INFLUENCE OF MINE SOIL PROPERTIES ON WHITE OAK SEEDLING GROWTH: A PROPOSED MINE SOIL CLASSIFICATION MODEL[1]

J. M. Showalter[2], J. A. Burger, C. E. Zipper, J. M. Galbraith, and P. F. Donovan

Abstract

Appalachian landowners are becoming increasingly interested in restoring native hardwood forest on reclaimed mined land. Trees are usually planted in topsoil substitutes consisting of blasted rock strata, and reforestation attempts using native hardwoods are often unsuccessful due to adverse soil properties. The purpose of this study was to determine which mine soil properties most influence white oak (*Quercus alba* L.) seedling growth, and to test whether these properties are adequately reflected in a proposed mine soil classification model developed for application in field assessments of mine soil suitability for reforestation. Seventy-two three-year-old white oaks were randomly selected across a reclaimed site in southwestern Virginia that varied greatly in spoil/site properties. Tree height was measured and soil samples adjacent to each tree were analyzed for physical, chemical, and biological properties. Our proposed mined land classification model used rock type, compaction, and slope aspect as mapping criteria. Tree height, ranging from 15.2 to 125.0 cm, was regressed against mine soil and site properties. Mapping units were not well correlated with differences in tree height. Microbial biomass, pH, exchangeable potassium, extractable inorganic nitrogen, texture, aspect, and extractable phosphorous accounted for 52% of the variability in tree growth. The regression model shows that white oaks were most successful on northeast-facing aspects, in slightly-acidic, sandy loam, fertile mine soils that are conducive to microbial activity. Nutrient availability, although found to be highly influential on tree growth, was not adequately represented in the classification model. We recommend that pH be included as a classification criterion, as it was correlated with all nutrient variables in the regression model.

Key Words: Site index, native hardwoods, mine soil classification.

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[2] J. M. Showalter was a Graduate Research Assistant and J. A. Burger is Professor of Forest Soil Science, Department of Forestry, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061. C. E. Zipper and J. M. Galbraith are Associate Professors and P. F. Donovan is Laboratory Specialist Senior, Department of Crop and Soil Environmental Science, Virginia Polytechnic Institute and State University.

Introduction

The eastern deciduous hardwood forest of Appalachia is one of the most valuable, productive, and diverse temperate forests in the world (AFPA 2002). This forest is important, both environmentally and economically, throughout the Appalachian region. However, several thousand hectares of this forest are being removed each year due to surface mining, and few reclaimed mines are restored to native forest.

Over 500,000 ha of land have been surface-mined in the eastern United States since the implementation of the Surface Mining Control and Reclamation Act (SMCRA) in 1978 (Office of Surface Mining 1999). Federal and state regulations based on the SMCRA have helped improve water and environmental quality as well as the safety of active and reclaimed mines, but common reclamation procedures emphasizing revegetation with agronomic grasses are not conducive to reforestation (Angel et al. 2005). Mine soils restored using procedures that have been commonly applied in Appalachia since SMCRA are often compacted, salty, and infertile and do not support native forest plant communities. Large areas of land have mostly been reclaimed to grassland or wildlife habitat (grassland with wildlife shrubs). Many reclaimed grassland sites have low productivity and are often abandoned from active management. Restoration of native forests on such sites would create a valuable economic alternative and add ecosystem services including watershed control, water quality, carbon sequestration, and wildlife habitat.

Black locust (*Robinia pseudoacacia* L.) and a variety of other early-successional trees are able to survive and grow on these mined sites (Vogel and Berg 1973, Filcheva et al. 2000). However, these species have little commercial value and do not provide the same level of ecosystem services as the native, mixed, mesophytic hardwoods that are usually present prior to mining. In this area, where fire and other disturbances are common on ecological time scales, oaks (*Quercus* spp.) represent a mature successional stage in forest development (Johnson et al. 2002). They are an essential component of the native hardwood forest, and their replacement on these sites would be a positive step toward the return of commercially-valuable hardwood forests.

Mine spoils can have highly variable physical and chemical properties, ranging from very acid pyritic materials to alkaline shales (Sencindiver and Ammons 2000). Compared to native soils, mine spoils can be high in rock fragments, have low moisture content, low porosity, poor structure, and high bulk density (Bussler et al. 1984). Chemical properties such as high pH, high soluble salt level, and low nutrient levels can also adversely affect tree growth (Torbert et al. 1990). Understanding how the combinations of different properties affect tree growth would aid in classifying and mapping mined land, and in developing successful forestry practices. With an appropriate classification system, mined land sites could be mapped and classified for reforestation suitability, and reforestation decisions such as tree species selection could be based on site characteristics and soil types.

Therefore, objectives of this study were: (1) to understand the relationship between mine soil properties and white oak (*Quercus alba* L.) growth across a broad gradient of spoil types and potential site quality classes; and (2) to test the usefulness of a forest site quality classification model (Burger et al. 2002) for predicting white oak growth on mined land.

Methods and Procedures

Site Description and Classification

In a previous study, Burger et al. (2002) developed a preliminary mine soil quality classification model that included three criteria: rock type, compaction, and aspect (Fig. 1). These criteria were based on a conceptual model of mine soil quality factors that included soil strength or density, air/water balance, soil temperature, and nutrient level. The mapping criterion rock type (Fig. 1) is a field indicator of soil air/water balance and nutrient level. The level of soil compaction is an indicator of soil strength and air/water balance, while aspect is an indicator of air/water balance and soil temperature. A weighting factor (WF) was assigned to each of the three criteria to reflect estimated relative importance (Burger et al. 2002). Each sampling site was classified by assigning a value of 1 to 5 for each criterion, multiplying that value by its respective WF, and summing these products to obtain a soil/site quality class (SQC) ranging from I to V (Burger et al. 2002), expressed as Roman numerals as per traditional expression of site quality gradients for forestry. Our study was used to test the site classification model and to determine if the criteria used adequately represented the factors that influenced white oak growth.

