SOIL PRODUCTIVITY MODEL TO ASSESS
FOREST SITE QUALITY ON RECLAIMED
SURFACE MINES

by

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Forestry

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December, 1992

Blacksburg, Virginia
ABSTRACT

The Surface Mining Control and Reclamation Act (SMCRA) of 1977 requires that mine operators reclaim mined land to achieve productivity levels equal to or greater than premined conditions. Presently, the standard for evaluating reforestation success is based solely on tree-seedling survival. This method is an estimator of stand density and not an indication of site productivity. There exists a need to evaluate mine soils based on their capability of growing merchantable timber. This model would aid the reclamation process by providing a means for assessing mine soils based on their quality and productivity.

Seventy-eight fixed-area plots in Virginia and West Virginia were selected to evaluate the effects of mine soil/site properties on tree growth. These plots ranged from 0.02 to 0.04 ha and consisted of 5- to 9-year-old eastern white pine (Pinus strobus). A 1-m deep pit was dug at the base of one representative tree on each plot to determine rooting depth and physical and chemical properties of the subsurface horizons. Two randomly-located surface soil samples (0-10 cm) were also collected for analysis of chemical and physical properties. Plot information collected included number, identification and total height of non white pine tree species, percent cover, biomass, percent slope, position on slope, aspect, and overburden
type. White pine growth information was collected during the dormant season and included ground line diameter, internode distances, total height and needle samples.

Multiple regression analysis was used to model the effects of mine soil properties on white pine tree growth. Results indicate that the properties most correlated with tree growth were rooting volume, defined as the depth to a restrictive layer, slope percent, soil extractable phosphorus and manganese content and electrical conductivity.

Using this information, a productivity index (PI) equation was developed based on the modeling techniques of Kiniry (1983) and Gale (1987). The model is based on the premise that limiting soil and site characteristics affect a specie's optimum root distribution and thus its aboveground productivity. Each soil horizon characteristic is weighted by its importance to a specie's optimum proportional root distributions.

The developed PI model was verified using a white pine data set ranging in age from 11 to 15 years that was obtained from 14 reclaimed mines in Virginia. The PI was significantly correlated with aboveground biomass and site index. Similar results were observed when PI and site index were added separately into a Schumacher-type equation predicting biomass.
ACKNOWLEDGEMENTS

My heartfelt thanks go out to my lovely wife Lisa Marie. She continued to support me in this endeavor, no matter my temperament. She was someone I could discuss my project with and more often then not, set me straight. To my daughter Emma, I say thank you for amusing yourself while I worked.

I am thankful for the guidance and support given by my major advisors Dr. James Burger and Dr. James Johnson. Their insightful suggestions often extracted me from difficult situations. To Dr. Daniels, thank you for making time to be on my committee.

I would like to acknowledge the assistance of William Rutlin and David Mitchem who worked long and hard hours on this project. But make no mistake boys, this project still would have been completed without you. I would like to thank John Torbert for his assistance and many words of wisdom.

I would like to thank the Office of Surface Mining (OSM) for funding this project. This project could not have been completed without the assistance of Tim Probert of Pocahantus and Andy Clapp of Humphries who took time out from there busy schedules to help locate study sites. I would like to thank the secretaries Mary Jane Whitescarver,
Nancy Chapman, Sue Snow and Peggy Quarterman for all their help.

Finally, I would like to express my gratitude to my parents, Geri and Adam Andrews, for their love and constant support (both financial and emotional) throughout my life.
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CHAPTER I

INTRODUCTION AND OBJECTIVES

Reclamation of surface-mined land for forest use under the Surface Mining Control and Reclamation Act (SMCRA - Public Law 95-87), requires grading of cast overburden, topsoil replacement, and fertilizer application, as necessary, to achieve productivity levels equal to or greater than premined conditions. However, based on tree seedling survival and growth on unmined reference areas, it is not certain whether forest land reclaimed according to these specifications actually regains original productivity levels. Some physical and/or chemical properties of reconstructed soil have shown decreased productivity when compared to original forest soils (Vogel, 1981).

Different reclamation approaches can result in a wide range of forest site productivities. Across 36 reclaimed sites in Virginia, all of which had 10-year-old white pine, Torbert and co-workers (1988) found site indices ranging from 9.1 to 33.5 m. Assuming these stands are harvested at age 35, the white pine stand growing on an area with a site index of 110 would yield over 10 times the volume of wood in the stand with a site index of 35. Furthermore, the timber quality on the better site would be greater since a larger proportion of the harvested wood would be high-value sawtimber as opposed to lower value pulpwood. Thus, a
harvest from the site index 110 stand may yield 20 to 30 times the return of a harvest from the site index 35 stand.

To reclaim strip mines to "unmanaged forest land" PL 95-87 mandates that subsequent stand productivity equal or exceed premined conditions and the establishment of a diverse assortment of tree species exceeding 30 cm in height at densities of over 1000 stems/ha, together with a 70% ground cover five years after the initial establishment. It is difficult to justify reclamation productivity standards for tree production that are based on tree survival and a 30 cm size standard, with no evidence of the ability of reclaimed sites to produce a saleable product. Non-producing trees are no more valuable to a tree farmer than non-producing crops are to an agricultural farmer. Reclamation standards for forest land uses must be based on potential wood production, not potential tree survival.

In the United States the most widely used method for predicting forest site quality is site index, defined as height at a base age. However, many site index curves are not constructed for stands less than 20 years old. Because of this limitation, many of these reclaimed mine sites are unsuitable for determining site index.

Another method to predict site quality is the use of soil and site characteristics as indicators of productivity through use of regression equations. The multiple linear
regression model is developed to be used in areas not yet planted or in stands too young to use site index. Studies have shown that various combinations of soil and site factors provide accurate estimates of growth when combined in multiple regression equations. However, despite its popularity, this approach has several weaknesses. These models can have large positive prediction bias and include biologically insignificant variables, may have low precision, and may suffer from multicollinearity.

Another approach that uses the soil as an indicator of site productivity is the productivity index. This model converts soil property data into estimates of soil productivity based upon the assumption that soil is a determinant of tree growth because it provides an environment for root growth. The main assumption of the productivity index concept is that overall productivity is proportional to root growth, the greater the root growth the greater the above-ground growth. This model was initially developed by Kiniry and others (1983) for agricultural crops but later modified to be used for forest species. Gale and others (1991), successfully used it to predict white spruce (Picea glauca) productivity in the Lake States. This approach integrates "effective properties" throughout the rooting zone to produce a measure of productivity potential. This productivity estimator is straightforward, easy to use,
and can be an accurate predictor of site quality on young stands.
OBJECTIVES

A productivity standard for forestland is needed by the mining community in order to appropriately judge reclamation of forest soils. This would aid in the reclamation process, allow for a means of assessing the success of reclamation, and provide valuable information for the subsequent management of the forest. Accordingly, the objectives of this study are:

i) To establish the functional relationships between tree growth potential during the first ten years and specific mine soil properties.

ii) To develop a soil productivity estimator for trees based on mine soil properties.
CHAPTER II

LITERATURE REVIEW

Surface Mining

At the turn of the century, production of bituminous coal and lignite was approximately 200 million tons per year. By 1978, production increased to 654 million tons and, most likely, will exceed 2 billion tons annually by 1995 (Follett, 1980). Approximately 57 percent of this coal will be removed using surface mining methods (Follett, 1980).

Surface mining consists of removing the topsoil, rock, and other strata to recover the mineral or fuel deposit that lies below. Compared to underground methods, surface mining offers distinct advantages. It makes possible the extraction of deposits which, for physical reasons, cannot be mined underground; provides safer working conditions; usually results in a more complete recovery of the deposit (70-90 percent); and is generally cheaper in terms of cost-per-unit of production (Doyle, 1976).

Where deposits occur in rolling or mountainous country, contour surface mining is commonly practiced. This is the case for the coal fields of Appalachia because of the rugged topography. Contour mining consists of removing the overburden above the coal bed by starting at the outcrop and proceeding along the hillside. After the deposit is exposed
and removed, additional cuts are made until the ratio of overburden to coal makes it uneconomical to remove any more of the product. This type of mining creates a bench on the hillside, bordered on the inside by the highwall, which may range from a few feet to a hundred feet in height.

A method commonly associated with contour strip mining is auger mining. It is usually used to recover additional coal after the coal-overburden ratio has rendered further contour strip mining uneconomical. Currently, the general rule of thumb for estimating the economic threshold of strip mining is a coal:overburden depth ratio of 1:10. Auguring allows extraction of coal by boring horizontally into the seam and removing the coal much as shavings are produced from a carpenter’s bit.

Prior to 1977 in Virginia and 1972 in West Virginia, surface mining was conducted by the "shoot and shove method". Blasted rock was pushed over the side of the mountain so the coal could easily be removed. Outslopes created by discarded overburden were often unstable, causing erosion and landslides. Other adverse effects related to surface mining include acid mine drainage into streams, loss of prime forest and farm lands and collapsing highwalls. At this time reclamation generally consisted of hydroseeding the outslopes with black locust (*Robinia pseudoacacia*) and
planting three rows of white pine (Pinus strobus) along the edge of the bench.

The detrimental effects of these mining practices on the environment received the attention of Congress and the nation in the 1970's, leading to increasingly stringent state laws. Consequently, federal legislation established national environmental protection standards for the coal surface mining industry resulting in the enactment of PL 95-87, the Surface Mining Control and Reclamation Act of 1977.

The Act required mine operators to make plans in advance of mining activities to prevent problems during mining. This plan has to be submitted to the state regulatory committee, and, if accepted, a permit is granted for the mine for up to five years. In order to ensure that the approved plan will be followed and the area properly reclaimed, the operator has to post a performance bond. This submitted plan contains the following detailed information:

1. existing geologic and environmental conditions.
2. mining methods to be used and a schedule of all mining and reclamation activities.
3. methods to be used during mining to comply with the Act's performance standards for controlling and preventing damage to resources and property and protecting health and safety.
4. methods to be used for reclaiming the land for productive use after mining has ended. These uses include hayland/pastureland, rangeland, cropland, wildlife habitat, recreational land,
commercial land, unmanaged forestland and managed forest land.

In the Appalachians, hayland/pastureland, because of the low costs of implementation, has most often been the post-mining land use chosen. However, most of this land remains unused for grazing or hay production, its intended purposes, because it is often in inaccessible locations. Reclaimed sites five years and older often succeed to low value pioneering woody vegetation while others experience die-back due to inadequate maintenance. Consequently, many coal mine operators are realizing that the maintenance and repair costs of hayland/pastureland offsets the initial lower cost of establishment, compared to forest land. Another problem with hayland/pastureland is that many operators have difficulty demonstrating productivity of these lands. For these reasons forestry as a designated post-mining use is gaining in popularity in the southern Appalachian coalfields. Another important reason for the shift toward tree crops is landowner interest. Economic analyses have shown that investments in wood production have greater potential than those in hayland/pastureland (Zipper, 1986).

**Silvics of White Pine**

In 1914, Frothingham wrote: "of all the trees in eastern North America, white pine (Pinus strobus) best combines the qualities of utility, rapid growth, heavy
yields, and ease of management". Eastern white pine is the largest of northeastern conifers and, from the beginning of logging, has been a most valuable species. The range of white pine extends from Newfoundland, Canada to northern Georgia (Fowells, 1965). Eastern white pine grows best on moist sandy loams and in a cool humid climate where summer temperatures average 17-22° C and where more than half of the annual precipitation occurs in summer.

This species commonly varies from 24.4 to 30.5 m in height at maturity (Harlow et al., 1979). Site index at age thirty-five ranges from 8.2 to 17 m in the Lake States (Gevorkiantz, et al., 1930), 10.7 to 16.8 m for New England (Prothingham, 1914), and 14.9 to 29.9 m for the southern Appalachians (Doolittle, 1958). Site indices increase towards the southern latitude due to an increase in length of growing season and amount of precipitation. The southern Appalachians are also free from two serious white pine enemies; blister rust (Cronartium ribicola) and white pine weevil (Pissodes strobi) (Cope, 1932). Among the major timber species of the Georgia mountains, white pine was unsurpassed in rate of height growth (Ike et al., 1968).

White pine exhibits a sigmoidal growth pattern with a short early period of growth, a long period of rapid growth, and an extended period of declining growth until death (Beck, 1971a). White pine grows at an average rate of 40
cm/yr between the ages of 10 and 20 and 50 cm/yr for the ages of 20 to 30 but declines to 36 cm/yr at age 50, 13 cm/yr at age 100, and to 5-7 cm/yr from age 165 years to death (Fowells, 1965). White pine can live for 450 years and attain heights of over 60 m and diameters exceeding 3.7 m (Harlow et al., 1979).

Topographic factors that have some effect on white pine are aspect, slope position, and slope percent (Brown and Stires, 1984). Brown and Stires (1984) determined that white pines in a stand in Ohio were 1.3 m shorter at age 35 on southwestern aspects compared to northeastern aspects.

White pine development does best on moist sandy loam soils or those with a small proportion of clay (Harlow et al., 1979) but also does well on well-drained sandy soils (Fowells, 1965). White pine site quality increases with an increase in the coarseness of A and B horizons (Gaiser and Merz, 1958) and with better drained texture-dependent classes (Husch and Lyford, 1956). White pine site quality decreases as the stone content increases due to excessive drainage and reduced water holding capacity (Carmean, 1975). Ike and Huppuch (1968) determined that if the silt contents were greater than 26% and 22% in the surface and the subsoil, respectively, and if the site had rapid litter breakdown, white pine growth would be high.
White pine is more shade tolerant than most pines (Vogel, 1981). In a species trial on a reclaimed mine site in southwestern Virginia, Torbert et al. (1985) found that white pine seedlings had a higher survival rate than four other pine species planted in tall fescue.

Depending on the stage of growth, white pine responds to different site conditions. Factors that affect growth during the first several years of establishment are often different from factors that affect later rapid growth (Brown and Stires, 1981). The erratic early growth is primarily a function of planting shock, freeze damage, and competition from herbaceous species. Later growth is more regular and is a direct function of site conditions.

Mine Soil Properties and Tree Growth

Trees have been used for revegetating surface mined lands since the early part of this century. During the decades from the 1920’s through the 1950’s, various state agencies, in cooperation with mine operators, planted millions of trees in the Midwest and Appalachian coal regions. Some of these tree-planting activities were mandated by state laws that were written in response to public concern over the future use of mined land, while many more trees were planted by state agencies and citizen groups without legislative mandate. Some tree planting was
mandated by laws that were enacted to ensure the productivity of post-mined land. Many of these tree plantations are now forest stands 30 to 50 years old.

Surveys of these older sites show the productivity of stands in both the Eastern and Interior coal regions to be equal to and sometimes better than the productivity of pre-mining soils. Thompson and coworkers (1986) found excellent growth of both hardwoods and pines on mined sites that were planted in 1965 in Eastern Kentucky. In southern Illinois, white oak (*Quercus alba*) planted on a stony spoil bank had a site index of 94; no higher site index for white oak has been reported in that state. A stand of yellow-poplar (*Liriodendron tulipifera*) on similar spoil had a site index of 97 (Ashby et. al 1980). These are two examples of the productivity of mine soils; however, numerous examples of vegetation failures exist.

