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A Soil Productivity Index Based Upon Predicted Water Depletion and Root Growth

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The relationships between soil properties and soil productivities have been a concern of soil science for centuries. Simonson (1962) credits the Chinese with using a type of productivity index 40 centuries ago. Methods for quantifying the relationships have varied. The objective of this study was to formulate a method that would rely upon data relating root growth to soil properties. The conceptual model is shown in Figure 1.

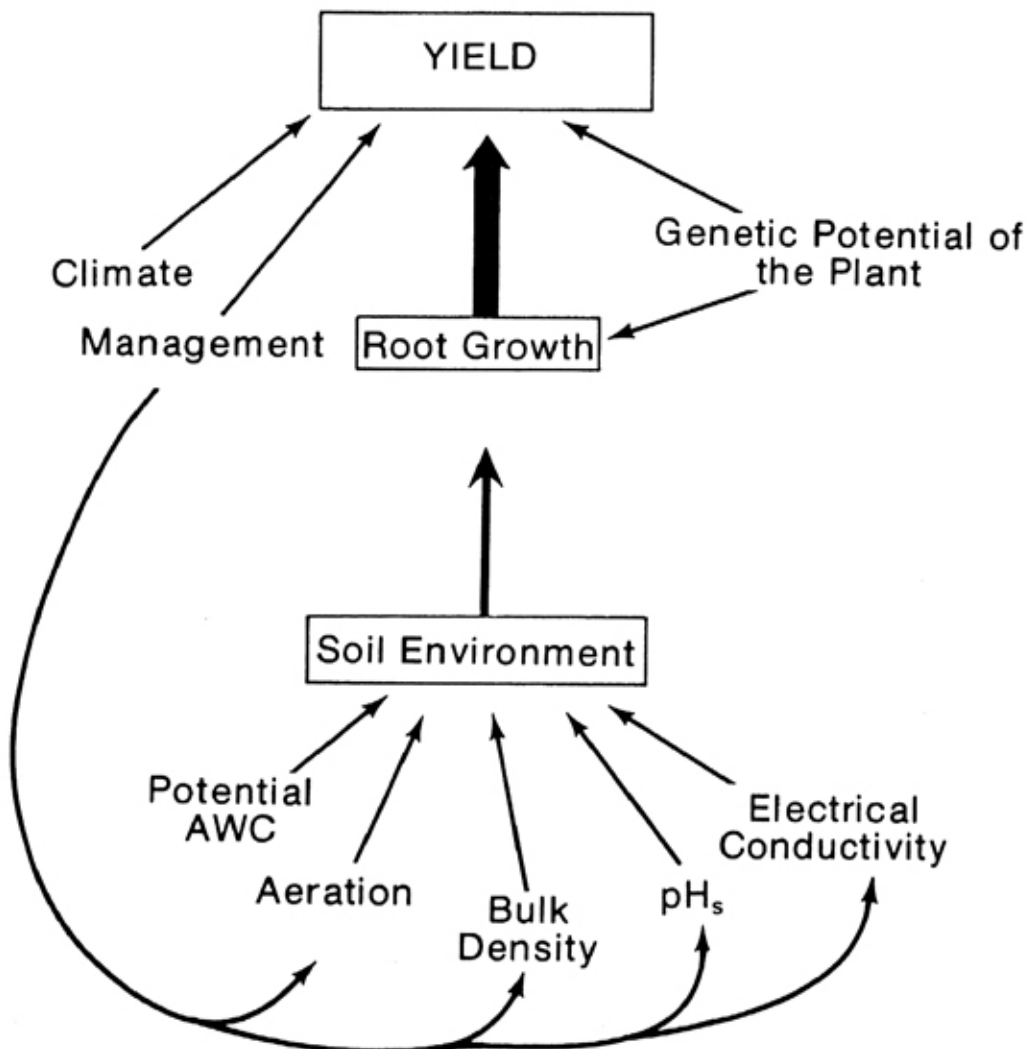


Fig. 1. Conceptual model for the study.

Yield is assumed to be a function of root growth which is, in turn, a function of the soil environment. Other yield parameters such as climate, genetic potential of the plant and levels of management were considered to be describable in terms of yield response. Thus they could be combined with the soil parameters in a more complete prediction of yield.

This study was aimed at describing the soil environment in terms of the soil's sufficiency for root growth as related to five soil parameters—potential available water storage capacity, aeration, bulk density, pH and electrical conductivity. The authors were encouraged by Pearson's (1966) summary of root responses to soil environmental parameters and have used his approach of describing each root response function in terms of relative root growth (sufficiency values of 0 to 1.0). Selected root response functions, presented here, constitute the authors' best estimates made from existing literature. Each function remains researchable. The conceptual model and method of arriving at the predicted profile of rooting are thought to be the most important contribution of this study.

Each of the five root response functions describes the fractional sufficiency (values of 0.0 to 1.0) for values of one soil parameter. The product of all five sufficiencies was considered to describe the fractional sufficiency of any soil layer for root growth. This approach, which permits any one parameter to be limiting, was similar to that taken by Storie (1933) who related productivity to soil properties. The approach presented here differs from that of Storie in that the authors attempt to describe root growth first and then relate it to productivity.

The first activity was to estimate the profile of root fractions that would exist under ideal soil conditions (RI). That ideal profile was then limited by multiplying RI by the products of the five fractional sufficiencies for each depth increment within the soil. This approach predicted the profile of root fractions for a given soil relative to the ideal soil. The sum of predicted root fractions (values between 0 and 1.0) was taken as the productivity index.

Methods

The four parts of the study were: (1) estimation of root distribution under ideal soil conditions; (2) establishment of response curves relating root growth to soil properties; (3) formulation of a productivity index from parts one and two; and (4) farm-field plot studies for regression analyses of yields of maize vs productivity index.

Estimation of Root Distribution in Ideal Soils

Estimation of root distribution in ideal conditions was made from water depletion studies by Horn (1971) who monitored the profile of water in a Menfro soil (Typic Hapludalf, fine-silty, mixed, mesic) under a canopy of maple trees (*Acer saccharum*). Horn described the profile of water use in

terms of fractional depletion of the available water storage capacity where the upper limit was that volume of water observed in the spring and the lower limit was the 15 bar volume of water. Horn's equation for predicting the profile of fractional depletions from a moist soil was:

$$L_D = 0.152 \log (R + \sqrt{R^2 + 6.45}) - 0.152 \log (D + \sqrt{D^2 + 6.45}) \quad [1]$$

where L_D was the fractional depletion for a given depth; D was the depth in the profile and R was the rooting depth.

Horn's equation describes an inverse hyperbolic sine curve and it described the profile of fractional depletion with a correlation coefficient of 0.90. The authors assumed that the profile of fractional depletions reflects the profile of root distribution in soils which, like the Menfro, lack water tables. The rooting depth at the Horn site was 356 cm. Although no variable rooting depths were studied, it was assumed that Horn's equation can be used to predict root profiles in other ideal soils if the plant-determined rooting depth R is known for that particular plant canopy.

Evidence for the validity of the above assumption is provided by the studies of Böhm *et al.* (1977) and Sivakumar *et al.* (1977) who determined soybean root distribution in Ida soils—fine, silty, mixed (calcareous), mesic Typic Udorthents—which are soils with profiles having no physical or chemical barriers to root growth. Horn's equation very closely predicts root distribution between 25 June and 8 July if R is taken as that depth containing 99 percent of the total roots. It does not predict the root distribution found by Böhm *et al.* (1977) and Sivakumar *et al.* (1977) during mid-July and August when upper layers were partially depleted of water.

Profiles of root fractions were predicted by integrating Horn's equation over 10 cm depth increments and for various assumed values of R . Units were depleted cm of soil which were then converted to a fraction of the total. That fraction was assumed to be the fraction of roots (RI). Table 1 presents predicted values for R 's of 200 cm and 100 cm. Figure 2 shows the profiles of predicted root fractions. The predicted fraction of roots for any depth increment was greatly influenced by the value of R .