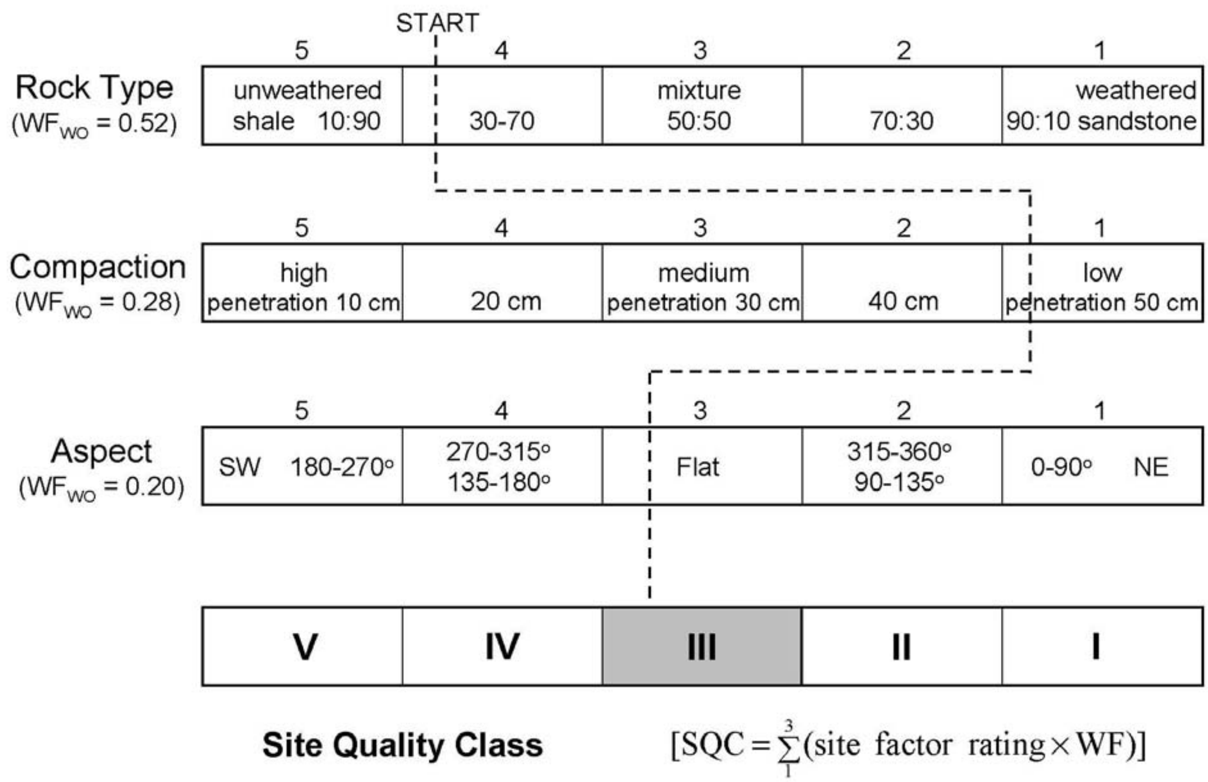


Figure 1. Site factor gradients used to determine overall mined site quality class (SQC). The field mapping criteria, rock type, level of compaction and aspect, are scored from 1 to 5 and the score is adjusted by multiplying by their respective weighting factors (WF). SQC is determined by summing the adjusted scores (Burger et al. 2002). The word "Start" shows an example culminating in a SQC III.

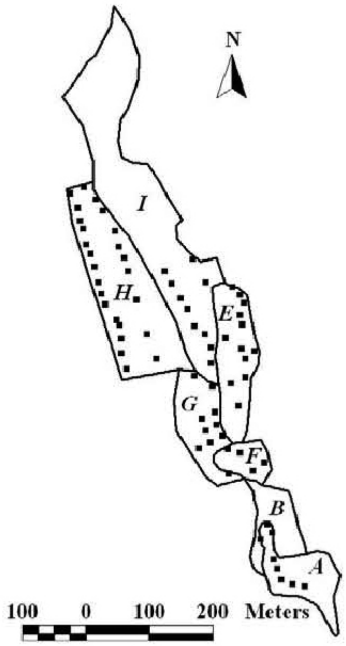
Our study was conducted during the summer of 2004. The study area is located in Buchanan County in southwestern Virginia on a reclaimed coal mine owned by Rapoca Energy Company. This area is in the Kanawha geologic formation, and various rock strata from above the coal seam were placed on the surface during reclamation. As a result, the reclaimed area has a wide variety of mine soil types, varying in both physical and chemical properties. Reclamation grading operations were conducted with the intent of avoiding surface compaction so as to create favorable conditions for reforestation.

In 2001, immediately after final grading, reclaimed soils were mapped using the proposed model and areas of the site with similar mine-soil characteristics were delineated as soil mapping units. For each mapping unit, SQC was determined using the model described above (Fig. 1). The site was planted in 2002 with native hardwoods at a density of 1482 trees ha^{-1} using species mixes appropriate for each mapping unit's soil properties and site quality. White oak was planted on all sites. White oak seedlings were obtained from the Virginia Department of Forestry state nursery. Those planted were of uniform grade and had a relatively uniform initial caliper and height. Herbaceous vegetation was applied uniformly over the site by a seeding contractor.

Field and Laboratory Methods

Total tree height and third-year growth were used to judge the accuracy of the SQC assignments. Seventy-two three-year-old white oak trees were randomly chosen across a range of spoil types, which included six mapping units (Fig. 2). White oak was chosen as the test species because it was a component of all species mixes, is a valuable timber species of the late successional native forest of the Appalachians, and is found throughout the Appalachians on a range of sites. Glyphosate was sprayed in a 1-m diameter circle around each tree at the beginning and in the middle of the growing season to minimize the effect of herbaceous competition on third-year growth. Total tree height and third-year growth were measured at the end of the third growing season, and averages were calculated for each mapping unit.

