THE USE OF PRODUCTIVITY INDEX TO PREDICT CORN YIELDS ON RESTORED PRIME FARMLAND[1]

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Abstract: A 4-year study was conducted to determine if corn yields could be predicted from a productivity index (PI) derived from physical and chemical properties of soil, including bulk density, cone penetrometer resistance, water-holding capacity, texture, pH, and other soil fertility factors. In our studies, correlation coefficients (r) between PI and yield varied from near 0 to 0.76 from one field or mining method to another. Such a wide range in values of r may be largely attributed to sampling variation over a short distance, whereas corn plants can explore a larger volume of soil thus compensating for poor physical conditions that by chance was collected to represent sampling points within a field. The site from which the highest r value was obtained had been planted to soybeans prior to planting corn. This area did not have the lowest bulk density nor did it have the highest corn yield, but it was the treatment that the model most nearly predicted the yield of corn. Bulk densities varied over time and in general decreased, but the correlation with corn yield also decreased. Corn yields may be achieved (i.e., target levels for bond release) even though PI values may indicate remedial treatments were necessary.

Introduction

The idea of using a productivity index (PI) to predict yield of crops is not new. In recent years, interests have been generated to test this concept of restored prime farmland following surface mining. An index based on the physical and chemical properties of reclaimed land would be useful to both the mining industry and regulatory officials as it could be used to predict the release of Phase III bond soon after Phase I requirements have been met. Phase III bond release is primarily contingent on demonstrating that crop yields have met standards for 3 years. As an evaluation criterion, crop yield is not only dependent on the quality of soil reconstruction, but also on weather conditions and on several options that can be classified under "management practices."

Therefore, it has been proposed here that a productivity index might

1) More accurately evaluate the adequacy of soil reconstruction, and
2) Provide a mechanism that could potentially allow bond release by the fifth year after Phase I bond release, provided adequate ground cover has been established, and reclamation standards other than yield have been met.

If a PI approach could accurately predict crop yields, then coal companies could "prove" that the productivity was returned, without actually growing the crops. On the other hand, if it indicated restoration would not likely be successful, remedial action to correct the problems could be taken earlier in the reclamation process. For "intermediate" situations, the company could either take a chance that Phase III bond will be achieved or "restart the clock" which results when remedial actions are taken. If Phase III bond is not met for these intermediate situations, remedial work such as deep ripping may be required, then bond release will be delayed.

The basic model from which we started was that of Wollenhaupt (1985). Various parameters of the original model were evaluated as well as unmodelled factors. This included topsoil and subsoil fertility (P and K), soil acidity (exchangeable Al), and cone penetrometer resistance. In their selection, consideration was given to incorporating the

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fewest number of parameters that are not only predictive of root growth, but would not become cost-prohibitive to the users of model.

The model is being tested for soil profiles and corresponding yields taken from data obtained on the River Queen Mine in Muhlenberg County in western Kentucky. Several additional sites were evaluated in other areas of Kentucky and Indiana, but due to manuscript length restrictions, these data will not be reported here.

Literature Review

Productivity Indices

Over the past 60 years in the United States, a variety of quantitative expressions have been proposed to compute a soil productivity index from soil characteristics. Indices have been developed in response to specific needs in agricultural land use planning and in the equalization of land values and tax assessments (Huddleston 1984).

In 1979, Neill proposed an index such that yield was assumed to be a function of root growth, which in turn, was a function of soil environment (fig. 1). Her model was designed to evaluated soil horizons within soil profiles in terms of their potential available water storage capacities, aeration, bulk densities, pH's, and electrical conductivity's and the sufficiency level of each horizon to promote root development. The product of these five sufficiency factors was then multiplied by a depth-dependent root weighting factor for each horizon based on an ideal corn root development model. The sum of these products over a given soil profile was defined as the productivity index.