Soil productivity is a function of mine soil properties. Properties that productive forested mine soils have in common from region to region are an absence of toxic materials, a low coarse fragment content, a moderately acid soil reaction and a deep, uncompacted, loose and porous rooting medium.

Two physical properties that especially affect mine-soil productivity are percentage of coarse fragments and depth to a restrictive layer (Daniels and Amos, 1981). Minesoils
derived from hard rock overburden often have a coarse fragment content of 30-60% (Bell, 1982). Large boulders and fragmented rock pieces are common. During the mining operation, overburden rock is shattered by blasting, and, as a result, the soil material consists of pulverized unweathered rock material. Blasted siltstone spoils generally have a higher percentage of rocks and coarse fragment than sandstone spoil (Daniels et al., 1983). In minesoils the storage of plant available water is low because of the coarse texture and high rock content. Preve (1983) determined that germination of white pine seedlings was three times greater on siltstone spoils than sandstone spoils due to more moisture retention at the surface, but survival was one and a half times better on sandstone spoils than siltstone spoils.

Depth to a restrictive layer is another physical property controlling productivity. The restrictive layers may be vesicular salt crusts on the surface, subsurface bedrocks, coal seams, or traffic pans (Daniels and Amos, 1981). Of these, the most prevalent restrictive layers are traffic pans. Traffic pans are hard subsurface horizons of fines, mostly derived from siltstones, that have densities greater than 1.7 g·cm⁻³. Ashby (1982) contends that present regulations requiring the replacement of overburden materials by heavy machinery leads to a compacted cap of
fine-textured, relatively impervious soil fines over a compacted lower rooting medium. Such layers inhibit root penetration and perch water to create anaerobic conditions. Daniels and Amos (1981) found pans in 60% of the pits they excavated while mapping mine soils in southwestern Virginia.

When this compacted layer is on the surface, it sheds water and leads to high rates of runoff and erosion and results in drouthly soils poorly suited for plant growth. Bulk densities of minesoils, especially at the surface, are usually greater than those on undisturbed soils due to their higher coarse fragment content, immature pedogenic nature, and lack of structure (Ciolkosz et al., 1980). Pedersen et al. (1980) found low final infiltration rates and high bulk densities on reclaimed mineland sites in Pennsylvania. Fehrenbacher et al. (1982) determined that high bulk densities of graded cast overburden may have reduced corn (Zea mays) yields in western Illinois.

Many reforestation studies conducted in the last 10 years confirm Ashby’s (1982) contention that current regulations are not sufficiently specific to ensure that mine soils are handled properly when trees are prescribed as the post-mining land use (Bussler et al., 1984; Torbert et al. 1988; Schoenholtz and Burger, 1984). The major constraints to optimum tree growth cited in these studies were improper overburden types resulting in extremes in pH;
compacted surface and subsurface layers; inadequate infiltration; percolation, and drainage due to massive structure; and fine textured soils with low macroporosity. Plass (1987), in a review of forestry as a post-mining land use, maintained that regulations should allow physical and chemical characteristics of the mine soils to be equivalent to the properties of local forest soils that result in optimum productivity. He suggested that the topsoiling requirement be optional and based on site-by-site needs and that regrading standards for forest plantations allow more frequent undulations and a rough, rocky surface to reduce compaction. The recommendations are similar to those made by Ashby (1982).

Acidity, soluble salts, and nutrient deficiencies are three chemical problems commonly associated with the revegetation of Eastern coalfields (Daniels and Amos, 1984). At low pHs, the concentrations of metals such as Al, Mn, Cu, Zn and Fe increase due to increased solubility and the increased activity of certain acid-producing iron bacteria (USEPA, 1971). Cummins et al. (1965) measured possibly toxic levels of Mn, Fe, Al and S in eastern Kentucky mine spoils. Also, in eastern Kentucky, Barnhisel and Massey (1969) found possibly toxic levels of Cu and Zn to oats (Avena sativa). Certain forms of nitrifying bacteria cannot exist at low pHs, reducing the levels of nitrate-N.
Phosphorus availability is also low due to P fixation by Fe and Al. The availability of P is also low at high pHs due to precipitation reactions with Ca.

Deficiencies of plant-available N and P are the two most commonly reported nutrient deficiencies on minesoils (Plass and Vogel, 1973). Plant available N in the original soil is often deeply buried during mining operations. Very little nitrogen weathers from parent material, so plant available forms must come from atmospheric inputs, fertilizers, or N-fixing plants. Many minesoils are P deficient for most plant species, and fertilizers are often fixed into unavailable forms. Although rock materials usually have high amounts of P, it is generally in a form that becomes available only over a long time. Typically, levels of immediately-available P are low, and fixation of fertilizer P by Fe and Al is high.

Fertilizer may improve growth and survival, but its effectiveness depends, in part, on the amount of herbaceous competition (Bengtson et al., 1973). Weed competition can be greatly stimulated by applications of soluble fertilizers. Pines seem to be more adapted to minesoils because of their association with mycorrhizal fungi which are effective at extracting slowly available forms of P (Preve et al., 1984).
Soluble salt concentrations have been a problem in several Eastern coal mines soils (Torbert et al., 1988; McFee et al., 1984). In general, soluble salts affect plant osmosis. Soluble salts may also affect metabolic processes such as CO$_2$ assimilation, protein synthesis, respiration and phytohormone turnover (Mengel and Kirkby, 1982). In an eastern Kentucky coalfield, Evangelou and Thom (1984) reported that Mg-toxicity is a common symptom of excessive salt levels, because Mg-salts are more soluble than Ca and other salts.

Since the enactment of PL 95-87, these and other characterizations of post-law mine soils have been made, and there has been much debate over procedures for handling mine soils to achieve maximum productivity for a given crop in a given region. However, still lacking is a definitive association of tree productivity with combinations of mine soil properties on which to base mine soil-handling procedures. Once the functional relationships between tree growth and mine soil properties are established, the productivity of mine soils can be predicted. These predictions can serve as productivity indices that can be compared with the productivity of undisturbed sites and serve as a measure of success in restoring forest land to its original capacity.
Evaluation of Site Quality

Forest site quality is defined as the sum total of factors affecting the capacity to produce forests or other vegetation. It is derived from tree measurements which are integrated factors of all the biological and environmental influences on tree growth (Ralston, 1964). These factors can be grouped as climatic, edaphic and biological (Spurr and Barnes 1980). Determination of site quality can be separated into direct and indirect methods, those measured directly from forest growth or those estimated from site attributes (Carmean, 1975).

Direct methods are procedures that measure the site quality in various expressions of tree growth, such as basal area, and tree volume. Site quality can be measured directly for only a few forests where accurate long-term records of stand development and growth have been maintained. Generally, it can only be estimated using indirect means.

Indirect methods estimate site quality from site attributes. These methods can be divided into quantitative methods (site factor analysis) and qualitative methods (which divide the land into units with similar characteristics).
History of Modeling Growth

From the early 1920's, the need for standard methods of site classification was recognized. There was much controversy over which of three different methods should be used to measure site quality. One method that was strongly favored was an expression of volume, the standard system used in Germany at the time (Bates, 1918). Another practice which was favored was a system of "forest site-types" (Zon, 1913). This system was based on plant indicator species, which followed the works of Cajander (1926). The third system was one that used height growth as an index of site quality (Graves, 1906). Height growth could be accurately measured, was simple to use, widely applicable, and considered free from the effects of stand density.

In 1923, the Society of American Foresters determined that volume prediction was the utmost measure of site quality and recommended construction of yield tables for well-stocked forest stands (Carmean, 1975). A standard method was not recommended, but opinions favored the use of height growth as an index of site quality. Currently, site index, based on height growth, is the most widely accepted method for predicting site quality.
Site Index

In the United States, site index is the average height of the dominant, or dominant and codominant, portion of an even-aged stand at a specified age. This standard age is generally 50 years in the eastern United States and 100 years for the longer-lived species of the west coast (Spurr and Barnes, 1980). Other standard ages are sometimes specified for a particular species or region.

One important reason for using dominant height as a site productivity indicator is because it is considered to be fairly independent of stand density. However, although height is perhaps the best single tree measure related to site productivity of a given species, it does not necessarily mean that it is unrelated to other factors. In particular, extremes in stand density may influence height growth. This phenomenon has been shown by Lynch (1958) and Barrett (1973); although, a significant decrease in dominant height growth does not usually occur until the density is fairly high. Dominant height does not seem to be affected by normal plantation densities.

Spurr (1952) was critical of height/age relationships but concluded that height growth is perhaps the single best measure of site, although not perfect. This conclusion was later supported by Vincent (1961) when he determined, with
regard to the drawbacks imposed by nature, that it is still
the best indicator of site quality.

The usual method of determining site index on the basis
of tree height depends upon the use of a height-age growth
curve to estimate the height at a standard age. Most such
curves for American species have been developed using
methods described by Bruce (1926). These methods involve
measuring the height and age of stands and fitting an
average height-age curve to the data. Using the curve as a
guide (called anamorphic curves), a series of curves is
harmonized to have the same form and trend. There are
several weaknesses to this method. First, the technique is
only sound if the average site quality is the same for each
age class. Secondly, it is assumed that the shape of the
height-age growth curve is the same for all sites.
Actually, height-growth patterns vary in different parts of
the range of a species and also in local areas of
contrasting soils and topography.

To avoid errors associated with anamorphic curves,
polymorphic curves are used. It has been determined that
tree height growth is polymorphic and that many species have
different height growth patterns for areas that differ
greatly in climate, soil, topography, and site quality
(Carman, 1975). Stem analysis is now the most widely used
method for collecting data, and nonlinear regression models
are subsequently used for developing site index curves that express polymorphic tree height growth patterns.

For site index to give valid results, the site must have an even-aged overstory where the heights of dominants have not been strongly influenced by stand history. Juvenile growth rates are often inconsistent with rates in a mature stand. Therefore, young stands often give misleading estimates, and many site index curves are not even constructed for stands less than 20 years old. Jones (1969) found that 20- or even 30-year-old stands can give unreliable results.

For the above reasons, and because many lands are unoccupied by trees, many sites do not have stands suitable for determining site index. Also, this method is always related to a particular species. A site may contain a certain species, but the land manager may wish to know the site potential for a different species. Site index does not provide this type of pertinent information unless conversion graphs are available for both the species of interest and the species already established on the site.

Another shortcoming of site index is that it is only an index for potential yield. It is generally not suited to other purposes such as characterizing a site for silvicultural prescription. For instance, one location with a high site index may readily be reforested after a
disturbance or harvest, but another, with a similar index, may not.

**Growth Intercept**

The growth intercept method uses a selected period of early growth as an index of site quality rather than the long-term height growth. Wakely (1954) first proposed this system which is usually based on the total length of the first five internodes produced after the tree has reached 1.3 m tall. This method was developed for conifers having easily recognizable internodes which mark annual height growth.

The growth intercept model is useful in areas where trees are too young for site index estimation. For areas with young trees, the growth intercept has several advantages; (i) total age and total height need not be measured, avoiding measurement errors and simplifying fieldwork; (ii) measuring internodes above breast height eliminates the period of erratic early height growth; and (iii) many site index curves do not extend to ages younger than 15 or 20 years (Carmean, 1975).

While growth intercept is useful in certain situations, it has limitations. Mainly, early height growth of a tree is not always an indication of the height it will reach at maturity. For example, variability in soil horizons may
result in a tree growing rapidly in its youth but slowing before reaching maturity.

For loblolly (Pinus taeda), shortleaf (Pinus echinata) and slash pines (Pinus elliottii), the 5-year intercept above breast height has proven better correlated with site quality than has total height in a test of trees from a plantation 20 years old (Wakely and Marreo, 1958). Beck (1971b) and Brown and Stires (1981) have developed different versions of growth intercept methods to predict white pine site index in the southern Appalachians and Ohio, respectively. The technique has also been adapted to red pine (Pinus resinosa), Douglas fir (Pseudotsuga menziesii), southern pines, and other species on which annual whorls are apparent (Carmean, 1975).

**Height-Intercept Quotients**

An alternative to growth intercept is the height intercept quotient proposed by Wilde (1964). He felt that the irregularities in height growth are caused by the following conditions; (i) deficiency of nutrients in the surface soil layers, (ii) competition with herbaceous ground cover, (iii) composition of soil profile, and (iv) ground water or seepage. The effects of these factors are reflected in the ratio of the average height increment (H) and the 5-year intercept (I), calculated in centimeters on a
per annum basis. For example, a 20-year-old stand with an average height of 7.6 m and total length of the 5-year intercept of 254 cm has the H/I ratio of \[
\frac{(7.6 \text{ m} \times 100 \text{ cm})}{20} / \frac{254 \text{ cm}}{5} = 0.75.
\]

Stand types that would exhibit a fractional H/I quotient are those established on areas which are reasonably free of herbaceous competition. These stands usually show rapid early height growth, which is the time that determines the size of the 5-year intercept. However, as the stand ages, the canopy begins to close causing an increase in competition for water and nutrients and resulting in a reduction of tree growth.

The opposite occurs when there is competition at the time of plantation establishment. On such sites, the early growth is retarded until the tree canopy suppresses the weed competition allowing growth to increase. Consequently, the initially-low H/I ratio will be near or exceed 1.0 at rotation age. Another time when this occurs is as the tree ages. Roots grow into deep nutrient rich soil layers or the capillary fringe of a water table, increasing tree growth at a later age.

Wilde (1964) felt that with the H/I ratio, a quick silvicultural appraisal of stands composed of species that develop internodes would be possible. Such an evaluation would reflect the behavior of soil properties on tree
growth, but also the unmeasurable influences of ground water fluctuations, deep nutrient bearing strata, and the competition of the ground cover vegetation.

**Vegetative Indicators**

Another indirect method in assessing site productivity is through the use of ground vegetation. The possibility of using understory vegetation for prediction of tree growth has been recognized for many years (Cajander, 1926). Understory species with a relatively narrow ecological amplitude can be indicators of site quality. Plants act as "phytometers" of site quality by integrating many growth-related factors which are difficult to measure directly (Daubenmire, 1976).

The use of plant indicators or communities is more useful in temperate regions where fewer species exist than it is in warmer regions. It is not applicable in areas which have been harvested or burned repeatedly or in areas that have been cultivated or fertilized or are used for pastures.

Using vegetation to assess site quality in North America has been demonstrated by Pfister (1984), Corns and Pluth (1984), and Kotar (1986). In the Lake States, a habitat-type classification system was developed. A habitat-type is any land unit that can support a particular
type of climax plant association. An assumption of this system is that understory floristic composition of disturbed stands does not differ significantly from mature stands after a relatively short period of recovery. A field guide describing 21 habitat-types is in wide use by private, state and federal foresters. This guide includes the following information for each type; (i) successional trends and relative stability of different successional stages, (ii) estimates of site index and volume production of major tree species, and (iii) silvicultural prescriptions for major commercial forest types (Kotar, 1986). Using vegetation for site quality assessment does have limits due to its response to understory light conditions, disturbances, and chance (Spurr and Barnes, 1980).