Soil samples were taken to a 40-cm depth within a 50-cm radius from the base of each tree. Samples were air dried and passed through a 2-mm sieve, and an array of physical and chemical properties were measured. Bulk density was determined using the excavation method (Blake 1965), and coarse fragment content was determined by sieving using a 2-mm screen. Soil particle size was determined using the hydrometer method (Bouyoucos 1936). Total soluble salts were measured in a 1:5 soil:water mix with an electrical conductivity meter (Bower and Wilcox 1965), and pH was determined in a 2:1 water-soil suspension using a pH meter. Nitrogen (N) mineralization potential was measured following anaerobic incubation (Bremner 1965a), and inorganic N was determined using a 1.0-M KCl extraction method (Bremner 1965b). Total N and carbon (C) were measured using a dry combustion C-N analyzer (Vario MAX Instruction Manual 2000). Exchangeable cations were extracted using the ammonium acetate method and analyzed using an ICP spectrophotometer (SpectroFlame Modula Tabletop ICP 1997, Spectroanalytical Instruments, Germany; Thomas 1982). Available nutrients were found using the Mehlich I test, and available phosphorus (P) was measured using the sodium bicarbonate method (Olsen and Sommers 1982).



Site classification of six mined land map units.

Unit Label	Rock Type	Compaction	Aspect	Site Quality	Site Class
A	2	2	3	2.2	II
E	2	4	3	2.8	III
F	3	2	4	2.9	III
G	4	4	5	4.2	IV
H	5	3	4	4.2	IV
I	1	1	5	1.8	II

Figure 2. Soil/site quality classification and mapping of the Rapoca reclamation site in southwestern Virginia. The data points on the map indicate locations of selected white oaks that were used to test the classification criteria. Values are based on the site quality class scheme in Figure 1.

Site factors including aspect, slope, and distance from native forest were also determined for each tree. Aspect was scaled by assigning numerical values starting at 1 for a northeast aspect and decreasing in value in either direction around the compass to 0 for a southwest aspect.

At the end of the growing season, the trees were excavated and soil adjacent to tree roots was used for the characterization of soil microbial properties (Table 1). Soil was kept at 4^{o}C and was processed within 2.5 weeks of collection. For an estimate of microbial activity, dehydrogenase concentration was determined using a 2,3,5-triphenyltetrazolium chloride (TTC) indicator (Tabatabai 1982). Microbial biomass was measured by chloroform fumigation (Anderson and Domsch 1978, Gregorich et al. 1990, Jenkinson and Powlson 1976).

Leaves were harvested in mid-August from the upper portion of the crown, dried at 65^{o}C for 7 days, and ground to pass through a 1-mm sieve. Nitrogen was determined using the C-N analyzer referenced above. Potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), and P were determined by dry-ashing the samples, extracting the nutrient elements using a 6N HCl solution, and analyzing the extracts with the ICP spectrophotometer referenced above (Jones and Steyn 1973).

Table 1. Mean values and ranges for tree height and soil/site properties associated with each tree on the study site.

Variable		Mean	Min	Max	St Dev	CV
Tree Height (cm)		56.4	15.2	125.0	22.5	40.0
<u>Site Properties</u>						
Aspect †		0.27	0.0	1.0	0.29	107.44
% Slope		24	0	55	16	69
Dist from Native Forest (m)		69	6	162	41	59
<u>Physical Properties</u>						
% Silt + Clay		45	17	64	9	20
% rock fragments		35	21	51	6	16
Bulk Density (fine earth) (g $cm^{3\ -1}$)		0.96	0.61	1.39	0.18	18.27
<u>Chemical Properties</u>						
EC (dS m^{-1})		0.92	0.14	4.72	1.03	112.29
pH		5.2	3.2	7.8	1.5	27.8
Anaerobic N (mg kg^{-1})		9.96	0.49	62.95	10.12	101.66
KCl extractable N (mg kg^{-1})		5.20	1.59	21.55	3.52	67.78
P (mg kg^{-1})		7.24	0.92	34.86	5.75	79.44
	K	33.5	8.7	72.3	13.2	39.5
	Ca	542.3	54.0	1426.4	368.3	67.9
	Mg	142.0	24.9	267.2	62.6	44.1
	Zn	2.2	0.8	5.9	1.1	50.6
Melich I Available	Mn	19.8	6.1	52.2	11.1	56.0
Nutrients (mg kg^{-1})	Cu	1.1	0.4	1.8	0.3	25.9
	Fe	41.9	12.0	138.9	24.3	58.0
	B	0.09	0.05	0.20	0.04	47.67
Total N (%)	N	0.05	0.03	0.15	0.02	41.95
Total C (%)	C	1.08	0.30	4.39	0.76	70.53
	Ca	252.5	44.5	539.9	117.1	46.4
Exchangeable cations	Mg	100.5	27.9	147.0	23.2	23.1
(mg kg^{-1})	K	161.5	28.4	343.6	73.2	45.3
	Na	65.1	16.0	107.2	17.0	26.1
CEC (cmol+ kg^{-1})		3.01	0.99	5.65	1.11	37.02
<u>Biological Properties</u>						
Dehydrogenase (mg kg^{-1})		11.42	0.25	80.83	15.47	135.46
Microbial biomass (mg kg^{-1}) (dissolved organic carbon)		38.1	3.3	201.8	35.8	93.9

† aspect was calculated using a continuum where southwest = 0 and northeast = 1.

