Natural Reformation of Mined Land Reclaimed by Scrapers

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Abstract. The objective of this study was to examine the reformation of surface mined land reclaimed by scrapers. The experiment was conducted at the Arch of Illinois, Inc. Denmark Mine, in Perry County, Illinois. The soils selected for this study were reclaimed in 1977, 1981, and 1985. A non-mined soil and a soil reclaimed by the shovel-truck system in 1989 were included for comparisons. The textural properties of the reclaimed soils were restored to a level similar to that of the non-mined soil, but the reclaimed soils had a higher amount of soluble salts. Soil pH of the reclaimed soils were higher and close to neutral, particularly for soils reclaimed in 1985 and 1989, as compared to the non-mined soil. Generally, the reclaimed soils had a higher bulk density and penetrometer resistance but lower macroporosity. Air permeability, saturated hydraulic conductivity, and cumulative infiltration were highly variable across the selected soils and with depth. However, the results showed that bulk density and penetrometer resistance were lower and macroporosity was higher in the soils that were recently restored. Additionally, extremely poor hydraulic properties were obtained in the reclaimed soils. This study also revealed that the tilth of non-mined soil is far better than that of the reclaimed mined soils, even though some of the mined soils had been reclaimed more than a decade ago.

INTRODUCTION

Coal is one of the most important sources of energy in the United States of America. Surface mining of coal is an important industry in the Midwest. The first coal mining operation was reported by French explorers along the Illinois river in 1679 (Cassidy, 1973). However, the first conventional open pit mining was not started until the 1800's. In Illinois, some 98,400 hectares of land have been affected by surface mining activities (Personeau and Spivey, 1990), of which about 56,600 hectares of the mined land have been reclaimed.

One of the major problems resulting from surface mining operations is the drastic change of the soil profile. Disrupting the soil environment can cause an adverse effect in the hydrologic balance in adjacent areas. The extent of soil disruption depends upon the reclamation methods used. There are many ways to reclaim surface mined land, the scraper, shovel-truck, drag-line, and bucket-wheel excavator systems are the most common methods used in Illinois.

Reclamation of surface mined land creates a new soil profile, generally producing a different soil texture and structure than that prior to mining. These changes can affect both the physical and chemical properties of the soil. However, the major problem with reclaimed mined land is soil compaction. Compaction of soil can destroy soil structure, increase penetration resistance and greatly reduce macroporosity (Jansen, 1982; Potter et al., 1988; and Theseira and Chong, 1989). The reduction in macroporosity can lead to unfavorable hydraulic properties and poor water infiltration, which may increase soil erosion potential. Compacted soil can restrict plant root development and reduce crop yield (McSweeney et al., 1987; and Thompson et al., 1987).

Public law 95-87, also known as the United States Federal Surface Mining Control and Reclamation Act of 1977, requires that soil be restored as close as possible to the conditions prior to mining and also be graded to its original contour. Furthermore, the replaced rooting medium must be of specific textural characteristics that will assist in achieving a productivity level equal to or better than the pre-mining condition.

In the past, most of the mined land research was conducted on recently reclaimed soil or on soil that has been reclaimed two or three years. Some of Illinois mined lands have been reclaimed for more than a decade. In order to have a better understanding and for management of reclaimed mined land, it is important to study the reformation and development of mined soil over time. The main objective of this research was to evaluate surface mined soil which was reclaimed over ten years ago.

MATERIALS AND METHODS

Site Description

The experimental site was located at the Arch of Illinois, Inc. Denmark Mine, in Perry County, Illinois. Prior to mining, the area was predominantly Stoy silt loam (fine-silty, mixed, mesic Aquic Haplaudalf). After mining, the soil was classified (Grantham and Indorante, 1988) as Swanwick (fine-silty, mixed non-acid, mesic Typic Udorthent).

The sites selected for this study included soils reclaimed in 1977, 1981, and 1985 by scrapers. A non-mined Stoy silt loam and a soil reclaimed in 1989 by the shovel-truck method were also included for comparative purposes (the detailed reclamation procedures used for the shovel-truck site are not available). On all the reclaimed areas, fertilizers were applied shortly after the reclamation work was completed. Additionally, mixed vegetation including sweet clover (Melilotus spp.) and smooth bromegrass (Bromus inermis Leyss) was planted as cover crops to reduce erosion. However, the soil reclaimed by the shovel-truck system was planted in wheat (Triticum aestivum L.) and the non-mined area was covered mainly with tall fescue (Festuca arundinacea Shreb.) at the time of sampling.

Sampling Methods and Experimental Procedures

Soil samples were collected in the summer of 1990. In this study, it was assumed that the variability within each selected soil was negligible. On each soil, an area of 15 x 15 m was used and a grid was developed at intervals of 3 m. Penetrometer resistance was measured at each intersection of the grid. Therefore, a total of 36 penetrometer resistance measurements were obtained on each selected site. The penetrometer resistance was measured to a depth of 100 cm using a constant velocity auto-recording penetrometer (Hooks and Jansen, 1986). After the penetrometer resistance measurements were taken, a 3 x 4 m pit was excavated at the center of the selected area using a backhoe. Profile classification was performed by soil scientists from the Soil Conservation Service at Jackson County, Illinois. The pit was dug to a depth of 1.5 m. Three undisturbed core samples (10 cm long and 7.94 cm in diameter) were obtained at 20 cm increments using a portable undisturbed soil core sampler (Chong et al., 1982) to a depth of 80 cm. The undisturbed cores were obtained from the north, west and east sides of the pit. Composite soil samples were also collected from the same depths at each layer for textural and chemical analyses.

Soil pH was determined by the potentiometric method using a 1:1 soil-water mixture (Eckert, 1988). The tritrimetric Walkley-Black method was used for measuring soil organic matter (Schulte, 1988). Electrical conductivity was measured on a 1:2 soil-water mixture by a conductance bridge (Jackson, 1958). Extractable phosphorus (P) was extracted with Bray P-1 solution and analyzed on a spectrophotometer at 660 nm (Knudsen and Beegle, 1988). Exchangeable potassium (K) was extracted with neutral 1 N ammonium acetate and analyzed on a flame photometer (Brown and Warncke, 1988).

Soil physical properties studied included penetrometer resistance, soil texture, infiltration, saturated hydraulic conductivity, macro- and microporosity, air permeability and bulk density. Soil texture was determined by the hydrometer method (Gee and Bauder, 1986). The infiltration of each soil core was measured by the ponding method (1 cm of water head), in the laboratory. After measuring infiltration, the soil core was saturated by capillary action over a period of 24 hours. The saturated hydraulic conductivity (K_{sat}) of the soil was determined under a unit gradient set-up. After K_{sat} was measured, the soil core was weighed and then put on a tension table at a suction of 250 cm of water for 48 h to determine macro- and micro-porosity of the soil. The 250 cm of water suction was arbitrarily chosen as the boundary between micro- and macro-porosity. The soil core was immediately weighed after it was removed from the tension table to prevent moisture loss by evaporation. Air permeability (K_{air}) was measured by a constant pressure gasometer (Corey, 1986).

After K_{air} was determined, the soil core was oven dried at 105°C to determine bulk density. Total porosity of the soil was calculated from the relationship of bulk density and particle density. Particle density was assumed to be 2.65 g/cm^3.

RESULTS AND DISCUSSION

The textural results and description of each soil profile are shown in Table 1. The results reveal that the texture of the reclaimed soil has been restored to a textural class comparable to that of the adjacent non-mined soils. However, the mined soil had a sub-angular blocky and firm structure, which was quite different than that of the non-mined soil. Detailed description of all the profiles is available elsewhere (Moroke, 1991)[1].

Table 2 gives the data of selected soil chemical properties. The pH values of the non-mined soil and the soil reclaimed in 1977 and 1981 decreased with increas-

[1] Moroke, T.S. 1991. Pedological evaluation of reclaimed surface mined soil. M.S. Thesis, Plant and Soil Science Department, Southern Illinois University at Carbondale, IL.

Table 1. Soil textural analysis results and classification ofselected soils at the Denmark mine area, Perry County, IL

Depth (cm)	% Sand	% Silt	% Clay	Textural Class
		Non-mined Stoy Silt Loam		
0 - 20	18.95	66.75	14.30	Silt loam
20 - 40	13.72	49.54	36.74	Silt clay loam
40 - 60	12.11	43.10	44.79	Silt clay
60 - 80	17.98	47.21	34.81	Silt clay loam
		1977 (Scraper)		
0 - 20	20.35	58.30	21.35	Silt loam
20 - 40	25.65	54.73	19.62	Silt loam
40 - 60	28.40	49.16	22.44	Loam
60 - 80	22.65	49.90	27.45	Clay loam
		1981 (Scraper)		
0 - 20	21.55	49.03	29.42	Clay loam
20 - 40	19.72	48.84	31.44	Silt clay loam
40 - 60	17.03	52.13	30.84	Silt clay loam
60 - 80	19.67	50.85	30.84	Silt Clay loam
		1985 (Scraper)		
0 - 20	14.54	58.78	26.68	Silt loam
20 - 40	23.21	48.45	28.34	Clay loam
40 - 60	23.11	44.05	32.84	Clay loam
60 - 80	27.20	45.02	27.78	Loam
		1989 (Shovel-Truck)		
0 - 20	30.04	45.26	24.70	Loam
20 - 40	18.14	53.84	28.02	Silt clay loam
40 - 60	36.96	35.01	28.03	Clay loam
60 - 80	37.57	34.44	27.99	Clay loam

Table 2. Mean of chemical properties measured on the selected reclaimed mined soil at the Denmark mine area, Perry County, IL.

			Scraper	- - - - - - - - Shovel - Truck - - - - - - - -		
Depth(cm)	N	Non-Mined	1977	1981	1985	1989
			pH (1:1)			
0 - 20	6	7.3	7.1	7.2	5.0	6.0
20 - 40	6	5.4	7.3	6.8	6.0	6.0
40 - 60	6	4.0	7.1	4.7	7.2	7.8
60 - 80	6	3.9	5.3	4.1	7.5	7.7
			Organic Matter (%)			
0 - 20	6	1.11	1.26	1.12	1.21	1.34
20 - 40	6	0.46	1.11	0.31	0.70	1.51
40 - 60	6	0.28	0.30	0.52	0.26	0.10
60 - 80	6	0.21	0.30	0.21	0.29	0.10
			Electrical Conductivity (mho x10^{-5})			
0 - 20	6	11.5	+	10.0	10.0	15.5
20 - 40	6	+	10.0	10.0	15.5	27.0
40 - 60	6	+	34.0	21.0	44.5	41.0
60 - 80	6	+	43.0	22.0	75.0	43.0
			Potassium (Kg/ha)			
0 - 20	6	306.5	220.6	194.5	156.8	263.2
20 - 40	6	203.8	100.8	102.7	146.0	149.7
40 - 60	6	165.8	100.8	126.9	132.5	132.9
60 - 80	6	53.1	93.3	166.5	141.5	151.6
			Phosphorus (kg/ha)			
0 - 20	6	24.1	53.2	28.6	32.5	45.9
20 - 40	6	20.2	36.4	23.0	33.0	44.8
40 - 60	6	25.2	20.7	21.3	26.3	12.9
60 - 80	6	34.7	15.1	42.0	27.4	11.8

+ Denotes value close to zero.

ing soil depth, and the non-mined subsoil (40-60 cm) had the lowest pH values among all soils selected in this study. The pH of the soil reclaimed in 1985 and 1989 increased with increasing depth (up to pH = 7.8). The results also revealed that the reclaimed mined soil generally had a high pH, except in the subsoil (40-80 cm) reclaimed in 1981.

Table 2 also indicates that soil reclaimed by scrapers had a slightly higher organic matter (OM) content than the non-mined soil and soil reclaimed by the shovel-truck method. Higher organic content in the reclaimed soils may be a result of the mixing of soil materials during the reclamation processes and/or decomposition of planted vegetation. For the soil reclaimed by the shovel-truck system, Table 2 shows that the OM content was higher than 1.3% in the surface soil (0-40 cm) but dropped sharply to a value of 0.1% below the 40 cm depth. Overall, the organic matter contents of all the soils studied were within the average range found in most southern Illinois farm lands.

The electrical conductivity (EC) data indicated high variation among the reclaimed soils. EC for reclaimed soils were relatively higher than non-mined soil. This may be due to the accelerated weathering of minerals exposed to the atmosphere by the mining processes. Electrical conductivity of the non-mined soil was extremely low and was undetectable below a soil depth of 20 cm. The non-mined soil was not disturbed by mining operations, therefore it is very likely that soluble salts may have leached out and/or leached deeper down in the soil profile.

Chichester and Hauser (1991) observed increased phosphorus (P) in the reclaimed soil as compared to the non-mined soil. Similar results were found in this study. Generally, there was a decrease of P with increasing depth in the reclaimed soil, but, the opposite pattern was observed for the non-mined soil. Phosphorus content showed less variation within and among the soils studied in contrast with Potassium (K) content. The non-mined soil had a higher K content in the 0 - 60 cm layer than the reclaimed soil. Perry county is classified as a region of low supplying power for P and K (Illinois Agronomy Handbook, 1990). The results obtained in this study show that both P and K values of the reclaimed soils remained in the low level.

The results of bulk density, total porosity, macro-porosity, micro-porosity and penetrometer resistance are shown in Table 3. Bulk density tended to increase with increasing depth for both reclaimed and non-mined soils. Furthermore, bulk density of the non-mined soil was significantly lower than that of the reclaimed soil (alpha = 0.05). Even though the results of bulk density showed a large variation between soils and depths, the linear relationship of bulk density versus depth was significant for soil reclaimed in 1977, 1981 and 1989, but, no linear relationship was found for the non-mined soil and soil reclaimed in 1985. The soil reclaimed by scrapers in 1977 had the highest bulk density (average was 1.74 g/cm^3) in the subsoil (20 to 80 cm), followed by soil reclaimed by the shovel-truck system (1.71 g/cm^3), soils reclaimed in 1985 and 1981, and the non-mined soil (1.49 g/cm^3). Soil reclaimed by the scrapers in 1981 and 1985 had an average bulk density of 1.65 g/cm^3 in the subsoil. These results indicated that soils reclaimed in 1981 and 1985 were less compacted, which might be attributed to the improvement in restoration techniques and/or awareness of the compaction problems. Since the non-mined soil had the lowest soil bulk density, it had the highest porosity (average was > 42%) of all soils studied. In contrast, the total porosities of all the reclaimed subsoil (from 20 to 80 cm) were less than 39%, except for the soil reclaimed in 1981 by scrapers in the 20-40 cm depth. Most of the pores in the reclaimed soil were micropores, particularly for soil reclaimed by the shovel-truck system. More than 99% of the porosity was determined to be micropores. The macro-porosity in the reclaimed soil was much lower than that of the non-mined soil, especially for soil below the 40 cm depth (see Table 3). The decrease in macro-pores may have a tremendous impact on the movement of water and air in soil, since preferential flow of these fluids depends upon the availability of macro-pores. The amount of macro-pores is generally related to the degree of soil compactness. This relationship shown in Figure 1, is a strong inverse relationship between bulk density (BD) and macro-porosity ($= 49.85\ BD^{-5.37}$, with $r^2 = 0.61$) was obtained. Therefore, it can be concluded that the reduction of porosity in a compacted soil is usually at the expense of macro-pores.

The average penetrometer resistance versus depth for each of the selected soils are presented in Figure 2 (each point on the graph is an average of 36 measurements). The figure reveals that there was little variation in penetrometer resistance in the surface layer (0 - 20 cm) among soils studied. However, below the 20 cm depth, the soil reclaimed by scrapers in 1977 had the highest penetrometer readings (>2 MPa), followed by soils reclaimed in 1981 and 1985. Figure 2 also indicates that the non-mined soil and soil reclaimed in 1985 by the scraper had very similar penetrometer readings. The soil reclaimed by the shovel-truck system had the lowest penetrometer resistance. It should be recalled that soil reclaimed by the shovel-truck system had the second highest bulk density of all the soils studied. Generally, a high soil bulk density value results in a high penetrometer reading. However, in this case the results obtained were an exception to the rule. This discrep-

ancy might be due to variable water content in soils when the penetrometer readings were taken. The average penetrometer resistance and the degree of water saturation in each soil depth at sampling are given in Table 3. It shows that soils reclaimed in 1985 by scrapers and shovel-truck method had the highest water content at the time of sampling. Soil restored by the shovel-truck method had a water content close to field saturation. It has been reported that penetrometer resistance of 2.0 MPa will severely impede plant root proliferation (Taylor and Gardner, 1963). Figure 2 reveals that soils reclaimed in 1977 and 1981 by the scraper method had penetrometer readings over 2.0 MPa in the 20 - 80 cm depth. Although there was a wide variation in penetrometer resistance among all the soils studied, Figure 2 clearly shows that soils reclaimed more recently had lower penetrometer resistance values.

Table 4 presents the results of infiltration, saturated hydraulic conductivity, K_{sat}, and air permeability, K_{air}. The results of these three physical properties were highly variable across depths and among the selected soils. Generally, the non-mined soil had a relatively higher infiltrability of water. In contrast, the infiltration of all the reclaimed subsoil was very low, and for some layers water movement stopped before one hour. The saturated hydraulic conductivity of all the soils in the 0 to 20 cm was less than 0.51 cm/h. The non-mined subsoil (40 - 60 cm) had a K_{sat} value higher than 2.5 cm/h. But, as the soil depth increased, like all the subsoil in the reclaimed land, the K_{sat} became very low and most of the time the K_{sat} was close to zero. The same result was observed for air permeability.

Table 3. Mean of physical properties measured on the selected soil at the Denmark mine area, Perry County, IL.