Soil-Site Evaluations

Another indirect measure of site quality is the use of site properties as indicators of productivity. The multiple linear regression model has been a favorite in research because of its statistical and biological interpretability. These models allow regression of several types of nonlinear relationships using the appropriate transformations. The most common way to do this is to express the relationship between site index and site properties using stepwise multiple regression procedures or other multivariate
techniques. These equations are developed to be used in areas not yet planted or in young stands where conventional site index or growth intercept cannot be used. The following simple additive model is often used;

\[ SI = a_0 + a_1 x_1 + a_2 x_2 + \ldots + a_n x_n \]

where "x" is a site variable and "a" is the regression coefficient.

Different studies have shown different factors to be significant depending on the species, the factors examined, their intensities and the manner in which they were measured and expressed, and the relationship (both biological and statistical) between the "independent" variables. It is important that these variables not be strongly correlated with one another (Grey, 1983).

Many studies concerning the relationship between site quality and soil properties have been done for a variety of tree species (see reviews by Carmean, 1975; Hagglund, 1981; and Grey, 1983). The relative importance of different variables varies a great deal between studies. Successful soil-site studies in the U.S. have been able to account for 65-85% of the variation in height growth for forest trees (Carmean, 1975) with age accounting for a majority of the variation (51% of the variation in height in a white pine model (Brown and Stires, 1984)). The removal of age
increases the sensitivity of the model to detect site factors affecting the entire range of growth. Generally, the predictability of growth decreases as variation among sites increases. This modeling approach is especially useful when predicting site quality on a site with no trees.

Studies have shown that various combinations of soil and/or topographic factors can be combined in multiple regression equations to provide accurate, indirect estimates of height growth and site quality for a number of species. Most studies have shown that variables affecting available soil moisture are most closely related to site productivity. Where surface features are relatively flat or soils uniform, site quality estimates have been based on soil properties alone (Coile, 1952). Where surface features are not uniform, topographic variables are often included to increase the precision of the prediction estimate (Carmean, 1967).

Despite the popularity of the regression method for ecosystem models, this conventional approach has several weaknesses (Verbyla and Fisher, 1989). First, soil-site quality models developed with stepwise multiple regression procedures can have a large positive prediction bias and can include biologically insignificant predictor variables (Verbyla, 1986). For example, McQuilkin (1974) showed that the standard regression statistics of soil-site equations
are not reliable indicators to determine the accuracy of the model. He developed an equation using black oak (*Quercus velutina*) in Missouri that had an $R^2$ of 0.66 and a standard error of 1 m. When the equation was validated using independent data, the correlation between the observed and predicted site indices had an $R^2$ of only 0.01 and a standard error of 1.81 m. These errors were undetectable until the equation was tested with independent data.

Second, most validated soil-site quality models have relatively low precision. For example, Shoulders and Tiarks (1980) developed soil-site quality regression models for loblolly pine and slash pine in the Gulf Coastal Plain of the United States. When the models were validated with independent data, the predicted site index was within 1.5 m of observed site index for only 58% of the loblolly pine and 63% of the slash pine plots.

A third problem with the conventional approach is that models are usually developed from randomly selected plots; therefore, the best sites are unlikely to be selected. Yet, intensive silviculture is often feasible on only the best sites. A model that reveals relationships only in the range of poor to good sites may not be useful in identifying site factors associated with the best sites. Because of this problem a deliberate attempt should be made to sample a wide range of sites (Harrington, 1986).
Another problem that diminishes the interpretability of models is independence of variables. Most environmental variables are related in various ways. This situation creates the statistical problem of multicollinearity where each variable is a linear combination of the other variables. Multicollinearity inflates variances of the regressor variables such that $R^2$, t-test, and F-test values become misleading or wrong. Multicollinearity compromises the validity of the model.

Another type of model that relates soil-site properties to tree productivity is the classification tree. Classification trees are discriminant models structured as dichotomous keys and have several advantages when compared with linear regression analysis. Classification trees discriminate by sequentially selecting the predictor variable that best partitions sample cases into purest class memberships (Verbyla, 1986).

Figure 1 depicts an example of a classification tree which discriminates prime sites as a function of stone content and soil depth. It was determined that prime sites were associated with soils deeper than 40 cm that had a stone content less than 32.5%. Ponderosa pine site index was the greatest at pH values of 6.0-6.5 in northwestern California.
Figure 1. Classification Tree (Verbyla, 1987).
A large tree with too many variables will have a low accuracy because it uses spurious relations of the sample. While a tree that uses too few variables will also have a low accuracy if it does not use all important predictor variables.

In 1989, Verbyla and Fisher developed a simple classification tree for southern Utah to predict prime sites for ponderosa pine as a function of percent sand and pH. He found that the classification tree correctly classified 71 of the 77 sample cases. He compared this to a regression site-quality model and found that the regression model had a high positive prediction bias and was essentially useless. He concluded that the classifier is easy to understand, and because of the few measurements required, easy to use in the field.

**White Pine Soil-Site Studies**

Eastern white pine is the major commercial species used for reclamation of mined land in the central Appalachians. It is a widely distributed tree species, ranging from northern Georgia northward to Newfoundland and westward to Minnesota. The species occurs naturally throughout the mountains of Virginia and West Virginia and in northeastern Kentucky. Most of the soil/site studies performed on this species have been conducted to the north of the southern
Appalachian coal fields (Mader, 1976, Czapowskyj and Struchtemeyer, 1958). In general these studies indicate that white pine growth is primarily influenced by a variety of soil physical properties and topographic features. All of these studies were conducted on white pine that were established on natural undisturbed soils. Torbert et al. (1988), however, reported that the heights of 10-year-old white pine on reclaimed mine soils in Virginia were correlated with depth to a restrictive layer and soluble salt level as measured by electrical conductivity.

Brown and Stires (1984) developed soil-site equations containing only soil and topographic factors which could be used for estimating potential height growth and site quality. Using tree age and four significant soil and topographic factors, four separate multiple regression equations were developed for estimating height growth and site quality of white pine planted on old-field sites in Ohio. Those equations were as follows:

<table>
<thead>
<tr>
<th>Model</th>
<th>( H_t ) (ft)</th>
<th>( R^2 )</th>
<th>( S_y ) (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>i)</td>
<td>7.823+1.586(Age)+0.120(Percent distance from ridge)+2.29[cos(Azimuth-45)+1]</td>
<td>0.670</td>
<td>5.73</td>
</tr>
<tr>
<td>ii)</td>
<td>17.841+1.525(Age)+0.107(Percent distance from ridge)-160.1511(1/Total soil depth, inches)+1.987[cos(Azimuth-45)+1]</td>
<td>0.729</td>
<td>5.20</td>
</tr>
<tr>
<td>iii)</td>
<td>5.776+1.496(Age)+0.105(Percent distance from ridge)+0.126(Thickness of A Horizon, inches)+1.900[cos(Azimuth-45)+1]</td>
<td>0.732</td>
<td>5.18</td>
</tr>
</tbody>
</table>
iv) \( Ht. (ft) = 13.288 + 1.479 \text{ (Age)} + 0.10 \text{ (Percent distance from ridge)} + 0.812 \text{ (Thickness of A Horizon, inches)} - 110.973 \left( \frac{1}{\text{Total soil depth, inches}} \right) + 1.797 \left[ \cos(\text{Azimuth} - 45) + 1 \right] \)

In each of the equations, age accounted for 51% of the total variation in heights of trees (Brown and Stires, 1984).

Equation 1, containing only topographic factors, accounted for approximately two-thirds of the total variation in heights of trees in study plots, and estimates based on the equation should be within acceptable limits for most purposes. Adding either total soil depth or thickness of the A horizon increased the variation accounted for by approximately 6%, while adding both soil factors increased total variation accounted for in the equation to more than 75%. Equation 1 containing only topographic factors was the least reliable, and equation 4, which contained topographic factors and both soil factors, was the most accurate (Brown and Stires, 1984).

Mader (1976) used stepwise regression to predict white pine growth using soil and site characteristics in Massachusetts. He found that the development of detailed site description and soil information by horizons, accurately predicted several growth parameters. Equations that were based on only topographic features had no predictive value. Addition of easily determined soil physical characteristics gave reasonable results. The best
results were obtained when more complicated soil chemical and physical properties were included.

Several factors were consistently important in the various equations. Increases in silt and clay in the A horizon were associated with better sites, probably due to better moisture holding capacity in the primary rooting zone (Mader, 1976). It was also found that increased silt and clay in the B horizon was associated with poorer site quality, probably due to reduced aeration and root growth. Site index increased with increasing pH of the B or C horizon, indicating better fertility. Increased stone and gravel content (>2mm fraction) in the A horizon were also associated with higher site quality, with the reverse being true for the B horizon. Better sites had more nitrogen in the A horizon and more organic matter in the B, but less in the A. In general, both the physical and chemical properties of the B and C horizons influenced site quality.

Following are several of the equations Mader (1976) found to best predict site quality.

<table>
<thead>
<tr>
<th>Equations</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT = 5.49 + 0.280(Age)</td>
<td>0.76</td>
</tr>
<tr>
<td>HT = -6.10 + 0.284(Age) + 0.171(Si+Cl-A) - 0.305(DR.CL.)</td>
<td>0.88</td>
</tr>
<tr>
<td>+ 0.854(pH-A) + 0.0735(S-B) + 0.299(CM-A)</td>
<td></td>
</tr>
<tr>
<td>+ 0.0631(ST-A) - 0.00409(Si-B) - 0.500(Ca-B)</td>
<td></td>
</tr>
<tr>
<td>+ 0.0586(SL%) - 0.0473(ST-B) - 0.124(CM-B)</td>
<td></td>
</tr>
<tr>
<td>CVT = -423.7 + 5.57(Age) + 11.83(Si-A) + 4.79(S-B) + 10.3(CM-A) + 26.0(OM-B) - 5.94(AW-B) + 105.0(K-A) - 1.89(BSAT-A)</td>
<td>0.65</td>
</tr>
</tbody>
</table>
BFT = 184,129+2362(Age)+2068(Si-A)+1367(S-B)
-2965(DR.CL.)+2219(CM-A)+1248(Si-B)-3548(Ca-B)
-890(AW-B)

Where:

HT = Height
CVT = Total cubic foot volume
BFT = Board feet
Age = Age
Si+Cl = Silt plus clay in A-horizon
DR.CL. = Drainage class
pH-A = pH of A horizon
CM-A = Coarse fragment content of A horizon
ST-A = Stone Content A horizon
Si-B = Silt in B horizon
Ca-B = Exchangeable Ca in B horizon
SL% = Slope percent
OM-B = Organic matter B horizon
AW-B = Available water in B horizon
K-A = Exchangeable K in A horizon
BSAT-A = Base saturation in B horizon

Ike et al. (1968) attempted to predict white pine
growth in the Georgia Blue Ridge Mountains from soil and
topographic site factors using stepwise regression
procedures. They found that eastern white pine grew best on
level bottoms in sheltered coves at low elevations. Growth
rates decreased with increasing elevation and steepness of
slope and was poorest on ridge sites.

They determined that the following factors also
indicated good site quality: (1) silt content greater than
26 percent in the surface soil and greater than 22 percent
in the subsoil; (2) no buildup of an unincorporated H humus
layer. Sites with H layers thicker than three-tenths of an
inch were generally poorer than sites where humus
incorporation in the topsoil was evident. Following is the equation that best predicted site index in this study:

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Variable</th>
<th>( R^2 )</th>
<th>( \text{Sy} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.684080</td>
<td>1/Age</td>
<td>0.68</td>
<td>0.03809</td>
</tr>
<tr>
<td>-0.000039</td>
<td>Elv</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+0.00044</td>
<td>Pos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.00047</td>
<td>SOS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+8.1145 \times 10^{-7}</td>
<td>(BAS)^2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Where:
- Age = Age
- Elv = Elevation
- Pos = Position on slope
- SOS = Steepness of slope
- BAS = Basal area

Gaiser and Merz (1958) looked at the relationship of white pine site index to soil and topographic variables. They found that white pine growth increased with an increase in the thickness of the A horizon. White pine also grew slower where the surface and subsurface soil had finer textures.

Growth of white pine was related to the moisture equivalent and permanent wilting point, possibly because texture has important effects on soil moisture (Gaiser and Merz, 1958). They also suggested that topography is an important variable in estimating site quality but found that in this old field study area, aspect, topographic, position, and slope were not useful.
Young (1954) used regression techniques to correlate physical properties of forest soils and white pine site index. As site index decreased, the depth of the A horizon (including the organic layer) and the percent stones (>2 mm) in the B horizon increased. The form of the equation follows:

\[
\text{Site index} = 65.01 - 2.95(\text{depth of A horizon}) \\
+ 0.15(\% \text{ stones in B horizon})
\]

The two variables accounted for 58% of the variation in site index. The equation was tested by direct measurement of site index and did not differ by more than 3 feet.

Hannah (1971) tested for functional relationships between soil-site factors and site index at base age 30 and 50. Three factors were important in predicting site index at age 30; thickness of the A horizon, thickness of the A plus upper B horizon, and aspect. Addition of the interaction terms for aspect and silt content as well as silt and sand content of the B horizon improved the overall equation.

Total depth of the A plus B horizon was the best single indicator of site quality. As the thickness of the solum (A plus B horizon) increased, site quality increased. Site quality was also highest on southern and northwest slopes but decreased when silt content of the horizon increased.
The soil-site equation for base age 50 was similar to the equation developed for base age 30. Percent clay in the B horizon was the only new variable. As the clay content increased, site quality decreased, indicating high proportions of clay may cause compact layers and poor aeration, inhibiting root growth. Following are the equations for base age 30 and 50;

\[
SI_{30} = 42.55 + 0.068(X_1) - 1.08(X_2) - 0.29(X_3) + 0.04(X_4) - 0.002(X_5) + 0.008(X_6)
\]

\[
SI_{50} = 58.69 + 0.08(X_1) - 1.6(X_2) - 0.15(X_3) + 0.06(X_4) - 0.002(X_5) + 0.01(X_6) - 0.1(X_7)
\]

Where:  
\( X_1 \) = Aspect  
\( X_2 \) = Depth of A horizon  
\( X_3 \) = Depth of A plus upper B horizon  
\( X_4 \) = \((\text{Depth of A plus upper B})^2\)  
\( X_5 \) = (Aspect) (% silt in B horizon)  
\( X_6 \) = (% sand in B horizon) (% silt in B horizon)  
\( X_7 \) = % clay in B horizon

Czapowskyj and Struchtemeyer (1958) determined that three variables were significantly related to dominant and codominant height of white pine. Their study showed that 82% of the variation in height was due to age, percent silt in the A horizon, and the thickness of the B horizon. The following equation was derived;

\[
Y = -40.98 + 1.88(\text{age}) + 0.41(\% \text{ silt in A horizon}) + 0.8(\text{thickness of B horizon})
\]

The results indicated that white pine height increases with an increase in silt content of the A horizon. Higher
silt contents increase water availability during the growing season. An increase in B horizon thickness increases growth due to greater rooting volume.