Data Analysis

Tree height was regressed with site quality class to determine if the classification criteria represented factors influencing tree growth (SAS 2004). A multiple regression analysis was conducted to identify soil and site properties exerting effects on tree height. The independent variables were transformed based on established relationships with tree growth (Henderson et al. 1990, Kiniry et al. 1983, Fisher and Binkley 2000). Potassium and available N were transformed using the square root function, and microbial biomass and pH were transformed using a natural log function. An arc sine function was used to transform aspect and silt+clay percent in order to achieve a normal distribution (Little and Hills 1978). Backward Cp and R-squared selection were used to eliminate variables based on multi-collinearity and biological significance. Two experimental trees were eliminated based on differences in growth pattern. One tree had a double stem, while the other was much larger than any of the other trees. Two additional outliers were eliminated based on soil properties. Both had P levels over 10 times higher than any of the other samples. Therefore, statistical analyses were performed with $n = 68$.

Foliar samples were analyzed for nutrient sufficiency and balance using the Diagnosis and Recommendation Integrated System (DRIS) (Beaufils 1973). This analysis involves comparing the variance in foliar nutrient levels and nutrient ratios between the subpopulation of trees that are most successful ("reference population" = upper quartile) and the rest of the population. Ratios of the reference population were used as a standard by which imbalances in the remaining trees were assessed. A nutrient index for a given foliar nutrient level 'A' is developed using the following equation:

$$\text{Nutrient 'A' index} = \frac{[f(A/B) + f(A/C) + \ldots + f(A/N)]}{z}$$

where

$$f(A/B) = ((A/B)/(a/b) - 1) \times (1000/CV) \text{ when } A/B \geq a/b,$$

or,

$$f(A/B) = (1-(a/b)/(A/B)) \times (1000/CV) \text{ when } A/B < a/b,$$

where A through N are the levels of foliar nutrients of interest, A/B is the nutrient ratio of the target population, a/b is the nutrient ratio of nutrient A to nutrient B for the reference subpopulation, z is the number of functions in the equation, and CV is the coefficient of variation of the reference population (Walworth and Sumner 1987). The closer the nutrient index is to zero, the closer it is to the level of the reference population or the optimum. If it is negative, the nutrient is deficient, and if it is positive, the nutrient is in excess. The sum of the absolute values of the nutrient indices were added to obtain a nutrient balance index (NBI). The higher the number, the greater the nutrient imbalance and the poorer the tree growth. If the NBI is close to zero, foliar nutrient concentrations are close to optimal.

This analysis can be used to develop nutrient norms for a given plant species. Populations that are fertilized at various levels are compared, and the nutrient levels in plants that are most successful are used as norms. In this study, we used foliar nutrient levels to compare relative nutrient deficiencies and imbalances within a single population of young white oak trees. Nutrient means of the upper quartile of the population based on tree height were used as the standard against which foliar levels were compared. This analysis was done to find relative levels of nutrient imbalances among trees on the study site. It was simply used to distinguish between the nutrient levels of trees that were growing relatively well on certain sites and trees that were growing poorly.

Results and Discussion

Average values for total tree height and third-year growth for each mapping unit were plotted as a function of site quality. Results for total tree height and third-year growth were virtually the same; therefore, total tree height was used for all evaluations (Fig. 3). We hypothesized that tree growth would decrease as site quality decreased, where Class I is highest quality and Class V is lowest. The data show a trend, but the relationship between tree growth and designated site quality for the mapping units was not significant ($p > 0.1$). Measured tree growth showed that site quality was incorrectly assigned to several of the mapping units. This showed that the classification criteria used in the proposed model do not represent all the soil and site factors influencing tree growth, and that additional classification criteria are needed to adequately estimate site quality.

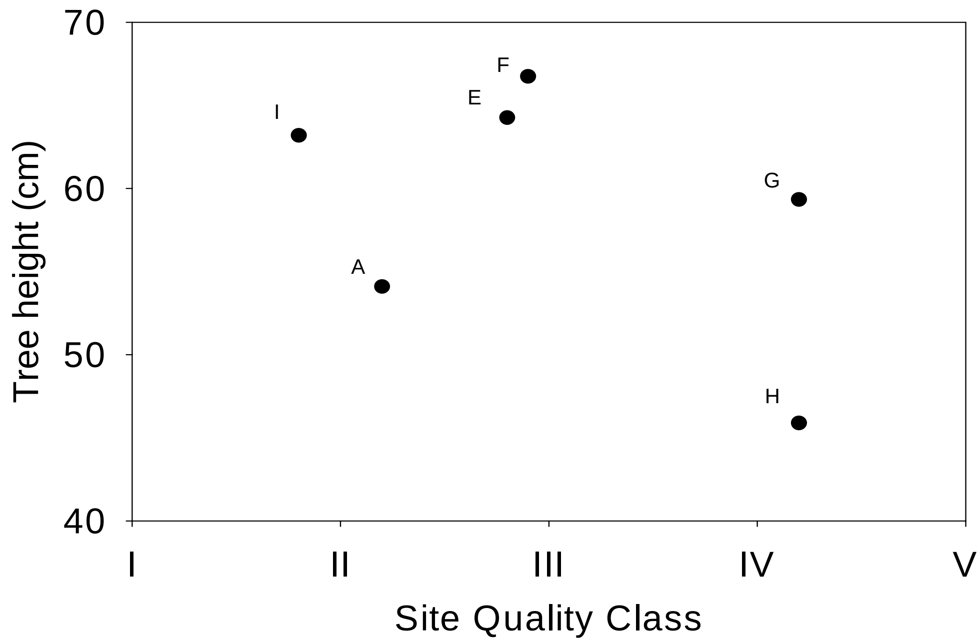


Figure 3. Mean tree height as a function of soil/site quality for mapping units based on a preliminary classification scheme proposed by Burger et al. (2002).