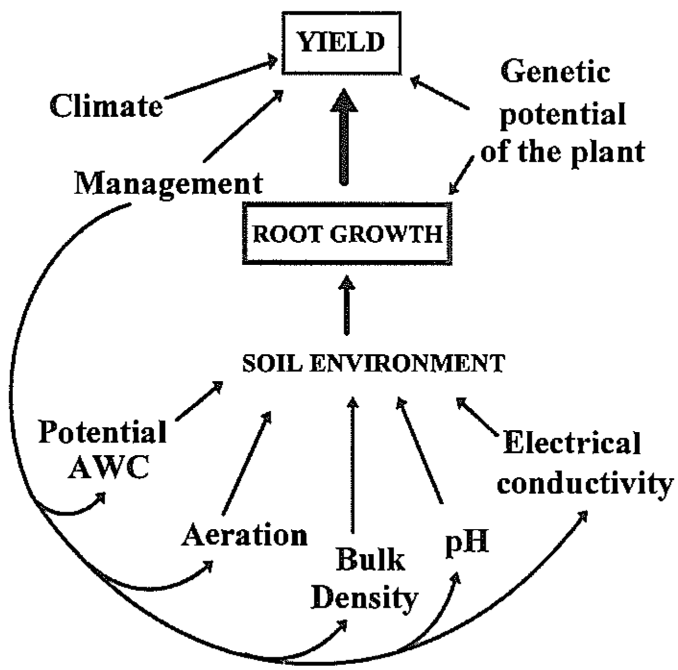

Figure 1. Conceptual PI model after Kiniry et al. (1983)

Pearce et al. (1983) built from the concept proposed by Neill (1979) and streamlined it to consider only three major soil characteristics: bulk density, available water, and pH. Bulk density sufficiency was redefined to reflect various soil texture classes. While Neill assumed an ideal rooting depth for corn of 200 cm, Pearce et al. (1983) used a critical soil rooting depth of 100 cm. Both models assumed that nutrients are not limiting to plant growth.

In 1985, Wollenhaupt made further refinements and made adjustments to the sufficiency equations. He normalized the root distribution curve between the upper and lower horizon boundaries, solved the integral for centimeter increments, and found that relationship approached a power function.

Soil Factors Introduced in This Study

The soil characteristics of P and K concentrations, total acidity, and cone penetrometer resistance were introduced as sufficiency factors in the model developed herein because these factors may vary independently from physical properties, and thus we did not assume they have an index of 1. Subsoil fertility was considered essential to adequate root growth and beyond the control of surface management techniques. The model allows cone penetrometer data to be used as a substitute of bulk density.

Total acidity, especially exchangeable Al, of the subsoil has been demonstrated to be a significant factor that can potentially impair crop yields (McKenzie and Nyborg 1984). Acidity can be a consideration in soils and overburden materials associated with coal surface mining in the Midwest. Another parameter we are considering in place of, or along with exchangeable Al is pH measured in a 1:1 M KCl to soil suspension. In Wollenhaupt's 1985 model, the pH was measured in dilute $CaCl_2$ (Hoyt and Nyborg 1972) or it was estimated from the pH measured in water by subtracting a constant (0.5).

Newly constructed prime farmland soils commonly exhibit excessive soil strength and an absence of continuous macropore networks. Consequently, root growth is often severely inhibited because provisions for water movement, aeration, and root system extension are lacking (Hooks and Jansen 1986).

Data presented by Thompson et al. (1987) from three mine soils, indicate that within each soil horizon, as cone penetrometer resistance increases, average root density decreases. This was a significantly (negative) correlation between the average root length density of the 67-88 cm and 89-110 cm depth segments to the cone penetrometer resistance over the 23-110 cm depth averaged across soil treatments. This effect appears to be most profoundly noted for soils at the Captain Mine in Perry County, Illinois on fields where soil reconstruction was achieved using the mining wheel-conveyor spreader system.

