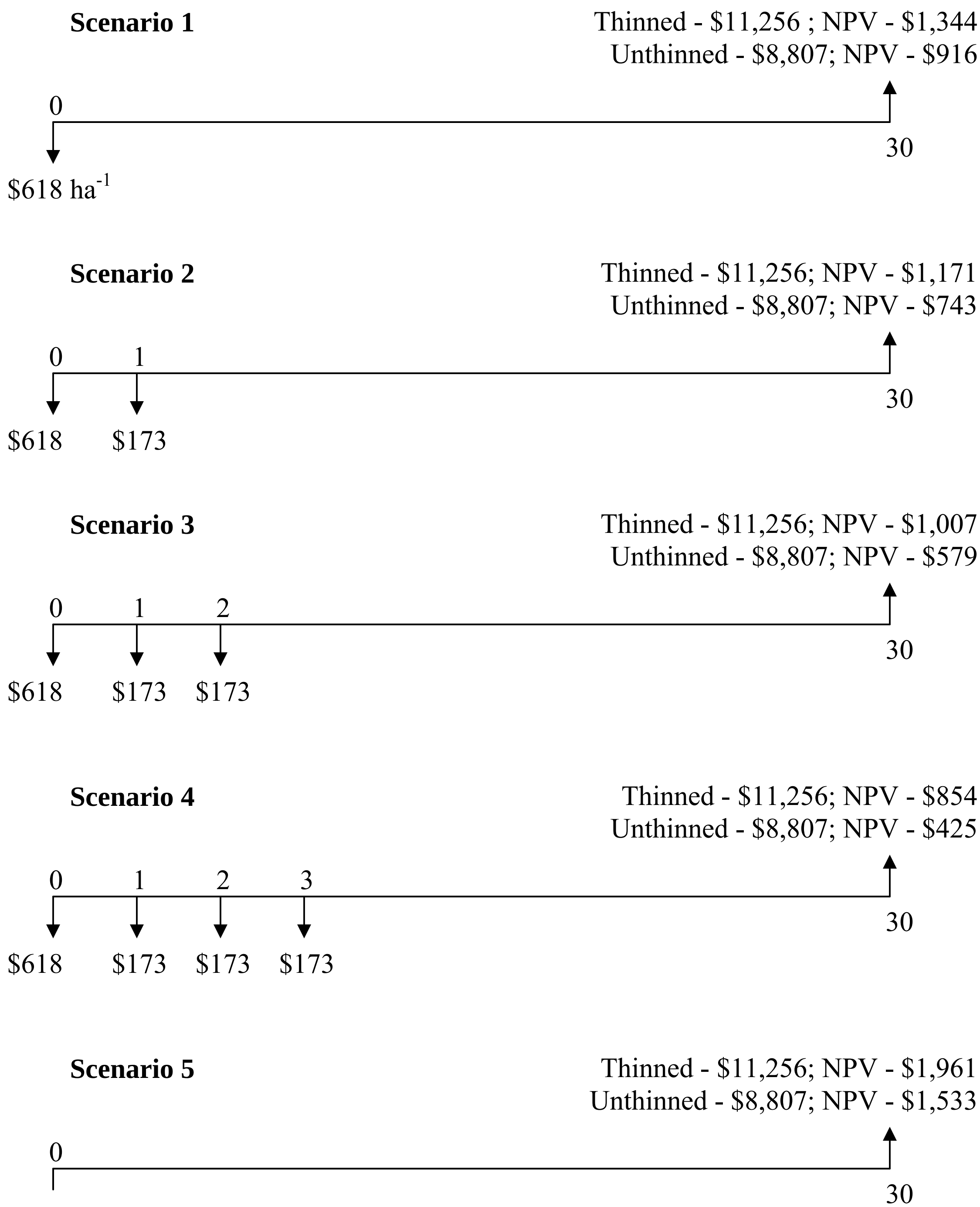

Figure 3-4. Cash flow diagrams for thinned and unthinned treatments under Scenarios 1-5 at age 30 for a white pine stand growing on a reclaimed surface mine in southwestern Virginia.

Table 3-2. Net present value ($ ha^{-1}) at 6% interest and internal rate of return by thinning treatment and stand age for a 26-year-old white pine stand growing on a reclaimed surface mine in southwestern Virginia.