The spectrum of measured site and soil physical, chemical and biological properties hypothesized to influence tree growth is presented in Table 1. In nearly all cases, values ranged considerably among the sampled points. For example, slope steepness ranged from 0 to 55 and slope aspect covered the spectrum from northeast to southwest. Bulk density of the fine earth fraction ranged from 0.61 to 1.39 g cm^{-1} and silt plus clay ranged from 17 to 64%. Chemical properties were also highly variable, with soil exchangeable nutrients ranging by an order of magnitude. Spoil pH ranged from 3.2 to 7.8 and EC ranged from 0.14 to 4.72 dS m^{-1}. Microbial activity was virtually absent on some sites and quite prevalent on others. As a result of this broad range in soil and site properties, tree height ranged from 15 to 125 cm.

To better understand which soil and site factors were influencing white oak seedling growth, tree height was regressed against soil and site properties using data for all 68 trees. From greatest to least importance in the regression model, microbial biomass, pH, extractable soil K, total extractable inorganic N, % silt + clay, aspect, and extractable soil P were found to be the most important factors influencing white oak growth on this site (Table 2). Over 52% of the variation in tree height was described by the seven soil and site factors:

$\textbf{\textit{Tree ht}} = 33.10 + 9.19\ln(\textbf{\textit{bio}}) - 29.01\ln\textbf{\textit{pH}} + 6.61\sqrt{(\textbf{\textit{K}})} + 10.05\sqrt{(\textbf{\textit{N}})} - 61.15\text{arc sin}(\textbf{\textit{siltclay}}) + 11.33\text{arc sin}(\textbf{\textit{as}}) + 0.02(\textbf{\textit{P}})^2$

$\mathbf{R^2=0.5205}$

Table 2. Variables and standardized coefficients for the regression model describing 52% of the variation in tree growth.

Variable	Standardized Coefficient	P Value
Bio = biomass of microbes (mg L^{-1})	0.40622	0.004
pH = pH (-log[H+])	-0.40334	0.0068
K = potassium (mg kg^{-1})	0.38567	0.0019
N = total extracted nitrogen (mg kg^{-1})	0.35289	0.0048
Siltclay= % silt + clay	-0.26324	0.0345
as = aspect (0 to 1 scale SW to NE)	0.24696	0.0318
P = phosphorus (mg kg^{-1})	0.19187	0.0796

Mean values of the significant soil properties varied widely among mapping units (Table 3). These areas are easily distinguished by their vastly different physical, chemical and biological properties, suggesting that their map unit delineation was warranted. However, these properties also varied considerably within mapping units.

Table 3. Mean values for height and soil/site properties that were included in the regression model for each mapping unit.

Variable	Mapping Unit					
	F	E	I	G	A	H
Height (cm)	66.74	64.26	63.19	59.33	54.10	45.89
Microbial biomass (mg kg^{-1}) (chloroform fumigation)	84.15	32.51	38.96	64.38	66.95	16.59
pH	6.57	4.64	4.75	6.22	6.19	4.96
Melich I Available K (mg kg^{-1})	33.22	36.04	39.47	30.17	45.71	29.09
Available N (mg kg^{-1})	11.19	4.02	4.99	8.04	6.47	3.43
% Silt + Clay	42.93	50.39	49.34	43.39	47.50	39.84
Aspect †	0.13	0.73	0.19	0.00	0.00	0.17
P (mg kg^{-1})	7.12	6.77	9.31	6.52	8.88	6.63

† Aspect was calculated using a continuum where southwest = 0 and northeast = 1.

Microbial biomass was represented with a mean of 38.1 mg kg^{-1} of microbial organic C; it was skewed toward lower levels, with many sites having virtually no microbes, and only a few sites having levels above 100 mg kg^{-1} (Fig. 4). Microbial biomass was positively correlated with tree growth. Since correlation does not necessarily imply causation, it is unknown whether microbial populations have a significant effect on tree growth or whether microbial biomass responded to the site factors that influenced tree growth. The fact that microbial biomass was independent of other regressors in the model suggests that it is a causative factor. Symbiotic mycorrhizal colonization of the tree root systems would be an example of causation. In any case, microbial activity is a good indicator of soil quality (Miller 1998), as microbes play important roles in decomposition of organic matter, N mineralization and fixation, and symbiosis. Hutson (1980) found that low population densities of organisms on industrial reclamation sites led to significantly less degradation of oak leaves than on control sites. Microbes are the main mechanism for the release of plant-available nutrients from organic matter (Brady and Weil 2002). In his discussion of techniques for reclaiming with native hardwoods, Miller (1998) stated that the development of a healthy and diverse soil microbial population through replacement of topsoil is essential to the establishment of native trees.