			Scraper	- - - - - - - Shovel - Truck - - - - - - -		
Depth (cm)	N	Non - Mined	1977	1981	1985	1989
			Bulk Density (g/cm³)			
0 - 20	3	1.47	1.42	1.49	1.41	1.58
20 - 40	3	1.50	1.62	1.54	1.69	1.73
40 - 60	3	1.45	1.78	1.65	1.67	1.65
60 - 80	3	1.52	1.82	1.70	1.64	1.76
			Total Porosity (%)			
0 - 20	3	44.70	46.37	43.64	46.84	40.31
20 - 40	3	43.57	38.93	41.63	36.07	34.82
40 - 60	3	45.13	32.74	37.87	36.86	37.70
60 - 80	3	42.60	31.43	35.69	38.03	33.44
			Microporosity (%)			
0 - 20	3	32.63	30.73	34.68	32.07	33.29
20 - 40	3	33.70	31.63	32.37	31.00	33.84
40 - 60	3	37.66	29.34	34.63	32.39	37.23
60 - 80	3	37.14	31.18	34.91	31.58	32.49
			Macroporosity (%)			
0 - 20	3	7.99	10.39	5.93	9.68	3.71
20 - 40	3	++	5.05	5.40	4.34	0.68
40 - 60	3	5.16	2.32	2.40	2.19	0.93
60 - 80	3	3.35	2.64	2.07	2.88	0.94
			Soil Strength (MPa)			
0 - 20	36	0.74	0.72	0.56	0.68	0.75
		(0.82)*	(0.63)	(0.79)	(0.75)	(0.85)
20 - 40	36	1.07	2.10	1.28	1.27	0.85
		(0.81)	(0.77)	(0.69)	(1.00)	(0.96)
40 - 60	36	1.33	2.52	2.18	1.29	0.85
		(0.81)	(0.91)	(0.83)	(0.92)	(0.95)
60 - 80	36	1.48	2.26	2.10	1.34	0.88
		(0.90)	(0.99)	(0.92)	(0.87)	(1.00)
80 - 100	36	1.52	2.35	1.97	1.47	2.43

* Values in parenthesis indicate the degree of saturation of the soil at the time of sampling. Water content data at 80 - 100 cm were not available.

++ Denotes damaged core samples.

Figure 1. The relationship between macroporosity and bulk density. The data in the figure is a combination of all the core samples obtained from the selected soils (both mined and non-mined) on the Denmark mine, Perry County, IL.

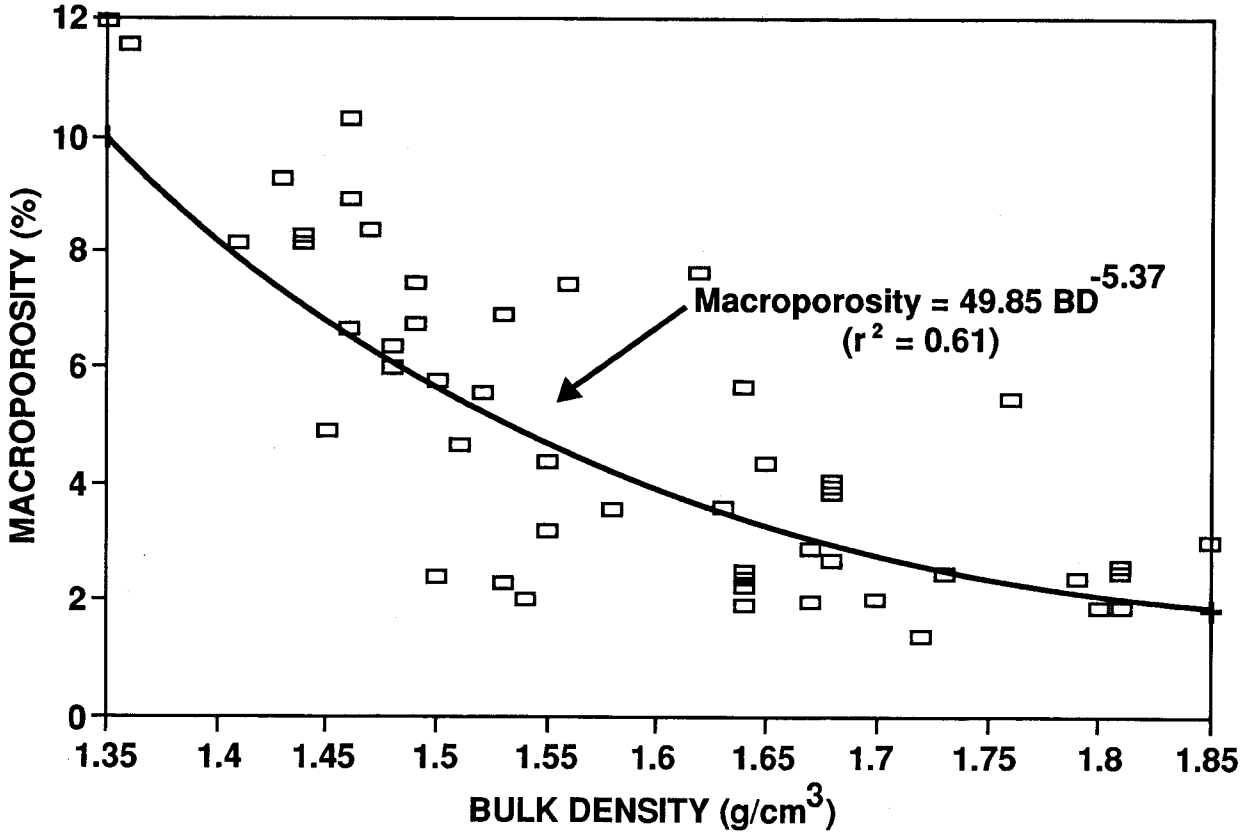


Table 4. Air permeability, 1 hr cumulative infiltration, and saturated hydraulic conductivity measured on soils selected at the Denmark mine area, Perry County, IL.

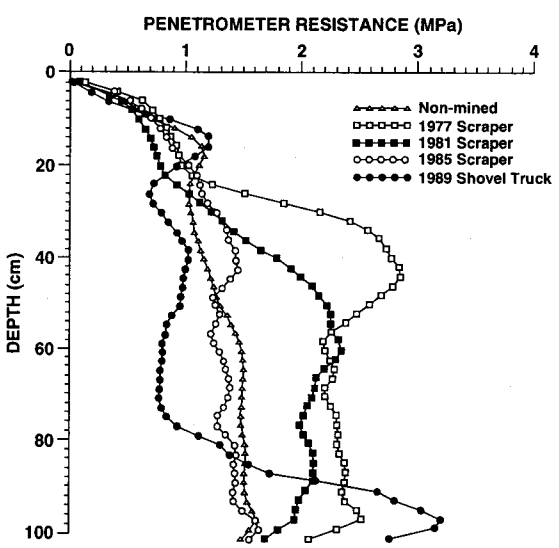
			Scraper	- - - - - - - - Shovel - Truck - - - - - - - -		
Depth (cm)	N	Non-Mined	1977	1981	1985	1989
			Air Permeability (10^{-11} m^2)			
0 - 20	3	1.50	1.74	3.49	1.99	0.84
20 - 40	3	+	0.09	1.83	0.63	+++
40 - 60	3	3.06	0.69	0.97	+++	+++
60 - 80	3	1.51	1.99	+++	0.22	+++
			Cumulative Infiltration (cm) at 1 h			
0 - 20	3	0.81	1.64	4.72	1.38	0.80
20 - 40	3	+	0.36	0.57	0.39	0.56
40 - 60	3	2.52	0.31	++	0.20	++
60 - 80	3	2.73	++	1.13	0.54	0.93
			Saturated Hydraulic Conductivity (cm/h)			
0 - 20	3	0.34	0.32	0.51	0.38	0.25
20 - 40	3	+	**	0.23	**	+++
40 - 60	3	2.54	+++	**	+++	+++
60 - 80	3	**	+++	+++	+++	+++

+ Denotes damaged core samples.
++ Denotes infiltration stopped before 1 hr.
+++ Denotes value too low to be measured.
** Denotes that two out of three samples were measured zero.

CONCLUSIONS

The texture of the rooting media in the soils reclaimed by the scraper and the shovel-truck methods was restored comparably to that of the non-mined Stoy silt loam. The pH of the reclaimed soils was generally higher than that of the non-mined soil, particularly for soil below the 20 cm depth. Organic matter and phosphorus content among the soils studied were not significantly different, but potassium was highly variable among the soils and between depths. In the reclaimed mined soils, soluble salts were high and increased with increasing depth. In contrast, soluble salts were very low in the non-mined soil, especially in the subsoil region (20 - 80 cm). The penetrometer resistance data showed that the soil reclaimed by scrapers in 1977 had the highest soil compaction followed by 1981, 1985, and the non-mined soil. The soil reclaimed by the shovel-truck system had the lowest penetrometer resistance because of high soil water content at the time of sampling. In contrast, the soil reclaimed by scrapers had a lower bulk density than that of the soil reclaimed by the shovel-truck system. However, there is a general decrease in soil penetrometer resistance in soils that were recently reclaimed. The majority of the pores found in the reclaimed soil were micropores, which limited the movement of both air and water in the profile. This conclusion is also supported by results obtained for infiltration, hydraulic conductivity and air permeability experiments. Additionally, macro-porosity was shown to be inversely related to bulk density. This study also revealed that the tilth of the non-mined soil is far better than that of the reclaimed mined soils, even though some of the mined soils had been reclaimed more than a decade ago.

Figure 2. Average soil penetrometer resistance profiles of selected soils on the Denmark mine, Perry County, IL (each curve was an average of measurement).



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Development of a Soil Productivity Index for Use in Prime Farmland Reclamation

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Abstract. Under current federal regulations coal operators are required to grow row crops to prove the productivity of reconstructed prime farmland soils as a prerequisite for Phase III bond release. This study was conducted to determine whether a calculatable index based on the physical and chemical characteristics of the reconstructed soil could be used to accurately predict soil productivity based on corn yield. Soil parameters measured for 30 locations on the River Queen Mine in Muhlenberg County, western Kentucky included: bulk density, cone penetrometer resistance, water holding capacity, phosphorus, potassium, exchangeable aluminum, particle size distribution, and pH. Wheat and corn yield data will be used to further analyze the model as they become available.

INTRODUCTION

In recent years considerable interest has been generated in the concept of developing indices to predict the productivity of croplands on the basis of their physical and chemical soil characteristics. The potential usefulness of such productivity indices (PI) is of special significance as applied to soils reconstructed following the surface mining of prime farmlands.

Current federal regulations governing prime farmland reclamation do not allow release of Phase III bond any sooner than 5 years after the requirements of Phase I have been met. Bond release is primarily contingent on demonstrating that row crop yields with adjustments for weather conditions 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 which 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.

Thus, bond release might be achieved without necessitating the actual growing of corn and other crops as required by most midwestern states as is the case in Kentucky. This would also reduce risks for the coal company for annual planting, management, and harvesting of row crops, and associated soil disturbance, as often companies may have to contract these responsibilities to a third party.

With these goals in mind, a PI model was developed that represents an outgrowth of models put forth in the literature within the past 10 years. The model of Wollenhaupt (1985) in particular was tailored to meet the yield prediction needs associated with reconstructed prime farmland soils in the Midwest. Select parameters previously unmodelled were introduced because of their significance in soil restoration. These include subsoil: soil fertility (phosphorus and potash), soil acidity (exchangeable Al), and cone penetrometer resistance. Consideration in their selection was given to incorporating the fewest number of parameters that are not only predictive of root growth, but also provide a cost-efficient means of measurement to the operator.

The model is being tested for soil profiles and corresponding yield data extracted from a data set of 30 locations from a test field at the River Queen site in Muhlenberg County in western Kentucky over a 3-year period.

LITERATURE REVIEW

Requirements for Reconstructing Prime Farmland Soils Following Mining

Soil replacement regulations which affect prime farmlands following mining require that the minimum depth of soil and substitute material used in soil reconstruction be 48 inches (122 cm), "or a lesser depth equal to the depth to a subsurface horizon in the natural soil

that inhibits or prevents root penetration, or a greater depth if determined necessary to restore the original soil productive capacity" (Kentucky Natural Resources and Environmental Protection Cabinet, 1986).

Productivity Indices

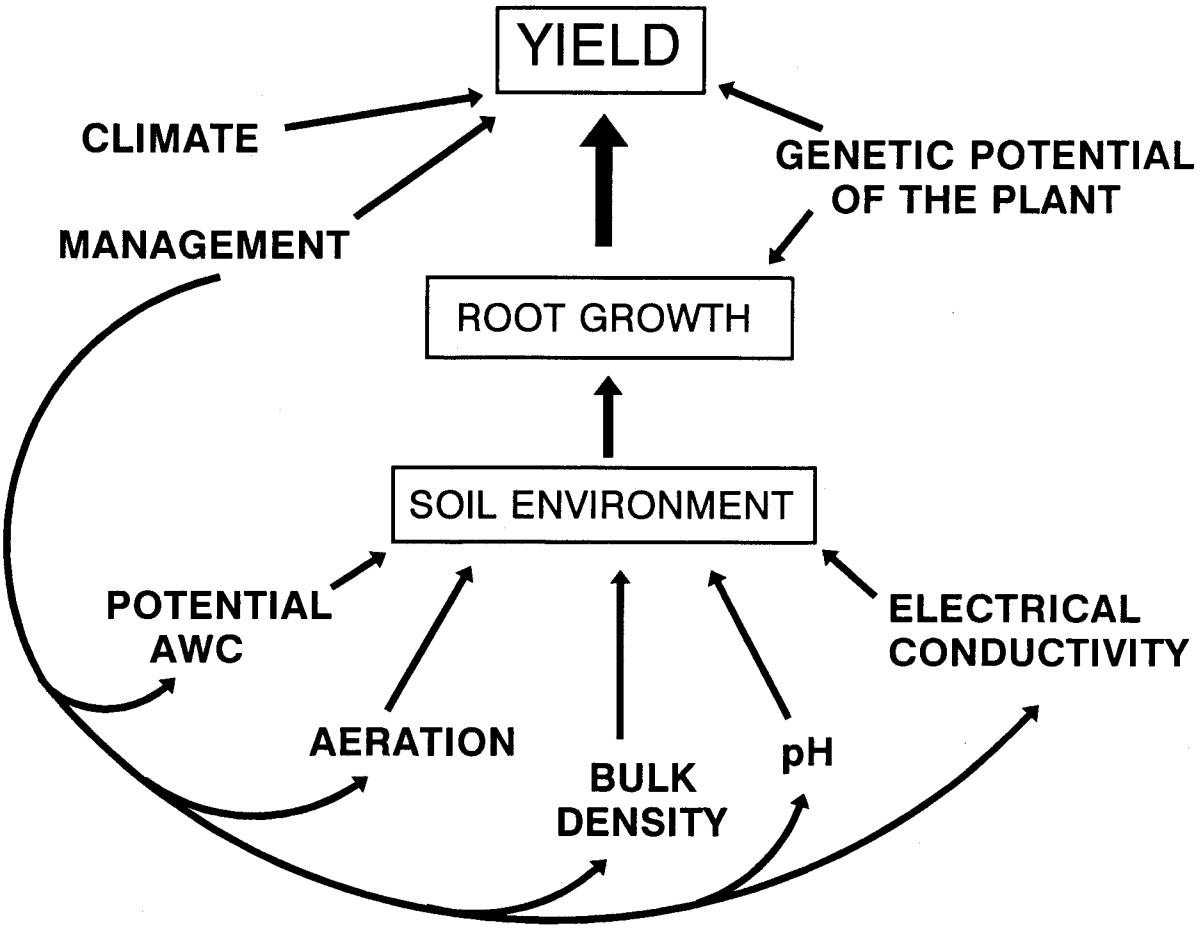
Over the past 60 years in the United States, a variety of quantitative expressions have been proposed for the purpose of inducing soil productivity from soil characteristics. These indices have been developed in response to specific needs in agricultural land use planning and in the equalization of land 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 (Figure 1). Her model evaluated horizons of soil profiles in terms of potential available water storage capacity, aeration, bulk density, pH, and electrical conductivity and the sufficiency level of each to promote root development. The product of these five sufficiency factors was then multiplied by a depth-dependent root weighting factor per 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.

Pierce et al., (1983) built off 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, Pierce 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 refined the model further by considering the four root development sufficiency factors of bulk density, available water, pH, and electrical conductivity. Adjustments to sufficiency equations were made. Bulk density was considered to be dependent not only on texture class, but also on hydraulic conductivity. Available water was redefined as water held between the matric potentials of 10 and 1500 kPa. The sufficiency of pH was modified after that reported by Pierce and associates and the sufficiency of electrical conductivity was modified after Kiniry et al., (1983).

Figure 1. Conceptual model presented by Kiniry et al., (1983).



Wollenhaupt (1985) normalized the root distribution curve between the upper and lower horizon boundaries, solved the integral for centimeter increments, and found the relationship to approach the power function

$$Y = ax^b$$

where:

y = root weighting factor

a, b = constants

x = horizon depth.

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. Subsoil fertility was considered essential to adequate root growth and beyond the control of surface management techniques.

Total acidity, especially exchangeable Al, of the subsoil has been demonstrated to be a significant factor which can potentially impair crop yields (McKenzie and Nyborg, 1984). Acidity can be a consideration in the soils and overburden materials associated with coal surface mining in the Midwest.

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 of provisions for water movement, aeration, and root system extension are lacking (Hooks and Jansen, 1986).

Data presented by Thompson et al., (1987) indicate that within each soil horizon, as cone penetrometer resistance increases, average root density decreases. This effect appears to be most profoundly evidenced in the 67-88 cm and 89-110 cm layers studied for soils at the Captain Mine in Perry County, Illinois on fields where soil reconstruction was achieved using the mining wheel-conveyor spreader system.

LABORATORY METHODS

Experimental Site

An experimental site was established on the River Queen Mine operated by Peabody Coal Company near Central City in Muhlenberg County, in western Kentucky. The site selected for "prime" soil reconstruction was a preparation plant waste gob on which a 50 cm layer of mine spoil had been deposited. The spoil was composed of a mix of acid, sandstone, shale, mudstone, and siltstone.