Estimation of Soil Sufficiency For Root Growth

Response curves relating root growth to soil properties were developed from studies selected on the basis of having the best measure or the best documentation of individual soil properties. The selection of only five soil parameters was a deliberate attempt to consider only the minimum set that might describe the chemical and physical nature of the rooting zone. The omission of N-P-K and micronutrients as parameters was based upon the observation that such elements are mobile within the plant system and

Table 1. Predicted soil water depletion and root fractions (RIs) for an ideal soil with plant-determined rooting depths, R, of 200 cm and 100 cm.

Depth Increment (cm)	R = 200 cm		R = 100 cm	
	Depleted cm Soil (cm)	Predicted Fraction of Roots (RI)	Depleted cm Soil (cm)	Predicted Fraction of Roots (RI)
0- 10	2.481	.190	2.023	.314
10- 20	1.717	.132	1.260	.196
20- 30	1.375	.105	.918	.143
30- 40	1.152	.088	.694	.108
40- 50	.986	.076	.528	.082
50- 60	.853	.065	.395	.061
60- 70	.742	.057	.285	.044
70- 80	.648	.050	.190	.030
80- 90	.566	.043	.108	.017
90-100	.492	.038	.034	.005
100-110	.426	.033		
110-120	.365	.028	6.435	1.000
120-130	.310	.024		
130-140	.260	.020		
140-150	.212	.016		
150-160	.168	.013		
160-170	.127	.010		
170-180	.088	.007		
180-190	.052	.004		
190-200	.017	.001		
	13.037	1.000		

most deficiencies can be corrected by either surface soil or foliar applications.

Each response curve was converted into a form that predicted the fractional sufficiency of that property for root growth with a value of 1.0 assigned to the non-limiting condition and 0.0 assigned to the totally limiting condition.

Sufficiency of Potential Available Water Storage Capacity - The assumption was that potential available water storage capacity (PAWC) of 0.20 or larger was non-limiting. The following linear equation was used to describe sufficiency of PAWC (SUFFPAW)

$$\text{SUFFPAW} = \begin{cases} 1.00 & \text{if PAWC} \geq .20 \\ \text{PAWC}/.20 & \text{if PAWC} < .20 \end{cases} \quad [2]$$

See Figure 3. Three methods were used to estimate PAWC for each soil layer: measured volume of water at planting minus 15 bar volume; $\frac{1}{3}$ - 15

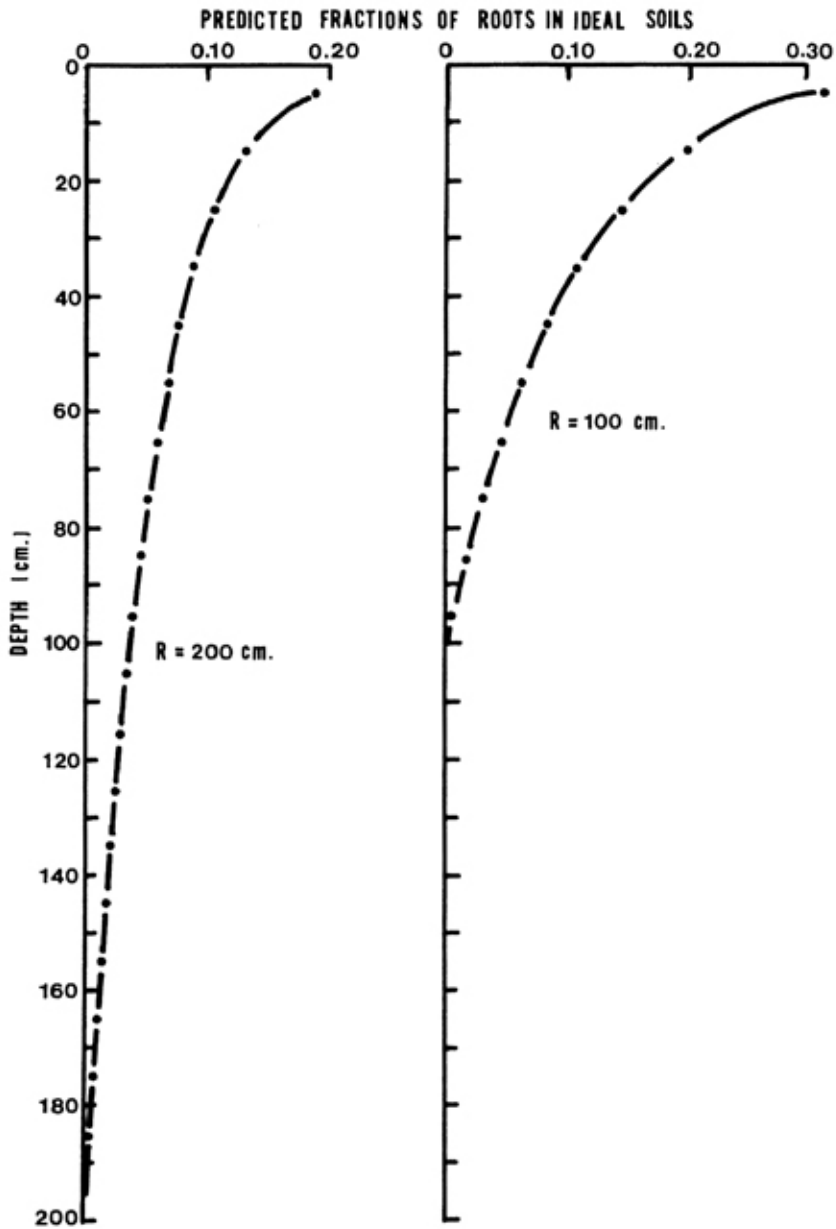


Fig. 2. Predicted profiles of root fractions in ideal soils (RI's) for plant-determined rooting depths (R) of 200 cm and 100 cm. The predicted fractions constitute a weighting factor when used to calculate the productivity index (PI).

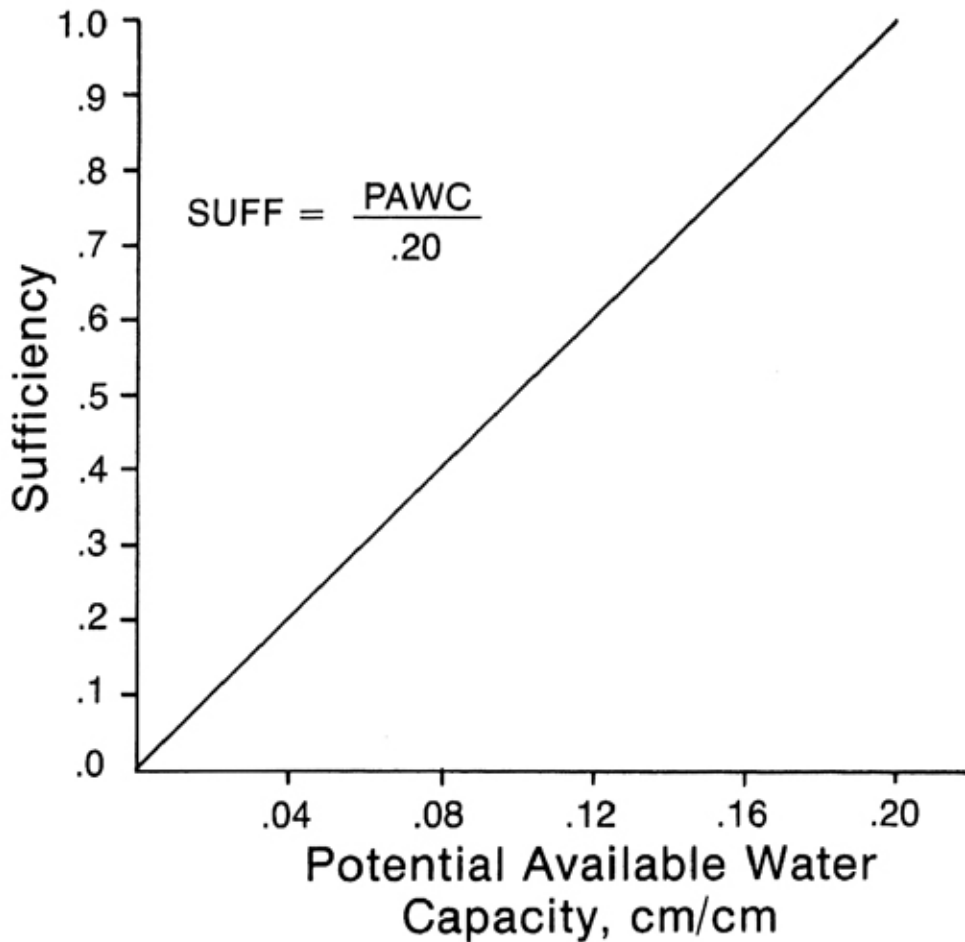


Fig. 3. Sufficiency of potential available water storage capacity (SUFFPAW) used.

bar volumes predicted from clay content; and $\frac{1}{3}$ - 15 bar volumes estimated from textural class.