Age and Treatment	Management Scenario*									
	1		2		3		4		5	
	NPV ($)	IRR (%)	NPV ($)	IRR (%)	NPV ($)	IRR (%)	NPV ($)	IRR (%)	NPV ($)	IRR (%)
Age 26:										
Thinned	622	8.9	449	7.9	286	7.1	132	6.5	1240	---
Unthinned	587	8.8	414	7.7	251	7.0	97	6.3	1205	---
Age 30:										
Thinned	1344	10.2	1171	9.3	1007	8.6	854	8.1	1961	---
Unthinned	916	9.3	743	8.4	579	7.7	425	7.2	1533	---

*Scenario 1: $618 ha^{-1} establishment costs only.
Scenario 2: $618 ha^{-1} establishment cost and $173ha^{-1} herbicide cost in first year.
Scenario 3: $618 ha^{-1} establishment cost and $173ha^{-1} herbicide cost in years 1 and 2.
Scenario 4: $618 ha^{-1} establishment cost and $173ha^{-1} herbicide cost in years 1, 2, and 3.
Scenario 5: All costs to age 5 paid by mining company.

From this simulation, it can be seen that if sawtimber production is the management objective, and the desired rotation age is around 30 years, thinning near mid-rotation is a better economic decision than leaving the stand to grow in an unthinned state, especially considering that the average diameter of unthinned trees is only projected to be 26.2 cm at age 30 and only 66% of the stand volume is in sawtimber.

Conclusions

The results of this investigation reveal that, at a site index of 32.3 m, this stand is more productive than established averages for white pine in the southeastern United States. Additionally, volume growth rates of 11.1 m^3 ha^{-1} yr^{-1} in the thinned plots compare favorably with productive stands of loblolly pine found in the southeastern U.S., thus demonstrating the potential of reclaimed surface mines to support productive forests. Thinning the stand at age 17 rapidly increased the diameter growth of the residual trees. Volumes and values for the stand were no different at age 26; however, at each treatment's respective growth rates based on a stand table projection, stand values were significantly higher for the thinned treatment by age 30 due to a shift in the diameter distribution of this treatment toward the sawtimber size classes. These trends in terms of thinning response are similar to trends found in white pine stands growing on native soils, and as such, it appears that white pine growing on reclaimed surface mines can be managed similarly to plantations on native soils. Economic analysis of stand value information revealed that stands growing at this level of productivity on reclaimed mined lands should provide landowners with favorable returns on their investment even when establishment and weed control costs are borne by the landowner. When establishment costs for stands at this level of productivity are borne by the mining companies as part of the reclamation process as required by the SMCRA, the before-tax NPV the landowner could realize is $1,961 ha^{-1}.

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

Executive Summary

As noted previously, terrestrial carbon markets provide a potentially important 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 further upon alternative carbon sequestration payment schemes for promoting reforestation of reclaimed mined lands, and particularly on the differences that these alternative schemes might have on incentives for forest management. The two carbon payment schemes considered are (1) an annual payment based upon total accumulated on-site carbon, and (2) an annual payment based upon only the incremental carbon accumulation in a given year. The method of comparatives statics analysis is used to determine the effects of these payments upon optimal forest management on converted mine sites. Findings demonstrate that an annual payment based upon total accumulated carbon will have the effect of lengthening the optimal rotation length of timber on converted sites, which keeps carbon stored on-site for a longer period of time, and means less frequent harvesting activity. We further demonstrate that an annual payment that is based on the increment of carbon accumulation in a given year may have the effect of shortening rotation length of the timber, reducing the length of time that carbon is stored on the converted sites.

Experimental

It is unclear how carbon markets might work for forest-based carbon on a large scale, and in particular the specifics of how payments might be structured are unknown. Certainly, payments for general land use changes that do not recognize actual measures of carbon storage will not adequately reward management contributions, and may have little effect on terrestrial carbon sequestration efforts. In our previous analysis, we considered two payment schemes that are based on carbon grown or accumulated on a forested site (see Quarter 3, 2004 and Quarter 1, 2005 reports). However, these schemes may provide substantially different incentives for management. It might be anticipated that an annual payment based upon accumulated carbon would encourage a longer rotation length that would keep the carbon on-site for a longer period of time, while the payment based upon annual growth of carbon could generate an incentive to shorten the rotation length in order to keep the timber and carbon stock growing closer to the highest rate. To examine these contentions in a rigorous framework, we use comparative statics analysis, which determines potential directions of change in optimized variables (Amacher et al., draft ms.)