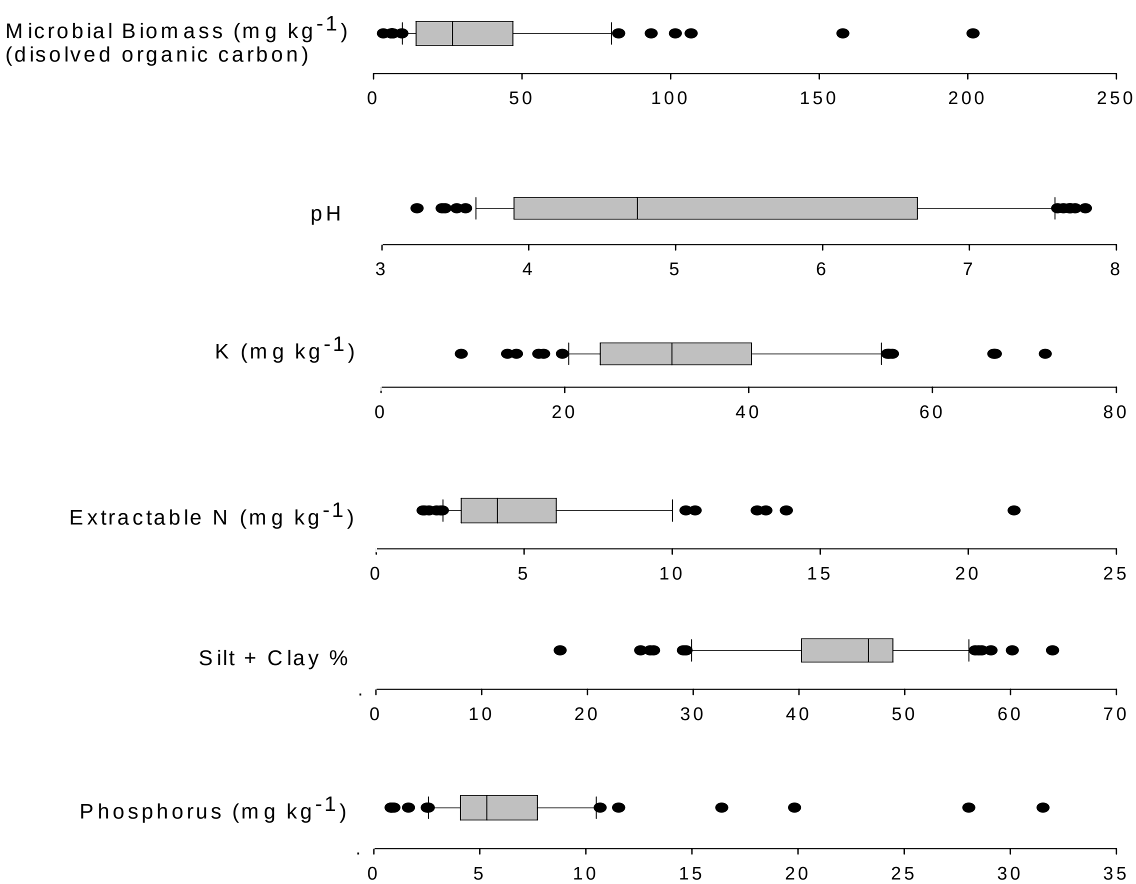


Figure 4. Box plots for variables in the regression model, listed from most to least important to tree growth.

Mine soil pH ranged from 3.2 to 7.8 with a mean of 5.2 (Fig. 4). It had a significant negative correlation with tree growth and was the second most important variable in the regression model. Mine soil pH is related to many other chemical and biological properties. It is closely related to spoil type and is a master variable determining nutrient availability (Brady and Weil 2002).

The average level of soil N measured across the study area was 5.20 mg kg^{-1} (Fig. 4). This level is considered deficient (Fisher and Binkley 2000), suggesting that the higher levels found on some sites would have a positive impact on tree growth. Levels of K and P ranged widely, with P skewed toward smaller amounts while K was more evenly distributed. Soil P, K, and N were positively correlated with tree growth and were found to be statistically significant components of the regression model. Tree growth was a function of the square root of the level of N and K and the level of P squared, which are typical response relationships. Nutrients that were collinear with K, including Ca and Mg, were removed from the regression analysis; therefore, K may be seen as representing a group of cations important to tree growth.

Soil types ranged from loamy sands to sandy loams with 17 to 65% silt + clay (Fig. 4). Percent silt + clay was negatively correlated with tree growth. This negative correlation suggests that oak trees grow better in sandier mine soils. This effect may be caused by low hydraulic conductivity and poor drainage in the more finely-textured mine soils, or it may be because silt + clay content correlates with chemical factors that influence tree growth. Torbert and colleagues (1990) also found a strong positive correlation between percent sand and tree growth.

Aspect ranged from northeast to southwest. Tree height was positively correlated to aspect increasing from southwest to northeast. Northeast aspects are more mesic and cooler during the growing season, making them more conducive to tree growth.

Because soil fertility factors played a dominant role in the model of tree growth as a function of soil and site properties (Equ. 2), foliar nutrient concentrations were analyzed to better understand the role of soil fertility on tree growth.

The nutrient levels of the reference population were much closer to levels found in foliage from white oaks growing in the native Appalachian hardwood forest. Auchmoody and Hammock (1975) found levels of 25.6 mg $kg^{-1}$for N, 1.5 mg kg^{-1} for P, 7.3 mg kg^{-1} for K, 4.7 mg kg^{-1} for Ca, 0.9 mg kg^{-1} for Mg, and 1.0 mg kg^{-1} for Mn (Table 4, col. 2). These trees were located on a mixed oak stand in the Fernow Experimental Forest in Parsons, West Virginia. The upland oak site index was 66 and the stand was 60 years old. Foliage samples were taken from the upper part of the crown in late August. A comparison of these nutrient levels with those occurring on our study site shows that foliar N levels are insufficient on the mine site, while P and K are sufficient and Ca, and Mg are in excess compared to these native forest levels.

DRIS nutrient analyses showed that N, K, and Ca were deficient or in excess and that ratios of N/K, K/Ca, and K/Mg were out of balance (Table 4). This suggests that levels of N, K, P, Mg, and Ca are all influencing the growth of these trees on these sites. The nutrient indices suggested that trees on all mapping units were deficient in N and P and had an excess or sufficiency in Ca and Mg (Table 5). K was either sufficient or slightly deficient, depending on the mapping unit.

Table 4. DRIS foliar nutrient ratios for good and poor populations of three-year-old white oaks on a mine site in Virginia.

