MEASURING MINE SOIL PRODUCTIVITY FOR FORESTS[1]

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Abstract: The Surface Mining Control and Reclamation Act (SMCRA) of 1977 requires that mine operators reclaim mined land to achieve crop productivity levels equal to or greater than premined conditions. The standard for evaluating reforestation success is based solely on tree-seedling survival; however, survival is an estimator of stand density and not an indication of site productivity. The purpose of this study was to develop a model for estimating mine soil productivity based on the capability of growing merchantable timber. 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. 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. A productivity model was developed based on the premise that limiting soil and site characteristics affect a species' optimum root distribution and thus its aboveground productivity. The developed 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 model was significantly correlated with aboveground biomass and site index. Similar results were observed when predicted productivity estimates and site index values were added separately into established biomass equations.

Additional Key Words: reforestation, forest productivity, productivity models, forest site quality.

An Argument for Restoring Forests on Mined Land

Forest land as a designated postmining land use is gaining in popularity with coal operators in Virginia, Kentucky, and West Virginia. In Virginia, the Division of Mine Land Reclamation estimates that 80% to 85% of all reclaimed land is in a forest land use. Although hayland/pasture has been the predominant postmining land use in Kentucky, the Division of Field Services of the Kentucky Department of Surface Mining reports that reclamation efforts have been steadily shifting toward the use of trees. Hayland/pasture (like industrial and residential uses) is considered a higher-order land use than forestry; thus, conversion from premining forested conditions to these higher-order land uses is allowable under the provisions of Public Law 95-87 (U.S. Department of the Interior, Office of Surface Mining Reclamation and Enforcement 1988), and is desirable to a degree, in order to diversify the economic base of localities (Zipper 1986).

However, most of the hayland/pastureland created as a result of mining is going unused for its intended purpose because it is often in remote areas, is unfenced, and is often too steep to traverse with agricultural equipment. Areas 5 years of age and older are succeeding to mostly low-value pioneering woody vegetation, while other areas are experiencing vegetation dieback due to inadequate maintenance of mine soil fertility levels required by these domesticated grasses and legumes. Consequently, coal mine operators are realizing that maintenance and repair costs of hayland/pastureland offset the initially lower cost of establishing pastures instead of trees. There is also an increasing concern in the coal industry about the difficulty of demonstrating the productivity of

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hayland/pastureland in order to obtain bond release.

Another reason for this shift toward tree crops is landowner interest. Economic analyses are showing that investments in wood production have greater potential than those in forage production (Zipper 1986, Torbert and Burger 1993). The States of the Appalachian coal belt (Pennsylvania, West Virginia, Virginia, Kentucky, Tennessee, Alabama), particularly the portions that are mined for coal, are already heavily forested. Forestry and forest products are major contributors to the economic base of these States. Added-value analyses for Virginia show that the forest industry is the single most important industry in the State, employing at least 150,000 workers (Hall et al. 1987).

Importance of Productive Mine Soils for Forests

Forestry-based economies are dependent upon production and utilization procedures that are very much analogous to those used in agriculture. Forest trees are a cash crop like corn and soybeans; the only difference is the length of the production period. And like agricultural crops, the production of tree crops varies greatly with climate, soil conditions, and cultural practices. Foresters, like agronomists, are continually striving to improve genotypes and planting stock, and to improve soil conditions and fertility to maximize crop production. And landowners, whether they are growing tree crops or agricultural crops, measure their success (and livelihood) based on the tons of saleable plant products (wood fiber or grain) produced per unit land area.

Although reclamation to original land productivity levels is the intent of the law (Public Law 95-87, the Surface Mining Control and Reclamation Act), this intent is not reflected in current regulations. To reclaim surface mines to "unmanaged forest," regulations require only that a diverse assortment of tree species exceeding 30 cm in height at densities greater than 1,000 stems per hectare be established 5 years after initial planting. No productivity standard is required. A productivity standard for wood production that is based on tree survival and a 30-cm size standard, with no evidence of the ability of the reclaimed site to produce a saleable product, is not reasonable. As is the case for other crops, reclamation standards for forests should be based on the site's potential to produce, and not based only on tree survival.

Different reclamation approaches can result in a wide range of forest site productivity. Across 36 reclaimed sites in Virginia, all of which had 10-year-old white pines, Torbert et al. (1988a) found site index (a measure of forest site quality based on predicted heights of trees at age 50) ranging from 35 to 110 ft. Assuming these stands are harvested at age 35, a white pine stand growing on an area with a site index of 110 will yield over 10 times the volume of wood as a stand growing on an area with a site index of 35. Furthermore, the timber quality on the better site will be greater, since a larger proportion of the harvested wood will be in the high-value sawtimber category, as opposed to the low-value pulpwood or intermediate-value small sawlog categories. Thus, a harvest from the site-index-110 stand may yield 20 to 30 times more money than a harvest from the site-index-35 forest. These drastically different levels of productivity that result on reclaimed mine soils demonstrate the need to be able to estimate productivity and to determine which mine soil properties must be controlled during reclamation to produce high-quality forest land.