To determine the effect of a carbon payment on stand management, we consider the revenue component of our landowner decision model, which includes a carbon payment, and assume that a landowner would seek to maximize this function:

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

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 form of the decision model (4.1) incorporates an annual carbon payment that is based upon the total accumulated carbon stored on the forested site. Results for a payment based upon annual increments of carbon growth are derived in a parallel fashion. Further, for tractability we have modified the revenue portion of our original decision model by assuming that carbon volume is a direct function of stand age, and thus carbon accumulates in an identical fashion through each of an infinite number of timber rotations.

The first order necessary condition for finding a maximum of (4.1) is determined to be as follows:

$$\frac{\partial R}{\partial t} = pQ'_f(t) + s_c x(t) - ipQ_f(t) + ic_f - ic_0 - iR = 0 \tag{4.2}$$

The second order sufficiency condition is, then:

$$\frac{\partial^2 R}{\partial t^2} = pQ''_f(t) + s_c x'(t) - ipQ'_f(t) < 0 \tag{4.3}$$

Taking the total derivative of (4.2) yields:

$$\left[Q'_f(t) - iQ_f(t) - i\frac{Q_f(t)e^{-it}}{(1-e^{-it})}\right]dp + \left[i + \frac{e^{-it}}{(1-e^{-it})}\right]dc_f + \left[-pQ(t) + c_f - c_0 - i\frac{dR}{di} - R\right]di$$

$$+\left[pQ''_f(t) + s_c x'(t) - ipQ'_f(t)\right]dt + \left[x(t) - i\frac{\int_0^t x(z)e^{-iz}dz}{(1-e^{-it})}\right]ds_c = 0 \tag{4.4a}$$

The above condition (4.4a) provides a consistent framework for determining the effect of price, costs, interest rate, and carbon payment on optimal stand management when the annual carbon payment is based upon cumulative carbon found on the site each year. A similar derivative also can be determined when the carbon payment is based only upon the incremental accumulation of carbon in a given year:

$$\left[Q_f^{'}(t) - iQ_f(t) - i\frac{Q_f(t)e^{-it}}{(1-e^{-it})}\right]dp + \left[i + \frac{e^{-it}}{(1-e^{-it})}\right]dc_f + \left[-pQ(t) + c_f - c_0 - i\frac{dR}{di} - R\right]di$$

$$+\left[pQ_f^{''}(t) + s_c\dot{x}^{'}(t) - ipQ_f^{'}(t)\right]dt + \left[\dot{x}(t) - i\frac{\int_0^t \dot{x}(z)e^{-iz}dz}{(1-e^{-it})}\right]ds_c = 0$$

where $\dot{x}(z)$ is the incremental change (time derivative) in on-site carbon.

Results and Discussion

Using the implicit function theorem and (4.4a), we identify the relationship between our management variable, rotation length, and an annual carbon payment based on total accumulated carbon, as follows:

$$\frac{dt}{ds_c} = -\frac{\left[x(t) - i\frac{\int_0^t x(z)e^{-iz}dz}{(1-e^{-it})}\right]}{\left[pQ_f^{''}(t) + s_c x^{'}(t) - ipQ_f^{'}(t)\right]} \geq 0 \qquad (4.5)$$

The denominator is negative, according to the second order sufficiency condition for a maximum. As long as carbon volume is an increasing function of stand age, the numerator is necessarily positive, as the terminal cumulative carbon quantity x(t) would be greater than what amounts to a weighted average quantity across time (time weighted by the discount rate). In this case, an increase in (or initial introduction of) an annual payment that is based upon accumulated on-site carbon will have the effect of lengthening the timber rotation. An increase in rotation will keep carbon on-site for a longer period of time before the stand is harvested. In addition, on-site management activity will occur less often.

Similarly, the condition can be derived from (4.4b) to explain the direction of change in rotation length for a change in a carbon payment that is based upon annual increments of carbon:

$$\frac{dt}{ds_c} = -\frac{\left[\dot{x}(t) - i\frac{\int_0^t \dot{x}(z)e^{-iz}dz}{(1-e^{-it})}\right]}{\left[pQ_f''(t) + s_c\dot{x}'(t) - ipQ_f'(t)\right]} \begin{matrix}\le \\ \ge\end{matrix} 0 \qquad (4.6)$$

In this case, the condition cannot be signed definitively. However, it is clear that an undetermined combination of positive interest rates and/or rotation lengths that push incremental growth ($\dot{x}$) beyond its peak could make this condition negative, where an increase in the carbon payment would shorten the optimal rotation length. With this potential outcome, carbon would be held on-site for a shorter period of time in order to gain the benefits of a younger plantation with a faster growth of timber and accumulation of carbon.