Reconstruction of a subsoil was accomplished by depositing a Sadler silt loam soil to a depth of 50 cm over the spoil. A 20 cm topsoil layer composed of silt loam A horizon material (organic matter | 1.5%) was deposited during the Spring of 1988. All soil deposition was accomplished through the use of scraper pans (Semalulu, 1992).

The field was ripped to 60 cm depth prior to fertilizer additions with a 'Rome' ripper that has four shanks approximately 75 cm apart. Phosphorus and K fertilizers were surface broadcast. The area was planted to wheat (Pioneer 2555) in the fall of 1990 and harvested in June, 1991. Soil samples and penetrometer measurements were taken in early July from the same areas where wheat yields were collected.

Soil Sampling

A tractor-mounted Giddings coring machine was used to collect soil samples on a grid comprising 30 field locations. Two samples at each location were taken approximately one foot apart; each core was to a maximum depth of 30 in (76 cm). Sampling locations were separated by 80 ft (24.38 m) longitudinally and 50 ft (15.24 m) laterally.

Cone penetrometer resistance was introduced to the productivity index model as a potentially efficient alternative to bulk density as a measure of soil compaction. Although bulk density sampling can be accomplished across a wider range of soil moisture conditions, data collection and analysis are more time-consuming than that required for cone penetrometer resistance. Cone penetrometer resistance measurements can be rapidly accomplished when soil is sufficiently moist. 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 were performed by the Dept. 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 pH was determined using a glass universal electrode (Van Lierop, 1990; Eckert, 1988; and The Council on Soil Testing and Plant Analysis, 1980). Exchangeable aluminum was determined employing the titration method of Yuan (1959). Available P and K were determined by the Mehlich III (M-3) extraction (Tucker, 1988a; Tucker, 1988b).

Percent sand, silt, and clay were determined by the pipet method of Gee and Bauder (1986). 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 29 cm/s. A 30° right-circular cone point of 6.45 cm (1 in) cross-sectional area was employed after the methods of Hooks and Jansen (1986). Measurements were recorded on chart paper. A replicate measurement at each sample location was taken. Areas under the recorded curves were integrated as representative of psi of resistance.

PI MODEL DEVELOPMENT

The productivity index model tested is a sum of products. Each soil test value is assigned a sufficiency factor ranging between 0 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 which comprise that profile. Conceptually the model is depicted in Figure 2.

The equation for the subject 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

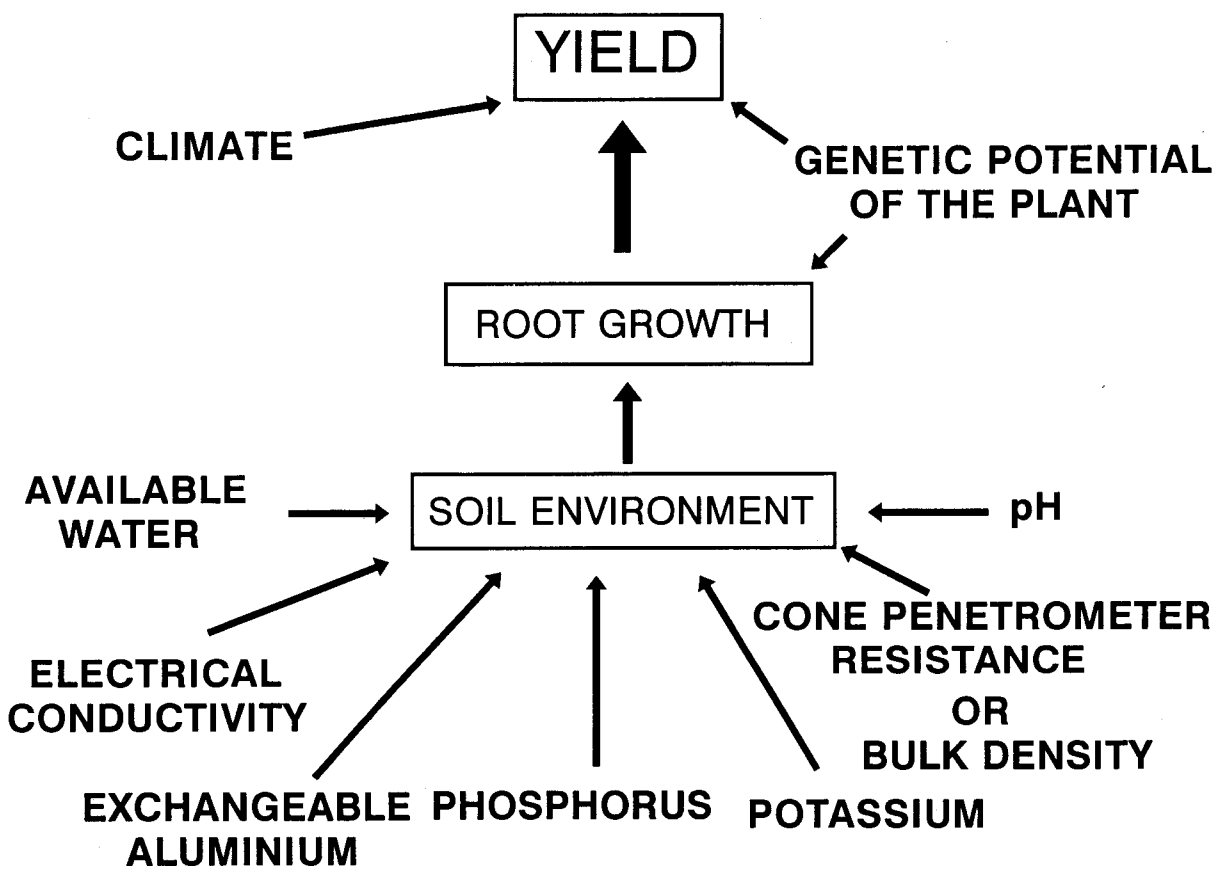
EA_i = exchangeable aluminum sufficiency for the ith soil layer

CPR_i = cone penetrometer resistance sufficiency for the ith soil layer

WF_i = root weighting factor for the ith soil layer.

Sufficiency equations developed by previous workers were adopted for: bulk density (Wollenhaupt, 1985), available water (Kiniry, 1983 and Wollenhaupt, 1985), pH (Pierce et al, 1983 and Wollenhaupt, 1985), and

Figure 2. Revised conceptual model.



electrical conductivity (Kiniry, 1983 and Wollenhaupt, 1985). For the purpose of this application electrical conductivity and hydraulic conductivity (in relation to its effect on bulk density sufficiencies as calculated in the model) were assumed to be non-limiting in their effect on root growth.

Sufficiency curves were developed for the remaining parameters. Linear equations were used to describe the sufficiency functions of both P and K (University of Kentucky, 1990). Because it has been shown by Woodruff and Parks (1980) and others that corn roots do not obtain P and K below certain soil depth, it was assumed that:

IF UDEPTH $\geq$ 61 THEN KSUFF = 1:PSUFF = 1

where:
UDEPTH = upper depth of the ith soil layer in cm
KSUFF = potassium sufficiency
PSUFF = phosphorus sufficiency.

Based on soil test data (Univ. of Kentucky, 1990) it was assumed that K and P soil test data in excess or within the medium soil test range were sufficient for plant root development.
Therefore,
IF P > 60 THEN PSUFF = 1
IF K > 300 THEN KSUFF = 1.

Furthermore, the following ranges in P and K values were used to define linear equations relating soil test values to sufficiency.
IF P $\geq$ 30 AND P < 60 THEN PSUFF = .0833P + .5
IF P $\geq$ 10 AND P < 30 THEN PSUFF = .0125P + .375
IF P $\geq$ 0 AND P < 10 THEN PSUFF - .04P + .1
IF K $\geq$ 200 AND K < 300 THEN KSUFF = .0025K + .25
IF K $\geq$ 90 AND K < 200 THEN KSUFF = .0023K + .3
IF K $\geq$ 0 AND K < 90 THEN KSUFF = .0044K + .1

Findings from subsoil acidity studies that have examined the effect of exchangeable aluminum on forage yields from the crops of barley and alfalfa as conducted by McKenzie and Nyborg (1984), Hoty and Nyborg (1972), and Webber et., al (1982) were used as a basis for determining the relationship of exchangeable aluminum to exchangeable aluminum sufficiency, as follows:
IF EA = 0 THEN EASUFF = 1
IF EA > 0 AND EA < .033 THEN EASUFF = -.03EA + 1
IF EA $\geq$ .033 AND EA < .22 THEN EASUFF = -.012EA + .975
IF EA $\geq$ .22 AND EA $\leq$ .27 THEN EASUFF = -.08EA + 2.075
IF EA > .27 THEN EASUFF = .1
where:
EA = exchangeable aluminum in meq/100g
EASUFF = exchangeable aluminum sufficiency.

Soil strengths demonstrated as limiting and non-limiting to the development of ideal corn root distributions with depth were developed after yield data presented by Thompson et al (1987). The following assumptions were made and incorporated into the model:
IF LDEPTH $\leq$ 15 THEN CPRSUFF = 1
IF CPR $\leq$ 200 THEN CPRSUFF = 1
IF CPR $\geq$ 400 THEN CPRSUFF = 0.1
IF CPR > 200 AND CPR < 400 THEN CPRSUFF = -.0045 CPR + 1.9

where:
LDEPTH = lower depth of the ith soil layer in cm
CPRSUFF = cone penetrometer resistance sufficiency
CPR = cone penetrometer resistance in psi

The root weighting factor was taken after Wollenhaupt (1985, and personal communication, 1992), such that

$$WF = .04295\ (\text{soil depth})^{0.68351}$$

The model is programmed in GW BASIC for batch processing of data on IBM PC-compatible equipment.

Model Verification

Productivity indices generated by the model will be tested for their predictive capability by determining their correlation coefficients with corn yield at the 5 and 10 percent confidence limits.

PREDICTIVE CAPABILITY OF THE MODEL

Assessment of the predictive capability of the model in terms of accurately forecasting corn yield continues. Corn production figures from the subject site should be available in the late Summer of 1992. Wheat harvest data (Figure 3) obtained during June, 1991, are being used on a preliminary basis for the purpose of model testing.

Selected soil sampling points representing a range in wheat yields have been used to test the proposed model. These same data were used as input for the model developed by Wollenhaupt, and trends and differences between the two sets of calculated PIs noted. In all cases, electrical conductivity was assumed to have a sufficiency of 1, and hydraulic conductivity was assumed to be non-limiting in the calculation of an adjusted bulk density based on soil texture.

Because of the preliminary nature of the model at this printing, no further discussion will be offered. Testing of the model using both wheat, and eventually corn yield data is scheduled. Results from the wheat and perhaps data from other laboratories will be reported in August, 1992.

SUMMARY

A productivity index model which represents an expansion of current thought and a tailoring to the specific mine reclamation needs of midwestern prime farmlands was developed. It considered the added effects of soil fertility (P and K) acidity in the form of exchangeable Al, and cone penetrometer resistance as an optional measure of soil compaction. Corn yield data will not be collected until the late summer of 1992 for the soil conditions measured. Analysis of the model continues.

ACKNOWLEDGMENT

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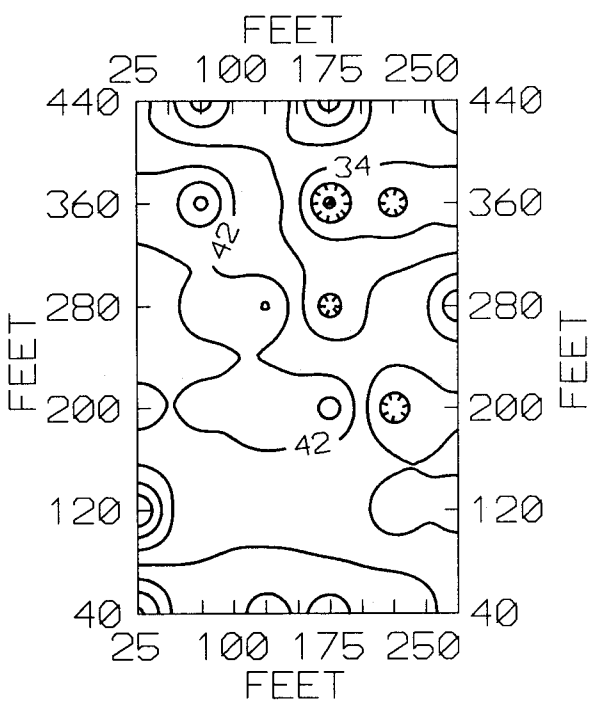
Figure 3. Wheat yield at River Queen Mine 1991.



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Bulk Density Response to Placement Methods and Remedial Measures in Reconstructed Prime Farmland Soils[1]

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Abstract. Experiments were conducted in cooperation with Peabody Coal Company at two surface mine sites. Soil bulk density was determined at multiple depths and locations within experimental plots using both volumetric core samples and gamma ray attenuation.

At the River Queen site, a Sadler silt loam soil was reconstructed in distinct A & B horizons during 1983 using scraper placement and dozer grading. For plots planted immediately in notill corn, subsoil bulk density has gradually decreased over time. Multiple ripping of some plots did not affect this rate of decrease. Initial planting in alfalfa with no ripping produced a slight decrease in subsoil bulk density, whereas a, more dramatic decrease was indicated for plots initially planted in black locust.

Two methods were investigated for placement of Sadler and Belknap silt loam prime farmland soils at the Gibraltar site. Plots were constructed in 1982-83 using (a) scraper placement and dozer grading of both A & B horizons and b) truck placement of A & B horizons by end dumping with grading of each horizon by dozers. In all cases, ripped plots exhibited lower bulk density than non-ripped plots. There was no significant difference between the two placement methods studied with regard to subsoil bulk density.

INTRODUCTION

Successful reclamation of prime farmland soils was specifically mandated by the landmark U.S. Surface Mining Control and Reclamation Act (Public Law 95-87,m 1977). The U.S. Soil Conservation Service was charged with identifying specific criteria for evaluating productive potential of prime farmland and thereby insuring compliance with the law. The result has been the identification of target yield requirements for specific crop-soil-location situations.

Soil bulk density is widely recognized as a physical property which is indicative of crop production potential (Barnes, 1971). Regulatory agencies have recognized the adverse effects of excessive soil bulk density upon productivity and have encouraged development of methods for controlling compaction during soil reconstruction. The objective of this study was to evaluate various means of avoidance and remediation relative to the long-term productivity of reconstructed prime farmland soils.

[1]The investigation reported in connection with a project of the Kentucky Agricultural Experiment Station and is published with the approval of the Director of the Experiment Station as paper no. RIS 91-48.

REVIEW OF LITERATURE

The adverse effects of excessive soil compaction have been extensively documented during the last two decades (Barnes, 1971 and Soane et al., 1981). This problem is exacerbated by the growing use of large agricultural field machinery with relatively high axle loading ($\geq$ 9 Mg). Taylor et al. (1980) showed that such equipment can cause compaction of subsoil below the depth of conventional tillage even when surface contact pressure is no greater than that of smaller equipment. The effect of such deep compaction has been shown to persist for decades (Graecen and Sands, 1980).

Obviously, the use of heavy off-road equipment in the transportation and reconstruction of severely disturbed soil profiles can contribute to severe persistent soil compaction. The U.S. Bureau of Mines commissioned a study of different methods of reconstructing prime farmland soil in the midwestern United States (Albrecht, 1984). Three methods of replacing subsoil or rooting medium were investigated: scrapers, bucket-wheel excavator/spreading conveyor, and backdumping with trucks. In each method scrapers were used to deposit a layer of topsoil. All methods resulted in excessive subsoil compaction, which was caused by scraper traffic during topsoil deposition. Dunker et al.

(1991) have shown that when topsoil was deposited without traffic on subsoil, significantly high crop yields and significantly lower subsoil cone penetration strength resulted.

Powell et al. (1985) and Barnhisel et al. (1986) presented the results of research in Kentucky aimed at identifying preferable methods of prime farmland reconstruction. At the Peabody Coal Company River Queen mine near Central City, experimental plots were constructed to determine the effects of deep tillage or ripping and deep rooting crop species upon the amelioration of a silt loam prime farmland soil reconstructed by scraper placement and dozer grading. At the nearby Gibraltar mine, the effects of placement method and post-placement deep tillage on the physical properties and productive potential of two prime farmland soils were also examined.

This study presents the results of field determinations of subsoil bulk density in order to:

1. Determine the comparative effects of different species of vegetation, planted immediately following reconstruction, on amelioration of excessive subsoil compaction.
2. Determine the effect of deep tillage or ripping on reduction of subsoil bulk density.
3. Determine the effect of placement method on initial subsoil bulk density and on changes in bulk density over time.