In 1968, Stratton and Struchtemeyer developed the following soil-site regression equation for white pine height in southwestern Maine.

\[
Y = 1.89 - 12.84(X_1) + 0.003(X_2) + 0.04(X_3) - 0.009(X_4) \\
+ 0.02(X_5)
\]

\[R^2 = 0.895\]

where: \(Y\) = log of the height of the dominant and codominant trees
\(X_1\) = reciprocal of age
\(X_2\) = pH of surface soil
\(X_3\) = stone content of A horizon
\(X_4\) = interaction of available moisture and drainage class
\(X_5\) = stone content of C horizon

Age at breast height was the most important variable affecting height accounting for 80% of the variation. This equation indicates that with an increase in age, pH and stone content of the surface soil and the interaction of drainage class and available moisture in the top 76.2 cm of soil, height increases. Height decreased as the stone content in the C horizon increased due to the negative influence of stones on rooting space, aeration and moisture.

Copeland (1958) conducted a study to quantify the relationships of certain physical soil properties to site index of western white pine in northern Idaho, northeastern
Washington, and western Montana. White pine site index (base age 50) was correlated with effective soil depth, depth to a zone of reduced permeability, and the available water-holding capacity in the top 91 cm of soil. This work resulted in the following equations:

\[
\begin{align*}
Y &= 46.69 + 0.7(\text{depth}) \\
Y &= 44.35 + 0.82(\text{depth to zone of reduced permeability}) \\
Y &= 53.23 + 1.92(\text{AWC})
\end{align*}
\]

All three equations showed good agreement when used to estimate site index. Effective soil depth resulted in the best correlation with actual site index.

**Ecosystem Models**

An ecological classification system expresses the interrelationships between; (i) vegetation (groundcover, understory, and overstory) and physiography, (ii) vegetation and soils, and (iii) physiography and soils (Barnes et al., 1982). Physiographic and soil factors strongly determine the composition, size, and productivity of vegetation. Physiography determines the microclimate and water movement. Soil characteristics strongly control plant composition, size and productivity. Vegetation acts as a phytometer that integrates these two factors and their interactions and is reflected in its size, composition, and productivity.
A model using the ecological approach has been in use by the Forest Research Station of the southwestern German state of Baden-Württemberg since 1946. Regional areas are broken down into growth districts which have a relatively homogeneous macroclimate and a characteristic pattern of landforms, soils, and groundcover vegetation. Within each growth district, site units are classified into a hierarchical system. Interrelationships among physiography, soils, and vegetation are determined, and these factors are used to distinguish and map different site units.

A primary feature of the system is that the site units are evaluated on the basis of growth and productivity of important commercial species. Ground cover species that indicate similar conditions of moisture, nutrients, local climate, or pH are grouped together and named for a characteristic plant (Spurr and Barnes, 1980).

A silvicultural guide is prepared to accompany the site map. Each site unit describes in detail the silvicultural prescription and the potential productivity of each species or species mixture. This system has become the basis for silvicultural planning throughout Baden-Württemberg.

Multiple-factor methods using soil, topography, and vegetation have been used in California. Since 1947, soil-vegetation surveys of public lands have been applied. Generally, this type of system has been regarded as too
intensive, expensive and impractical for American forests (Spurr and Barnes, 1980).

Soil Productivity Models

To solve the problems associated with site index and regression and multivariate analysis while still incorporating biological relationships, site classification models have been developed. These models have contained both subjective and empirical information that relate soil properties to productivity (Baker and Broadfoot, 1977; Harrington, 1986; Gale and Grigal, 1991). Soil productivity has received much attention for several decades, mostly with agronomic crops (Huddleson, 1984).

This approach attempts to describe the relationship between plant productivity and effects of soil properties on optimum vertical root distributions (Kiniry et al., 1983) (Figure 2). The main assumption is that a plant’s vertical root distribution is genetically controlled and fully expressed under optimum soil/site conditions. If a soil/site property inhibits root growth, changes in the optimum root distribution will occur, negatively affecting aboveground biomass and reducing site quality. Productivity indices (PI) are based on levels of soil/site characteristics that are considered optimum for the vertical root distribution of a tree species. The calculated PI
Figure 2. Conceptual model for the study by Kinyi (1983).
reflects a soil's potential for root growth with the assumption that optimum conditions for root growth will result in the highest aboveground yield (Kiniry et al., 1983). High PI values have been related to high yields for agronomic crops (Larson et al., 1983).

Most of these models are additive, summing the effects of soil/site properties on yield (Huddleson, 1982; Walker, 1976; Fenton et al., 1971). In additive models, several soil/site properties are assigned numerical values according to their relationship to growth. These numbers are either summed, or they are subtracted from a maximum rating of 100 to derive a final rating. A major advantage of additive systems is that many different soil properties, both singly or in combination, can distinguish small differences in productivity. Another advantage is that no single factor can have enough weight to influence the final rating. Limitations of this system arise from its complexity. As the number of factors increases, so does the difficulty in juggling factor ratings so the final ratings are realistic (Huddleson, 1984). One possible effect is the calculation of negative ratings. When each of several factors are limiting, the final productivity rating can be negative. The opposite is true when only a single rating is severely limiting. In this case the model may not be sensitive
enough to distinguish when a factor is totally limiting, suggesting that growth may only be slightly hindered.

Some classification models are multiplicative and more closely follow the dynamics of interacting and complex systems. Multiplicative systems assign separate ratings to each of several properties, then take the product of all factor ratings as the final soil rating. Unlike the additive system this approach has the advantage of allowing a single factor to dominate the rating. If a single factor is severely limiting to growth, this fact is reflected in the final rating. Another advantage is that the overall rating can never be negative.

For each of the properties in the model, a root growth response function is developed. These functions quantify the influence of each property on root growth. Once the response is formulated, a "sufficiency" (based on the shape of the response function) is derived and normalized between 0.0 and 1.0. A value of 1.0 represents the level of a soil property that does not impede root growth, and a value of 0.0 represents the level that totally inhibits root growth. An intermediate value, such as 0.70, indicates that root growth is 70% of the growth observed at levels where growth is not inhibited.

The original multiplicative model developed by Kiniry and others (1983), was in the form,
\[ \text{PI} = \sum_{i=1}^{r} E (A \times B \times C \times D \times E \times X \times RI)_i \]

Where:
- \( A \) = sufficiency of potential available water storage capacity.
- \( B \) = sufficiency of aeration.
- \( C \) = sufficiency of bulk density.
- \( D \) = sufficiency of pH.
- \( E \) = sufficiency of electrical conductivity.
- \( RI \) = optimum fraction of roots in a soil horizon and was based on an equation developed by Horn (1971) to describe water depletion patterns with depth for a soil under sugar maple.
- \( r \) = number of 10 cm increments.

The terms \( A, B, C, D, \) and \( E \) were normalized to range from 0.0 to 1.0 and related the levels of soil properties to their "sufficiency" for optimum root growth (Kiniry et al., 1983). The root distribution (RI) was determined from measurements of water depletion patterns at incremental depths in the profile using an equation developed by Horn (1971). The equation was based on the optimum vertical rooting distribution of a sugar maple (Acer saccharum) stand. The soil, a fine-silty mixed mesic Typic Hapludalf, had no known limitations to rooting depth, which was 356 cm.

The fractional distribution of roots in each 10 cm depth increment of soil was the RI value for that increment. Two RI's were developed based on rooting depths of 100 and 200 cm and would be suitable for annual and perennial crops, respectively. The RI term was also standardized to range from 0.0 to 1.0, with the product of all the terms summed over \( r \), the number of 10-cm thick soil layers within the
rooting depth. Thus, the calculated PI ranged from 0.0 to 1.0.

Pierce et al. (1983, 1984), Larson et al. (1983), and others reduced Kiniry's et al. (1983) equation to the form:

\[
PI = \sum_{i=1}^{r} \left( A \times C \times D \times WF_i \right)
\]

eliminating the sufficiency rating for aeration (B) and electrical conductivity (E). The weighting factor (WF) was equivalent to RI as used by Kiniry et al. (1983). The r was the number of pedogenic horizons within the rooting depth and not the number of 10-cm thick horizons.

Based upon Neill (1979) and a model modified by Pierce et al. (1983), Doll and Wollenhaupt (1985) proposed the following numerical productivity model for mine soils in South Dakota;

\[
PI = 100 \times \sum_{i=1}^{n} \left( \text{TOP} \times \text{AWC}_i \times \text{SAR}_i \times \text{BD}_i \times \text{HC}_i \times \text{WF}_i \right)
\]

Where:
- PI = Productivity Index
- E = Summation from i=1 to n
- TOP = Topographic position
- AWC = Available water holding capacity
- SAR = Sodium Adsorption Ratio
- EC = Electrical Conductivity
- BD = Bulk Density
- HC = Hydraulic Conductivity
- WF = Rooting Depth Weighing Factor

In Doll and Wollenhaupt's (1985) equation, topographic position, available water holding capacity, bulk density,
hydraulic conductivity and a soil depth weighting factor were employed to calculate productivity. These measurable properties were selected based upon the experimental properties and the experience of the authors; other soil properties could have been selected.

Non-root zone factors that affect agricultural yields were not included in the equation. They felt that, while climate, insects and other factors affect crop productivity, these factors are highly variable on a yearly basis and were only meaningful when attempting to quantify actual crop yield. According to Burley and Thomson (1987), since climate is not altered, it should not be included in the model. Soil productivity equations examine the portion of the landscape that is actually being disturbed. The soil productivity equations are attempts to predict the potential of only the soil.

In contrast, Rogowski (1985) combined Lieth's (1975) Miami Model (climate alone) with a slightly modified soil productivity model developed by Kiniry et al. (1983) to assess the site productivity potential before and after mining. Relative productivity of a site \( P \) in \( g \cdot m^{-2} \cdot yr^{-1} \) is as follows:

\[
P = \sum_{i=1}^{m} B_i E_i W_i \sum_{j=1}^{n} X_{ij}
\]
Where:

- B = biomass productivity, previously defined in equation 1 and 2.
- E = summation operator over i = 1, 2..., m horizons, or layers.
- W = relative root distribution weighting function to 1 meter depth.
- II = product operator
- x_{j...n} = productivity factors, n = 6
- x_j = 1 = available water, by volume
- x_j = 2 = moist bulk density at 1/3 bar g/cm^3
- x_j = 3 = aeration porosity, by volume
- x_j = 4 = pH, in 1:1 H_2O
- x_j = 5 = electrical conductivity (EC), ds/m
- x_j = 6 = other factors, such as sodium absorption ratio, topography, or nitrogen content

Productivity factors are based on readily available data and are computed individually for each horizon by considering the minimum or the maximum required for plant growth. These values are then multiplied together to show where the potential problems are. The products are, subsequently, multiplied by an appropriate weighting factor for each horizon, approximate plant root distribution, summed and multiplied by a site productivity potential (B) giving an overall site productivity index.

The author cautioned that the resulting model should be used as a relative predictor of productivity and states two reasons for this:

i) Values used in the computations of productivity factors, such as bulk density, pH, water availability, and mean annual values of temperature and precipitation are distributions in space and time, spanning a range of values with different probabilities of occurrence.
ii) For a given year or a given point within a site, results may differ considerably for those predicted, although on an average the model should predict correctly.

Gale (1987), modified these agronomically-based multiplicative productivity index (PI) models to predict site quality for natural stands of red pine (Pinus resinosa), jack pine (Pinus banksiana), trembling aspen (Populus tremuloides), red maple (Acer rubrum) and white spruce (Picea glauca). She felt that one disadvantage of these equations was that the rating for an individual soil horizon could be considerably lower than the sufficiency rating for any soil property within that horizon (Gale, 1987). A five factor model, for example, might have factor ratings of 0.90 for each sufficiency, but the overall rating would only be 0.73.

Gale (1987) used the geometric mean for the individual ratings to arrive at a horizon rating. Thus, if all the factors were 0.90, the rating would be 0.90. The geometric mean gives equal weight to proportional differences in factor ratings and not to absolute differences as in the original model. The sufficiency rating for a property is based on the level at which it is optimum or limiting to root growth, independent of other properties (Gale, 1987).

To broaden the applicability of Gale's model, topography (percent slope) and climate were included. Other
work has shown that these characteristics are important in describing differences in site productivity (Brown and Stires, 1984).

\[
R = \prod_{i=1}^{r} ([A \times B \times C \times D]^{1/4} \times WF)_{i} \times [S \times CL]^{1/2}
\]

Where:

A = sufficiency of potential available water
B = sufficiency of aeration
C = sufficiency of bulk density
D = sufficiency of pH
S = sufficiency of topography (percent slope)
CL = sufficiency of climate
r = number of pedogenic horizons
WF = weighting factor

The WF used in Gales equation is based on vertical root distributions developed by Gale and Grigal (1987). Exponential decay curves were developed based on vertical root distribution among shade tolerance classes of trees. For each horizon the WF was calculated as the difference between the cumulative estimates \((Y_i - Y_{i-1})\) for each soil depth \((d_i)\) to a maximum depth of 200 centimeters. For white spruce, which was considered a midtolerant species, the curve \(Y_i = 1 - 0.96d_i\) (where \(Y_i\) is the cumulative fraction of total roots to a depth \(d_i\)) was used.

The author used regression analysis to evaluate the significance of linear relationships between PI, site index, and mean annual increment (MAI). Due to the importance of age in predicting MAI, Gale used a Schumacher-type equation (Schumacher, 1939).
This equation, as a measure of site quality, performed better in younger plantations than in older plantations. The PI is a better index of site quality in younger stands because of its use of soil characteristics and optimum vertical root distributions (Gale, 1987). The PI model, which is based on mineral soil characteristics, is more applicable in younger stands that have less organic accumulation than older stands. Wells and Jorgensen (1975) determined that nutrient uptake of loblolly pine (Pinus taeda) shifted from the mineral soil to the forest floor with increasing stand age from 20 to 40 years. A tree's vertical root distribution changes with age and with soil properties. Coile (1937) estimated that a tree's root system reaches its maximum depth at a fairly early age, approximately 10 years. This age will vary with the tree species and vary with changes in soil properties.

This review of productivity estimators suggest that regression analysis to develop an equation for prediction purposes may not accurately predict site quality due to the problems mentioned above. The productivity index, though, appears to have potential for predictive purposes, especially in young stands similar to those on post SMCRA plantations. Once relationships between growth and soil variables are determined, response curves for each of the model variables can be developed using information from this
study. A decay curve explaining the optimum rooting fraction of white pine has previously been developed by Gale (1987) and facilitates the construction of the model.
CHAPTER III

Effects of Minesoil Properties on Young White Pine (Pinus strobus) Height Growth in the Appalachian Coalfields

INTRODUCTION

The Eastern Coal Region of the U.S. is predominantly forested. Following strip mining, the reclaimed land is often returned to forest under the provisions of the Surface Mining Control and Reclamation Act (SMCRA - Public Law 95-87). When unmanaged forest is selected as the post-mining land use, coal companies must establish a forest that exceeds 1,000 stems/ha over 30 cm in height after five years. The opportunity exists to create a new forest with a variety of commercially valuable species; however, reclamation practices must be tailored to suit the survival and growth of trees.