Nutrient	Native Unfertilized White Oak Nutrient Levels†	High Height Growth‡		Low Height Growth		F-test for Variance Ratio	P Value
		Mean	CV	Mean	CV		
N	25.60	22.75	12.62	17.99	28.82	3.26	0.0104*
P	1.50	1.74	21.97	1.30	40.37	1.88	0.1575
K	7.30	7.48	19.52	8.03	30.03	2.73	0.0272*
Ca	4.70	8.73	29.87	10.93	46.77	3.84	0.0039*
Mg	0.90	1.75	43.61	2.56	42.75	2.07	0.1045
Mn	1.00	2.09	67.47	1.41	112.0	1.25	0.6329
N/P	17.07	13.54	19.78	15.02	35.96	4.07	0.0028*
N/K	3.51	3.12	17.10	2.53	45.93	4.74	0.0010*
N/Ca	5.45	2.81	27.97	2.02	53.66	1.91	0.1491
N/Mg	28.44	15.53	43.70	8.77	60.79	0.62	0.1994
N/Mn	25.60	35.43	166.7	50.04	121.3	1.05	0.9450
P/K	0.21	0.24	31.82	0.17	46.24	1.08	0.9226
P/Ca	0.32	0.21	30.27	0.15	57.43	1.76	0.2063
P/Mg	1.67	1.20	51.00	0.65	69.86	0.54	0.1017
P/Mn	1.50	2.37	160.6	3.22	112.0	1.12	0.7340
K/Ca	1.55	0.95	39.14	0.92	65.36	2.62	0.0332*
K/Mg	8.11	5.42	60.08	3.79	56.48	0.43	0.0245*
K/Mn	7.30	3.59	0.29	5.72	0.27	1.13	0.7203
Ca/Mg	5.22	5.55	32.37	4.56	35.81	0.83	0.5907
Ca/Mn	4.70	4.19	0.44	7.78	0.42	1.04	0.9934
Mg/Mn	0.90	0.84	0.65	1.82	0.38	0.70	0.3268

† From Auchmoody and Hammock, 1975.

‡ Upper quartile of the population.

* Significance at a 0.1 level.

Table 5. Mean nutrient indices for three-year-old white oaks located across six mapping units.

Map Unit	N Index	P Index	K Index	Ca Index	Mg Index	NBI
H	-37.95	-30.66	17.59	18.86	32.16	137.22
A	-4.08	-13.04	-9.68	0.47	26.34	53.61
E	-3.97	-3.22	-4.18	5.68	5.69	22.74
I	-10.51	-14.17	6.26	10.49	7.93	49.36
G	-4.36	-16.31	-2.09	7.87	14.88	45.51
F	-6.40	-23.05	-7.46	10.62	26.29	73.82

When these nutrient indices were added (absolute values) using the DRIS technique to create a nutrient balance index (NBI), the values show that there is a relationship between the extent of imbalance and the amount of tree growth ($p = 0.0001$) (Fig. 5), despite the fact that many other factors besides fertility are also affecting tree height. The dashed line represents a nutrient imbalance above which further height growth is unlikely (Walworth and Sumner 1987). Tree height is severely limited when the NBI is greater than 200. Mapping unit H had the lowest tree height growth levels, the lowest predicted site quality, and the highest nutrient imbalances. This further supports the importance of nutrient levels in the designation of spoil quality and the ability of trees to grow in certain spoil materials. These DRIS results strongly support the inclusion of an indicator of soil available N, P, and K in the classification model.

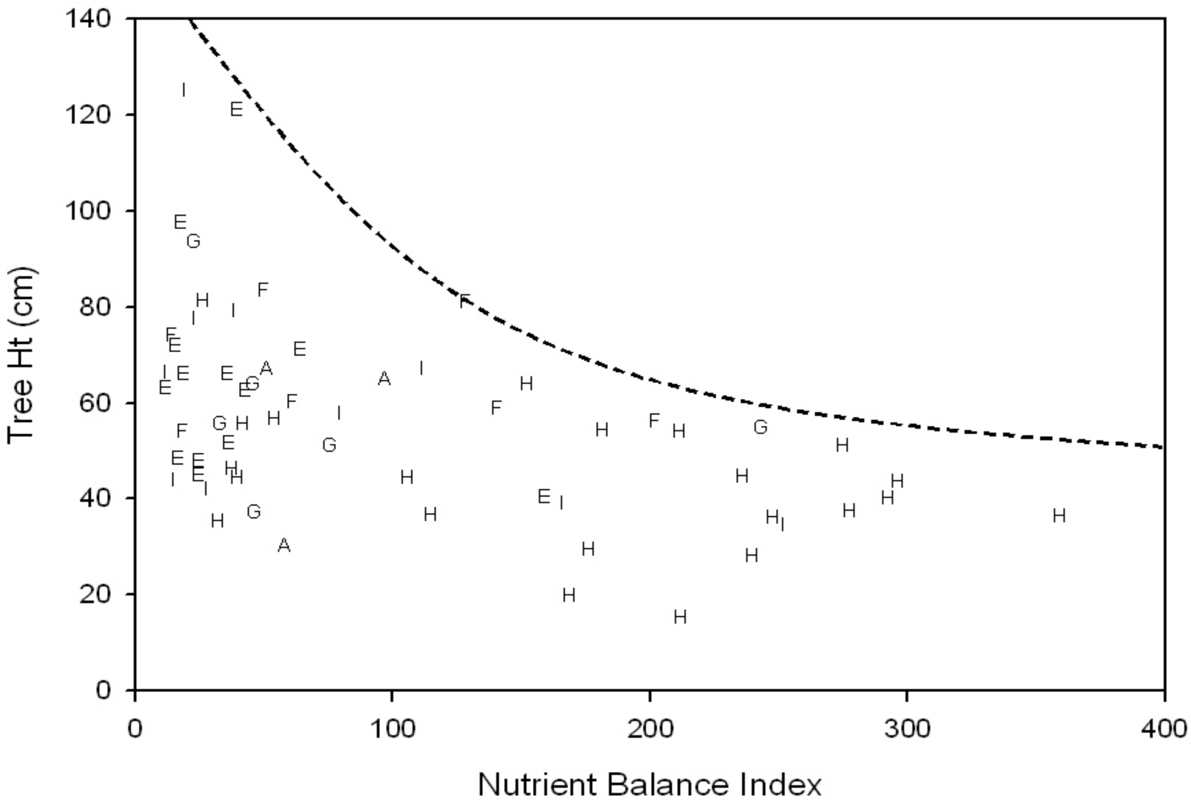


Figure 5. Tree height as a function of nutrient balance for 65 three-year-old white oak seedlings across six mapping units. The dashed boundary line represents a tree height limit for a given NBI.