Methods

Soil Sampling

A tractor-mounted Giddings coring machine was used to collect soil samples from various field locations. In general, two samples, approximately 1-foot apart, were taken at each location; all cores were at least 30 in. (76 cm) in length. One core was used to independently evaluate bulk density; the other core was used for other physical and chemical properties. In general, sampling locations were on a 50- by 50-ft (15.2- by 15.2-m) grid. The number of sampling sites per field varied, but always exceeded 25 within an individual data set.

Cone penetrometer resistance was introduced into the PI model as an alternative to bulk density. Since bulk density or cone penetrometer data may not always be available, a working relationship between the two measurements was proposed to increase the application of the PI model to a wider set of conditions. Bulk density data may be obtained over a wider range of soil moisture conditions, whereas cone penetrometer resistance data are most accurate when the moisture is near field capacity. Both penetrometer resistance and bulk density have been demonstrated as adequate predictors of root system performance, especially in the deeper regions of the root zone (Thompson et al. 1987).

Soil Testing

Soil tests for available plant nutrients were performed by the Department of Agronomy and the Soil Testing Laboratory of the University of Kentucky. Bulk density was determined using a procedure modified from the core method described by Blake and Hartge (1986). Water and KCl salt pH's were determined using a glass electrode (Van Lierop 1990, Eckert 1988, and the Council on Soil Testing and Plant Analysis 1980). Exchangeable Al was determined employing the titration method of Yuan (1959). Available P and K were determined by the Mehlich III extraction (Tucker 1988a, Tucker 1988b). Sufficiencies for P and K were based on data and recommendations of Semalulu 1992, and University of Kentucky's AGR-1 Lime and Fertilizer Recommendations 1990.

Percent sand, silt, and clay were determined by the pipette method of Gee and Bauder (1986). In the PI model, texture is used in a subroutine to "weight" the contribution of each particular depth increment. It also was used with bulk density to calculate hydraulic conductivity. Water-holding capacity was determined using a standard method developed by Klute (1986). Water-holding capacities were calculated from moisture values obtained at field capacity and wilting point.

A continuous-recording cone penetrometer was used on a tractor-mounted Giddings coring machine at a constant rate of 2.9 cm/s. A 30^o right-circular cone, 6.45 cm^2 (1 in^2) in cross-sectional area, was employed after the methods of Hooks and Jansen (1986). Measurements were recorded on a system developed in Illinois, similar to that described by Hooks et al. (1993). Replicated measurements at each sample location were taken. Areas under the recorded curves were integrated as representative of pounds per square inch of resistance.

Experimental Sites

Several sites have been used to collect data for the PI model. We chose sites to represent soils reclaimed with scraper pans and/or end-dump trucks. These sites also had a range of reclamation practices, including different soil depths, soil chemical and physical properties, time following soil replacement, ripped versus nonripped, cropping sequence or crop rotation, and test crops. However, since corn is required as one of the test crops in Midwestern States, corn yield measurements may have been separated in time, and perhaps space, for some of these locations.

PI Model Development

The PI model tested is a sum of products. Each soil test value is assigned a sufficiency factor ranging between 0.1[3] and 1.0, which indicates adequacy to promote root growth. The product of these sufficiencies for each soil layer in a profile is multiplied by a root weighting factor, which is a function of soil depth. The PI for a single soil profile is the sum of the PI's for the soil layers that make up that profile. Conceptually, the model is depicted in fig. 2.

The equation for the conceptual model is

$$PI = \sum_{i=1}^{i=n} [BD_i \cdot AWC_i \cdot pH_i \cdot EC_i \cdot P_i \cdot K_i \cdot EA_i \cdot CPR_i \cdot WF_i],$$

where

- n = number of layers in the soil profile,
- BD_i = bulk density sufficiency for the ith soil layer,
- AWC_i = available water holding capacity sufficiency for the ith soil layer,
- EC_i = electrical conductivity sufficiency for the ith soil layer,
- P_i = phosphorus sufficiency for the ith soil layer,
- K_i = potassium sufficiency for the ith soil layer,
- EA_i = exchangeable aluminum sufficiency for the ith soil layer,
- CPR_i = cone penetrometer resistance sufficiency for the ith soil layer,
- WF_i = root weighting factor for the ith soil layer.