Eastern white pine (Pinus strobus), which occurs naturally throughout the Eastern Coal Region, is one of the most common commercial tree species used in reclamation. It is moderately tolerant of shade, makes rapid juvenile growth, and can produce merchantable sawtimber in 35 to 40 years (Balmer and Williston, 1983). Previous studies have shown that eastern white pine grows well under a variety of well-drained soil conditions, however, on reclaimed surface mines survival and growth are often highly variable due to
unfavorable soils (Vogel, 1981). Restricted rooting depths, high soluble salt concentrations, extremes of pH, poor drainage, and soil compaction are the most common soil limiting factors that occur on reclaimed mined lands that negatively affect tree growth (Torbert et al., 1988).

Since SMCRA requires that mining companies post bonds to ensure successful reclamation, there is a significant economic incentive for coal companies to establish stands of trees that survive and make rapid early height growth. Bond release is not guaranteed until inspections show that land productivity and revegetation have been achieved. This study was initiated to evaluate the performance of 78 white pine stands established on reclaimed mined lands under the provisions of SMCRA and to investigate the relationship between mine soil physical and chemical properties and early tree growth prior to bond release. In traditional forest management, understanding the relationship between soil properties and tree growth is useful in matching tree species to specific sites. However, in mineland reclamation, information on soil-site-tree growth relationships would provide the opportunity to construct minesoils best suited to the tree species of interest.
METHODS

Area Description

The study area encompassed reclaimed coal mines located in Wise County, Virginia and Mercer, Wyoming, and McDowell Counties in West Virginia (Figure 1). The native topography is fairly steep (>25%), and most sites support a thin mantle of infertile soils such as the Typic Dystrochrepts (Doolittle, 1958). Most of the coal-bearing strata contain varying amounts of pyrite, which has the potential of causing acid mine drainage (Vogel, 1981). The predominant natural vegetation in Appalachia is the mixed hardwood forest. Overall site quality is poor, with approximate site index (base age 50) for white pine being 18.2 m (Doolittle, 1958). Nonforested lands contain mostly agricultural landuses in particular pastureland.

Study Area

During the summers of 1990 and 1991 seventy-eight stands, on 14 different mines were selected to include a wide range of tree growth and site conditions. At each site a fixed area plot between 0.02 ha and 0.04 ha was established. All plots were located in 5-9-year old eastern white pine plantations established by hand planting 2-0 seedlings.
Figure 1. Location of 14 reclaimed mines in Virginia and West Virginia.
Field Sampling

On each plot all trees were tallied, and total height, ground line diameter, and internode distances were recorded for all white pine following growth cessation. One white pine per plot was cut down and the rings counted to determine the exact stand age. A dormant season foliar sample was collected from the penultimate whorl of each white pine on the plot, and foliage was composited into a single sample for the plot (White, 1954).

On each plot, slope percent, aspect, slope position, and distance and direction to the closest natural forest stand were measured. At two random locations surface horizon bulk density was measured using the excavation method, described by Blake (1965). To estimate functional rooting depth, soil strength was measured using a cone penetrometer at twenty-five locations, randomly located along a diagonal line across the plot. A force of 2070 KPa was applied to the penetrometer. When the desired pressure was achieved, a depth reading was taken.

A soil pit was dug at the center of each plot near the base of a representative tree. The selected tree exhibited no signs of suppression or damage and was selected if its height was judged to be similar to the surrounding trees. In each pit, a taxonomic profile description was completed. Descriptors included depth of each horizon, color, texture,
structure, consistence, and abundance and depth to mottles. Soil samples were collected from each of the delineated horizons to be used for nutrient analysis. Also, from each horizon, two fist-sized soil clods were obtained to determine subsurface bulk density (Blake, 1965). Soil depth was determined as the depth to solid rock or a traffic pan.

Ground cover was assessed along a diagonal transect at 100 locations at evenly-spaced intervals. At each point, the presence or absence of ground cover was noted, and percent ground cover for the plot was calculated by determining the percentage of sampling points within the plot with ground cover observed. At two points along the transect, where the vegetative cover was considered typical, all vegetation was clipped within a 0.5 m² subplot and separated into three categories; dead, live, and live legumes. This provided a measure of ground cover vigor and biomass.

**Laboratory Methods**

Soil samples were returned to the lab, air-dried, and sieved using a 2-mm screen to separate coarse fragments. Particle-size distribution was determined using the hydrometer method. Soil pH was determined in a 1:1 soil/water mixture with a glass electrode (McLean, 1982), and soluble salts were determined by measuring the
electrical conductivity (EC) of a 1:5 soil/water extract (Bower and Wilcox, 1965). Organic matter content was determined using a LECO carbon analyzer. Kjeldahl nitrogen (TKN) was determined by digestion with concentrated H₂SO₄ with an Hg catalyst. Ammonium resulting from the digestion was measured using a Technicon Autoanalyser II. Phosphorus was extracted with NaHCO₃ (Olsen and Dean, 1982) and determined by spectrophotometry. Concentrations of exchangeable cations (Ca, Mg, K, Fe, Al, and Mn) were determined using a Jarrell-Ash ICAP-9000 inductively coupled plasma emission spectrometer after extraction with 1N NH₄OAC. Inorganic nitrogen was measured by extracting exchangeable ammonium, nitrate, and nitrite using a KCl extractant and analyzed using the Technicon Autoanalyzer II. Foliar nitrogen concentrations were determined using a micro-Kjeldahl method (Bremner, 1965), while other foliar nutrients (P, K, Mn, Mg, Ca and Fe) were determined using an ICAP following dry ashing as described by Jones and Steyn (1973).

**Statistical Analysis**

Multiple linear regression analysis was used to identify the relationships between tree height and mine soil properties. Scattergrams were generated for each variable and transformations of soil/site variables, where
appropriate, were performed to improve statistical fit. Several candidate models were derived from forward, backward, and stepwise procedures. Diagnostics for multicollinearity (correlation matrix, variance inflation factors (VIF's) and condition numbers) were conducted since soil/site studies are notorious for multicollinearity among regressors. To refine the model, several diagnostic techniques were used to determine if high influence observations existed. For each observation, $h_{ii}$, DEFITS, DFbetas and Cook's D were derived. Since the purpose of this regression analysis was to identify important soil/site variables, standardized regression coefficients were also obtained.

Since these stands were too young to use traditional dependent variables (i.e. site index) several different measures of growth were derived. Tree height growth was separated into absolute and relative growth measures. Absolute growth was separated into four different components; total height at five years of age, 2-year and 3-year terminal growth, and height growth above a free-to-grow (FTG) point. Two- and three-year terminal growth refer to the average growth of the final two and three years before age five. The FTG point was identified as the tree height where the next year's height growth exceeded the average of the two previous years' by 100%. Two and three year

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terminal growth and the growth above the free-to-grow-point represent the relatively rapid and less erratic growth which is more responsive to soil/site factors and less influenced by non-site factors. Since growth may be related to initial tree size at the beginning of the growth period, relative height growth was calculated using the following equation:

$$RGR = \frac{(\ln W_1 - \ln W_2)}{(t_2 - t_1)}$$ (van den Driessche, 1992) \[1\]

where RGR is the 2-year relative growth rate in cm·cm⁻¹·yr⁻¹, and W₁ is the height at the end of the fifth growing season at time t₁ and, W₂ is the height at the end of the third growing season at time t₂.

RESULTS AND DISCUSSION

White Pine Growth Characteristics

All plots were located in white pine plantations or in plantations consisting of pines and naturally regenerated hardwood species. Tree densities ranged from 193 to 162,598 stems per ha with an average of 687 planted white pine per ha. White pine represented only about 5 percent of the total number of stems on the plots; the remaining stems consisted mostly of naturally seeded sourwood (Oxydendrum arboreum), and red maple (Acer rubrum), and natural or planted black locust (Robinia pseudoacacia) (Table 1). These three species comprised over 77% of the tallied stems.
with sourwood accounting for 59%. Planted white pine was ranked third in importance behind sourwood and red maple. Red maple was located on 92% of the plots, second only to white pine. In total, 30 different tree species were found on the 78 plots (Table 1). This information emphasizes the reality that these pine plantations are not monocultures. Many former species return and thrive on these lands after the reclamation process.

The average five-year-old white pine tree height in this study was 1.5 m (Table 2). Of the 78 plots sampled, the largest individual tree encountered was nearly 4.5 m tall at age 5. This tree occurred on the plot that had the greatest average height of 3.2 m. The smallest individual tree at five years of age, was 0.4 m tall and occurred on the plot that averaged 0.64 m in height.

Generally, early growth was slow (based on height at age 5) averaging only 17.2 cm per year for the first three years. This early growth rate of white pine is largely influenced by non-site factors such as planting techniques, seedling quality, and herbaceous competition (Brown and Stires, 1981). However, once past this early phase of slow growth, the average growth increment increased to 38.8 cm per year for the final two years.

A major concern with determining the relationship between soil properties and tree height growth at young ages
Table 1. Relative frequency (%), density (stems/ha) and importance values of tree and shrub species on 78 sites located on reclaimed strip mines in Virginia and West Virginia.

<table>
<thead>
<tr>
<th>Species</th>
<th>Relative Frequency</th>
<th>Density 2</th>
<th>Importance Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sourwood (Oxydendron arboreum)</td>
<td>11.84</td>
<td>59.45</td>
<td>71.29</td>
</tr>
<tr>
<td>Red Maple (Acer rubrum)</td>
<td>13.32</td>
<td>14.36</td>
<td>27.68</td>
</tr>
<tr>
<td>White Pine (Pinus strobus)</td>
<td>14.48</td>
<td>4.62</td>
<td>19.10</td>
</tr>
<tr>
<td>Black Locust (Robinia pseudoacacia)</td>
<td>9.44</td>
<td>3.61</td>
<td>15.46</td>
</tr>
<tr>
<td>Yellow Poplar (Liriodendron tulipifera)</td>
<td>8.70</td>
<td>2.80</td>
<td>10.70</td>
</tr>
<tr>
<td>Sweet Birch (Betula lenta)</td>
<td>7.22</td>
<td>2.87</td>
<td>10.09</td>
</tr>
<tr>
<td>Bristly Locust (Robinia fertilis)</td>
<td>1.29</td>
<td>8.73</td>
<td>10.02</td>
</tr>
<tr>
<td>Sassafras (Sassafras albidum)</td>
<td>5.06</td>
<td>1.30</td>
<td>6.36</td>
</tr>
<tr>
<td>Mountain Laurel (Kalmia latifolia)</td>
<td>3.33</td>
<td>0.53</td>
<td>3.86</td>
</tr>
<tr>
<td>Black Cherry (Prunus serotina)</td>
<td>2.96</td>
<td>0.13</td>
<td>3.09</td>
</tr>
<tr>
<td>Autumn Olive (Elaeagnus umbelata)</td>
<td>2.22</td>
<td>0.22</td>
<td>2.44</td>
</tr>
<tr>
<td>Winged Sumac (Rhus copallina)</td>
<td>1.67</td>
<td>0.74</td>
<td>2.41</td>
</tr>
<tr>
<td>Northern Red Oak (Quercus rubra)</td>
<td>2.22</td>
<td>0.09</td>
<td>2.31</td>
</tr>
<tr>
<td>Serviceberry (Amelanchier arborea)</td>
<td>2.59</td>
<td>0.18</td>
<td>2.77</td>
</tr>
<tr>
<td>Dogwood (Cornus florida)</td>
<td>1.48</td>
<td>0.07</td>
<td>1.55</td>
</tr>
<tr>
<td>Minor Species 4</td>
<td>12.18</td>
<td>1.10</td>
<td>13.28</td>
</tr>
</tbody>
</table>

1 Percentage of samples in which a species occurs.
2 Number of individuals of a given species per unit area as a percentage of the total of all species.
3 Addition of the two separate measures for a given species.

4 Smooth Sumac (Rhus glabra)        Hickory (Carya glabra)
Chestnut Oak (Quercus prinus)       Holly (Ilex opaca)
Sycamore (Platanus occidentalis)    Sweet Crabapple (Malus coronaria)
Staghorn Sumac (Rhus typhina)       Scrub Oak (Quercus myrtifolia)
Virginia Pine (Pinus virginiana)    Black Alder (Alnus glutinosa)
Red Bud (Cercis canadensis)         Eastern Hemlock (Tsuga canadensis)
White Ash (Fraxinus americana)      Black Willow (Salix nigra)
Yellow Buckeye (Aesculus octandra)  White Oak (Quercus alba)
Table 2. Means and ranges of tree and ground cover stocking and growth for 78 plots located on reclaimed mines in Virginia and West Virginia.

<table>
<thead>
<tr>
<th>Vegetation Measure</th>
<th>Mean</th>
<th>Range</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stocking and Growth</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White pine (stems/ha)</td>
<td>687</td>
<td>193-2868</td>
<td>564</td>
</tr>
<tr>
<td>Total density (stems/ha)</td>
<td>14901</td>
<td>193-162598</td>
<td>24456</td>
</tr>
<tr>
<td>5-yr. height (cm)</td>
<td>157.0</td>
<td>63.6-322.7</td>
<td>64.7</td>
</tr>
<tr>
<td>Terminal 2-yr growth (cm/yr)</td>
<td>38.8</td>
<td>10.0-68.2</td>
<td>14.8</td>
</tr>
<tr>
<td>Terminal 3-yr growth (cm/yr)</td>
<td>32.7</td>
<td>10.4-56.8</td>
<td>12.2</td>
</tr>
<tr>
<td>Height growth above the FTG point (cm/yr)</td>
<td>50.5</td>
<td>13.0-77.7</td>
<td>14.1</td>
</tr>
<tr>
<td>2-year RGR (cm cm^{-1}yr^{-1})</td>
<td>0.40</td>
<td>0.19-0.57</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Ground Cover</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare soil (%)</td>
<td>15</td>
<td>0-70</td>
<td>18</td>
</tr>
<tr>
<td>Legumes (%)</td>
<td>11</td>
<td>0-63</td>
<td>13</td>
</tr>
<tr>
<td>Herbaceous biomass (kg/ha)</td>
<td>5414</td>
<td>206-21491</td>
<td>4036</td>
</tr>
</tbody>
</table>
is the influence of herbaceous vegetation (Brown and Stires, 1981). Early height growth of many tree species is often retarded due to the competition of weeds. To minimize this problem, five different measures of height growth were investigated, as previously discussed. Each was correlated with herbaceous cover and herbaceous biomass for the plantations between five and six years of age (Table 3). Since two year terminal height growth had a weak and non-significant correlation with both herbaceous cover \((r = -0.10, p = 0.20)\) and herbaceous biomass \((r = -0.08, p = 0.21)\), it was selected for use in model development.