Although numerous studies have evaluated tree growth on mine soils (Brenner et al. 1984, Ashby et al. 1980, 1982), very few studies have attempted to "predict" tree growth or SI from mine soil or topographic variables. Considering that one of the intentions of Public Law 95-87 is to ensure that mined land is returned to its premining level of productivity, it is necessary that the relationships between mine soil properties and forest productivity be developed and understood by coal operators, regulatory personnel, and landowners.

Research Approach

To develop an estimator of mine soil productivity, a data base for young white pine (*Pinus strobus*) was used that contained both soil/site and growth information. Seventy-eight plots (ranging from 0.02 to 0.04 ha in size) from 14 reclaimed surface mines in Virginia and West Virginia were used in this study.

White pine growth information was obtained at the end of the 1990 and 1991 growing seasons. Internode distances, total height, and ground line diameter were measured on all white pine. This information was used to derive four growth measures: total height at age 5, 2- and 3-year terminal growth, and a free-to-grow point. Two- and three-year terminal growth refers to the final 2 and 3 years of growth up to age 5. The free-to-grow point was defined as the average annual growth rate that occurred after the year that height exceeded the average of the two previous years by 100%.

Percent slope was measured on all plots. A soil pit (1 m^3) was located in the center of each plot at the base of a representative tree that exhibited no signs of suppression or damage. Subsurface soil samples were collected to determine effective rooting depth. Soil depth was measured as the depth to solid rock or to a traffic pan. Mineral soil samples were collected from each of the delineated horizons down to a depth of 1 m. Bulk density was determined for each of the subsurface horizons using the clod method (Blake 1965).

Two soil sampling points were randomly located on the plot to obtain surface soil samples (0 to 10 cm). At each of these locations surface bulk density was measured using the excavation method described by Blake (1965).

Soil samples were returned to the laboratory, air-dried to a constant moisture content, sieved using a 2-mm screen to separate coarse fragments, and analyzed for percent sand, silt, and clay using the hydrometer method. Soil pH was determined using 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). Phosphorus was extracted with $NaHCO_3$ (Olsen and Dean 1982) and determined using a Jarrell-Ash plasma emission spectrometer.

An independent data set that included 14 sites on 7 reclaimed mines located in southwestern Virginia planted with white pine between the ages of 11 and 15 was used to validate the developed mine soil productivity estimator called productivity index (PI). Correlation analysis was used to determine the linear relationships between PI, SI, and aboveground biomass. Site index for individual trees was calculated using Beck's equation (1971a) for polymorphic curves, and biomass was calculated using Kinerson and Bartholomew's biomass equation (1977). Beck's intercept equation is useful to determine SI in stands younger than 20 years old (Balmer and Williston, 1983). Regression analysis was used to determine the significance between PI, SI, and aboveground biomass (Gale et al. 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. Because of the importance of age in influencing changes in biomass, a Schumacher-type equation (Schumacher, 1939) of the form

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

was used to compare predictions of aboveground biomass using the two site quality indices with age (Gale et al. 1991).

Model Development

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

$$PI = \sum_{i=1}^{r} (A \times B \times C \times D \times E \times RI)_i. \qquad (1)$$

In equation 1, 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 is summed over r, which refers to the number of 10-cm increments within the rooting depth. The RI term is the optimum fraction of roots in a soil horizon, based on Horn's water depletion curve (1971). Each model component 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. Operationally, for each depth increment the levels of each of the measurable soil properties are assigned a sufficiency value. These values are multiplied together with the RI for the ideal soil for that depth increment. Finally, the resulting values for each depth increment are summed to give the PI for the entire rooting depth.

Gale (1987) modified this equation, using the geometric mean, which gives equal weight to proportional differences in factor ratings and not to absolute differences. She also modified the equation to include percent slope and climate. Following is the form of her equation:

$$PI = \sum_{i=1}^{r} ([A \times B \times C \times D]_i^{1/4} \times WF) \times [SI \times CI]^{1/2}, \tag{2}$$

where A was the sufficiency of potential available water, B the sufficiency of aeration, C the sufficiency of bulk density, D the sufficiency of pH, SI the sufficiency of percent slope, and CI the sufficiency of climate. The weighting factor (WF) was based on a curve developed by Gale and Grigal (1987) for midtolerant species.