A regression equation was developed from hydrometer determinations of clay fraction (CLAY) and pressure plate determinations of 15 bar water that were converted to volumes by assuming a bulk density of 1.3 g/cm^3 . The equation is

$$PV15Bar = 0.014 + 0.711 \text{ CLAY} \quad [3]$$

This equation was developed from 235 samples (one profile from each field) with CLAY ranging from 0.05 to 0.63. The r^2 was 0.88.

Table 2. Textural Potentials for Retention of Available Water

Textural Class Name	Estimated $\frac{1}{3}$ bar Vol. (cm/cm)	PAWC (cm/cm)	Sufficiency SUFFPAWC (fract.)
Coarse sand	.06	.02	.10
Medium sand	.08	.03	.15
Fine sand	.12	.06	.30
Loamy sand	.14	.07	.40
Loamy fine sand	.18	.11	.55
Sandy loam	.22	.13	.65
Fine sandy loam	.22	.13	.65
Loam	.28	.15	.75
Silt loam	.36*	.21*	1.00
Silt	.32*	.26*	1.00
Silty clay loam	.40*	.15*	.75
Sandy clay loam	.33	.13	.65
Clay loam	.38	.13	.65
Sandy clay	.40	.10	.50
Silty clay or clay (.4 - .5 clay)	.43*	.10*	.50
Silty clay or clay (.5 - .6 clay)	.46*	.06*	.30
Silty clay or clay (>.6 clay)	.47*	.04*	.20

*Estimated from equations (3, 4, 5) and taken as the median for the clay range of that textural class.

A similar regression equation was developed for $\frac{1}{3}$ bar volume of water (PV3BAR) from data of Kroth *et al.* (1960), Bohnert (1967) and Horn (1971) using measured values of bulk density.

The equation is

$$PV3BAR = 0.300 + 0.293 CLAY \quad [4]$$

This equation was developed from 185 samples with CLAY ranging from 0.5 to 0.63. The r^2 for this equation was 0.54. The first method of estimating PAWC took measured volume of water (method described later) minus PV15BAR values from equation [3]. The second estimate was obtained by subtracting equation [3] from equation [4]. This gave

$$PAWC = 0.286 - 0.418 CLAY \quad [5]$$

These equations were developed for textural classes having predominantly silt and clay. They are linear in contrast to the quadratic equations described by Petersen *et al.* (1968). Even so, they predict similar values of PAWC. The third method of estimating PAWC uses textural class. Table 2 shows estimated values and corresponding sufficiencies. Equations [3], [4], and [5] were used to estimate values for silty and clayey textural classes.

Other textural class estimates of PAWC were made from the work of Petersen *et al.* (1968), Salter *et al.* (1965) and Jamison *et al.* (1958).

Sufficiency of Aeration - Sufficiency of aeration (SUFFAER) for each soil layer was estimated from the field-determined values of air-filled porosity at planting time for that layer plus all layers above. The rationale was that diffusion of oxygen and carbon dioxide should be functions of air-filled porosity above that layer. Table 3 shows an example of the procedure as applied to the means of air-filled porosities for 14 plots on Field 21, Boone County, classified as Mollic Albaqualfs. Air-filled porosity, S , was converted to a form of relative resistance by forming the reciprocal $1/S$ and then summing relative resistances by the integral $\int 1/S dz$. Relative conductance was considered to be the reciprocal of relative resistance.

To convert the relative conductance values into sufficiencies the attempt was to arrive at a critical value for air-filled porosity, a value above which no root restriction would be observed and below which root restrictions would exist. The critical value arrived at was $S = .08$. The value has been reported to be within the range of .05 to .10 by Vomocil and Flocker (1961) and Cannell (1977). The array of values of air-filled porosities was inspected and the critical value of .08 was selected because it provided relative numbers for profiles that were related to drainage class estimates.

Sufficiency of Bulk Density - Bulk density (Db) of each soil layer was used as the parameter most closely related to mechanical impedance of root growth. Mechanical impedance is also related to soil texture, soil moisture and soil structure (Bar-Yosef and Lambert, 1981; Cannell, 1977; Towner, 1974; Pearson, 1966). Those relationships were not quantified. The works of Blanchar *et al.* (1978), Tackett and Pearson (1964) and Taylor and Gardner (1963) were used to predict sufficiency of bulk density (SUFFBD). The prediction equation was

$$\text{SUFFBD} = \begin{array}{ll} 1.00 & \text{if } Db \leq 1.30 \\ 1.88 - 0.68 Db & \text{if } 1.30 < Db \leq 1.55 \\ 5.98 - 3.32 Db & \text{if } 1.55 < Db \leq 1.80 \\ 0.00 & \text{if } Db > 1.80 \end{array} \quad [6]$$

where Db was measured bulk density in g/cm^3 . See Figure 4.

The predicted sufficiency of 1.0 for densities of 1.30 or less and the change in slope at a bulk density of 1.55 are in agreement with the findings of Tackett and Pearson (1964). The slope of the sufficiency-density curve at densities above 1.55 gm/cm^3 was derived from the work of Blanchar *et al.* (1978).

Sufficiency of pHs - Equations predicting sufficiency of pHs (SUFFPHS) were developed from the work of Adams and Lund (1966) who reported the

Table 3. Example of the Procedure for Calculating Sufficiencies of Aeration for Field 21, Boone County (means of 14 mollic Albaqualfs)

Depth (cm)	Calculated			Critical			Calc. Cond. Crit. Cond. (Suff.)
	S*	$\int_0^z \frac{1}{S} dz$ Relative Resistance	$\left[\int_0^z \frac{1}{S} dz \right]^{-1}$ Relative Conductivity	S*	$\int_0^z \frac{1}{S} dz$ Relative Resistance	$\left[\int_0^z \frac{1}{S} dz \right]^{-1}$ Relative Conductivity	
0- 10	.14	71.43	.01400	.08	125	.00800	1.00
10- 20	.13	148.35	.00674	.08	250	.00400	1.00
20- 30	.10	248.35	.00403	.08	375	.00267	1.00
30- 40	.07	391.21	.00256	.08	500	.00200	1.00
40- 50	.04	641.21	.00156	.08	625	.00160	.97
50- 60	.03	974.24	.00103	.08	750	.00133	.77
60- 70	.06	1141.21	.00088	.08	875	.00114	.77
70- 80	.08	1266.21	.00079	.08	1000	.00100	.79
80- 90	.06	1432.88	.00070	.08	1125	.00089	.78
90-100	.08	1557.88	.00064	.08	1250	.00080	.80

*Where S = fractional air-filled porosity.