Sufficiency equations[4] developed by previous workers were adopted for: bulk density (Wollenhaupt, 1985), available water (Kiniry et al. 1983, Wollenhaupt 1985), pH (Pearce et al. 1983, Wollenhaupt 1985), and electrical conductivity (Kiniry et al. 1983, Wollenhaupt 1985). For this application, electrical conductivity and hydraulic

[3] Since the model is still undergoing refinement, the lower limit has not been fixer at this time. It is likely to reside between 0 and 0.1.

[4] These equations are imbedded into the computer program and affect the final PI value as various limits are meet. This program is being developed using a spreadsheet format. Copies should be available after the paper is given orally by writing the senior author.

conductivity (in relation to its effect on bulk density sufficiencies as calculated in the model) were assumed to be nonlimiting in their effect on root growth. The above model should be considered as a "working model"; some changes have occurred since we first introduced it (Barnhisel et al., 1992). The rationales for changes in the various equations that are used in the subroutines of the working model are presented there. The model is likely to be revised further when the remaining soil samples have been processed.

Results and Discussions

Productivity indices generated by the model were tested for their predictive capability by determining their correlation coefficients with corn yield at both the 5% and 10 % confidence limits. Erratic results have been obtained for such correlations. For some sites, medium to high r values have been obtained, whereas for other sites, r is essentially 0. Data will be presented from only two of the sites used for model verification, one in which poor results were obtained and one in which some treatments gave very good results.

A relatively large data set has been analyzed for the "Prime-on-the-Gob" site on the River Queen Mine. At this site, 30 locations for samplings of all parameters were established in a 5 by 6 matrix with 50-ft (15.25-m) a spacing between rows. Two approaches have been used, one using bulk density data, the other using cone penetrometer values. Calculated PI values and the corresponding corn yield for both approaches are given in table 1. In general, the overall size of the PI value was higher when the bulk density was used in the model than when cone penetrometer data was used. Correlation coefficients between the PI's computed using both bulk density and cone penetrometer data with their respective yield for this data set have been very disappointing and were 0.05 and 0.06, respectively. These poor correlations occurred even though there was a relatively wide range in yields and PI values occurred. It is likely that improvements in the ability of the model to predict the PI when cone penetrometer data are used PI can be made by incorporating changes in the sufficiency component of the equation, but at the present time, rational for making such changes has not been developed.

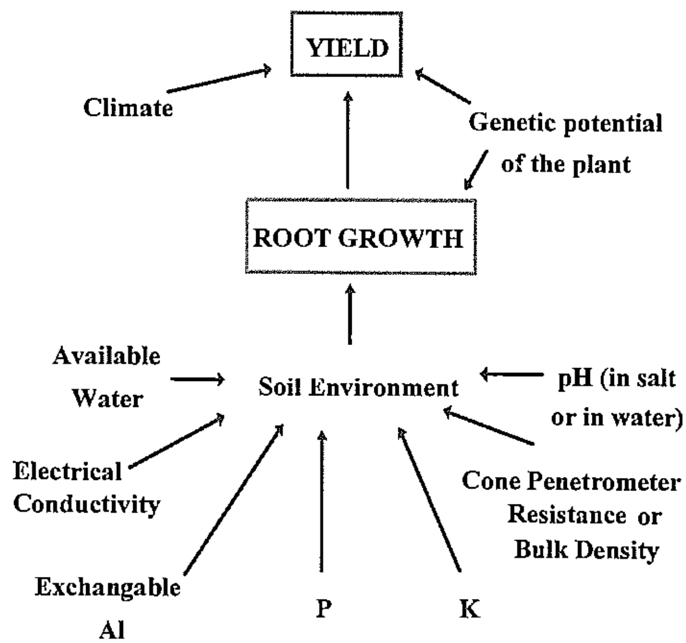

Figure 2. Revised conceptual model after Barnhisel et al. 1993.