We modified Gale's equation (1987), retaining the basic form but eliminating her sufficiencies for climate, aeration, and percent available water content, while adding sufficiencies for electrical conductivity and phosphorus. Our equation follows:

$$PI = \sum_{i=1}^{r} ([pH \times EC \times P \times BD]^{1/4} \times WF)_i \times [SI], \tag{3}$$

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 SI the sufficiency of percent slope.

Sufficiency Curve Development

Sufficiency curves, normalized between 0 and 1, were developed for each soil and site variable using information from either this study or previous sufficiency curves developed by Neill (1979), Pierce et al. (1983), and Gale (1987). The productivity index (PI) 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. Specifics on the derivation of these curves can be found in the work by Andrews (1992).

Model Evaluation

A significant proportion of the variation in site index (SI) was explained by PI using simple linear correlation (R^2 = 0.72) (fig. 1). Both the PI (fig. 2a, R^2 = 0.71) and SI were significantly correlated with aboveground biomass (fig. 2b, R^2 = 0.90).

The addition of PI to age was compared with the addition of SI to age when used in a Schumacher-type equation (Schumacher 1939). In this study, equations with SI explained more of the variation in stand production than did equations with PI (table 1). A problem with multicollinearity in the equation was detected due to the significant correlation between PI and age. Because of the problem of multicollinearity, PI was not as good a predictor of site quality as SI used in the Schumacher-type equation. Another potential problem with PI is neglecting to sample each separate soil 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 SI sampled (50 to 122 ft), SI's 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 (fig, 3; PI's ranged from 0.30 to 0.97).

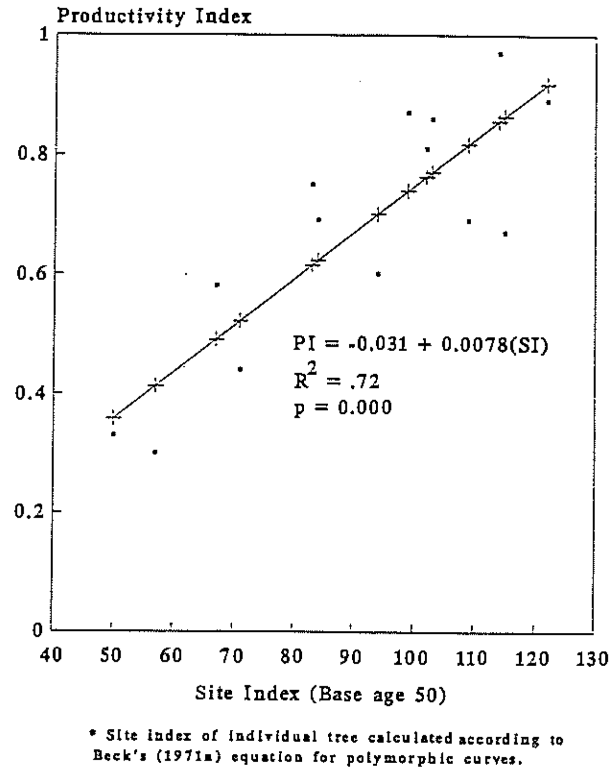

Figure 1. Relationship between site index (SI) and productivity index (PI) for 14 sites located in southwest Virginia.