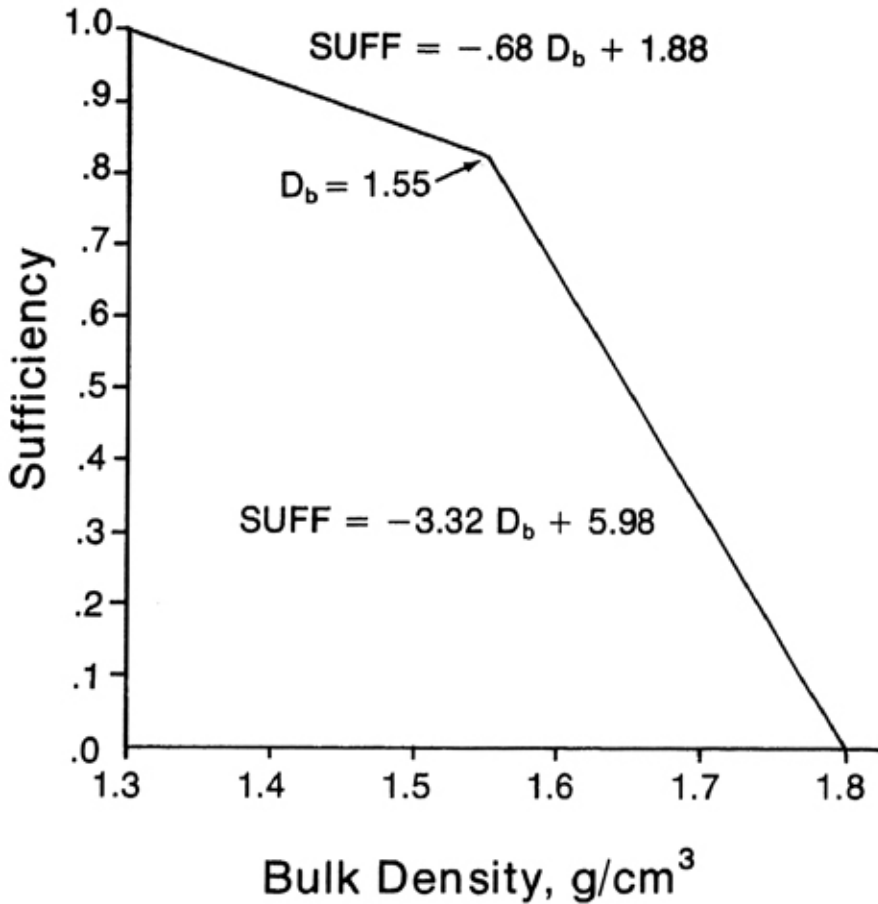


Fig. 4. Sufficiency of bulk density (SUFFDB) used in calculation of the productivity index.

effects of aluminum on cotton root penetration and the work of Blanchar *et al.* (1978) who studied pea root growth in relation to pHs and density. Misra *et al.* (1974) had shown that activity of aluminum species could be estimated from pH and ionic strength. Root length data were converted to relative roots lengths.

Values of pHs (pH in 1:1 mixture of soil and .01M CaCl_2) were estimated by subtracting 0.4 units from the reported values of pH (Woodruff 1967). The resulting equation was

$$\text{SUFFPHS} = \begin{cases} 1.0 & \text{if } 5.5 < \text{pHs} \leq 7.5 \\ 0.16 \text{pHs} + 0.12 & \text{if } 5.0 \leq \text{pHs} \leq 5.5 \\ 0.446 \text{pHs} - 1.31 & \text{if } 2.9 \leq \text{pHs} \leq 5.0 \end{cases} \quad [7]$$

See Figure 5. The sufficiency of 1.0 at pHs of 5.5 is in agreement with the findings of Fisher (1969) who concluded that soils limed to

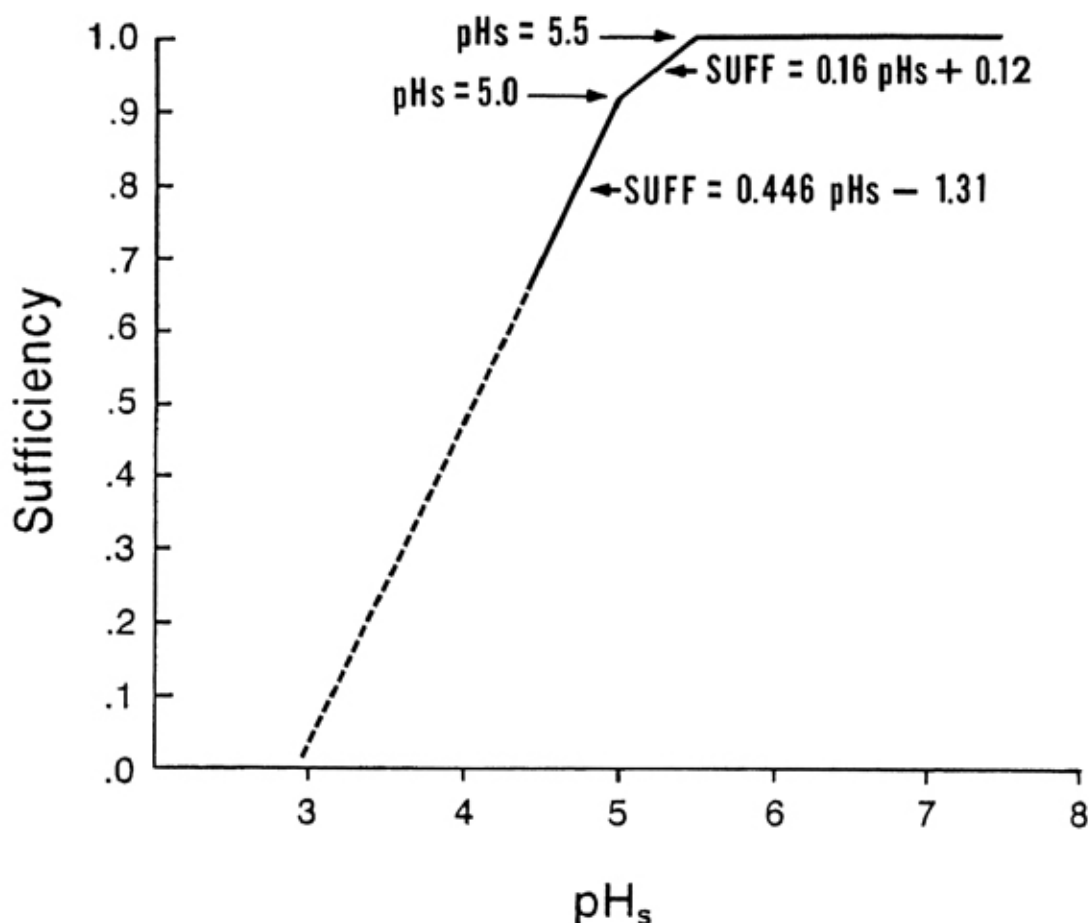


Fig. 5. Sufficiency of pHs (SUFFPHS) used in calculation of the productivity index.

pHs greater than 5.5 gave no increase in yield of corn, soybeans, wheat or cotton. It is also in close agreement with a regression equation calculated from the relative root lengths and pHs values estimated from the work of Adams and Lund (1966) ($\pm .02$ in the pHs range of 4.4 to 5.5). The slope of equation [7] for pHs less than 5.0 was derived from data reported by Blanchar *et al.* (1978). Extrapolation from pHs of 4.4 to 2.9 is without supporting data.