EXPERIMENTAL METHODS

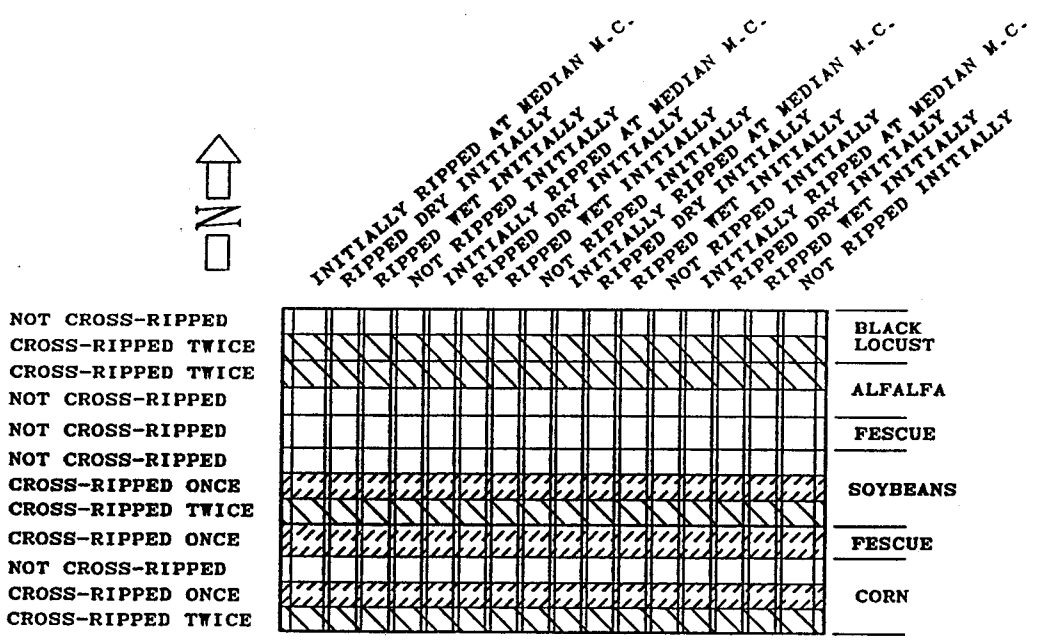
Experimental plots reconstructed using prime farmland soils at the River Queen and the Gibraltar surface mines of the Peabody Coal Company in northern Muhlenberg County, Kentucky as well as methods of measuring soil bulk density are described as follows.

River Queen Plots

An experimental soil profile was constructed during the fall of 1983 at the River Queen site from a disturbed Sadler (fine-silty, mixed, mesic, Glossic Fragiudalf) silt loam soil using scrapers and dozers. A mixed fine-silty subsoil (B horizon) material was deposited over graded spoil to an approximate depth of 80 cm (32 in.) in successive layers deposited by scrapers. Approximately 20 cm (8 in.) of low organic matter silt loam topsoil (A horizon) material was then deposited by scrapers and graded by wide-track dozers to minimize ground contact pressure.

A rectangular area 91 m x 145 m (300 ft x 475 ft) of reconstructed soil was established at the site (see Fig. 1). The area was divided into 16 plots, 7.6 m (25 ft) wide oriented N-S, separated by 1.5 m (5 ft) horizontal strips. Initial deep tillage treatments were then applied using a Rome ripper with parabolic shanks spaced 1.2 m (4 ft) apart to an approximate depth of 61 cm (24 in.). Soil

Figure 1. Diagram of experimental reconstructed prime farmland (Sadler Silt Loam) Soil at River Queen Mine showing vegetative and ripping treatments.



was ripped following reconstruction at three levels of moisture content: dry, 1/2 field capacity, and field capacity, with a non-ripped control. Each set of ripping treatments was replicated four times.

Various species of vegetation were superimposed on these experimental plots by subdividing the area in the E-W direction. Parallel strips or plots were established as follows from north to south (see Fig. 1): 15.2 m (50 ft), local black locust; 15.2 m (50 ft), alfalfa (Vernal variety); 9.1 m (30 ft), KY 31 tall fescue; 21.3 m (70 ft), no-till soybeans; 9.1 m (30 ft), KY 31 tall fescue; and 21.3 m (70 ft), no-till corn.

During 1985, the corn and soybean plots were disked and planted and two-thirds of each plot was ripped in the E-W direction. In 1986, the plots were disked and planted, then 1/3 of each plot was again ripped in the E-W direction. The plots planted in black locust, alfalfa and fescue were mowed in 1985 and 1986. In 1987, the black locust plot was disked to a depth of 15 cm (6 in.) and the alfalfa and tall fescue plots were treated with herbicide. Subareas of each plot were again ripped and the entire area was planted to no-till corn. During 1988-90, the area was planted in no-till corn, conventionally tilled corn and conventionally tilled grain sorghum, successively, with no additional ripping. Additional details concerning the experimentation associated with these plots is given by Powell et al. (1985).

Cylindrical soil cores (5 cm (2 in.) dia., 15 cm (6 in.) long) were collected from each ripping x crop plot area immediately after soil reconstruction (prior to any planting or ripping) in early 1984 using a Giddings hydraulic sampler. Initial bulk density was thus determined for each 15 cm (6 in.) layer of reconstructed soil. Additional core samples were collected in 1985 and 1986 in the corn plots and in 1987 in the alfalfa plots. In 1988, volumetric cores were collected and bulk density was also determined using a gamma ray attenuation gauge. The plots sampled in 1988 were: corn, never ripped; corn, initially ripped dry (N-S), cross-ripped (E-W) in 1985, 86 and 87; alfalfa, never ripped; and, black locust, never ripped. The corn, black locust and alfalfa plots were again sampled or measured in the fall of 1990 using a dual probe gamma density gauge and again in the fall of 1991 using volumetric cores.

Gibraltar Plots

Two soil profiles were reconstructed at the Gibraltar mine site using the previously described Sadler soil and a Belknap (coarse-silty, mixed, acid, mesic, Aeric Flavaquent) silt loam soil. Table 1 shows the horizon designations and depths for these two reconstructed soils.

Two methods were used to reconstruct the soils in the fall of 1982 and spring of 1983. Eight parallel strips, 21.3 m x 97.5 m (70 ft x 320 ft) were deposited of each soil using two equipment handling methods and using both direct placement and stockpiling (see Fig. 2). In the conventional method, 18.3 m^3 (24 cu. yd.) scrapers were used to deposit subsoil in successive layers or lifts of approximately 40 cm as needed. Grading was accomplished by dozers equipped with wide tread to reduce contact pressure. Approximately 20 cm (8 in.) of topsoil was deposited by scrapers and graded.

The other method involved the use of 32 m^3 (35 yd^3) end-dump trucks. The trucks deposited subsoil by horizon without driving on the plots. Grading of each horizon was done using wide track dozers. Topsoil was placed in identical fashion with final grading by dozers.

In the spring of 1983, alfalfa was planted at both ends of the area in 12.2 m (40 ft) strips, perpendicular to the main treatment plots. In the center, 12-row strips of corn and soybeans were alternated giving four replications. In the fall of 1984, one half of each main treatment strip was ripped to a depth of 61 cm (24 in.) at 1.2 m (4 ft) spacing, in the areas planted in corn and soybeans. Only corn was planted in the interior subplots in 1984 and 1985. In 1986, the entire area was planted in corn, including the end strips which had been in alfalfa for 4 years. During 1987-90, the entire area was planted in corn, soybean, wheat, and wheat, successively. Conventional tillage methods were used for seedbed preparation and row-crop cultivation as appropriate. Additional details concerning the experiment plot design at this site is given in Barnhisel et al. (1986).

A Giddings hydraulic sampler was used to extract volumetric bulk density cores from each of the soils prior to disturbance. Four replicated samples of 5.1 cm (2 in.) dia. x 15.2 cm (6 in.) cores were collected at depths of 0-15.2, 15.2-30.5, 45.7-61, and 76.2-91.4 cm (0-6, 6-12, 18-24 and 30-36 in.). Following construction of the plots, four replicated core samples were collected from each treatment strip at 15.2 cm (6 in.) depth increments to a depth of 91.4 cm (36 in.).

A dual-probe gamma ray density gauge was also used to measure in situ soil bulk density. In 1989, four replicated measurements were made in interior zone of the following treatment strips for both soil types: a)

Table 1. Horizon designation and depths of Sadler and Belknap soils (from Barnhisel et al., 1986).

Soil Series	Horizon	Depth from Surface (cm)
Sadler	Ap	0-18
Sadler	B2t, A'2	18-64
Belknap	Ap	0-20
Belknap	B21, B22g, B23g	20-90

direct scraper placement, never ripped; and, b) direct truck placement, never ripped. The measurement depths were 20.3 cm (8 in.), 50.8 cm (20 in.) and 61 cm (24 in.). In 1990, gamma density measurements were replicated 3 times for both soil types in the following treatment strips: a) direct scraper placement, never ripped; b) direct scraper placement, ripped; c) direct truck placement, never ripped; and, d) direct truck placement, ripped. Measurements were made at 5.1 cm (2 in.) depth increments to a depth of 91.4 cm (36 in.).

Soil moisture content was determined at each bulk density sampling location. When volumetric cores were used to determine soil bulk density (prior to 1989), soil moisture content was determined gravimetrically. In 1989, small samples were collected during the drilling of vertical access holes for the gamma density gauge. In 1990, soil moisture content was determined using a gauge which measured neutron scattering. This method has been shown reliable for measurement, below a depth of approximately 10 cm (Black et al., 1965).

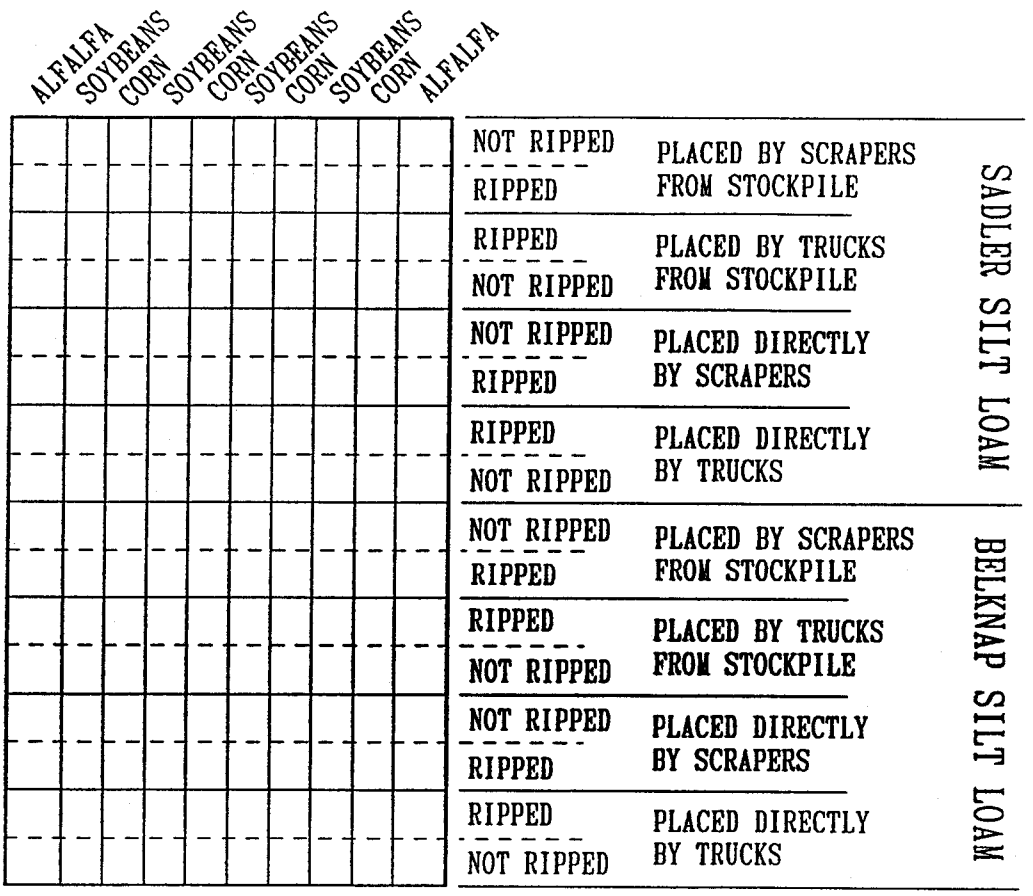
RESULTS AND DISCUSSION

River Queen Plots

Figures 3 and 4 present the results of the various determinations of subsoil bulk density versus depth at this site. Dry subsoil bulk density is plotted versus depth for each major treatment examined. Each profile represents the mean of four replicated measurements.

Comparison of subsoil bulk density versus depth profiles immediately after reconstruction indicates substantial compaction of this soil relative to its predisturbed state. Subsoil bulk density for the natural Sadler soil increased from approximately 1.43 Mg/m^3 at z = 23 cm (9 in.) to 1.63 Mg/m^3 at z = 83.8 cm (33 in.) (Powell et al., 1985). Subsoil bulk density following reconstruction was approximately 1.8 m^3/Mg for all plots below the depth of 38 cm (15 in.), except for the non-ripped plots planted in corn, which was approximately 1.7 Mg/m^3.

Figure 2. Diagram of experimental reconstructed prime farmland (Sadler and Belknap Silt Loam) soils at Gibraltar Mine showing placement and ripping treatments.



The corn plots which were never ripped exhibited gradual increase in subsoil density from reconstruction until 1988, followed by a notable decrease between 1988 and 1990. Measurements in 1991 were slightly higher than 1990, but confirm a slight decrease in bulk density over time. Only in 1988 was subsoil density as high as that in the corn plots which received the most ripping. The clear effect of all factors operating over time was to substantially decrease bulk density in the upper subsoil (40-60 cm), while having less effect on the deep subsoil (> 70 cm). It is not clear from these plots, however, that ripping affected a reduction in subsoil bulk density that would not have occurred by means of rooting actions or other natural phenomena.

The alfalfa and black locust plots were approximately equivalent in terms of deep subsoil bulk density from reconstruction to measurement in 1988. Higher subsoil bulk density in the black locust plots (for z > 50 cm) measured in 1988 probably resulted from the heavy disking used to destroy the black locust saplings in 1987.

Clearly, the notable reduction in subsoil bulk density in the black locust plots is the most intriguing result. An approximate reduction of 0.2 Mg/m^3 is indicated without the use of deep tillage. Additional field measurements will be made during the spring of 1992 to confirm this result. If the aggressive rooting behavior of black locust indeed created conditions whereby natural phenomena can further reduce subsoil bulk density, then this species could be an important consideration in prime farmland reclamation.

Figure 3. Soil bulk density profiles at various times in experimental plots, initially planted in corn, at the River Queen Mine.

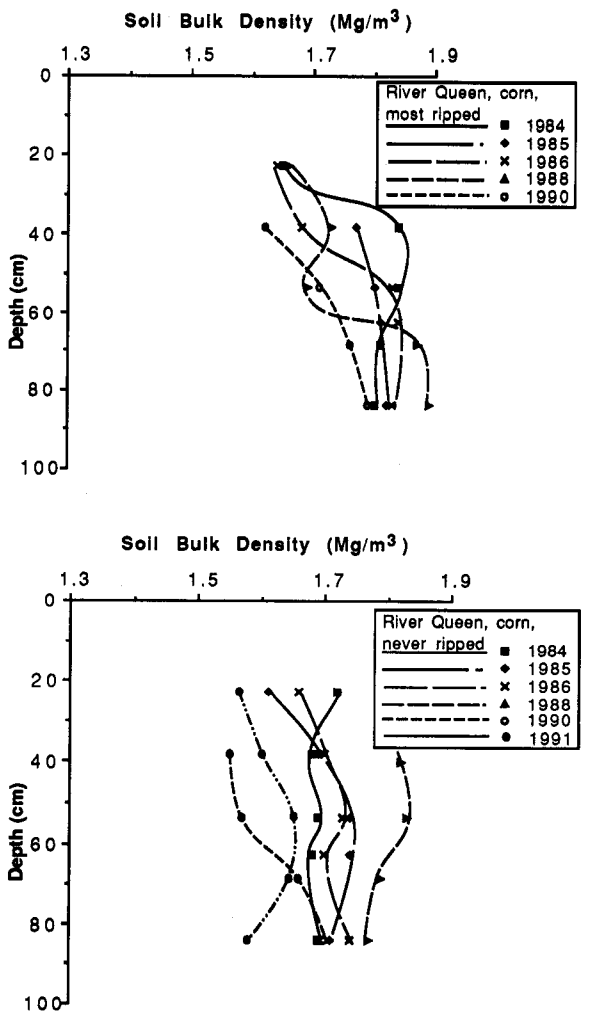
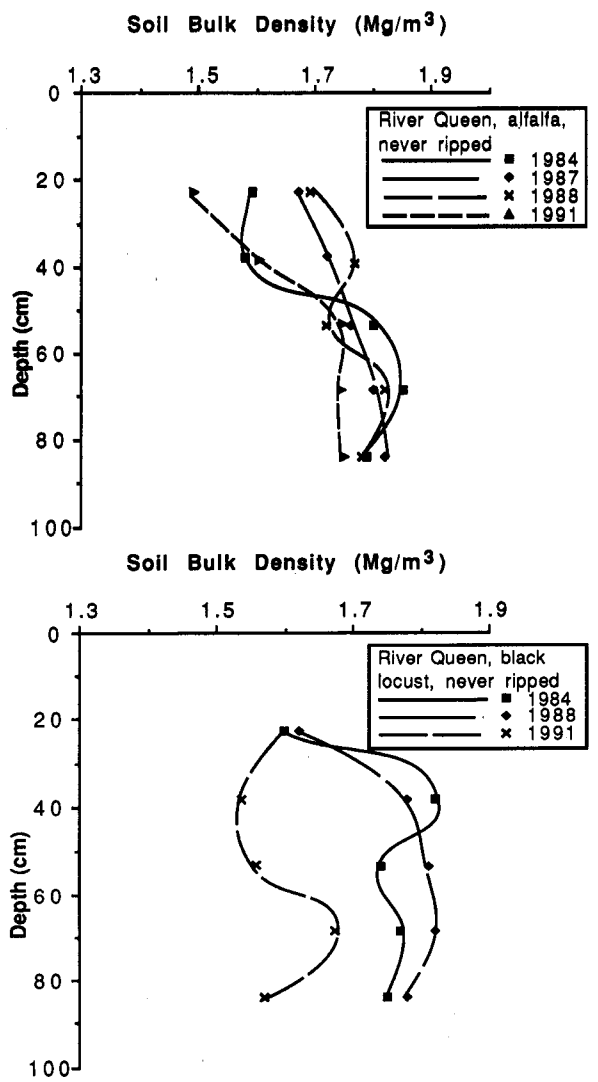


Figure 4. Soil bulk density profiles at various times in experimental plots, initially planted in alfalfa and black locust, at the River Queen Mine.