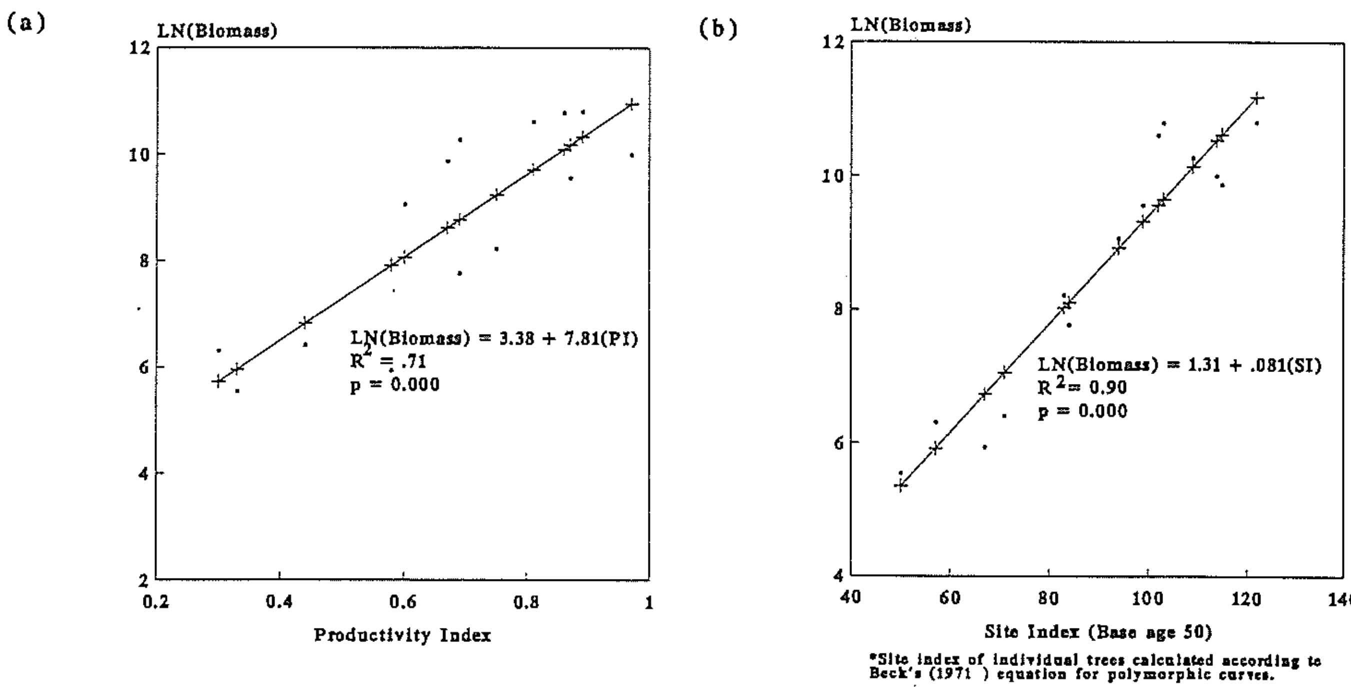

Figure 2. (a) Comparison of productivity index (PI) and biomass prediction; (b) comparison of site index (SI) and biomass predictions.

Table 1. Comparison of regression equations to predict tree biomass using productivity index (PI) versus site index (SI).

Equation	Adjusted R^2	P > F
LNBio = 7.42 - 42.03 (1/Age) + 6.86 (PI)	0.71	0.001
LNBio = 5.24 - 40.26 (1/Age) + 0.07 (SI)	0.94	0.001

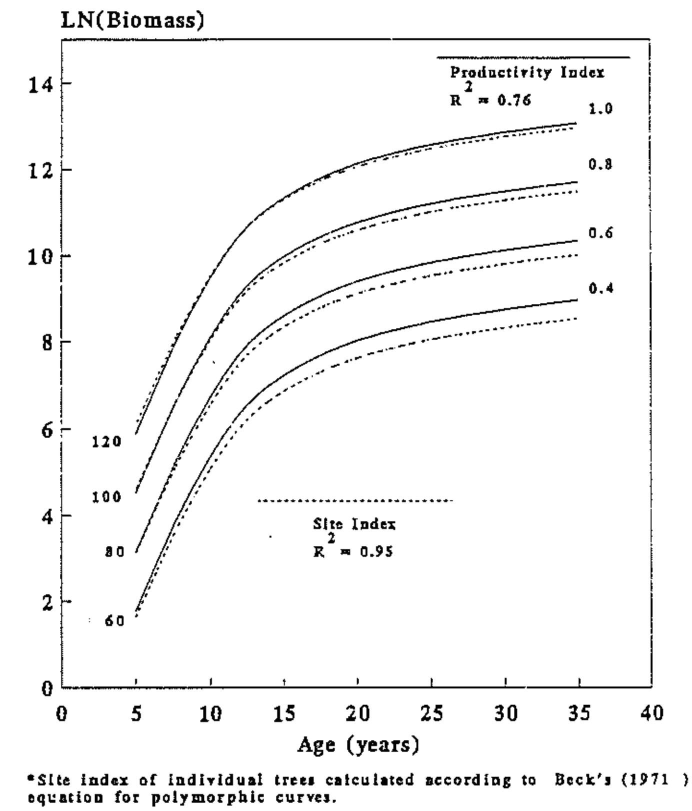

Figure 3. Comparison of tree biomass predictions with age, using either site index (SI) or productivity index (PI).

Assessing the accuracy of PI using SI lends uncertainty to the results. Problems with SI have frequently been reported in the literature (Monserud et al. 1990). However, the results of this model assessment indicate that PI can predict site quality with an acceptable accuracy.

Previous research has shown that as a measure of site quality the PI performs better in younger stands than in older (Gale et al. 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 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 (1935) 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 nonforested sites and in sites that are too young or old to use SI. 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 with 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 SI 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 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 SI 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 SI and tree biomass indicates that there is a practical application for applying this model on reclaimed minesites.

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