Sufficiency of Electrical Conductivity - An equation predicting sufficiency of electrical conductivity (SUFFEC) for root growth was developed from a study by Wadleigh *et al.* (1947) that was used by Richards (1969) to relate orchard grass green matter to electrical conductivity of

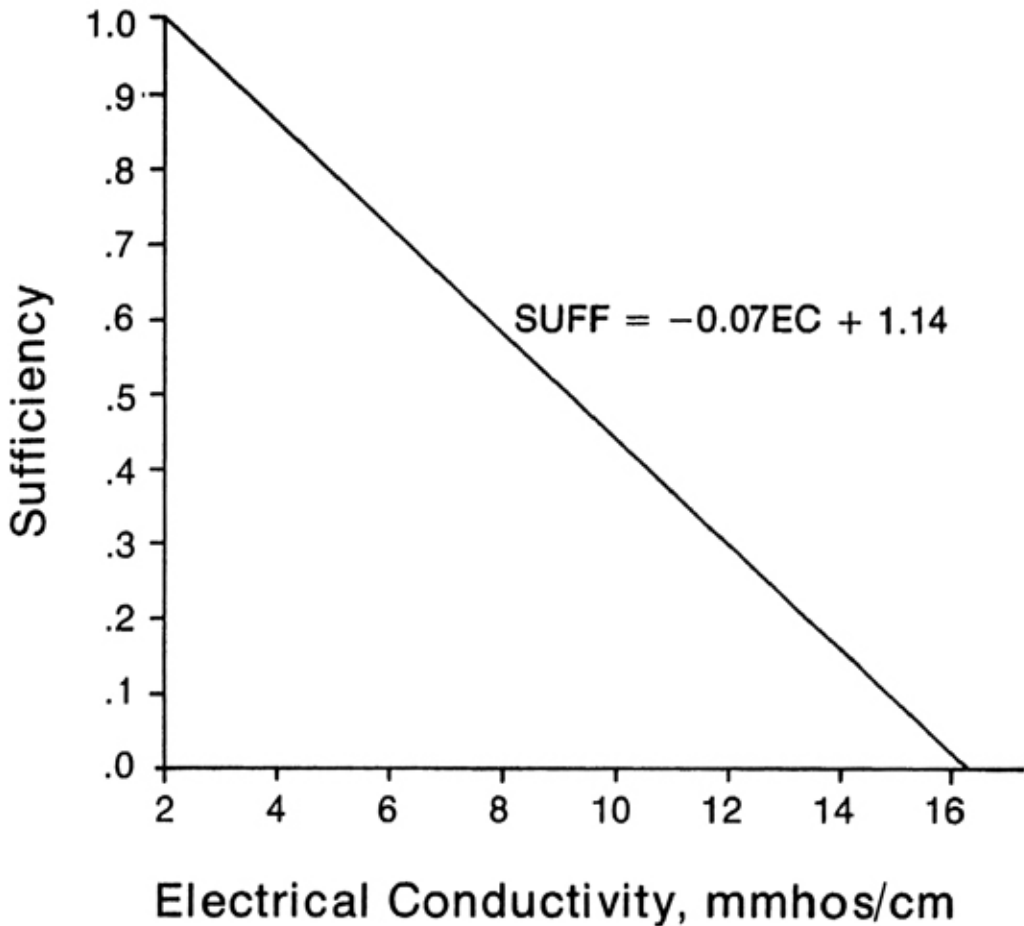


Fig. 6. Sufficiency of electrical conductivity (SUFFEC) used in calculation of the productivity index.

the soil saturation extract. The equation was

$$\text{SUFFEC} = \begin{cases} 1.00 & \text{if } EC \leq 2.0 \\ 1.14 - 0.07 EC & \text{if } 2.0 \leq EC \leq 16.0 \\ 0.00 & \text{if } EC \geq 16.0 \end{cases} \quad [8]$$

where EC is electrical conductivity in mmhos/cm (Figure 6). Root growth for corn was assumed to be equivalent to orchard grass top growth that was measured.

Electrical conductivity was not measured on most plot studies and sufficiencies were assumed to be 1.0. The evaluation provides for eventual use where fertilizer salts, salty irrigation water or salty areas in strip-mined lands will be evaluated.

Formulation of the Productivity Index

The authors' concept of the productivity index was one of comparing the predicted depth-distribution of roots in a given soil environment with the plant-determined rooting predicted under ideal conditions. The assumption was that root growth was proportional to productivity. Predicted root fractions under ideal conditions (Table 1 and Figure 2) were converted to soil determined root fractions by multiplying the ideal fraction (RI) for each depth increment by the fractional sufficiency of each soil parameter for that depth increment. The summation of the soil determined root fractions was a number between 0.0 and 1.0 that was taken as the productivity index. The procedure is expressed by the equation

$$PI = \sum_{i=1}^{i=r} (A \times B \times C \times D \times E \times RI)_i \quad [9]$$

where PI = the productivity index

A = SUFFPAW

B = SUFFAER

C = SUFFDB

D = SUFFPH

E = SUFFEC

RI = predicted root fraction in ideal soils

r = the total number of 10 cm depth increments in the plant-determined rooting depth R.

i = the 10 cm depth increment number (i = 1, 2, 3, . . . r)

Farm-field Plot Studies

Soil profile properties, yield, and weather were determined for 19 maize fields where 203 two-row plots were selected. Fields were selected in all major maize producing areas of Missouri (Figure 7). The dominant subgroups and textural families for each field are listed in Table 4. Fifteen fields were farm fields randomly chosen by the USDA-Statistical Reporting Service (SRS) national office. All plots within each field were also randomly selected. Four fields were University of Missouri experimental fields where five hybrids with three replications of each were chosen giving 15 plots per field.

Soil Sampling and Characterization - Soil sampling consisted of three cores, approximately 120 cm long and 4.2 cm in diameter, taken at each plot using a truck-mounted soil probe. Time of sampling was as soon after planting as possible. Two of the cores were taken at the ends of each two-row plot. They were immediately cut into 10 cm segments, placed in plastic bags, sealed and transported to the laboratory for determination of soil

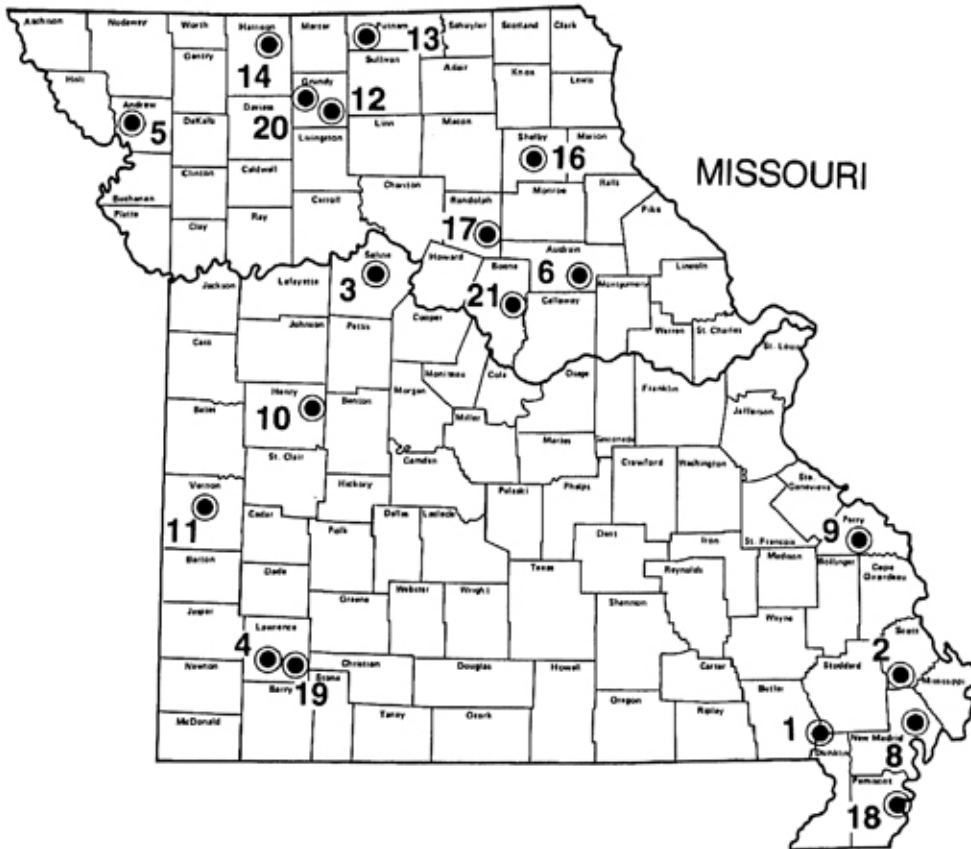


Fig. 7. Approximate locations of field plots.

moisture at planting, bulk density, aeration porosity and soil chemical properties. A third core for morphological description was taken within 1 meter of one of the two previous cores. The cores were wrapped in plastic, stored between the two halves of a split PVC pipe 7.5 cm in diameter, secured with masking tape and transported to the laboratory. These remained moist for as long as six months. The soil sampling procedure was designed to achieve rapid sampling, constrained by the requirement that our studies not interfere with farm field operations.