Gibraltar Plots

Figures 5 and 6 present the results of the various subsoil bulk density versus depth profiles measured at this site. The bulk density immediately after reconstruction was substantially greater than in the pre-mined state at all depths for both soil types and placement methods. Further, there is no clear indication, in either soil type, that placement method significantly affected bulk density immediately after reconstruction. This was somewhat surprising since only dozer traffic was applied to the plots constructed by truck placement. The results would indicate that for these soils and the conditions which prevailed at the time of placement, dozer traffic compacted subsoil as much as scraper/dozer traffic.

Bulk density measurements taken in 1989 in non-ripped plots indicate that subsoil bulk density increased for $z \geq 50$ cm (20 in.) and decreased for $z < 50$ cm. The exception to this was the truck-placed Belknap soil, where subsoil bulk density decreased at all depths, compared with the initial (1983) profile.

The 1990 measurements present contrasting behavior in the two soil types. In the Sadler soil, subsoil bulk density apparently decreased relative to the 1983 and 1989 measurements in both ripped and non-ripped plots. In the Belknap soil, however, subsoil density increased in the non-ripped plots compared to earlier measurements. Ripping appeared to decrease subsoil bulk density in both soils for both placement methods.

Table 2 presents a comparison of mean bulk densities measured in 1990 for the various experimental treatments, i.e. placement method and ripping, using Duncan's New Multiple Range Test (SAS, 1986). In the Sadler soil, ripping resulted in significantly lower bulk density (5% level) at the 61-76.2 cm (24-30 in.) depth in the truck-placed plots, whereas there was no significant reduction at any depth in scraper-placed plots. In the Belknap soil, ripping produced significantly lower bulk

Figure 5. Soil bulk density profiles at various times in experimental plots, reconstructed by two methods, in Sadler Silt Loam Soil at the Gibraltar Mine.

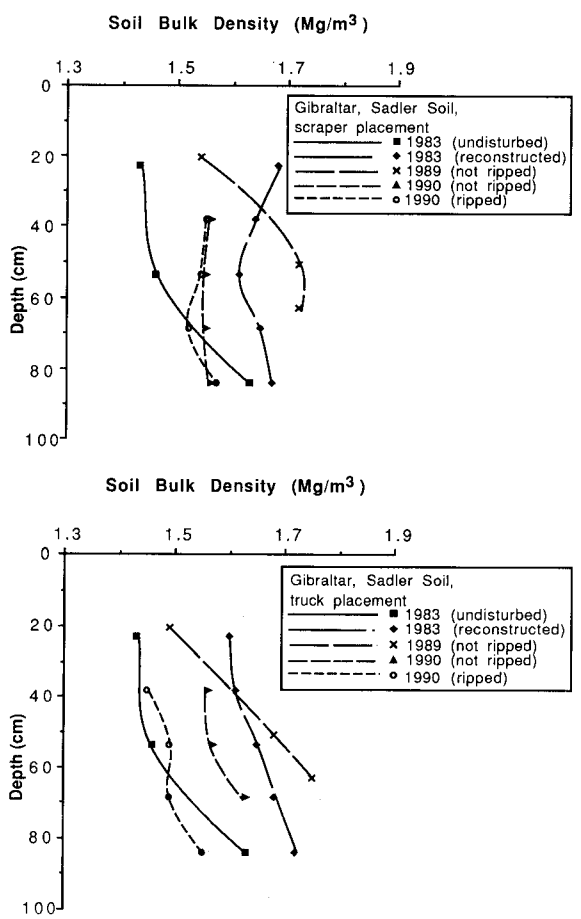
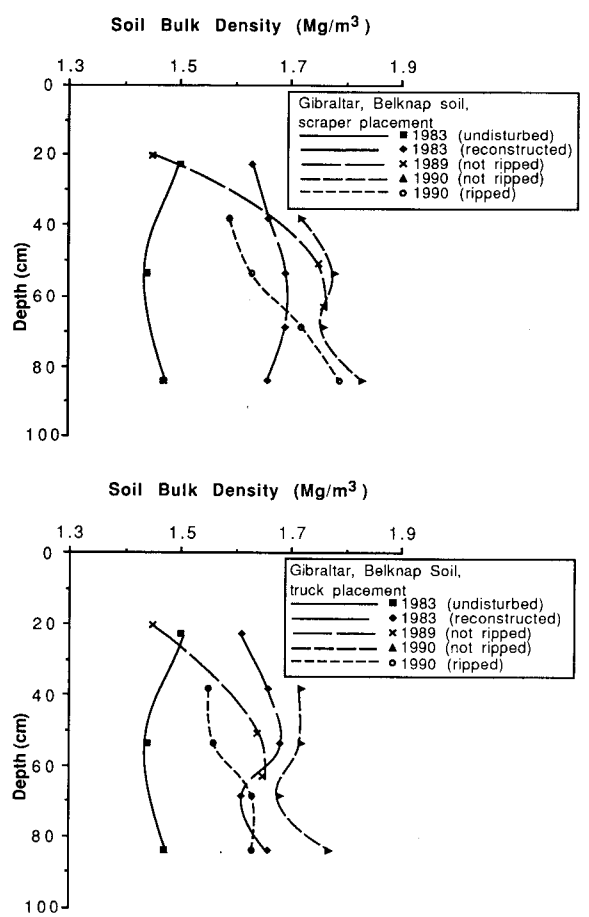


Figure 6. Soil bulk density profiles at various times in experimental plots, reconstructed by two methods, in Belknap Silt Loam Soil at the Gibraltar Mine.



density within all subsoil depths except 61-76.2 cm (24-30 in.) in the truck-placed plots, while reducing density only in the upper subsoil (30.5-61 cm (6-18 in.)) in scraper-placed plots. Significantly lower bulk density for truck placement was indicated only in the Belknap soil at the 76.2-91.4 cm (30-36 in.) depth in plots which were ripped.

In the Sadler soil, subsoil bulk densities measured in 1990 seem to be approaching that of the premining condition in all plots subjected to ripping. In the Belknap soil, however, subsoil bulk density remains substantially higher than that of the premining condition for all cases. In this soil, ripping substantially reduced subsoil bulk density, yet was unable to approach pre-disturbance levels.

CONCLUSIONS

The conclusions of the study are as follows:

1. Primary planting of a reconstructed prime farmland soil in alfalfa for three growing seasons resulted in a slight decrease in subsoil bulk density measured six years after reconstruction, whereas planting in black locust for the same time period produced a substantial reduction. Additional measurements will be taken in 1992 to confirm this result.
2. In all cases examined, ripped plots exhibited lower subsoil bulk density than non-ripped plots.
3. There was no significant difference between the truck and scraper placement methods with regard to subsoil bulk density.

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Table 2. The effect of placement method and deep tillage on subsoil bulk densities of two reconstructed prime farmland soils by Duncan's New Multiple Range Test

Depth (cm)	Truck Placement Not Ripped	Truck Placement Ripped (610 mm)	Scraper Placement Not Ripped	Scraper Placement Ripped (610 mm)
Sadler Silt Loam				
30.5-45.7	1.56a*	1.45a	1.56a	1.55a
45.7-61	1.57a	1.49a	1.55a	1.54a
61-76.2	1.63a	1.49a	1.55ab	1.52ab
76.2-91.4	—	1.55a	1.56a	1.57a
Belnap Silt Loam				
30.5-45.7	1.72a	1.55b	1.72a	1.59b
45.7-61	1.72ab	1.56c	1.78a	1.63bc
61-76.2	1.68ab	1.63b	1.76a	1.72ab
76.2-91.4	1.77a	1.63b	1.83a	1.79a

*At a given depth, mean bulk densities designated by the same letter are not different at the 5% level of significance.

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A Soil-based Productivity Index to Assess Surface Mine Reclamation

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Abstract. Need exists for a method to evaluate surface mine reclamation in the absence of test plots. Differential distribution of rainfall by summer thunderstorms, pests, soil variability, differential variety performance, and frequent problems with timing of spring planting all contribute to the difficulties of comparing yields among reclaimed and unmined sites. A soil-based productivity index developed at the University of Missouri-Columbia may provide a conceptual framework useful for developing a productivity index suitable for reclaimed minesoils. The concept of the productivity index is that the soil environment affects root growth, and that plant yield will be proportional to root growth. Five easily measured soil properties — aeration, pH, bulk density, potential available water-holding capacity, and salinity — were chosen to represent the soil environment. An equation was developed which uses sufficiencies of individual soil properties based upon optimum conditions in an ideal soil. A productivity index of 1.0 represents a soil with no rooting restrictions. The productivity index was designed to allow region- and species-specific modification. Examples of such modifications are presented. Additional research needed to futher refine the productivity index is discussed.

INTRODUCTION

Evaluating reclamation is costly and time-consuming. Law requires that for bond to be met, crop production on reclaimed minesoils must equal or exceed crop production on similar unmined soil. The comparison requires test plots on reclaimed and unmined soil. Need exists for a way to assess reclamation in the absence of test plots. A soil-based productivity index is discussed which appears to be a suitable method to evaluate surface mine reclamation. The productivity index is based upon the premise that root growth will be a function of the sufficiency of the soil as a rooting medium and that plant growth and yield will be proportional to root growth. This paper will discuss the rationale and justification for modifying a soil-based productivity index (PI) for use as a means to assess surface mine reclamation. The format will be to: 1) justify the need for a soil-based PI; 2) present the conceptual framework for a PI developed in Missouri; 3) discuss weaknesses of the PI as it relates to surface mine reclamation.

Numerous region-specific soil and overburden characteristics have been shown to affect plant root growth in reclaimed minesoils. In the northern Great Plains, overburden materials are often saline or sodic (Halvorson et al., 1980) If smectite is common in the clay fraction of sodic soils, clay dispersion reduces water infiltration and root penetration, which reduces plant yield (Doll et al., 1984). Migration of salts from the subsoil into the surface soil frequently reduces the rooting volume and causes accompanying declines in productivity (Halverson et al., 1980).

In western Kentucky, forage yields on surface mine spoils were limited by low water-supplying capacity and low available P. Plants were rendered draught-susceptible because the acid spoils restricted root growth (Barnhisel, 1977). Minesoils in West Virginia were characterized by acidity, stoniness, high bulk density, low porosity, and low water retention capacity. Reclamation of these soils is compounded by the acidic nature of the subsoils of unmined soils and by steep slopes (Thurman and Sencindiver, 1986). Minesoils in the Missouri glacial till landscapes are characterized by high bulk density, high contents of 2:1 clays, and low available P (Hanson et al., 1984).

Power et al. (1978) reported that texture, structure, exchangeable Na content, bulk density, compaction and the degree and length of slope — individually and in combination — control infiltration, runoff, and evaporation from reclaimed soils. McFee et al. (1981) found that water storage capacity and electrical conductivity were most frequently the properties causing plant growth responses on reclaimed soils. Minesoils generally have higher bulk density, lower porosity, lower permeability, higher coarse fragment content and lower available water-holding capacity than unmined soils (Brussler et al., 1984; Indorante et al., 1981), and these properties

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are affected by reclamation techniques (Schafer et al., 1980). Reclamation techniques also affect structure of minesoils, and thereby affect plant rooting patterns (McSweeney and Jansen, 1984).

Increasing depths of replaced topsoil — to certain minimum thicknesses which apparently vary with topsoil and subsoil properties, climate and crop characteristics — repeatedly have been shown to be positively correlated with crop yield (Halvorson et al., 1980; Power et al., 1981). Reduced hydraulic conductivity in replaced topsoil materials can reduce forage production, even when nutrient levels are adequate (Merrill et al., 1985). Quality of replaced topsoil in the northern great plains often affects forage quality, which, in turn, affects livestock performance (Schuman and Power, 1981). Wheat, barley, and corn yields were not increased by additions of N and P fertilizer on replaced non-saline, non-sodic topsoil (Halverson et al., 1986). Topsoil quality in reclaimed lands is a function of the chemical and physical properties of the unmined topsoil and of the reclamation procedures.

Optimum topsoil thickness for crop productivity on reclaimed minesoils is also a function of replaced subsoil properties, including chemical and physical characteristics and thickness (Doll et al., 1984; Fehrenbacher et al., 1982). Physical properties related to porosity and available water-holding capacities appear to be most important, and these are affected by reclamation techniques (Doll et al., 1984; Fehrenbacher et al., 1982). All of the reclamation problems listed above seem to be quantifiable in terms of the productivity index.

Public Law 95-87, mandated in 1977, has required that reclamation of minesoils be established by comparing crop yields from reclaimed soils with yields from similar, unmined soils. Limitations to this approach are many. Crop varieties suitable for unmined soils may perform differently on reclaimed soils. Crop test plots in reclaimed minesoils areas may attract rodents, pests, and diseases out of proportion to plot sizes. Magnitudes and patterns of soil variability probably will differ between unmined and reclaimed minesoils (Schroer, 1978), making yield comparisons between them difficult. Summer precipitation patterns can vary greatly over short distances, particularly in the continental interior, and the timing of precipitation during the growing season may profoundly affect crop yields (Thompson et al., 1991). Finally, establishing and maintaining crop test plots may involve serious logistical and management and fiscal problems for mine operators who often do not have the equipment or trained personnel for farming tasks.

Doll et al. (1984) and Wollenhaupt (1985) investigated soil-water characteristics in minesoils and reviewed results of years of studies of reclamation practices. They concluded that reclamation success could and should be evaluated by relating crop yields to properties of the reclaimed soils. Wollenhaupt (1985) investigated the suitability of an existing productivity index (PI) developed by Scrivner and coworkers (Kiniry et al., 1983) for minesoil evaluation and concluded that the PI possessed the following benefits:

1. It eliminates problems accompanying the use of reference areas, such as accounting for climate variability and management practices.
2. It can be used to design the best possible constructed soil profiles using available soil materials.
3. Soil conditions created during reclamation can be readily and quickly assessed and existing problems can be identified and corrected.
4. It could be used to justify partial or complete bond release.

THE SOIL-BASED PRODUCTIVITY INDEX

The concept of an index for assessing soil productivity is not new. Storie (1933) and Simonson and Englehorn (1938) attempted numerical rating of soil productivity. Huddleston (1984) and Henderson et al. (1990) reviewed the history and applications of productivity ratings. Huddleston's review is most applicable to agricultural soils. Henderson et al. focused upon the application of the Kiniry et al. (1983) PI for commercial forestry. The Kiniry et al. bulletin is out of print. Therefore, this manuscript will examine the conceptual framework of the Kiniry et al. (1983) PI in some detail.

The PI developed by Scrivner and his cooperators uses estimates of root distribution in the "ideal" soil. Root distribution was based upon water depletion studies (Horn, 1971) in an oak-maple forest on a Menfro silt loam (fine-silty, mixed, mesic Typic Hapludalf) on deep loess near Columbia, Missouri. Neill's (1979) thesis contains the literature review upon which was based the sufficiency factors for soil properties important to root growth. The Kiniry et al. (1983) bulletin (Neill is Kiniry's maiden name) is the culmination of the overall effort.

The fundamental concept of the PI is that root growth will be determined by the soil environment (soil properties), and plant yield will be proportional to root growth (Figure 1). Effects of climate, plant genetics, and 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" (Kiniry et al., 1983). Management affects yield directly, by controlling competition and disease, etc., and indirectly by affecting soil physical and chemical properties. The conceptual PI assumes optimum

management. Plant nutrient requirements were omitted because the elements, being mobile within the soil-plant system, are replenishable.

Neill (1979) identified five soil properties — potential available water storage capacity (PAWC), bulk density, soil pH, salinity (electrical conductivity(EC)), and aeration — as being easily measured soil parameters shown to influence plant root growth. The emphasis of the literature search was upon those soil properties identified to be important to growth of corn (*Zea mays* L.) and soybean (*Glycene max* (L.) Merr.) roots. Subsequent field quantification of the PI model resulted in loss of precision when aeration was included. Kiniry et al. (1983) attributed the inadequacy of the aeration factor to the dynamics of the time-depth distribution of soil areation. The complexity of this dynamic component of the soil system demands additional, long-term research.

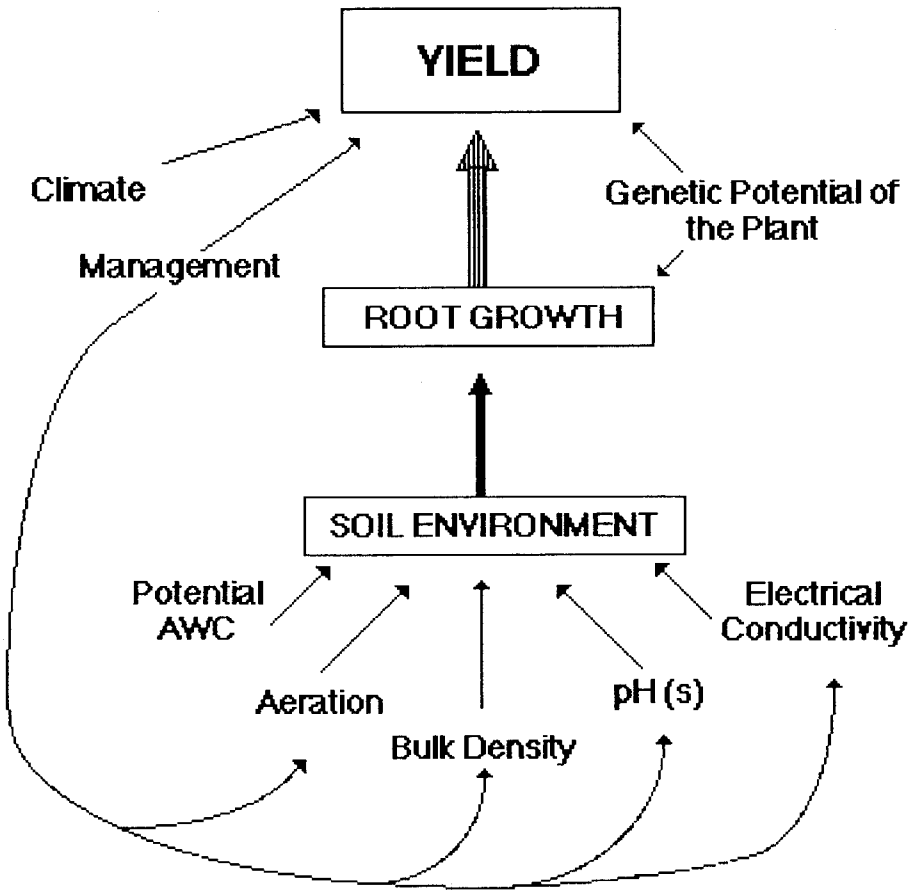
Root distribution in the "ideal" soil

The Menfro soil was chosen as the ideal soil because it contained no known physical or chemical impediments to root growth, and was occupied by deep-rooted perennial species — primarily sugar maple (*Acer saccharum*) and bitternut hickory (*Carya cordiformis*). The observed rooting depth during Horn's (1971) study was 356 cm. The inverse hyperbolic sine function which describes root distribution was developed from measurements of water depletion. Horn used the term "RI" to describe the fractional distribution of roots in 10 cm soil increments. The total of RI's is 1.00 because the RI is the decimal fraction of all roots in the profile. Kiniry et al. (1983) developed RI values for possible rooting depths of 100 cm and 200 cm (Figure 2). Kiniry et al. cautioned that the choice of rooting depth will affect the RI values for any increment of the soil profile. Greater rooting depth diminishes the importance of any individual RI increment because it represents a smaller portion of the whole.