Ground cover ranged from 30 to 100 percent, with 20 percent of the plots having less than 70 percent cover (Table 2). Legumes, mainly sericea lespedeza \((Lespedeza cuneata)\), and red clover \((Trifolium pratense)\) comprised only 10% of the total ground cover observed. Seeded herbaceous cover was predominantly orchardgrass \((Dactylis glomerata)\), and 'Kentucky 31' tall fescue \((Festuca arundinacea)\).

**Site and Minesoil Properties**

The minesoils varied widely in texture, from sandy to silty-clay loam and generally contained greater than 50% coarse fragments (Table 4). Approximately 25% of the profiles examined in this study had a readily discernible A
Table 3. Correlation coefficients ($r$) and significance value ($p$) for height growth measures and herbaceous vegetation for 35 white pine plantations aged 5 or 6 years.

<table>
<thead>
<tr>
<th>Height Growth</th>
<th>Herbaceous Cover (%)</th>
<th>Herbaceous Biomass (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r$</td>
<td>$p$</td>
</tr>
<tr>
<td>5-yr height</td>
<td>-0.17</td>
<td>0.10</td>
</tr>
<tr>
<td>Term. 2-year growth</td>
<td>-0.10</td>
<td>0.12</td>
</tr>
<tr>
<td>Term. 3-year growth</td>
<td>-0.14</td>
<td>0.11</td>
</tr>
<tr>
<td>Height growth above the FTG point</td>
<td>-0.46</td>
<td>0.04</td>
</tr>
<tr>
<td>RGR</td>
<td>-0.16</td>
<td>0.11</td>
</tr>
</tbody>
</table>
Table 4: Means and ranges of selected minesoil (upper 10 cm) and minesite properties from 78 reclaimed mines in Virginia and West Virginia.

<table>
<thead>
<tr>
<th>Minesoil Properties</th>
<th>Mean</th>
<th>Range</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect (degrees)</td>
<td>152°</td>
<td>1°-360°</td>
<td>115</td>
</tr>
<tr>
<td>Slope (%)</td>
<td>29</td>
<td>0-58</td>
<td>18</td>
</tr>
<tr>
<td>Depth to restrictive layer (cm)</td>
<td>78</td>
<td>31-112</td>
<td>22</td>
</tr>
<tr>
<td>Penetrometer (inches)</td>
<td>5.4</td>
<td>1.9-11.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Rock fraction (%)</td>
<td>54</td>
<td>2-88</td>
<td>15</td>
</tr>
<tr>
<td>Sand content (%)</td>
<td>29</td>
<td>10-73</td>
<td>11</td>
</tr>
<tr>
<td>Silt content (%)</td>
<td>11</td>
<td>5-25</td>
<td>5</td>
</tr>
<tr>
<td>Clay content (%)</td>
<td>8</td>
<td>3-17</td>
<td>4</td>
</tr>
<tr>
<td>Bulk density (Mg/m³) (Adjusted for coarse fragments)</td>
<td>1.02</td>
<td>0.64-1.94</td>
<td>0.08</td>
</tr>
<tr>
<td>pH</td>
<td>5.2</td>
<td>3.2-6.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Electrical conductivity (dS/m²)</td>
<td>0.32</td>
<td>0.02-1.97</td>
<td>0.32</td>
</tr>
<tr>
<td>Organic matter (%)</td>
<td>1.5</td>
<td>0.4-4.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Carbon (%)</td>
<td>1.2</td>
<td>0.2-4.9</td>
<td>0.97</td>
</tr>
<tr>
<td>Total Kjeldahl N (mg/kg)</td>
<td>567</td>
<td>156-1795</td>
<td>289</td>
</tr>
<tr>
<td>Anaerobic N (mg/kg)</td>
<td>12.7</td>
<td>0.4-67.9</td>
<td>12.7</td>
</tr>
<tr>
<td>Extractable P (mg/kg)</td>
<td>5.5</td>
<td>1.3-22.0</td>
<td>4.8</td>
</tr>
<tr>
<td>Exchangeable Mn (mg/kg)</td>
<td>15.9</td>
<td>1.5-57.7</td>
<td>11.2</td>
</tr>
<tr>
<td>Exchangeable K (mg/kg)</td>
<td>57</td>
<td>2-161</td>
<td>29</td>
</tr>
<tr>
<td>Exchangeable Ca (mg/kg)</td>
<td>260</td>
<td>5-1107</td>
<td>228</td>
</tr>
<tr>
<td>Exchangeable Mg (mg/kg)</td>
<td>154</td>
<td>1-517</td>
<td>125</td>
</tr>
<tr>
<td>Exchangeable Al (mg/kg)</td>
<td>1.3</td>
<td>0.5-27.6</td>
<td>2.9</td>
</tr>
<tr>
<td>Exchangeable Fe (mg/kg)</td>
<td>0.13</td>
<td>0.05-0.76</td>
<td>0.10</td>
</tr>
</tbody>
</table>
horizon, with minimal organic matter on the surface. No profile had an illuviated B horizon. The C horizon dominated in all of the profiles, and varied in spoil type, degrees of compaction, and thickness. Generally, no roots were found in C horizons that were classified as having a traffic pan (bulk density greater than 1.7 g/cm). Root growth was also arrested in C horizons that were composed of weathered coal or bedrock. When these restrictive layers were present, they were generally 25-90 cm below the surface and varied in thickness. Depth of these compacted layers defined the lower limit of rooting depth. Where compacted layers were absent, rooting depth was considered to be 100 cm.

**Minesoil Properties Affecting White Pine Growth**

A total of 32 independent variables representing site characteristics and minesoil physical and chemical properties were initially screened for inclusion in forward, backward and stepwise multiple regression models. Models selected from backward and forward procedures had 8 and 11 variables respectively and were discarded for the sake of parsimony. The stepwise model, which had 6 variables, was considered for further examination and refinement. In this model, the Ca variable did not have a significant partial F value and was discarded, although its inclusion improved the model’s fit. From a biological standpoint, Ca is a variable
that would not be expected to play an important role in the productivity of these sites and it's exclusion is biologically warranted.

To get a better understanding of correlation among the remaining regressors, a correlation matrix (Table 5), the condition numbers, and variance inflation factors (VIF) were examined. The condition number for this model was not high and indicated no multicollinearity problems. All of the VIF's in the model were low (< 2.0) indicating that multicollinearity problems were not serious for any of the regressors.

To refine the model, several diagnostic techniques were used to denote high influence observations. Cook's D statistic revealed 6 observations which were distinctly separated from the rest of the data and were deleted. Three other observations were removed from the data set because of suspect data. The regression analysis resulted in the following model:

\[
HG = 1.54 + 0.31\ln(RD) + 0.20\text{SQR}(P) - 0.005(1/EC) - 0.004(Mn) + 0.04(S) \tag{2}
\]

Where:

- \(HG\) = 2-year terminal growth (cm/yr)
- \(RD\) = Rooting depth to a restrictive layer (cm)
- \(\text{SQR}(P)\) = Square root of soil exchangeable P (mg/kg)
- \(EC\) = Electrical conductivity (dS m\(^{-2}\))
- \(Mn\) = Soil extractable manganese (mg/kg)
- \(S\) = Slope (%)

\(R^2 = 0.48\)
\(P>F = 0.000\)
Table 5. Correlation matrix for selected regressor variables from 78 reclaimed mines in Virginia and West Virginia.

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>D</th>
<th>pH</th>
<th>EC</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>Mn</th>
<th>Al</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>1.00</td>
<td>.02</td>
<td>.00</td>
<td>.18</td>
<td>.20</td>
<td>.42</td>
<td>.43</td>
<td>.24</td>
<td>.09</td>
<td>.18</td>
<td>-.13</td>
<td>.08</td>
</tr>
<tr>
<td>D</td>
<td>1.00</td>
<td>.43</td>
<td>-.29</td>
<td>-.01</td>
<td>.30</td>
<td>.26</td>
<td>.09</td>
<td>.03</td>
<td>-.07</td>
<td>-.12</td>
<td>.03</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>1.00</td>
<td>-.44</td>
<td>.07</td>
<td>.16</td>
<td>.23</td>
<td>.29</td>
<td>.45</td>
<td>-.29</td>
<td>-.36</td>
<td>.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td>1.00</td>
<td>.39</td>
<td>.16</td>
<td>.17</td>
<td>.49</td>
<td>.37</td>
<td>.72</td>
<td>-.28</td>
<td>.26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>1.00</td>
<td>.34</td>
<td>.50</td>
<td>.79</td>
<td>.73</td>
<td>.53</td>
<td>-.30</td>
<td>.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>1.00</td>
<td>.64</td>
<td>.46</td>
<td>.30</td>
<td>.42</td>
<td>-.47</td>
<td>.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>1.00</td>
<td>.52</td>
<td>.49</td>
<td>.43</td>
<td>-.47</td>
<td>.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>1.00</td>
<td>.88</td>
<td>.58</td>
<td>-.57</td>
<td>.66</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>1.00</td>
<td>.46</td>
<td>-.62</td>
<td>.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>1.00</td>
<td>-.45</td>
<td>.44</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>1.00</td>
<td>-.11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>

S = slope  
D = depth  
EC = electrical conductivity  
N = total Kjeldahl N  
P = exchangeable P  
K = extractable K

Ca = extractable Ca  
Mg = extractable Mg  
Mn = extractable Mn  
Al = extractable Al  
Fe = extractable Fe
The amount of variation explained by equation 1 \((R^2)\) was 48%. The \(R^2\)'s reported in other white pine soil-site studies, up to 85%, included large contributions from age. In Browns and Stires (1984) model, 51% of the total \(R^2\) was attributed to age, and only 28% was attributed to soil and topographic factors. Higher \(R^2\)'s were not found in this study due partly to the heterogeneity within each plot. Large spatial variability in minesoils in southwestern Virginia has been reported by Daniels et al. (1981).

Since the purpose of this regression was to identify important soil/site properties affecting tree growth, standardized regression coefficients (Table 6) were derived to allow a meaningful comparison among the regressors. This value is obtained when the variables are subtracted by their mean and then divided by their standard deviation. A comparison of standardized coefficients revealed that soil depth had the greatest effect on growth, but EC and extractable P were also important.

The functional relationships between rooting depth, tree growth, and the other soil variables are displayed in Figure 2a - 2d. The developed regression equation was used to calculate the curves. These curves were developed by holding the variables not represented in the figures constant at their mean values. Then values for various
Table 6. Standardized regression coefficients for the regression equation developed on 78 reclaimed mines in Virginia and West Virginia.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Standardized Regression Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Depth</td>
<td>.38</td>
</tr>
<tr>
<td>EC</td>
<td>.31</td>
</tr>
<tr>
<td>Exchangeable P</td>
<td>.27</td>
</tr>
<tr>
<td>Slope</td>
<td>.23</td>
</tr>
<tr>
<td>Extractable Mn</td>
<td>.14</td>
</tr>
</tbody>
</table>
Figure 2. Height growth of white pine on reclaimed mines as related to rooting depth and (a) slope, (b) soil P, (c) soil Mn, and (d) EC, based on equation 1. Variables not represented in the figures are held constant at their mean values.
combinations of each of the variables listed in the curves were inserted in the equations for calculations of estimated 2-year terminal growth. The curves were derived as a function of depth, due to the importance of depth on chemical and physical properties.

Rooting depth was the mine soil property most strongly related to height growth (Table 6). Previous studies have shown that rooting volume is a significant variable in predicting height growth in older white pine plantations (Torbert et al., 1988). Rooting volume was created by multiplying the depth to a restrictive layer by the percent of soil sized particles. In this study, rooting depth alone was more important than rooting volume, probably because white pine are capable of utilizing water held by rock fragments (Bussler et al., 1984), and the presence of rock fragments indicates a less compacted soil. In this study rock fragment content was negatively correlated with fine-earth-fraction bulk density \( r = -0.51 \). Mader (1976) found that an increase in coarse fragment content in the surface horizons improved white pine site quality.

The height of white pine was plotted as a function of the natural log of rooting depth (Figure 3a). Although there was considerable variability among sites, indicated by the scatter of data about the regression line, there was an obvious upward trend to a depth of 60 cm. In deeper soils
Figure 3. Relationship between white pine 2-year terminal growth and soil depth; (a) regression analysis performed on complete data set; (b) regression analysis performed on soils less than 60 cm and greater than 60 cm.
the relationship was not apparent (Figure 3b). Soils deeper than 60 cm had little or no effect on height growth at age five.

Throughout the range of white pine, soil depth is an important limiting factor. Brown and Stires (1984) found that with an increase in total soil depth, there was a corresponding increase in productivity. Deeper soils provide a greater exploitable rooting volume, nutrient supply and moisture holding capacity. The depth of minesoils can be limited by underlying bedrock, compaction from heavy equipment, or large boulders (Torbert et al., 1983). When restrictive layers are present they inhibit root penetration and perch water, creating anaerobic conditions. Meltzer (1964) noted that among six associates, white pine had the poorest ability to penetrate a compacted mineral subsoil (Larix decidua > Pinus silvestris > Betula verrucosa > Alnus incana > Picea abies > Pinus strobus).

Height growth was greater on steeper slopes (Figure 4). In natural forested stands the opposite is true because steeper slopes have greater runoff, shallower soils, and more erosion (Shoulders and Tiarks, 1980). However, on reclaimed mined lands, flatter sites are often subjected to greater vehicle traffic, resulting in more compaction, thus poorer drainage and aeration occurs. On steeper slopes, reclamation equipment use is restricted, resulting in less
Figure 4. Relationship between 2-yr. terminal growth and percent slope.

Growth = 24.0 + (0.3*Slope)

p = 0.000

r^2 = 0.21
compaction. This phenomenon is further borne out by the negative correlation between slope percent and soil bulk density ($r = -0.29$).

In this study two different expressions of the interaction of slope and aspect were investigated; it is assumed that, on steeper slopes, aspect has a greater effect on growth. Also these expressions reflect the fact that a southeast aspect ($225^\circ$) is the hottest, driest, and least productive aspect, whereas the northeast aspect ($45^\circ$) is the most productive. The first expression, proposed by Beers and others (1966), is mathematically stated as $B \cos (a-O)$ where $B$ is the amplitude, $a$ is the azimuth and $O$ is the phase shift that has historically been assumed to be $45^\circ$. An expression of aspect and slope was also developed by Stage (1976) in which the combined effect of slope and aspect were defined as the tangent of slope percent times the sine and cosine, respectively, of the azimuth. Neither expression significantly improved upon the slope variable alone. This may be due to the fact that white pine is very "plastic" and can grow under many different site conditions.

The most important chemical property affecting white pine growth was electrical conductivity (EC). Height growth decreased with increasing electrical conductivity (EC) (Figure 5). Salinity affects many different metabolic processes, such as $CO_2$ assimilation, protein synthesis,
Figure 5. Relationship between white pine 2-yr. terminal growth and soil electrical conductivity.