At a second location on the River Queen Mine, PI values were calculated using only the model with the bulk density term for four cropping and compaction removal treatments. At this site, strips of 100 ft (30.5 m) wide by 450 ft (137 m) were initially established in various crops, including soybeans, corn, black locust, and alfalfa. In addition, each strip was divided into four blocks that were ripped under three moisture conditions with one of these subplots being a nonripped control. After two years of the initial crops, the entire area was planted to corn. Correlation coefficients between corn yields from these plots and PI ranged from 0.06 to 0.76, and these data are shown in table 2.

The r values between corn yield and PI were highly correlated for plots that had been previously planted to soybeans, intermediate for black locust and alfalfa, and poor, if any, correlation between corn yield and PI for the plots that had been planted to continuous corn through 1989. The PI data given in table 2 were calculated for two sets of bulk density measurements, one taken in 1984 at the beginning of this study and the one in 1991. In all cases except for the continuous corn plots, the correlation coefficients decreased when PI was regressed against the 1991 bulk density data. The corn yields regressed against the two PI's were collected in 1987 midway between the times the bulk density data were collected. Weather can affect corn yields from one year to the next. However, correlations between corn yields made in 1988 versus the two PI data sets, corresponding to bulk densities collected in 1984 and 1991, had about the same range 0.07 to 0.79 (data not shown).

Table 1. River Queen Prime-on-the Gob corn yield and their respective PI's using cone penetrometer versus bulk density data.

Corn Yield, bu/a	Soil PI[5]	Soil PI[6]
108	0.557	0.653
116	0 223	0.346
118	0.258	0.375
120	0.192	0.422
128	0.427	0.530
131	0.466	0.630
132	0.475	0.672
134	0.233	0.573
138	0.279	0.550
140	0.230	0.544
140	0.300	0.476
145	0.247	0.373
147	0.411	0.532
150	0.233	0.567
150	0.222	0.458
151	0.398	0.543
152	0.189	0.352
153	0.243	0.437
154	0.269	0.439
156	0.446	0.465
160	0.235	0.462
162	0.235	0.362
165	0.278	0.499
168	0.480	0.568
170	0.237	0.396
170	0.409	0.495
180	0.324	0.446
Mean 146	0.305	0.488

[5] PI computed using the modified model and cone penetrometer data.

[6] PI computed using the modified model and bulk density data.

Table 2. Correlation coefficients (r) between PI and corn yield, River Queen Mine—Coleman Area.

	Initial crop			
Year[7]	Soybean	Corn	Alfalfa	Black Locust
1984	0.76	0.06	0.50	0.59
1991	0.70	0.14	0.13	0.31

[7] Year in which bulk density measurements were made.

It may not be much of a surprise that plots having been in continuous corn had the lowest correlation between PI and yield, but there were areas within these plots that also had good yields (data not shown). The predictive capability of the model increased, especially when the 1984 bulk density data were used, and when a legume had been grown the first 2 years.

For some unknown reason(s), the model based on the 1991 bulk density values had much lower r values, especially for alfalfa, as compared with the r value based on the 1984 bulk density. This poorer correlation was in spite of a slight decrease in the overall bulk density between the two years. A relatively small change in the negative direction occurred for soybeans.

Conclusions

Although some of the PI measurements were highly correlated with corn yields at the River Queen—Coleman site, it was poorly correlated at the other site on this same mine ("Prime-on-the Gob"). Even for the Coleman site, correlations between corn yield and PI ranged from 0.06 to 0.79 depending on the the cropping sequence, year the corn yield was collected, and the year the bulk density was measured.

We are hopeful that by adjusting the components within the PI equation, better and consistent correlations can be obtained. If this is not possible, then using PI to determine if Phase III bond release criteria for the return of the surface-mined land to it's original productivity have been meet by measuring soil properties will not be recommended. This is in spite of having met these yield criteria by actually growing various crops at all locations tested.

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