Scrivner reported the RI as a 10 cm depth increment to accommodate those persons not trained to recognize genetic soil horizons (C.L. Scrivner, personal communication). Soil scientists could use soil horizons as the sampling unit rather than 10 cm increments, and could determine RI values for individual horizons.

Yield prediction precision with the PI would probably be enhanced with the development of species-specific "ideal" root distribution patterns. Gale and

Figure 1. Conceptual framework of the Productivity Index. (From Kiniry et al, 1983).



Grigal (1987) reported differing root distributions among tree species in northern hardwood forests. Proportional root distribution by depth was a function of total rooting depth, successional status (species), and tree age.

Boudeman (1989) used the PI to attempt to predict yield of Korean lespedeza (*Lespedeza stipulacea*), red clover (*Trifolium pratens* L.), and alfalfa (*Medicago sativa* L.). He found that root distribution varied annually. Higher proportions of roots were in the surface 20 cm of the soil in 1987 (a relatively "moist" year) than in 1988 (a drought year). Additionally, root distribution varied with landscape position across a summit, shoulder, backslope, and footslope — probably as a result of lateral soil water movement. Boudeman reported that root distribution differed according to time and frequency of forage harvest.

Additionally, Boudeman (1989) observed that water depletion under the forage legumes was in a different pattern than observed by Horn (1971). In Boudeman's study, legumes first withdrew soil water from the surface, then progressively withdrew water from depth. Horn (1971) reported continuous water depletion throughout the profile, but with lesser amounts being taken with increasing depth increments. Boudeman suggested that the "ideal" root distribution Neill developed from Horn's work would have assumed a different appearance had it been based upon water extraction patterns of forage legumes.

Sufficiency factors

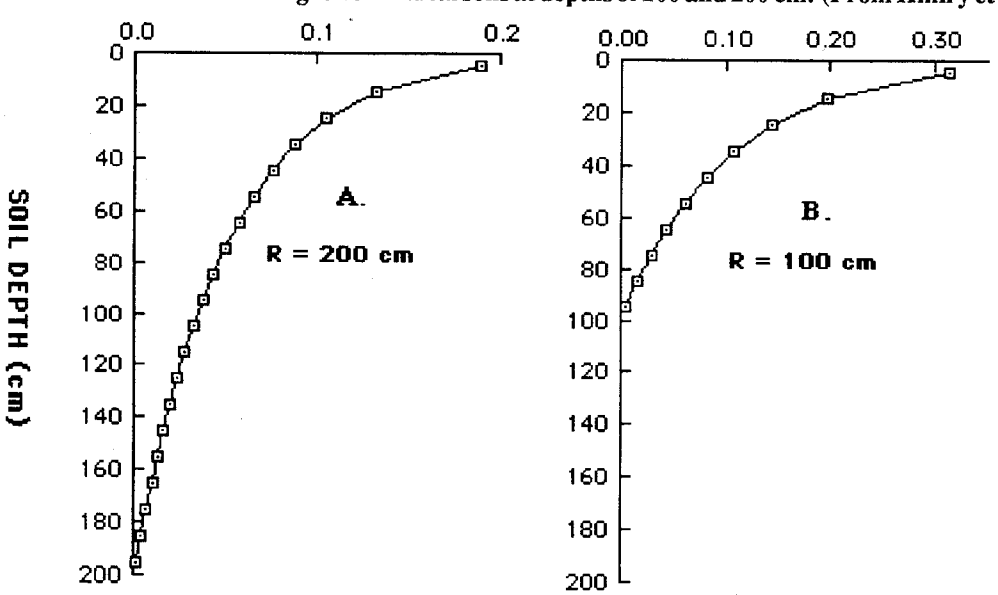
Each of the measured soil properties in the model requires a root growth response function. The response function is described as its "sufficiency" in comparison to a soil property which does not inhibit root growth. The ideal soil property would have a sufficiency of 1.0, and a soil property which permitted no root growth would have a sufficiency of 0.0. A sufficiency value of 0.50 indicates that root growth is potentially 50% of expected growth under unrestricted conditions.

Studies have shown that root growth is inversely proportional to soil strength measured as resistance to penetration. (Blanchar et al., 1978). Scrivner selected bulk density as an easily measured indication of soil strength. Soil strength is a function of soil texture, soil moisture at time of sampling, and soil structure (Towner, 1974; Pearson, 1966), so care must be taken in obtaining bulk density values. Method of sampling greatly affects the bulk density measurement. Indorante (1990) used the saran-clod method of bulk density determination in a Menfro at the site of Horn's (1971) work, and obtained lower sufficiency values than Neill (1979). Indorante's sampling method had eliminated interstitial voids between primary soil aggregates (prisms), giving him a higher bulk density measurement.

The bulk density sufficiency relationship (Figure 3) reveals that bulk densities less than 1.3 do not limit root growth. Between values of 1.3 and 1.55 root growth gradually declines. Above values of 1.55, root growth is rapidly diminished. Above values of 1.8, root growth is severely limited.

The interactions among soil structure and root growth require additional investigation. Hammer (1986) and Indorante (1990) observed forest tree roots growing on block and prism faces in subsoils. Conway-Nelson (1991) reported roots of native prairie species following joints in weathered sandstone and shale below the soil solum. In strongly structured soils, bulk density alone

Figure 2. Predicted fractions of root growth in ideal soils at depths of 100 and 200 cm. (From Kiniry et al., 1983).



may not be a precise estimate of root growth potential. In minesoils, McSweeney and Jansen (1984) observed profuse root growth with strongly structured material. In massive, reclaimed subsoils, the only roots were along desiccation cracks and often were flattened and compressed.

Soil pH is highly correlated with other soil chemical parameters, and was selected as the single, easily-measured soil parameter most representative of the soil chemical environment. However, soil pH is a dynamic component which varies temporarily and spatially with salt concentration of the soil solution, soil moisture, soil atmospheric conditions, and status of organic matter decomposition (Russell, 1973; Hammer et al., 1987; Peterson and Hammer, 1986). Rhizosphere studies using microelectrodes (Conkling and Blanchar, 1988) have shown that pH at the soil-root interface may not be the same as pH of the bulk soil solution. Soil pH measured in $CaCl_2$ will be a pH measurement less affected by soil solution rations than soil in water (Schofield and Taylor, 1955).

Figure 4 shows the sufficiency of pH. The threshhold pH for unlimited root growth is 5.5. The dotted line in Figure 4 represents an extrapolation performed by Kiniry et al. (1983) made in the absence of measured relationships. Development of root growth parameters is important in strongly structured acid soils, where ped faces may exhibit a different soil chemical environment than the bulk soil (Conway-Nelson, 1991). Additionally, some plants are known to be more tolerant than others of extremes in soil reaction. Species-specific work will be necessary to develop pH sufficiencies for agronomic crops.

Osmotic potential influences root growth in many regions, particularly semi-arid and arid environments in which salts are not leached from the soil profile by annual pulses of soil water. Electrical conductivity was chosen as a sufficiency factor in the PI because it is an

Figure 3. Sufficiency of bulk density (From Kiniry et al., 1983).

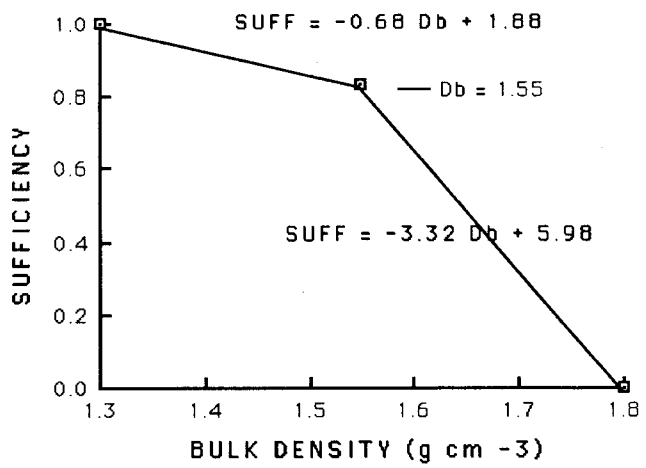
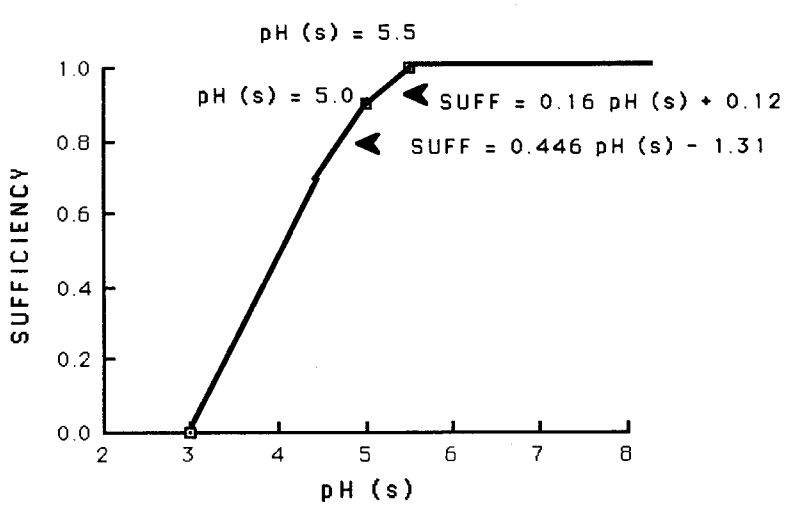


Figure 4. The sufficiency for pH(s) (from Kiniry et al., 1983).



easily measured parameter highly correlated with osmotic potential. In humid regions, EC can be eliminated from the PI equation.

The sufficiency relationship for EC is shown in Figure 5. This sufficiency factor was developed from work by Wadleigh et al. (1947) as modified by Richards (1969). Even in humid regions, some overburden materials used in surface mine reclamation contain salt concentrations and could necessitate the inclusion of the EC in a PI used to assess surface mine reclamation.

Potential available water storage capacity is the ability of the soil to supply water to plants in the absence of rainfall. The PAWC of a soil is influenced by texture, structure, and organic matter content. Unfortunately, PAWC is a static measure. It does not consider position in the landscape and the contribution of lateral subsurface water movement. This problem subsequently will be discussed in more detail.

The sufficiency of PAWC (Figure 6) is a linear relationship with a value of 1.0 when storage of soil water is 0.20 cm or greater cm^{-1} of soil depth. If soils contain rock fragments, a reduction in the sufficiency value is necessary. The reduction should be proportional to the volume of soil increment occupied by rock fragments. Silt and silt loam soils devoid of coarse fragments will have sufficiency of 1.0. It is likely that species-specific adjustments are necessary for this sufficiency factor.

The PI formula

The PI is calculated by measuring, for each soil depth increment or horizon, the soil properties upon which the sufficiencies are based. The soil property is converted to a sufficiency factor. Each depth increment is weighted by the RI factor for that increment in the ideal soil. The original productivity index was:

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

Figure 5. Sufficiency of electrical conductivity (From Kiniry et al., 1983).

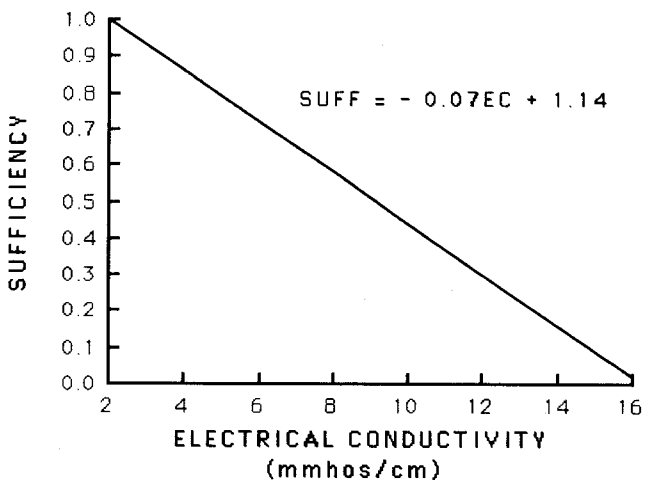
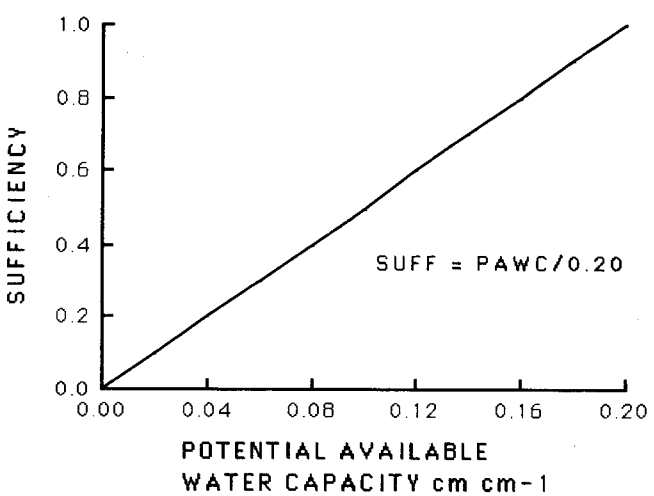


Figure 6. Sufficiency of potential available water capacity (From Kiniry et al., 1983).



where PI = the productivity index, RI = predicted root fraction in the ideal soil, and A through C = sufficiency factors for soil parameters 1 through 3, respectively, r = the total number of depth increments in the rooting profile, and i = the depth increment number (i = 1.2,3, .. r).

The PI formula can be modified for species-specific situations. Gale et al. (1992) modified the PI to develop RI values for soil horizons under white spruce (*Picea glauca* (Moench) Voss) plantations. The soil horizon-based PI was a better predictor of white spruce growth than the PI based upon incremental soil depth.

THE FLEXIBILITY OF THE PRODUCTIVITY INDEX

Scrivner (C.L. Scrivner, personal communication) predicted that the most important contribution of the PI would be its use as a conceptual framework from which to approach the interactions of plant roots with their soil environment. Those who have used the PI with this perspective have found it useful.

Camacho (1991) used a large soil data base in conjunction with growth data of leucaena (*Leucaena leucocephala*) and a massive literature review to develop a leucaena-specific PI for Central America. Camacho developed leucaena-specific sufficiency indices for soil pH, bulk density, and water-holding capacity. He reported that the soil pH sufficiency alone explained between 15 and 30% of variation in leucaena growth.

Leucaena habitat encompasses a broad ecological amplitude. Leucaena occupies sites whose conditions range from water-saturated for prolonged periods to extensive drought, when the tree drops its leaves. Camacho used the Thornthwaite water balance model (Thorthwaite and Mather, 1955) to develop an aridity index (AI) and a moisture index (MI) to account for climatic conditions during dry and wet periods. Sufficiency relationships were developed from each index. The PI developed from these sufficiency relationships explained from 25 to 99% of variance in leucaena yield in stands throughout Central America.

In addition to the previously mentioned refinement of equation [1], Gale et al. (1991) also developed species-specific sufficiency factors for the PI and used species-specific vertical root distributions developed by Gale and Grigal (1987). Gale et al. (1991) produced a sufficiency curve for depth to mottling to serve as the aeration sufficiency for white spruce, which occupies a wide range of soil drainage classes. They used texture-specific bulk density sufficiencies from Pierce et al. (1984). A sufficiency for topography was developed for white spruce, and, like Camacho (1991), they developed an index of aridity to account for climatic conditions. Gale et al. (1991) found the PI, as they modified it, to be a more precise predictor of white spruce growth in both young and old stands than site index. They recommended that sufficiency factors for nutrient requirements and stand age would further improve the PI.

Gantzer and McCarty (1987) used the unmodified Kiniry et al. (1983) PI to predict corn yield on a soil with varying thicknesses of topsoil and varying depths to a claypan. They found that 50% of the variation in PI was related to depth of topsoil and 62% was related to depth to clay. The PI was a better predictor of plant yield than topsoil or depth to clay. Regression analysis of yield on PI explained between 63 and 72% of the variation of yield within years. However, when a weather variable estimating total water use in July and August was used in conjunction with the PI, 82% of yield variance was explained.

CLIMATE AND SOIL WATER

One of the greatest challenges facing PI users is in addressing the dynamic nature of soil water and precipitation. The previous discussion indicated that some users have added climatic sufficiency factors to modified PI's to account for some of the yield variance produced by climatic and soil water conditions. The following discussion will clarify the need for more research in that arena.