Growth = 42.74 + (-12.29*EC)

p = 0.02

r^2 = 0.15
respiration and phytohormone turnover (Mengel et al., 1982). White pine is especially sensitive to soil salinity which will cause foliar injury that weakens the tree, leading to death (Hofstra et al., 1979; Townsend, 1984; Sucoff, 1975). In this study direct evidence of foliar injury was not found, but growth was negatively affected by increased EC.

McFee et al. (1984) determined that EC was the chemical property that was most frequently related to plant growth on reclaimed minesoils in Indiana and Illinois. Due to rapid weathering of newly exposed minerals, minesoils often have high levels of soluble salts (Torbert et al., 1988). These high levels usually decrease with time due to leaching.

The second most important chemical property affecting white pine growth is phosphorus. Phosphorus is a constituent of important organic compounds involved in metabolism and energy transfer in plants. Phosphorus deficiencies are widely recognized in minesoils in the Eastern Coal Region (Barnhisel and Massey, 1969; Smith and Sobek, 1978; Howard, 1979; Daniels and Amos, 1982; Torbert et al., 1988). Reasons for P deficiencies in minesoils usually include one or more of the following; i) overburden materials contain only small amounts of P-bearing minerals, ii) P compounds that are present are insoluble, especially in very acid or alkaline materials, and iii) there is no reservoir of organic P compounds (Vogel, 1981). Even when P
fertilizers are applied they are often quickly fixed into unavailable forms.

For many plants the soil P critical level is 10 ppm using the NaHCO₃ extraction method (Ministry of Agriculture Fisheries and Food, 1973). In this study, many trees grew well in the P deficient zone (Figure 6). This good growth may have been due to mycorrhizal colonization of tree roots, allowing exploitation by hyphae which may reach several centimeters from the root surface. This may result in the uptake of several times more P per unit root length than with nonmycorrhizal fungi. Also, mycorrhizae excrete organic acids that dissolve P compounds in the rhizosphere making it more available. According to Bolan et al. (1984), mycorrhizal roots are able to utilize phosphorus sources that are normally unavailable to nonmycorrhizal roots.

The last chemical property influencing height growth was exchangeable Mn (Figure 7). In general, height growth declined when exchangeable Mn levels exceeded 30 ppm. Soil manganese, alone, had a low significance value, but its inclusion improved the overall model for predicting 2-year terminal growth. Although this may result in "overfitting" the model, there may be some biological reasons for its inclusion. Manganese toxicity commonly occurs in strongly acid soils or in waterlogged soils (McFee et al., 1984). Barnhisel and Massey (1969) found that available Mn in
Figure 6. Relationship between white pine 2-yr. terminal growth and exchangeable P.
Figure 7. Relationship between white pine 2-yr. terminal growth and soil extractable manganese.
eastern Kentucky minesoils approached toxic levels, hindering the establishment of vegetation. McFee and others (1984) also found elevated levels of Mn in overburden materials where reduction of Mn occurred.

**Foliar Nutrition**

Foliar nutrition was investigated because soil N and P deficiencies are common in minesoils throughout the study area (Daniels and Amos, 1984). Foliar N and P ranged from 0.1 to 0.2 g/kg, with a mean of 0.19 g/kg, and 0.01 to 0.03 g/kg with a mean of 0.02 g/kg, respectively (Table 7). Mitchell (1939) reported that foliar levels of N and P in white pine seedlings were 0.22 and 0.02 g/kg, respectively, for good sites, and 0.16 and 0.01 g/kg for poor sites.

Foliar nutrient concentrations were used as independent variables in a stepwise regression, with 2-year terminal growth as the dependent variable. The resulting equation was non-significant.

**CONCLUSIONS**

Reclaimed mined lands can be very productive for young white pine. For example, in the best of 78 stands the 5-year-old white pine averaged 3.2 m in height. This minesoil was 92 cm deep, had a moderate pH (5.5), low bulk density (1.05 g/cc), was on a 38% slope, and had a loamy texture.
Table 7. Average values for foliar nutrient concentrations on seventy-eight 5-year-old reclaimed strip mines in Southwestern Virginia and West Virginia.

<table>
<thead>
<tr>
<th>Foliar Nutrients</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0.19</td>
<td>0.10</td>
<td>0.20</td>
<td>0.02</td>
</tr>
<tr>
<td>P</td>
<td>0.02</td>
<td>0.01</td>
<td>0.03</td>
<td>0.003</td>
</tr>
<tr>
<td>K</td>
<td>0.05</td>
<td>0.03</td>
<td>0.06</td>
<td>0.008</td>
</tr>
<tr>
<td>Ca</td>
<td>0.05</td>
<td>0.03</td>
<td>0.08</td>
<td>0.01</td>
</tr>
<tr>
<td>Mg</td>
<td>0.02</td>
<td>0.01</td>
<td>0.03</td>
<td>0.004</td>
</tr>
<tr>
<td>Mn</td>
<td>0.001</td>
<td>0.003</td>
<td>0.040</td>
<td>0.007</td>
</tr>
<tr>
<td>Al</td>
<td>0.002</td>
<td>0.001</td>
<td>0.004</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Since, all of the sites were created in the reclamation process, it should be standard procedure to create the best site for tree growth if forest land is the designated post-mining land use. Suitable soil material can be stockpiled and placed on the surface after the slopes are restored. Reducing vehicular traffic will eliminate or reduce compaction and increase rooting depth. Nutrient deficiencies or extremes in pH can be amended with soil additives, or a different topsoil or topsoil-substitute can be used. Although equation 2 was not developed for predictive purposes, it indicates the major soil and site factors which influence height growth at young ages. This analysis indicates that soils greater than 60 cm in depth, have greater than 9 mg/kg of soil extractable P, have low soil exchangeable Mn and electrical conductivity, and are on slopes will promote good growth. Since bond release occurs after five years, it is important that the trees are established and growing rapidly by that time. With proper reclamation, this could be a reality on all reclaimed mined lands in the Eastern Coal Region.
CHAPTER IV

A Soil Productivity Index to Evaluate Forest Site Quality of Reclaimed Surface Mines in the Appalachian Coalfields

INTRODUCTION

The Surface Mining Control and Reclamation Act (SMCRA, PL 95-87) has had a dramatic impact on coal strip mine practices in the eastern U.S. Reclaimed lands are returned to their original contours and reclaimed for a specified land use such as forest or hayland/pasture. For mined land reclaimed to forest, the law requires that each reclaimed hectare must have 1,000 stems at least 30 cm tall after 5 years. In order to meet this standard, minesoils must be reconstructed that are compatible with tree growth, and suitable ground covers must be used. The five year bond period has focused special attention on tree establishment and early growth, as reclamationists want their planted trees to survive and grow well enough to meet the regulatory standard.

This study was initiated to evaluate minesoil properties influencing the pre-bond-release height growth of white pine (*Pinus strobus*). Although the current inspection standards are based on density and a target height, the basis for adequate tree survival, stand growth, and the production of useful wood products will be a function of the
quality of the minesoil. Although early height growth is the primary interest of reclamationists seeking bond release, long-term growth is desired by landowners so that the plantations established will ultimately produce merchantable timber. The purpose of this study was to develop a soil productivity index (PI) to estimate short and long term site quality for timber crops. It integrates a series of soil physical and chemical properties into a single index of site quality that can be used to judge minesoil reclamation success.

**Soil Productivity Index**

The soil productivity index (PI) associates soil and site characteristics with the vertical root distribution of plants. The PI model is based on the idea that a tree has a certain genetic vertical root distribution and, under optimum soil/site conditions will produce the same proportional rooting pattern. If a soil or site property is limiting, the proportional root distribution will change, negatively affecting above ground growth (Gale and Grigal, 1991).

The original productivity index (PI) model was developed by Neill (1979) and had the following form:

\[
PI = \frac{1}{\sum_{i=1}^{r} (A \times B \times C \times D \times E \times RI)_i}
\]

[1]
where, $A$ is the sufficiency of potential available water storage capacity, $B$ the sufficiency of aeration, $C$ the sufficiency of bulk density, $D$ the sufficiency of pH, and $E$ the sufficiency of electrical conductivity. The product of these are summed over $r$ number of 10 cm increments within the rooting depth. The RI term was the optimum fraction of total roots in a given 10 cm soil increment, based on Horn’s (1971) water depletion curve. Each model component (response curve that converts soil property data into "sufficiencies" for root growth) is normalized to range from 0.0 to 1.0. A value of 0.0 indicates a totally limiting level of a soil property, and a value of 1.0 indicates an optimum level.

Pierce and others (1983) reduced Neill’s (1979) equation to the form:

$$\prod_{i=1}^{r} \left( A \times B \times C \times WF \right)_i$$ [2]

They eliminated the sufficiencies for aeration and electrical conductivity. Their weighting factor (WF) was also derived from Horn’s (1971) water depletion curve.

Gale (1987) modified these equations for white spruce ($Picea glauca$), red pine ($Pinus resinosa$), jack pine ($Pinus banksiana$) and red maple ($Acer rubrum$). She used the geometric mean, which gives equal weight to proportional differences in factor ratings and not to absolute
differences. She also modified these two equations to include percent slope and climate. Her equation for white spruce was:

\[ P_i = \prod_{i=1}^{I} \left( [A \times B \times C \times D]^\frac{1}{4} \times WF \right) \times [S1 \times Cl]^\frac{1}{2} \]  

where \( A \) is the sufficiency of potential available water, \( B \) the sufficiency of aeration, \( C \) the sufficiency of bulk density, \( D \) the sufficiency of pH, \( S1 \) the sufficiency of percent slope, and \( Cl \) the sufficiency of climate.

The weighting factor (WF) was based on a curve developed by Gale and Grigal (1987) for midtolerent species. They classified 34 different species into three tolerance classes based on successional status using Curtis's (1959) climax adaptation numbers. An asymptotic nonlinear equation of the form:

\[ Y = 1 - B^d \]  

was developed for each of the species where \( Y \) is the cumulative root fraction from the surface to soil depth \( d \) in centimeters, and \( B \) was the estimated parameter. This function describes the decreasing proportion of roots with increasing soil depth. High \( B \) values (0.97) were associated with a large proportion of roots at deeper soil depths, and lower values (0.92) were associated with a larger proportion of roots near the surface.
Gale's (1991) equation performed better in younger plantations than in older plantations. She determined that the PI is a better index of site quality in younger stands because of its use of mineral soil characteristics and optimum vertical root distributions. Wells and Jorgensen (1975) determined that nutrient uptake of loblolly pine (Pinus taeda) shifted from the mineral soil to the forest floor with increasing stand age. The PI model, which is based on mineral soil characteristics, is more applicable in younger stands that have less organic accumulation than in older stands. Therefore, a PI model that included the assumptions and considerations found in Gale's (1987) model was developed for minesoils in southeastern Virginia and West Virginia.

MATERIALS AND METHODS

Study Area

The study area consisted of seventy-eight eastern white pine plantations on 14 different reclaimed mines located in Wise County, Virginia and Mercer, Wyoming, and McDowell Counties in West Virginia. These sites were selected to include a wide range of tree growth and site conditions. At each site a fixed area plot between 0.02 ha and 0.04 ha was established. All plots were located in 5 to 9 year old
eastern white pine plantations established by hand planting 2-0 seedlings.

Field Sampling

On each plot all trees were tallied, and total height, ground line diameter, and internode distances were recorded for all white pine following growth cessation. One white pine per plot was cut down and the rings counted to determine the exact stand age. A dormant season foliar sample was collected from the penultimate whorl of each white pine on the plot, and the foliage was composited into a single sample for the plot (White, 1954).

On each plot, slope percent, aspect, and slope position were measured. At two random locations surface horizon bulk density was measured using the excavation method described by Blake (1965). To estimate functional rooting depth, a cone penetrometer was used. At twenty-five locations, randomly located along a diagonal line across the plot, the penetrometer had a force of 2070 KPa applied. When the desired pressure was achieved, a depth reading was taken.

A soil pit was dug at the center of each plot positioned at the base of a representative tree. The selected tree exhibited no signs of suppression or damage and was selected if its height was judged to be similar to the surrounding trees. In each pit, a taxonomic profile
description was completed. Descriptors included depth of each horizon, color, texture, structure, consistence, and abundance and depth to mottles. Soil samples were collected from each horizon and prepared for nutrient analyses. Also, from each horizon, two soil clods were obtained to determine subsurface bulk density (Blake, 1965). Effective soil depth was measured to solid rock or a root limiting traffic pan.

**Laboratory Methods**

Soil samples were returned to the lab, air-dried, and sieved using a 2-mm screen to separate coarse fragments. Particle-size distribution was analyzed using the hydrometer method. Soil pH was determined in a 1:1 soil/water mixture with a glass electrode (McLean, 1982), and soluble salts were determined by measuring the electrical conductivity (EC) of a 1:5 soil/water extract (Bower, 1965). Organic matter content was determined using a LECO carbon analyzer. Kjeldahl nitrogen (N) was determined by digestion with concentrated H₂SO₄ and with an Hg catalyst. Ammonium resulting from the digestion was measured using a Technicon Autoanalyzer II. Phosphorus was extracted with NaHCO₃ (Olsen and Dean, 1982) and determined by spectrophotometry. Concentrations of exchangeable cations (Ca, Mg, Fe, Al, K, and Mn) were determined using a Jarrell-Ash ICAP-9000 inductively coupled plasma emission spectrometer after
extraction with 1N NH₄OAC. Inorganic nitrogen was measured by extracting exchangeable ammonium, nitrate, and nitrite using a KCl extractant and analyzed using the Technicon Autoanalyzer II.

RESULTS AND DISCUSSION

Model Development

For this study Gale's (1987) equation was modified, eliminating sufficiencies for climate, aeration, and percent available water content while adding sufficiencies for electrical conductivity and phosphorus:

\[
PI = \prod_{i=1}^{r} \left( [pH \times EC \times P \times BD]^{1/4} \times WF \right) \times [Sl] \tag{5}
\]

where pH is the sufficiency of pH, EC is the sufficiency of electrical conductivity, P the sufficiency of phosphorus, BD the sufficiency of bulk density, and Sl the sufficiency of percent slope. In Chapter 1, it was determined that these soil and site properties were significantly related to white pine growth in the Appalachian coalfields. Kiniry et al. (1983), Pierce et al. (1983), Larson et al. (1983), and Pierce et al. (1984), among others, used Horn's (1971) water depletion curve to describe their optimum rooting distributions. Gantzer and McCarty (1987) determined that such depletion patterns may reflect the complex interactions
of soil and site properties on rooting patterns, and suggests that this curve may not accurately reflect rooting distributions. Therefore, the weighting factor developed by Gale and Grigal (1987) \((1 - B^d)\) for midtolerant tree species was used because it was derived from data accumulated on specific rooting habits of northern forest species.