Conclusions

In our analysis, we have found that: (1) under an annual payment based upon accumulated carbon, the rotation length of the stand increases unambiguously as payment increases (and consequently, as a payment of this form is introduced); and 2) increases in an annual payment based upon carbon increment may lead to a shortening of rotation length under some circumstances. A shorter rotation length would mean that carbon is removed from the site sooner, which could be undesirable if the carbon were expected to be released quickly back into the atmosphere, although it could also be desirable if the wood is transformed into durable products that continue to store carbon off site for a long time frame. These findings suggest that carbon payment structure should be considered carefully if incentives for potentially adverse management responses are to be avoided.

Literature Cited

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

Executive Summary

During the recent quarter, we initiated field sampling of mine sites selected randomly from VA, WV, KY, and OH mine-permit data bases, we established herbaceous biomass assessment plots, and we initiated field sampling of the herbaceous biomass assessment plots.

Experimental

As explained in the previous report, we randomly selected 20 mine permits each in Kentucky, Ohio, Virginia, and West Virginia for sampling using available data from state agencies, and we finalized a field sampling strategy to measure site properties (soil and vegetation) associated with forest productivity and carbon sequestration. During the current quarter, we initiated activities intended to obtain landowner permission for sampling of these sites and initiated sampling activities. An hourly wage employee, Mr. Dylan Evanylo, has been hired to accompany Dr. McGrath in field sampling.

We initiated a sub-study intended to aid herbaceous biomass assessment. One component of the minesoil sampling procedure is biomass assessment. The reason for including this component in the sampling procedure is to allow estimation of the above-ground biomass carbon present at each sampling location. However, the quantity of herbaceous biomass carbon present on a given site can be expected to vary throughout the growing season; this seasonal variation creates a problem for biomass carbon estimation because the sampling personnel will be on each mine site only one time. Therefore, we have initiated a sub-study for the purpose of characterizing the seasonal variability of herbaceous biomass on mine sites as a function of forest site quality. Four replications have been established in Virginia, two at the Powell River Project near Norton and two on the Flint Gap mine site near Coeburn. Each of these four replications includes soils of varying forest site qualities (treatments). Herbaceous biomass samples are being taken from each experimental plot throughout the growing season; each sample is being dried and weighed so as to estimate biomass carbon.

Results and Discussion

We selected more sites for sampling than available resources would allow to be sampled, expecting that site-access problems would occur. However, we did not fully anticipate the level of effort that would be required to obtain site access. Problems encountered are associated with identifying property owners (although the permit applications filed by mining firms with regulatory agencies contain landowner information, the mine permit databases do not), contacting the owners (those permit ownership records that we were able to obtain from agency contacts were out of date; some sites were listed as having multiple owners; some of the corporate owners identified by the permits were no longer in business, while private owners have been difficult to locate), and obtaining sampling permissions from those which we were able to identify and contact (although most owners were agreeable, some required that right-of-access agreements be drafted and signed, which requires involvement by both landowner and university legal personnel, while a minority have declined to cooperate) (Table 5-1).

Table 5-1. Status of mine site sampling process.

State	Permits Selected	Current Landowners Identified	Sites with Landowners Contacted	Permissions Obtained	Permission Request in Process	Sites Sampled
VA	17	9	8	6[a]	-	4
KY	20	2	2	2	4[c]	-
WV	20	6[b]	6[b]	2	4	-
OH	20	5	5	3	1	-

[a] Excludes two sites where landowner originally authorized sampling, but withdrew that authorization because of proximity to blasting on adjacent active mining that did not become apparent until researchers visited the site in question with the landowner's agent.

[b] Includes three sites where we believe current landowner has been identified and contacted, but that party has not yet confirmed ownership.

[c] Reclamation area supervisor of a regional KY DNR office has stated an intent to contact owners of four sites, and request permission for agency personnel to provide the researchers with site access.

As intended in development of procedures, two sampling personnel working together are able to sample each site in about one day. However, travel to the sites from state highways has proved more time-consuming than anticipated and often requires assistance by local personnel. The researchers have also encountered heavy and extended rainfall on several sampling trips that interfered with sampling progress. One modification of the sampling procedure was implemented: Because of vegetation density on some sites, the vegetation-assessment transect procedure has been eliminated from the sampling method and replaced with a more thorough assessment of the vegetation present at each soil-sampling point.

Herbaceous biomass assessment plots were established, and the first sample was taken in late May.

PROJECT TIMETABLE

Planned | Completed

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