The 10 cm segments of the two cores were weighed moist; dried at 70°C for 72 hours, weighed dry, and then ground to pass a 10 mesh sieve. The drying procedure, which permitted the samples to be used for soil tests for potassium (part of another study), removed 88 percent of water removed by drying at 105°C. Dry weights were corrected before calculating bulk density and volume of water at planting. Air-filled porosity at planting was estimated by assuming that particle density was 2.65 g/cm³. The dried and sieved samples from one profile per field were used to determine clay content by hydrometer and 15 bar water content by

pressure-plate extraction. The known clay contents were used to guide estimates of clay for all other samples by the field method of moistening and subjecting the sample to shearing action between thumb and fore-finger. The dried and sieved samples were also used for the determination of pHs.

Morphological descriptions were made from the plastic encased cores taken at planting time. Descriptive elements included moist colors (matrix and mottles), fraction of mottles, estimated clay fraction, textural class name, structure and horizon designation. Soil classification (Table 4) was according to Soil Taxonomy (Soil Survey Staff, 1975). The classification of cores rather than pedons led to some uncertainties, particularly where tongues of albic materials might have extended into argillic horizons.

Yield Determination - Yields of maize were determined on all farm field plots by USDA-SRS enumerators. All ears within each two-row x 4.57 m plot were harvested and the total ear weights were determined in the field. The first and last ears were sent to the SRS state office for determination of shelling percentage and moisture content. Those values plus the recorded row width were used to convert total ear weights to grain yield (kg/ha) at 15.5% moisture. Similar procedures were used on experimental fields for which yields were reported by Minor *et al.* (1978).

Relative Sufficiencies of Weather - Daily maximum and minimum temperatures were measured in each field using a Taylor min-max thermometer. Daily precipitation was recorded at each field from observation of a wedge type rain gauge. Weather sufficiency was calculated using a regression model developed by Leeper *et al.* (1974). That model uses weekly average maximum temperature, weekly total precipitation and plant-available soil moisture at planting as variables. Ten weeks of weather data centered around tasselling were used. Sufficiency of weather was calculated by assuming that plant available water was a non-limiting 25 cm at all fields and then predicting yields by the Leeper model. The maximum predicted yield was assigned a weather sufficiency of 1.0. All other fields were ratioed to that maximum.

Soil property data from the farm-field studies were used to generate productivity indices (PI) for each plot with each index having a sufficiency of weather as a component. Regression analyses of yield vs PI were then used to determine the best fit (highest value of r^2) when values of R were varied. Regression analyses and values of r^2 were also used to evaluate methods of estimating PAWC and aeration.

Table 4. Locations of Fields and Dominant Subgroups and Particle Size Classes of Soils.

Field Ident. No.	County in Missouri	Number of Plots	Dominant Subgroups According to Soil Taxonomy (1975)	Dominant Particle Size Classes
1	Dunklin	12	Typic Albaqualfs (5)*; Typic, Aquic and Albaquic Hapludalfs (3)	fine silty (11)*
2	Scott	12	Mollic and Typic Hapludalfs (8)	fine silty (5); fine loamy (5)
3	Saline	12	Aquic Argiudolls (5); Typic Argiaquolls (2); Cumulic Argiaquolls (2)	fine silty (12)
4	Lawrence	12	Fluventic Hapludolls (5); Mollic Hapludalfs (3)	fine silty (12)
5	Andrew	12	Aquic Argiudolls (7); Mollic, Typic and Aquollic Hapludalfs (3)	fine silty (9); fine (3)
6	Audrain	12	Mollic and Typic Albaqualfs (7); Udollic and Aerlic Albaqualfs (2)	fine (12)
8	New Madrid	8	Mollic and Ultic Hapludalfs (4); Aquollic and Albaquic Hapludalfs (2)	fine loamy (3); coarse loamy (3); sandy (2)
9	Perry	8	Typic Hapludalfs (4); Mollic Hapludalfs (3)	fine silty (6)
10	Henry	8	Typic Argiaquolls (5); Abruptic Argiaquolls (2)	fine (8)
11	Vernon	7	Aquic Argiudolls (3); Typic Argiudolls (1); Abruptic Argiaquoll (1)	fine (4); fine silty (4)
12	Grundy	8	Aquic Argiudolls (5); Udollic Ochraqualfs (2)	fine (8)
13	Putnam	8	Argiaquic Argialbolls (4); Typic Argialbolls (2)	fine (8)
14	Harrison	8	Aquic Argiudolls (3); Mollic Ochraqualfs (2)	fine (5); fine loamy (3)
16	Shelby	8	Mollic Ochraqualfs (3); Mollic Albaqualfs (3)	fine (8)
17	Randolph	8	Mollic Ochraqualfs (3); Mollic Albaqualfs (2); Typic Argialbolls (2)	fine (8)
18	Pemiscot	15	Typic Argiaquolls (2); Thapto-aqueptic Udifluvents (2); Aquic udifluvents (2); Mollic, Typic and Glossic Hapludalfs (3)	fine (3); fine silty (3); fine loamy (2); coarse loamy (2)
19	Lawrence	15	Fluventic Hapludolls (11); Typic Argiudolls (4)	fine silty (15)
20	Grundy	15	Typic Argiaquolls (9); Aquic Argiudolls (2); Argiaquic Argialbolls (2)	fine (14)
21	Boone	15	Mollic Albaqualfs (14)	fine (15)

*Numbers in parentheses indicate the number of plots meeting criteria for subgroup or family particle size class classification.

Results and Discussion

Values of R and PAWC Resulting in Best Estimates of Yield

The best fit between PI and yield was achieved when R was 100 cm or less, when PAWC was estimated from measured soil water, when aeration was omitted as a parameter and when weather sufficiency was included. R values of 200, 150, 100, 80, 70, 50, and 30 cm led to r^2 values of 0.38, 0.43, 0.53, 0.57, 0.59, 0.60, and 0.54, respectively. There was no significant difference between r^2 values of 0.53 and 0.60. Therefore, $R = 100$ cm was selected for examples shown in Table 5. The value of R determined the weighting given to each soil layer (see Table 1, equation [1] and Figure 2.) The model does not, at present, have inputs that weight each layer according to the depth-frequency of summer recharge of soil moisture. Such inputs would give a greater weighting to uppermost layers and the findings may be reflecting that fact. An R value of 200 cm more nearly approximates the authors' experience with water depletion studies with maize. It is also closer to the rooting depth for soybeans found by Böhm *et al.* (1977) and Sivakumar *et al.* (1977).

Of the three methods for estimating PAWC, measured water led to the highest values of r^2 . A value of 0.48 was achieved with R fixed at 100 cm. This was in contrast to values of 0.40 with PAWC estimated from textural class or predicted from clay content by equation [5]. The value of r^2 was increased to 0.53 by estimating PAWC from a combination using textural class sufficiencies (Table 2) for the top 30 cm of soil and below that, measured water. The combination method was used because it was observed that surface layers were partially dried at planting time when volumes of water were determined.

Sufficiency of Aeration and Yield Estimates

Inclusion of sufficiency of aeration, calculated as indicated in Table 4, reduced values of r^2 from 0.53 to 0.42. It may be that the method will be useable when the dynamics of the time-depth distribution of air-filled porosities are taken into account. The models of Holtan *et al.* (1975) included that kind of approach. The model described here, at present, contains a one-time (planting) observation.

Sufficiency of Weather and Yield Estimates

All regression analyses of PI vs. yield had a sufficiency of weather as a component of PI. Without sufficiency of weather, maximum values of r^2 were 0.20 as compared to r^2 of 0.53 for $R = 100$ and with weather sufficiency included.