A B coefficient (estimated parameter) of 0.96 was calculated for midtolerant species, this also was the calculated coefficient for white pine. The white pine coefficient was determined using 17 vertical root samples (Lutz et al., 1937). The weighting factor developed for white pine optimum rooting distributions used in this study is;

\[
Y = 1 - 0.96^d
\]  \[6\]

where \(d\) is the depth from the soil surface (Figure 1a). This curve is similar to the curve developed by Neill (1979) to describe his optimum rooting fraction (Figure 1b). The weighting factor (WF) for each horizon is calculated as the difference between the cumulative estimates for each soil depth.

**Sufficiency Curve Development**

For each of the properties in the model, a root growth response function was developed. These functions quantify the influence of each property on root growth. Once the
Figure 1. (a) Predicted root fraction with depth for midtolerant tree species (Gale et al., 1987) (b) Predicted root fraction with depth (Kiniry, 1983).
response is formulated, a "sufficiency" (based on the shape of the response function) is derived and normalized between 0.0 and 1.0. Sufficiency curves were developed for each soil and site variable using information from either this study, previous sufficiency curves developed by Neill (1979), Pierce et al. (1983), and Gale (1987), or from actual index values obtained from the literature. The productivity index was calculated by determining the sufficiency rating for each soil horizon characteristic in addition to the WF and site characteristics on each plot for white pine. Because topography is not horizon specific, its sufficiency was computed separately and multiplied by the PI. Sufficiency curves for each minesoil property used in the model are shown in Figures 2 through 6. Specifics on the derivation of these curves can be found in Chapter 1.

**Bulk Density:** Bulk density as a measure of resistance to root penetration provides little information on the continuity of pores or planes of weakness in the soil (Russell, 1977). Permeability, however, is a measure of the soil's ability to conduct water and air, which indicates the size and continuity of pores. Therefore, we used sufficiency curves of bulk density for optimum rooting that were developed by Pierce et al. (1984). They developed equations describing critical and limiting densities for
seven soil textural classes (Table 1). With each family
texture class, the sufficiency of bulk density was adjusted
according to the permeability of the soil horizon.

The sufficiency index for bulk density for each soil
horizon is calculated by first determining its family
textural class and then using the correct equation for that
texture (Figure 2). A sandy-textured horizon with a bulk
density of 1.2 g/cm² would have a sufficiency rating of 1.0,
while a clayey layer with a similar bulk density would only
have a sufficiency rating of 0.80.

pH: The pH sufficiency curve is similar to that of
Kiniry's (1983) and Gale's (1987). Wilde and others (1965)
found that good white pine growth is obtained on sites with
a pH ranging from 4.8 to 5.1. Spurway (1941) listed optimum
soil pH values for white pine as ranging from 5.0 to 6.0.
Compared with agronomic crops, conifers are better adapted
and are more productive on moderately acid soils (Pritchett,
1979). Part of this adaptation has to do with their
symbiotic association with mychorrhizal fungi which are
especially important to conifers (Marx, 1977). Most
ectomycorrhizae associated with conifers do not thrive when
the pH exceeds 6.5 (Theodorow and Bowen, 1969). Therefore,
the sufficiency rating was set to 1.0 for pH values between
5.0 and 6.0. pH's lower than 3.0 or higher than 8.0 were
Table 1. Nonlimiting, critical, and root limiting bulk densities for each family texture class.

<table>
<thead>
<tr>
<th>Family Texture Class</th>
<th>Nonlimiting Bulk Density</th>
<th>Critical Bulk Density</th>
<th>Root-Limiting Bulk Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy</td>
<td>1.60</td>
<td>1.69</td>
<td>1.85</td>
</tr>
<tr>
<td>Coarse loamy</td>
<td>1.50</td>
<td>1.63</td>
<td>1.80</td>
</tr>
<tr>
<td>Fine loamy</td>
<td>1.46</td>
<td>1.67</td>
<td>1.78</td>
</tr>
<tr>
<td>Coarse silty</td>
<td>1.43</td>
<td>1.67</td>
<td>1.79</td>
</tr>
<tr>
<td>Fine silty</td>
<td>1.34</td>
<td>1.54</td>
<td>1.65</td>
</tr>
<tr>
<td>Clayey: 35-45%</td>
<td>1.40</td>
<td>1.49</td>
<td>1.58</td>
</tr>
<tr>
<td>&gt;45%</td>
<td>1.30</td>
<td>1.39</td>
<td>1.47</td>
</tr>
</tbody>
</table>

Figure 2. Sufficiency curve of bulk density used for productivity index.
set at 0.50 since neither are totally limiting to growth. A linear relationship between optimum pH values and pH values of 3.0 and 8.0 were assumed (Figure 3).

Sufficient information from past studies is not currently available to develop individual suitabilities from the literature for slope, phosphorus or electrical conductivity; therefore, the construction of each of these curves is based solely on the data collected as part of this study.

**Slope:** The sufficiency curve for topography was developed using the white pine data base (Figure 4). Sufficiency for root growth was assumed to be reflected in aboveground growth and a linear curve was fit to the data. The derived relationship is contrary to what is generally found on natural soils. Shoulders and Tiarks (1980) found that on steeper slopes stand basal area decreased due to shallow soil and excessive runoff. However, on minesoils, steeper slopes prohibit reclamation equipment from repeatedly traversing the site, hence reducing compaction. On slopes > 35% a sufficiency value of 1.00 was assigned. Flat areas were assigned a sufficiency rating of 0.60 since this slope exhibited 60% of the optimum growth. A linear relationship was assumed between these values.
Figure 3. Sufficiency curve for pH used in productivity index.
Figure 4. Sufficiency curve for percent slope used in productivity model.

$\text{SUFFS} = 0.6 + 0.013(\text{Slope})$

Slope $> 35\%$, $\text{SUFFSL} = 1.0$
**Phosphorus:** Phosphorus deficiencies are widely recognized as a major plant limiting growth factor in the Appalachian region (Barnhisel and Massey, 1969). Phosphorus deficiencies usually occur on minesoils because overburden materials contain only small amounts of P-containing minerals, and P compounds that are present are usually insoluble.

Many trees in this study experienced poor growth when P levels were below 9 mg/kg. A critical level that closely reflected the P levels in this study was one determined for agronomic crops. For many agronomic plants the soil P critical level was determined to be 10 g/kg using the NaHCO$_3$ extraction method (Ministry of Agriculture Fisheries and Food, 1973). This value was considered to be optimum and was assigned a sufficiency rating of 1.00 (Figure 5). The lowest P level, 1.34 mg/kg, was assigned a sufficiency value of 0.40 since this level was not totally limiting to growth, and was exhibiting growth at 40% of that considered to be optimum. A curvilinear expression was then developed between these values based on the work in Chapter 1. Sufficiency ratings for soil extractable P at values less than 1.34 mg/kg were set at 0.40.

**Electrical Conductivity:** Due to rapid weathering of newly exposed minerals, minesoils often have high levels of
Figure 5. Sufficiency curve for soil extractable phosphorus used in productivity model.
soluble salts as measured by electrical conductivity (EC). Torbert et al. (1988) determined that electrical conductivity was the chemical property that was most related to white pine growth on reclaimed strip mines in southwestern Virginia. Townsend (1984) found similar trends in suppressed height growth with an increase in sodium chloride in soil solution. According to Sucoff (1975) white pine is sodium-chloride intolerant and susceptible to salt damage.

In this study, suppression of growth was experienced when EC exceeded 0.50 dS/cm. Therefore, values less than 0.50 dS/cm were assigned a sufficiency rating of 1.00 (Figure 6). The highest EC value encountered was 2.0 dS/cm and was assigned a sufficiency rating of 0.20 since it was not totally limiting to white pine growth and exhibited growth at 20% of the optimum. A linear relationship was assumed between these values. Sufficiency ratings for EC values greater than 2.0 dS/cm were set at 0.20.

Operationally, for each horizon, the levels of each of the measured soil properties are assigned a sufficiency value. These values are multiplied together and with the WF for the ideal soil for that horizon. Finally, the resulting values for each depth increment are summed to give the PI for the entire rooting depth and then multiplied with the sufficiency for slope (Table 2). The PI shown in Table
Figure 6. Sufficiency curve for electrical conductivity (EC) used in productivity model.
Table 2. Predicted root fractions for five horizons compared to that in an ideal soil.

\[
\sum_{i=1}^{n} \left( \frac{EC \times pH \times BD \times P_{i} \times WF}{P_i} \right) \times \text{Slope} = P_i
\]

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>0-10</th>
<th>10-30</th>
<th>30-60</th>
<th>50-80</th>
<th>80-100</th>
<th>0.90 X 0.80</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.96</td>
<td>0.90</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>0.50</td>
<td>0.92</td>
<td>0.48</td>
<td>0.62</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>0.96</td>
<td>0.92</td>
<td>0.72</td>
<td>0.54</td>
<td>0.40</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>0.94</td>
<td>0.37</td>
<td>0.17</td>
<td>0.40</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>0.33</td>
<td>0.30</td>
<td>0.11</td>
<td>0.05</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

\( P_i = 0.72 \)

Figure 7. Profile of soil sufficiencies for this soil and an ideal soil.
2 represents profiles of predicted root fractions compared to that predicted in an ideal soil. The profiles of sufficiencies shown in Figure 7 can be used to identify layers that are limiting to rooting and productivity, as well as the magnitude of those limitations.

**Statistical Evaluation**

An independent data set that included an additional 14 stands located in southwestern Virginia planted with white pine between the ages of 11 to 15 was used to evaluate our SPI model. The data from these stands were obtained using the same methods as previously described. Correlation analysis was used to determine the linear relationships between productivity index (PI), site index (SI) and aboveground biomass. Site index for each stand was calculated using the procedure of Beck (1971a), tree biomass was calculated using Kinerson and Bartholomew's (1977) equation. Beck's equation is useful to determine site index in trees younger than 20 years old (Balmer and Williston, 1983). Regression analysis was used to determine the significance between PI, site index and aboveground biomass (Gale, 1991). The performance of PI was then evaluated using multiple regression techniques, testing the predictive ability of SI versus PI in determining changes in aboveground biomass. Due to the importance of age in influencing changes in biomass, the equation

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LN Y = a + b/age + c(index)

by Schumacher, (1939) to compare predictions of aboveground
biomass using the two site quality indices with age (Gale, 1991).

**Model Evaluation**

When applied to the validation data sets, a significant
proportion of the variation in the measured site index was
explained by the PI using simple linear correlation ($R^2 = 0.72$) (Figure 8). Both the productivity index (Figure 9a, $R^2 = 0.71$) and site index were significantly correlated with
aboveground biomass (Figure 9b, $R^2 = 0.90$).

The addition of PI to age was compared to the addition
of site index to age when used in a Schumacher-type equation
(Schumacher, 1939). In this study, the equation with site
index explained more of the variation in stand production
than did the equation with PI (Table 3). A problem with
multicollinearity in the equation was detected due to the
significant correlation between PI and age. Due to the
problem of multicollinearity, PI was not as closely related
to site quality as site index used in the Schumacher-type
equation.

A potential reason that PI did not predict as well as
SI is that each separate soil horizon was not sampled. The
Figure 8. Relationship between site index and productivity index for 14 sites located on reclaimed minesites in southwestern Virginia.
Figure 9. (a) Comparison of PI and biomass prediction (b) comparison of site index and biomass predictions.
Table 3. Comparison of regression equations to predict tree biomass using productivity index (PI) versus site index (SI).

<table>
<thead>
<tr>
<th>Equation</th>
<th>Adjusted $R^2$</th>
<th>$P &gt; F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNBio = 7.42 - 42.03(1/Age) + 6.86(PI)</td>
<td>0.71</td>
<td>0.000</td>
</tr>
<tr>
<td>LNBio = 5.24 - 40.26(1/Age) + 0.07(SI)</td>
<td>0.94</td>
<td>0.000</td>
</tr>
</tbody>
</table>


upper 10 cm of soil were collected and consolidated into one sample, combining the A horizon with a portion of the C1 horizon. Since each soil horizon is important to root growth, precision of the PI model may be lost when soil horizons are not sampled separately but are composited (Gale, 1987).

Within the range of site index sampled (15.2 to 37.2 m), site indices of 60, 80, 100 and 120 produced similar results for aboveground biomass as did PI’s of 0.4, 0.6, 0.8 and 1.0, respectively (Figure 10, PI’s ranged from 0.30 to 0.97).

Previous research has shown that, as a measure of site quality, the productivity index performs better in younger stands than in older (Gale, 1991). It is a better index of site quality in younger stands because it uses the effects of soil characteristics on vertical root distribution. The PI model is based on mineral soil characteristics, and is more applicable in younger stands that have not accumulated thick organic layers. As a stand matures, a litter layer accumulates, shifting the rooting habits of the tree from extracting nutrients from the mineral soil to an increased emphasis on nutrients in the forest floor (Wells and Jorgensen, 1975). This was attributed to the depletion of mineral soil nutrients with increasing stand age and the
Figure 10. Comparison of tree biomass predictions with age using either site index or productivity index.

*Site index of individual trees calculated according to Beck's (1971a) equation for polymorphic curves.
increase in available nutrients in the forest floor (Wells and Jorgensen, 1975).

A tree’s vertical root distribution will change with age and with soil properties. Coile (1937) determined that a tree’s root system will reach its maximum depth by age 10. Our developed PI model incorporates the interactions among soil properties in addition to interactions between soil properties and roots. The PI model has the potential of being applied to a wide range of forested and non-forested sites, and to sites that are too young or too old to use site index. It also allows the user to predict the influences of soil modification on root growth and subsequent productivity (Larson et al., 1983). By applying values to individual sufficiency factors that depict modified soil conditions, a different PI can be calculated and compared to that from an unmodified soil.

CONCLUSIONS

Tree vertical rooting patterns affect the aboveground productivity. The PI model integrates the genetic rooting potential of a tree and its response to varying soil and topographic conditions. Sufficiency curves are used in the PI model to describe a tree’s root response to individual soil/site properties, relating root growth responses to aboveground productivity.
The PI can be used on forested and nonforested sites, and in stands that are too young or too old for traditional site index estimations. The profiles of sufficiencies can be used to identify layers that are limiting to root growth and productivity, as well as the magnitude of those limitations. The PI model not only can be used to predict site quality, but also as a tool to make judgments regarding a decrease in yield due to harvesting practices. For example the PI approach has been used to quantify the effects of erosion on large land areas (Larson et al., 1983; Pierce et al., 1983).

The developed PI model appears to have the potential of being used as an estimator of site quality for white pine on reclaimed strip mines. PI was significantly related to site index and biomass. Using a Schumacher equation to test the effect of the index added to age, SI predicted better than PI. This was a result of multicollinearity between age and PI. Although the sample size for this analysis was small, these reclaimed minesites represent a wide range of site qualities and soil characteristics. The high degree of accuracy of prediction of white pine site index and tree biomass confirms the efficacy of applying this model to reclaimed minesites.
LITERATURE CITED


VITA

The author was born in Detroit, Michigan in 1964. He completed his B.S. degree in Forestry at Michigan Technological University in 1989. He then attended Virginia Polytechnic Institute and State University and earned a Master of Science degree in Forestry in 1992. He currently is enrolled at Michigan Technological University pursuing his Doctorate in Forest Science.

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