The regression model and nutrient analysis show that the factors in the conceptual model for mine soil quality (soil strength, air/water balance, soil temperature, and nutrient levels) were not all limiting growth on this site. There were no variables in the final regression model indicating that density was a problem, suggesting that these mine soils were uncompacted. Air/water balance was represented in the regression model through the variables silt + clay and aspect, suggesting that water availability and aeration influenced white oak growth on this site. Soil temperature was represented in the regression by aspect. Nutrient availability was also an influential soil attribute on this site. It appeared in the regression model through soil variables characterizing N, P, and K concentrations. The importance of available nutrients was further supported by the foliar DRIS analysis, where NBI levels were inversely proportional to tree growth.

Thus, three factors of the factors represented by the regression model – air/water balance, soil temperature, and nutrient levels – were important to white oak growth on this site. Air/water balance and soil temperature effects were represented by the mapping criteria, but nutrient levels were not. Although rock type influences nutrient availability to some degree, it alone did not represent the variability of nutrient levels across sites. An added criterion that better represents nutrient availability is thus needed in the mine soil classification model.

Nutrient levels, although established as important criteria of soil quality, are not easily measured in the field and thus may not be useful additions to a field mapping tool. However, the essential soil nutrients influencing white oak growth on this site, according to both the regression model and the DRIS analysis, were correlated with pH (Table 6).

Table 6. Correlation coefficients of pH with soil nutrient levels and other soil properties on the study site.

	Correlation Coefficient	Significance
Total Extracted N (mg kg^{-1})	0.42067	0.0002
K (mg kg^{-1})	0.38222	0.0009
P (mg kg^{-1})	-0.23450	0.0507
Ca (mg kg^{-1})	0.77269	<0.0001
Mg (mg kg^{-1})	0.86313	<0.0001
% Silt + Clay	-0.24561	0.0376
Microbial Biomass (mg kg^{-1})	0.54324	<0.0001

The significant correlation of pH with nutrients and tree growth suggests that an intermediate pH may be optimal. Soil reaction has been used in the past to assess mine soil quality for agronomic crops, but it is often modeled as a positive linear relationship with productivity for all situations, where a higher pH indicates a better soil. Although pH levels up to 6.5 can lead to an increase in P availability and CEC, pH above this level can decrease the availability of some micronutrients (Brady and Weil 2002) and shift microbial composition, especially mycorrhizal relationships on which native trees depend (Killham 1994). High soil pH increases herbaceous competition. At high pH, grasses have a distinct advantage and often out-compete trees (Burger and Zipper 2002). Furthermore, pH was not well correlated to rock type on this site, varying widely within each mapping unit. For these reasons, we recommend that pH be added as an additional criterion with equal weighting for soil classification and mapping as shown in the diagram in Figure 6. We expect that incorporation of pH will utilize a transformation that assigns maximum values to pH at mildly acidic levels that favor P availability but without stimulating excess herbaceous vegetation growth. Further testing of this modified field classification model on additional sites is needed to validate its usefulness and weight the relative importance of the four criteria for major reclamation tree species.

	5	4	3	2	1
Rock Type (WF_{WO} = 0.25)	unweathered shale 10:90	30-70	mixture 50:50	70:30	weathered 90:10 sandstone
Compaction (WF_{WO} = 0.25)	high penetration 10 cm	20 cm	medium penetration 30 cm	40 cm	low penetration 50 cm
Aspect (WF_{WO} = 0.25)	SW 180-270°	270-315° 135-180°	Flat	315-360° 90-135°	0-90° NE
Soil pH (WF_{WO} = 0.25)	3.5 – 4.4	7.5 – 8.4	6.5 – 7.4	4.5 – 5.4	5.5 – 6.4
	V	**IV**	**III**	**II**	**I**

Site Quality Class $[SQC = \sum_{1}^{4}(\text{site factor rating} \times WF)]$

Figure 6. Modified site quality classification model showing the addition of a pH criterion to help estimate forest site quality class (SQC) for white oak seedlings. An equal weighting factor (WF) of 0.25 was assigned to all four classification criteria pending further testing.

Conclusions

This study tested a mine soil classification system that included rock type, compaction, and aspect as field mapping criteria (Burger et al. 2002). The study showed that additional criteria representing mine soil chemistry and fertility are needed for adequate characterization of mine site quality for white oak trees.

Our regression model of tree height as a function of site and soil properties showed that sandy loam soils with a northeast aspect, high nutrient levels, and high microbial populations were the most conducive to growth of young white oaks. Of these properties, soil particle size and aspect were represented in the existing classification model and accounted for the range in water/air balance (Burger et al. 2002). Nutrient availability was also a growth-determining factor, but it was not a component in the original classification model. Nutrient availability was well correlated with spoil pH, pH was correlated with tree growth, and pH is an easily-measured field property that could be included as a field classification criterion. Therefore, based on white oak response to mine soil properties, we recommend that pH be included as a classification criterion for mine soil mapping along with rock type, soil density, and aspect. A revised classification model will need further testing with an independent data set.

With species-specific soil quality maps, native tree species can be selected for planting based on the given quality of a reclaimed mined site, leading to increased survival and growth, more timely bond release for mine operators, and improved success restoring healthy native hardwood stands.

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