Examples of Predicted Root Patterns and Productivity Indices

Table 5 illustrates the method for converting the profiles of soil properties into predicted profiles of roots and into productivity indices with $R = 100$ cm. The first three soils in Table 5 are loess-derived soils of northern Missouri. The Typic Argiudoll, the Aquic Argiudoll and the Mollic Albaqualf exhibit increasing clay, increasing wetness and increasing acidity in the order listed. The Mollic Fragiudalf is a soil of southern Missouri and is the most acid and dense of the four soils.

The soils in the order listed above are from Fields 3, 5, 21, and 19, respectively (Figure 7). Figure 8 shows the predicted profiles of root lengths for three of the four soils. Sufficiency of aeration is included in Table 5 for illustrative purposes, even though the regression studies showed the prediction of yields of maize was more precise without considering aeration.

Yields vs Productivity Indices

Figures 9 and 10 depict the relationship between yield and PI for the best combination, which included correction for weather. Figure 9 shows PI for each plot in all fields vs plot yield. Figure 10 shows average PI for each field vs average plot yield for each field. The value of r^2 increased from 0.29 to 0.53 when averages were taken. Errors in yield estimates from two-row plots may be greater than the differences caused by soil variation within a field.

The low values of r^2 indicate a large component of unexplained variation. Unevaluated management variables could have been important. However, PI's and yields within each field displayed an equal amount of scatter. The r^2 value of 0.53 may be acceptable in light of the fact that sufficiency response curves and the R values of the simple deterministic model used remain researchable. In addition, errors of determination of soil input data were unavoidable in the method of gearing sampling to a farm field operation wherein the two-row plots could not be destroyed.

Table 5. Four Selected Examples of Profiles of Soil Properties and The Method of Conversion into Productivity Indices.

Typic Argiudoll, fine silty, mixed mesic. Field 3, Plot 7, Saline County

Depth Incr. (cm)	Course Frag. (fract) (Vol.)	Clay (fract) (wt.)	Db fines (g/cm ³)	pHs	½ bar*	15 bar*	PAWC*	Air F. Poros.	Sufficiencies				Predicted	
									PAWC	pHs	Db	Aer.	Ideal Root Fract.** (RI)	This Soil
					fraction of Vol*			fractions						
0- 10	-	.21	1.33	5.3	.36	.16	.20	.14	1.00	.97	1.00	1.00	.314	.305
10- 20	-	.22	1.33	5.4	.36	.17	.19	.14	.95	.99	1.00	1.00	.196	.184
20- 30	-	.22	1.32	5.5	.36	.17	.19	.14	.95	1.00	1.00	1.00	.143	.136
30- 40	-	.24	1.28	5.5	.37	.18	.19	.15	.95	1.00	1.00	1.00	.108	.103
40- 50	-	.28	1.25	5.5	.38	.21	.17	.15	.85	1.00	1.00	1.00	.082	.070
50- 60	-	.28	1.23	5.4	.38	.21	.17	.16	.85	.99	1.00	1.00	.061	.051
60- 70	-	.28	1.23	5.3	.38	.21	.17	.16	.85	.97	1.00	1.00	.044	.036
70- 80	-	.28	1.26	5.3	.38	.21	.17	.14	.85	.97	1.00	1.00	.030	.025
80- 90	-	.28	1.29	5.4	.38	.21	.17	.13	.85	.99	1.00	1.00	.017	.014
90-100	-	.26	1.32	5.5	.38	.20	.18	.12	.90	1.00	1.00	1.00	.005	.004
												PI =	1.000	.928

Aquic Argiudoll, fine, mixed mesic. Field 5, Plot 2, Andrew Co.

0- 10	-	.18	1.21	6.9	.35	.14	.21	.19	1.00	1.00	1.00	1.00	.314	.314
10- 20	-	.19	1.25	7.0	.36	.15	.21	.17	1.00	1.00	1.00	1.00	.196	.196
20- 30	-	.22	1.27	6.8	.36	.17	.19	.16	.95	1.00	1.00	1.00	.143	.136
30- 40	-	.24	1.29	6.4	.37	.18	.19	.14	.95	1.00	1.00	1.00	.108	.103
40- 50	-	.29	1.28	5.7	.38	.22	.16	.14	.80	1.00	1.00	1.00	.082	.066
50- 60	-	.32	1.30	5.3	.39	.24	.15	.12	.75	.97	1.00	1.00	.061	.044
60- 70	-	.39	1.33	5.2	.41	.29	.12	.09	.60	.95	.98	1.00	.044	.025
70- 80	-	.43	1.38	5.1	.43	.32	.11	.05	.55	.94	.94	1.00	.030	.015
80- 90	-	.43	1.42	5.1	.43	.32	.11	.03	.55	.94	.91	1.00	.017	.008
90-100	-	.43	1.40	5.3	.43	.32	.11	.04	.55	.97	.93	.97	.005	.002
												PI =	1.000	.909

Table 5. Continued.

Mollic Albaqualfs, fine, mont. mesic. Field 21, Boone Co. (mean of 15 plots)

0- 10	-	.21	1.32	6.5	.36	.16	.20	.14	1.00	1.00	.98	1.00	.314	.308
10- 20	-	.22	1.34	6.4	.36	.17	.19	.13	.94	1.00	.97	1.00	.196	.179
20- 30	-	.40	1.26	5.4	.42	.30	.12	.10	.60	.98	1.00	1.00	.143	.084
30- 40	-	.50	1.28	4.6	.45	.37	.08	.07	.40	.74	1.00	1.00	.108	.032
40- 50	-	.47	1.38	4.7	.44	.35	.09	.04	.45	.79	.94	.97	.082	.027
50- 60	-	.43	1.42	4.8	.43	.32	.11	.03	.55	.83	.91	.77	.061	.025
60- 70	-	.38	1.40	5.1	.41	.28	.13	.06	.65	.94	.93	.77	.044	.025
70- 80	-	.35	1.39	5.3	.40	.26	.14	.08	.70	.97	.93	.79	.030	.019
80- 90	-	.33	1.42	5.5	.40	.25	.15	.06	.75	1.00	.91	.78	.017	.012
90-100	-	.32	1.40	5.6	.39	.24	.15	.08	.75	1.00	.93	.80	.005	.003
												PI =	1.000	.714

Mollic Fragiudalf, fine, mixed, mesic. U. of Mo. S.W. Research Center, Lawrence Co.

0- 10	-	.15	1.36	5.5	.34	.12	.22	.15	1.00	1.00	.96	1.00	.314	.301
10- 20	-	.15	1.36	5.5	.34	.12	.22	.15	1.00	1.00	.96	1.00	.196	.188
20- 30	-	.33	1.41	4.2	.40	.25	.15	.07	.75	.56	.92	1.00	.143	.055
30- 40	-	.40	1.45	3.9	.42	.30	.12	.03	.60	.43	.89	.82	.108	.025
40- 50	-	.53	1.33	3.8	.46	.39	.07	.04	.35	.38	.98	.73	.082	.011
50- 60	-	.42	1.55	3.7	.42	.21	.11	.00	.55	.34	.83	.00	.061	.009
60- 70	-	.32	1.71	3.7	.39	.24	.15	.00	.75	.34	.30	.00	.044	.003
70- 80	-	.32	1.79	3.7	.39	.24	.15	.00	.75	.34	.04	.00	.030	.000
80- 90	.30	.28	1.79	3.8	.27	.15	.12	.00	.60	.38	.04	.00	.017	.000
90-100	.60	.28	1.59	3.8	.15	.08	.07	.01	.35	.38	.70	.00	.005	.000
												PI =	1.000	.592

*Predicted from equations [3], [4] and [5] and corrected for coarse fragments.