Thompson et al. (in press) used the PI to evaluate corn growth on the same set of plots for five years. Their research indicates that climatic variance produces large yield differences among years. Figure 7 reveals a nearly three fold (3.1 to 8.2 kg ha^{-1}) yield difference on plots with a PI of 0.34 and receiving no irrigation. Similar yield differences were noticed within other PI values, but the range seems to decline with increasing PI value. The problem is complex. Irrigated corn plots exhibited greater yields than plots receiving water only through rainfall (Figure 8). The PI explained a smaller percentage of variance in the mean yield for five years in in irrigated than in rain-fed plots (Figure 9). A second order polynomial explained 68% of the yield variance in rain-fed plots (Figure 9A), but only 44% of the variance was explained in irrigated plots (Figure 9B). All irrigation was concurrent. The reduction in explained variance on irrigated plots seems to indicate that the plants were at different stages of development (and therefore of ability to use soil water) on plots with different soils and PI's. Soils with different PI values might require different management practices for the same crop species.

The soil landscape will affect the temporal distribution of soil water. Henderson et al. (1990) addressed this problem, and referred to the water-supplying capacity of different geomorphic elements within water-

sheds. The PAWC sufficiency in the PI is a static measure incapable of accounting for the lateral subsurface distribution of water in a landscape. Data from Conway-Nelson (1991) show that when rainfall is relatively uniformly distributed on a native prairie during a growing season, the effects of landscape position are mitigated. For example, Figure 10 indicates little yield difference as a function of landscape position in the Taberville Prairie in 1990. However, in 1989, a drought year, landscape position profoundly affected yields in the prairie (Figure 11). The lower headslope, a concave position receiving subsurface water from a large surrounding area, had the highest yield which exceeded by a factor of three the yield in the upper headslope. Figure 11 contains three transects — a headslope transect, a backslope transect, and a transect across a convex finger ridge. In all three transects, yield increased downslope with increasing ability of the surrounding landscape to supply water to those lower positions. That the yield differences are a function of soil water can be further substantiated by Figure 12, which shows the temporal distribution of soil water in the surface horizons of the summit, noseslope, upper finger ridge and headslope. The higher resistance readings indicate lower soil water. The headslope had the lowest resistance readings among those represented. The figure also reveals the dynamic temporal characteristic of soil water. Until the temporal attributes of soil water can somehow be addressed, much of the annual variance in crop yield will result from the differential accumulation of water across the landscape.

Figure 7. Corn yield as a function of the productivity index for a five year period on rainfed plots near Columbia, Missouri (From Thompson et al., (in press)).

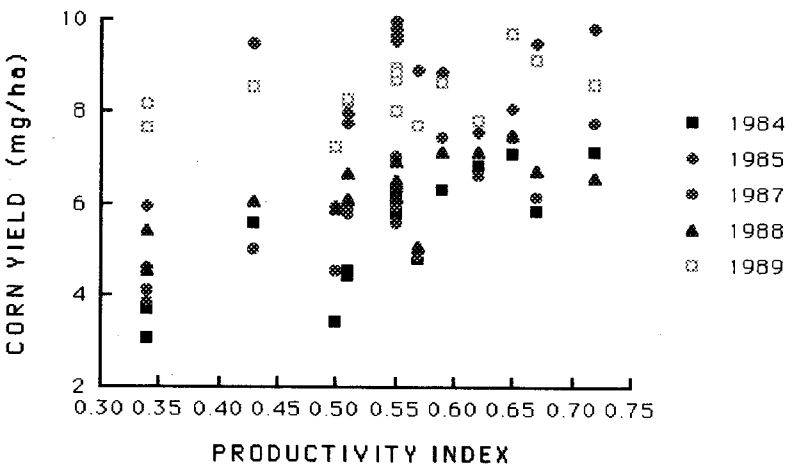
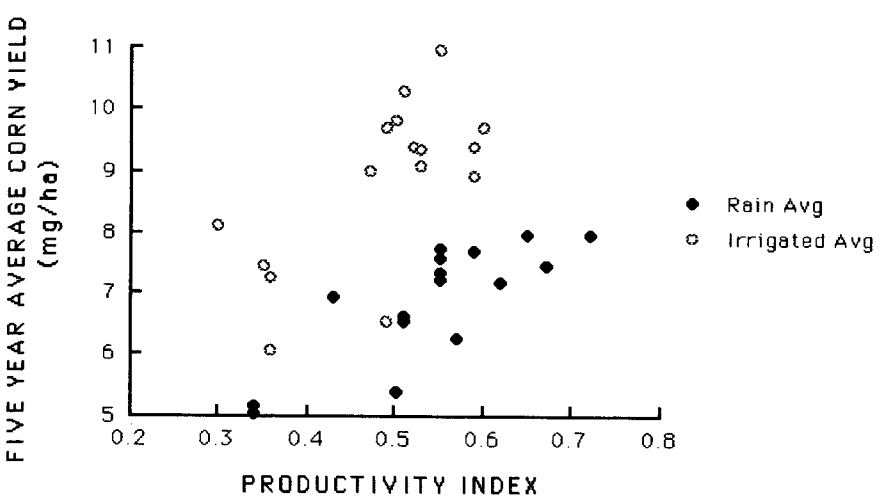


Figure 8. Five year average yield of rainfed and irrigated corn plots near Columbia, Missouri (from Thompson et al. (in press)).



CONCLUSIONS

The PI has been demonstrated to be an important method to quantitatively compare the potential productive capacities of different soils. It provides a conceptual framework from which researchers can approach region-, species-, and site-specific problems related to plant yield. The PI requires refinement for species-specific rooting distribution under "ideal" conditions. Region- or species-specific sufficiencies in addition to or different than those proposed by Kiniry et al. (1983) will probably be needed. The dynamic nature of the plant-soil-water continuum requires additional attention before the PI can be widely applied. However, the PI concept provides a focal point for researchers, and requires that the cause-and-effect relationships among plants and their environment be more closely examined that has been done in the past.

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Figure 9. Five year average corn yields for rainfed (A) and irregated (B) plots near Columbia, Missouri (from Thompson et al. (in press)).

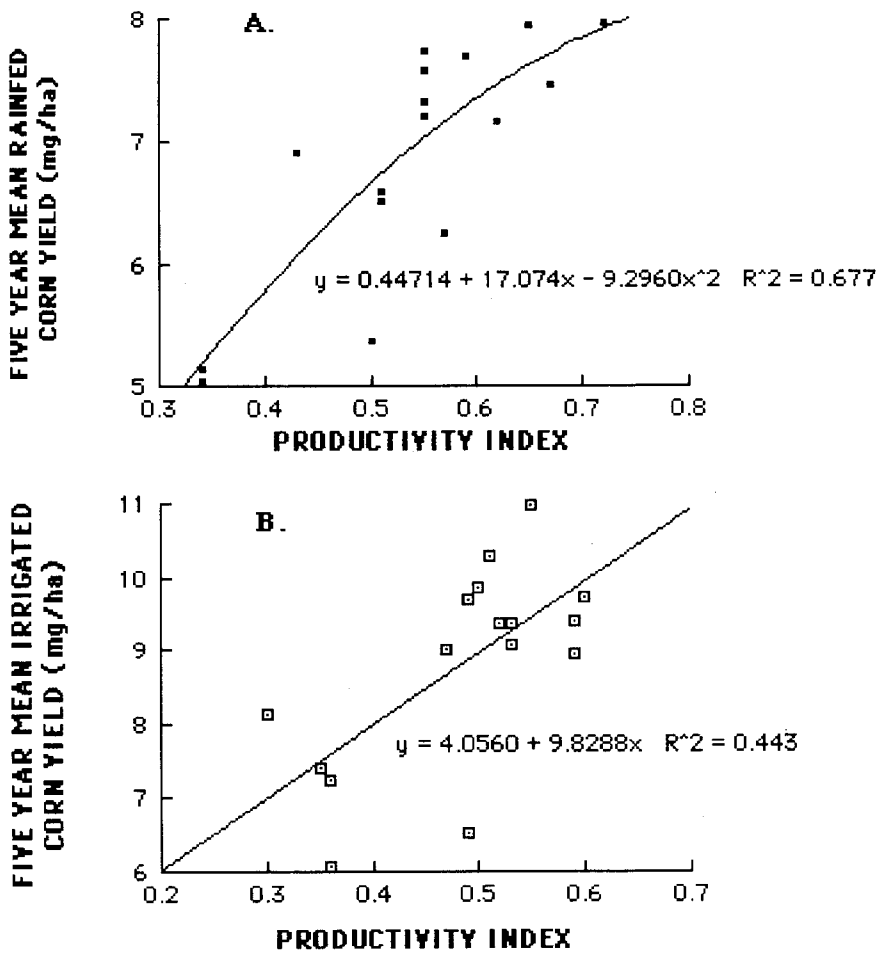

Figure 10. Total 1990 forage yield on Taberville Prairie, Missouri (from Conway-Nelson, 1991).

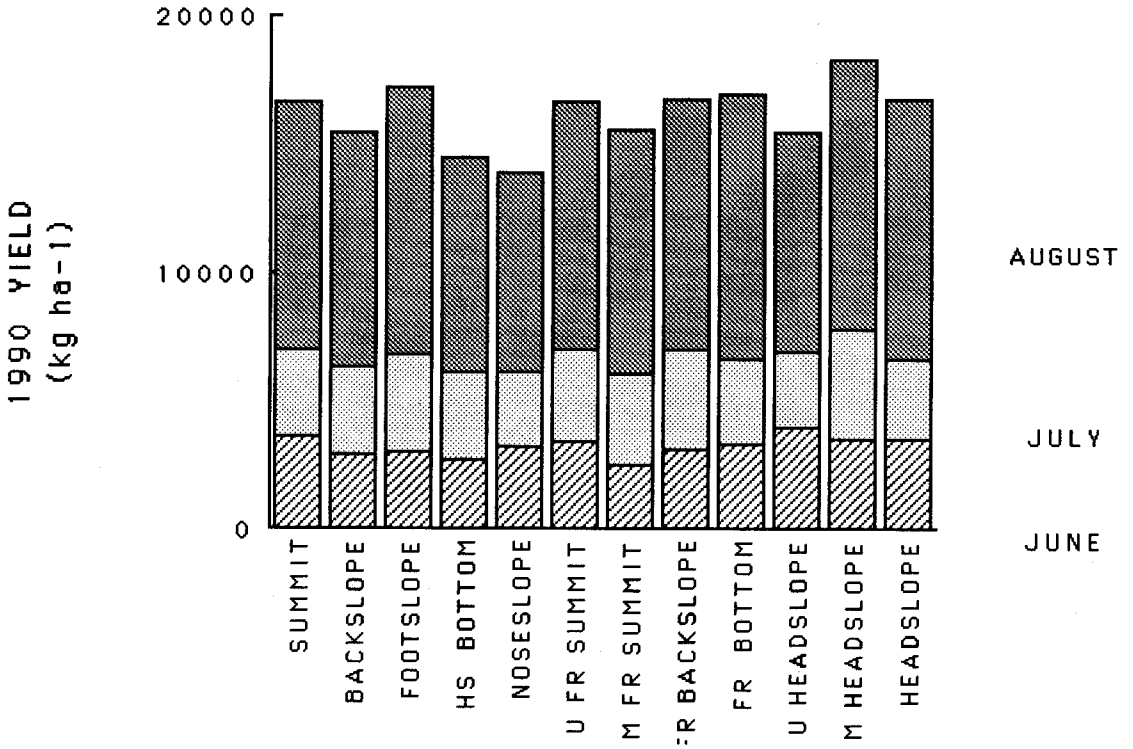

Figure 11. Total 1989 forage yield on Taberville Prairie, Missouri (from Conway-Nelson, 1991).

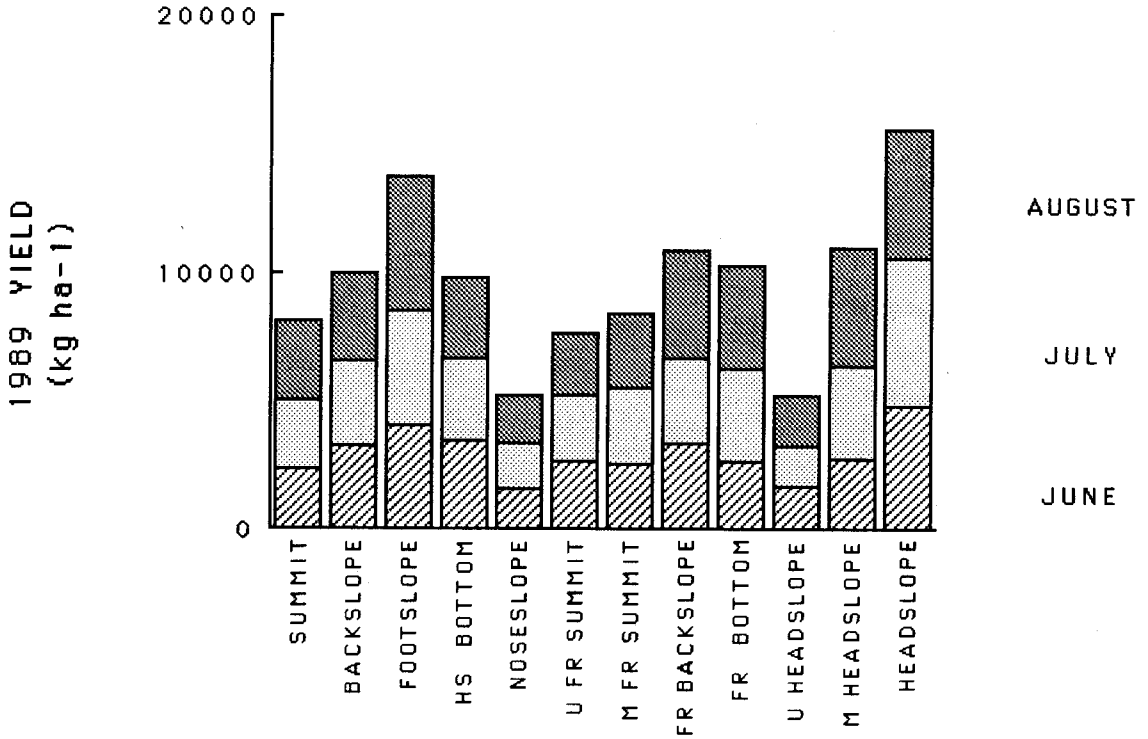

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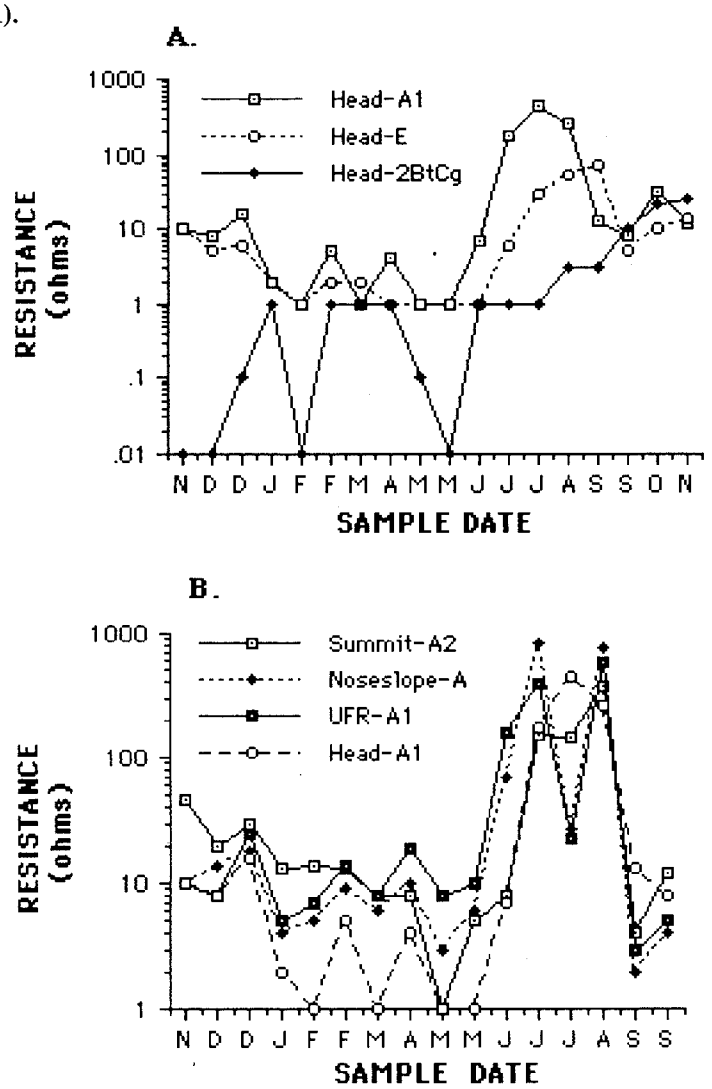
Figure 12. Water yields as indcated by resistance cell readings in a headslope profile (A) and hillslope transect (B) on Taberville Prairie, Missouri. Higher resistance readings indicate lower soil water conditions. Sampling was at three-week intervals beginning in November (from Conway-Nelson, 1991).



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Mapping and Classification of Minesoils: Past, Present, and Future

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Abstract. There was a time when reclamation of mined areas was not considered important in mining operations. After an area was mined, the landscape left behind was often simply a consequence of the coal extraction process. With passage of reclamation laws, notably the Surface Mining Control and Reclamation Act (SMCRA), reclamation became a routine part of mine operations. The soils left behind, once considered simply as spoil, became subject to intense management considerations. This is as it should be because the reclaimed soils will be around long after the coal is gone. This paper discusses the evolving concepts of reclaimed mine soil and presents a proposal for more intensive mapping and classification of this important resource.