**Predicted root fractions and PI from PAWC, pHs, and Db only.

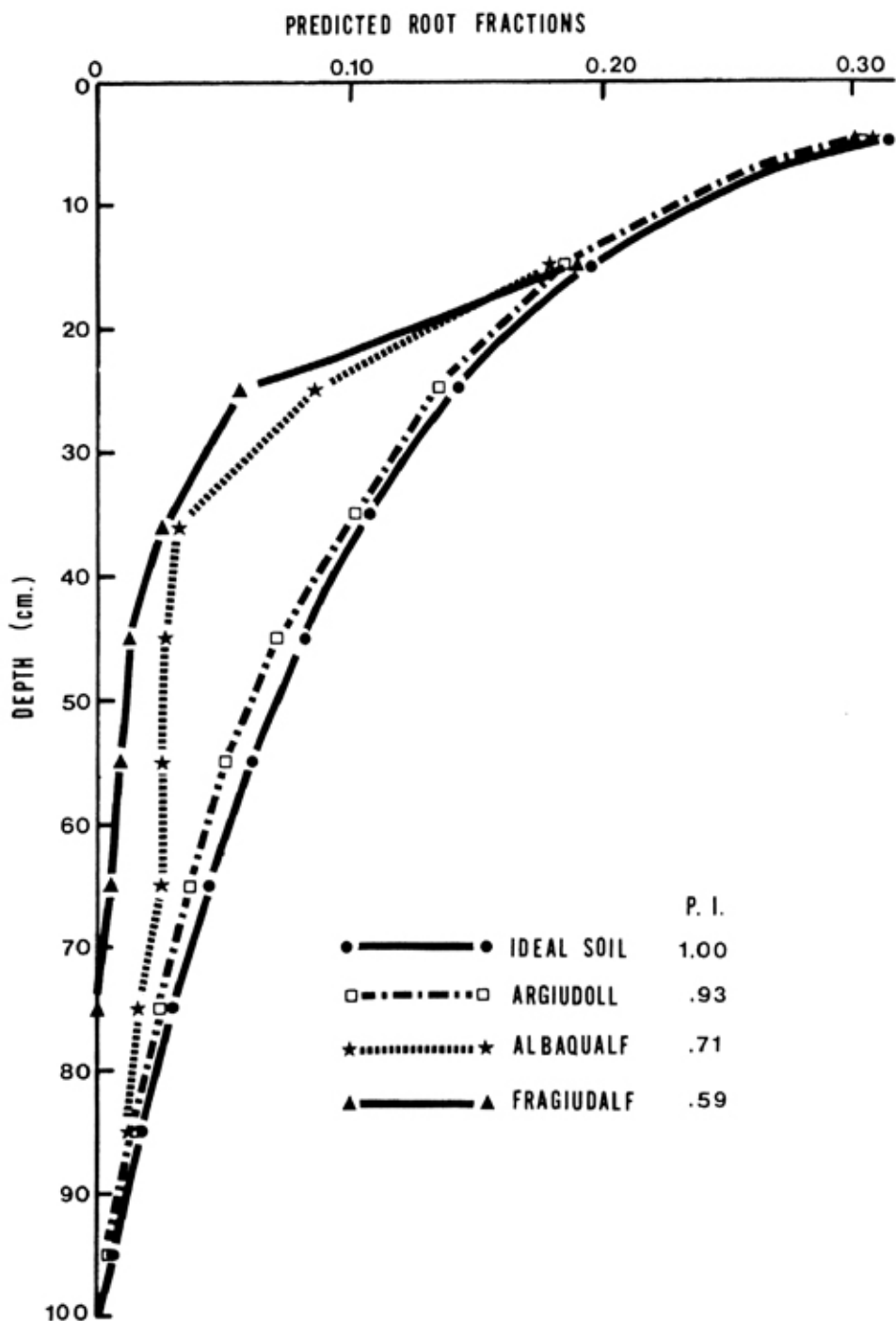


Fig. 8. Predicted profiles of root length fractions for three selected soils.

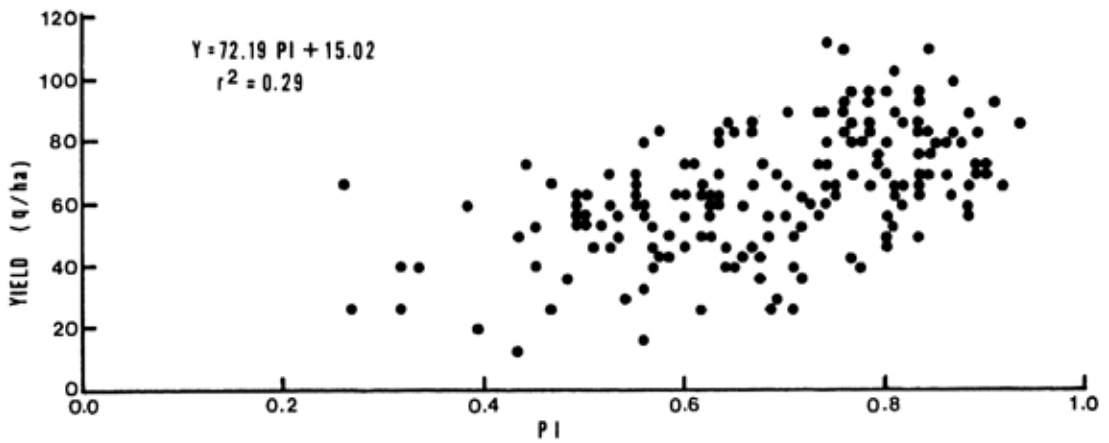


Fig. 9. Relationship between yield and PI for all maize plots in all fields.

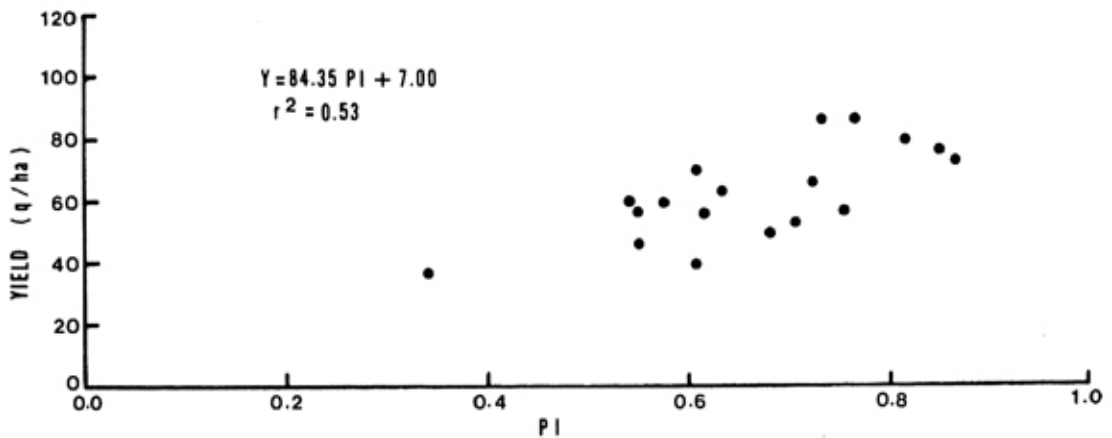


Fig. 10. Relationship between field average maize yields and field average PI.

Summary and Conclusions

A simple, quasi-deterministic model has been developed for providing a quantitative appraisal of the soil profile of yield determinants. All components of the model remain researchable but, even so, they provide a conceptual model for describing a very complex system.

When the model was applied to on-site evaluation of two-row maize plots, the value of r^2 was 0.29 with relative sufficiency of weather included. The value of r^2 was 0.53 when plot yields and plot PI were averaged for each field. This may indicate that errors in yield estimates from two-row plots were greater than any yield differences caused by soil variations within a field.

The best fit between PI and yield was obtained when the profile of root fractions was predicted from an R value of 100 cm. Measured volumes of water at planting were superior to volumes estimated from clay contents or from textural class. A method of evaluating aeration from air-filled porosity at planting was proposed but regression analyses showed that omission of aeration improved the fit. Thus, the yield predictions in this study were based upon the profiles of water volumes at planting, of bulk density and of pH.

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