INTRODUCTION

One of the purposes of surveying soils is to identify, on maps, soils that have similar use and management. Information in a soil survey report includes soil properties, soil classification, and use and management statements. Since the early 1950's these precepts guided soil survey on undisturbed lands, but in recent years environmental and planning concerns have greatly expanded the researches needed in soil survey and the uses of soil survey. One of the expanded uses of soil surveys in the past 15 years has been their application to surface mining and reclamation problems. The objective of this paper is to present and discuss the development of the mapping and classification of minesoils in response to these mining and reclamation problems.

MAPPING AND CLASSIFICATION OF MINESOILS

The Past

Research on the revegetation of surface mined land in the midwest dates back to the late 1920's (Croxton, 1928), but it was not until the 1940's that attempts were made to classify mine spoils (Lyle, 1980). An early attempt to devise a limited classification system was presented by Tyner and Smith (1945) in West Virginia. Their system of classification was in response to the 1945 West Virginia law which involved the establishment of vegetation on spoil. By classifying the spoil according to the prevailing surface hydrogen-ion concentration they determined which spoils were favorable for plant growth. As part of the classification they also related surface hydrogen-ion concentration to the geologic sections of the mined areas. It is interesting to note that the term "soil" was not used in their research to describe the plant growth material left from mining (spoil). At that time the spoil material was considered a by-product of the surface mining operation.

Limstrom and Deitschman (1951) developed a basic classification of spoil banks in Illinois. Acidity and texture of the of spoil materials were the two factors considered in the classification. Some of the spoil types described were: calcareous sand; acid silty clay loam; and calcareous silty clay. Their study revealed that the nature of surface mine spoils was a result of the character of the overburden and the method of mining used. The results of their classification system were used to determine the suitability of spoils for forest plantings. In another Illinois study, Grandt and Lang (1958) applied Limstrom's (1948) classification system to determine the suitability of the soil material from surface mined land for legume and grass growth. In both studies (Limstrom and Deitschman, 1951; Grandt and Lang, 1958) the spoil material was referred to as soil-sized particles and soil material. By this time, spoil material was beginning to be viewed as a soil or soil material.

During the late 1950's and 1960's, areas affected by surface mining were delineated on soil maps and

identified only as mine dump or strip mine (Fehrenbacher and Odell, 1959; Wascher et al., 1962). Soil surveys completed during the 1970's generally identified the mined land as Orthents, a suborder classification of the USDA Soil Taxonomy system (Soil Survey Staff, 1975). In some instances the graded mine spoil was classified differently than the ungraded spoil, as in the St. Clair County, Illinois soil survey (Wallace, 1978); or the acid spoil was differentiated from the nontoxic spoil, as in the Saline County, Illinois, soil survey (Miles and Weiss, 1978). Texture modifiers were also used in some instances. In both counties, the soil map unit descriptions for Orthents included descriptions of landform shape, soil variability, and interpretations for various land uses. Orthents were also listed in all of the interpretative tables. No representative site or pedon was described in the St. Clair County Survey, but a representative site for Orthents was listed in the Saline County Survey (Miles and Weiss, 1978) with no pedon description.

The Present

Ohio (Rubel et al., 1981) and West Virginia (Wright et al., 1982) were two of the first states to map minesoils, but Ohio was the first to name and classify the soils to the series level. The Morristown, Fairpoint, Bethesda, Enoch, and Barkcamp series were established in 1978 in Belmont County, Ohio. Even with the establishment of mine soil series, pedologists were still slow to define and map different soils (series) within surface mined areas. Pedologists felt that minesoils soils were inherently too variable and that mappable patterns of order were not apparent (Indorante and Jansen, 1984).

The reason for this view was the lack of a conceptual model that provided a basis for expecting order and allowed a trained pedologist to readily map it (Indorante and Jansen, 1984). On undisturbed land a soil genesis model is useful, but in areas disturbed by surface mining the soil genesis model applied in the usual way does little to help perceive spatial order. Mine soils are so young that the active factors of soil formation have had little or no effect. The lack of an appropriate conceptual model can cause the apparent complexity to be overwhelming, thus preventing the perception of order which is necessary to classify and map soils.

Indorante and Jansen (1984) proposed a conceptual soil-landscape model useful for perceiving order on surface mined land. With perception of order, mine soils can be mapped and classified. The concept postulated a relationship between soil character and: (1) mining methods; (2) reclamation or soil construction procedures; (3) preminesoils; and (4) premine geologic column. The procedure for applying the model is presented in Figure 1, and was successfully applied (Table 1, Figure 2) to the minesoils in the Perry County, Illinois Soil Survey (Grantham and Indorante, 1988).

Table 1. Chart for minesoil classification in Perry County, Illinois.

Method of soil construction	Shovel	Shovel, dragline, or dragline & dozer	Mining wheel or dragline & dozer	Scraper or scraper & dozer
Overburden texture after mining	Loamy	Loamy	Loamy	Silty
Rock fragments in control section	>35%	15-35%	<15%	<10%
Presence of carbonates in control section	Yes	Yes	Yes	No
Classification	Loamy-skeletal mixed (calc.), mesic Typic Udorthent	Fine-loamy, mixed (calc.), mesic Typic Udorthent	Fine-loamy, mixed (calc.), mesic Typic Udorthent	Fine-silty, mixed (non-acid) mesic Typic Udorthent
Series	Morristown	Lenzburg	Schuline	Swanwick

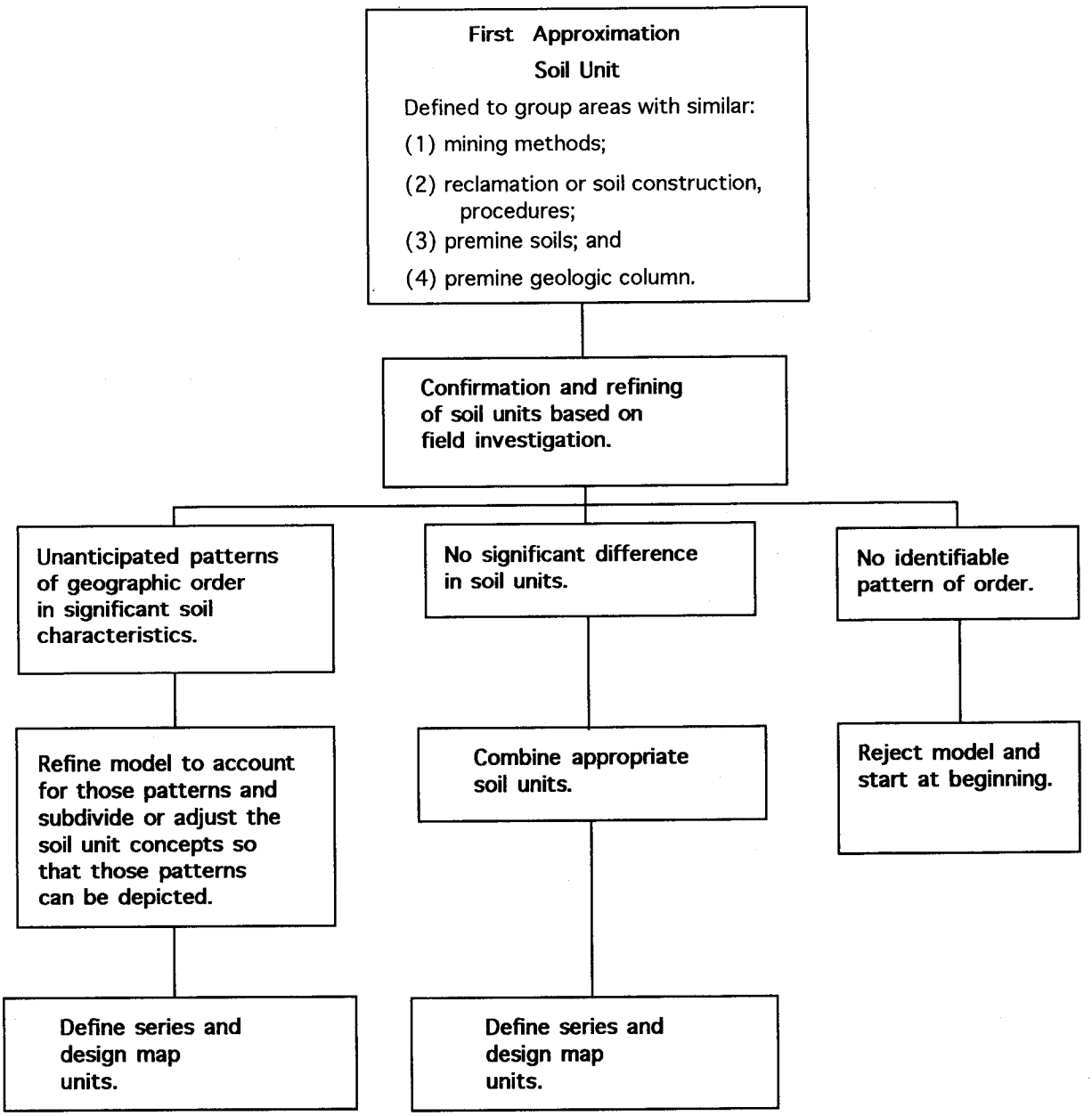
Adapted from Indorante and Jansen, 1984.

The Future

Many more mine soil series have been established and mapped since the original Ohio and West Virginia minesoil series (Soil Survey Staff, 1990). The soil series are Typic Udorthents, with particle size class (which includes rock fragments), reaction class, and soil temperature class being the main differences among the series. Researchers (Sencindiver, 1977; Smith and Sobek, 1978; Thurman and Sencindiver, 1986; Ammons and Sencindiver, 1990), however, have shown that the unique and important properties of minesoils are not always adequately defined by existing taxa within *Soil Taxonomy* (Soil Survey Staff, 1975).

To better define the taxa for minesoils, West Virginia researchers (Sencindiver, 1977; Smith and Sobek, 1978) proposed an amendment to *Soil Taxonomy*. The proposed amendment would create the suborder Spolents to encompass minesoils and other disturbed soils (Thurman and Sencindiver, 1986). Within this suborder are subgroups which are based on the lithology of the rock fragments in the particle size control section (Sencindiver, 1977; Smith and Sobek, 1978). Even though Spolents has not yet been formally adopted by

Figure 1. Flowchart for appying a conceptual soil landscape model to map and classify mine soils (after Indorante and Jansen, 1984).



Soil Taxonomy, the subgroup has been successfully applied to the mapping, classification, and interpretation of minesoils (Sencindiver, 1977; Smith and Sobek, 1978; Ciolkosz et al., 1985; Thurman and Sencindiver, 1986; Ammons and Sencindiver, 1990).

Other researchers have also described the need to develop and use new techniques and terminology to describe and characterize minesoils and drastically disturbed lands. McSweeney et al. (1984) proposed the term *fritted* to describe the artificial structure unique to constructed soils, and suggested that soil series separations should be made on the basis of these types of structural differences. Many properties of the mine soils are temporal in nature (eg. soil compaction) and this poses a special mapping and classification problem. Tugel et al. (1991) have designed a new type of map unit, an *undifferentiated association*, to describe and identify areas with on-going soil modification. The map unit is designed to describe spatial variability in soil properties that are use dependent and therefore a function of time. This scheme may very well fit the special mapping, classification, and interpretive needs of minesoils and drastically disturbed soils.

A Proposal For Improved Mine Soil Classification

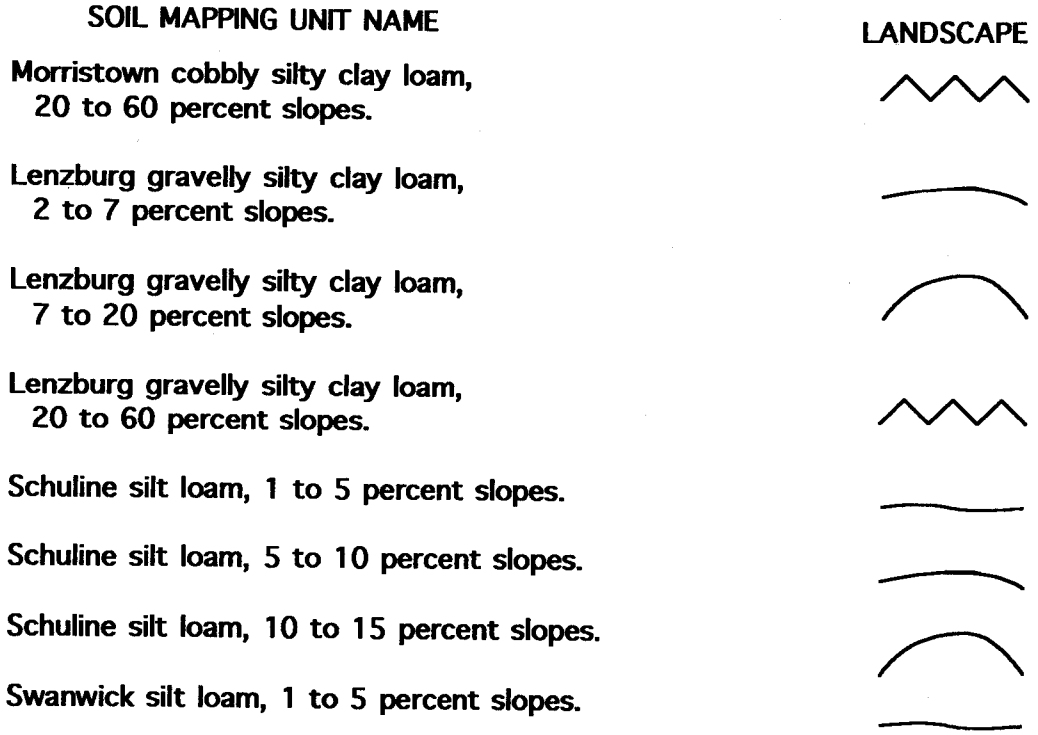
The mapping and classification of soils after surface mine reclamation should be an important part of the reclamation process. To best provide for post reclamation land use and to evaluate and understand reclaimed soils, a classification system needs to be developed that addresses the unique characteristics of mine soils. As in natural soils, many important soil properties can be quickly portrayed if reclaimed soils are well classified and mapped. Soil mapping and classification techniques developed for natural soils may not be appropriate for reclaimed landscapes.

Classification of mine soils should recognize both the attributes inherited from the pre-mine soils and pre-mine geological column as well as those consequential to reclamation methods. Inherited properties of mine soils include soil texture, coarse fragment content, pH, and topsoil color and thickness. Properties resulting from reclamation include density or compaction, slope, drainage, top soil thickness, and coarse fragment content.

The current soil classification scheme for mine soils is inadequate. Mine soil series are primarily focused at characterizing mine soils that were not reclaimed at all or were reclaimed prior to the Surface Mining Control and Reclamation Act (SMCRA) permanent program. This scheme is inadequate given the diversity of mine soils and changes in reclamation. There are thousands of acres of reclaimed mine soils that are not adequately classified.

Reclamation technology has improved as research has demonstrated limitations of old methods and introduced new methods. A new reclamation technique

Figure 2. Soil mapping units and corresponding landscapes for soils on surface-mined land in Perry County, IL (after Indorante and Jansen, 1984).



involving plowing to 1.2 m (48 in) deep has profound effect on soil properties and should be recognized in mapping and classifying of mine soils. Productivity indices assigned to existing series are not applicable to mine soils using improved reclamation techniques. Mine soils which have met productivity standards and mapped under the present scheme are under-assessed causing reduced property tax revenues to counties. This misclassification also reinforces the misconception that a mine soil is not adequately reclaimed under the law.

Problems with existing mine soil classifications include the failure to recognize the single most important factor limiting use and management in many cases. Research at the University of Illinois (Dunker et al., 1991) has identified compaction as the limiting factor in reclaimed mine soils in Illinois. Given the favorable chemical and textural characteristics of the soil materials, compaction resulting from certain reclamation methods is what usually limits crop yields by restricting root growth. The USDA soil classification scheme (Soil Survey Staff, 1975) recognizes root restricting soil layers and assigns a special symbol "d" to the layer. The top of a "d" layer is called a paralithic contact. If a paralithic contact is found within 50 cm of the soil surface, the soil is classified as shallow. There is a new technique involving a continuously recording penetrometer that shows promise in detecting the presence of a root restricting layer (Hooks and Jansen, 1985). This tool could be used to delineate areas of mine soils with compaction problems.

Another characteristic of mine soils that needs to be recognized is the thickness and organic matter content of the replaced surface layer or "A" horizon. In Illinois, for example, there are prairie soils that have a very dark and thick A horizon. Soils that developed under forest vegetation have thin and light colored A horizons. Productivity of these two soil types is different and the mine soils derived from such dissimilar materials should be recognized.

A third important, but currently unrecognized, criteria is drainage. Most mine soils are reclaimed in such a way that they are well or moderately well drained. In some cases mines may be reclaimed to produce wetter soils with somewhat poor or poor drainage. The classification scheme needs to allow for these wet soils.

Table 2 gives the criteria for classification of mine soils to taxonomic family. Soil series criteria are given in Table 3. There will be additional subdivisions of mine soils that recognize slope and unusual features such as acid subsoil or excessive stones in the surface. These special situations will be handled by series phases and map units. Description and classification of mine soils follows conventional pedological techniques given in the USDA soil survey manual (USDA, 1990).

Surface color has two classes. Dark colored soils have a surface horizon that is ≥15 cm thick with crushed color value ≤3 moist and ≥5 dry. These soils also have >1% organic carbon in the surface horizon and a base saturation ≥50% in the upper 100 cm. Surface horizons which do not meet these criteria are classified as light.

Moisture regime in the central part of the interior coal mining region includes Udic and Aquic subclasses. Wet soils are classified as Aquic. These soils show gley colors (chroma ≤2, value ≥4.5, moist) within 50 cm of the soil surface. Care must be taken to assure that the gley colors are due to wetness and not to inherited

Table 2. Sugested minesoil taxonomic family classification criteria for central part of interior coal mining region.

	Class					
Criteria	A[1]	B	C	D	E	F
1. Surface color	light (Ochric)	dark (Mollic)				
2. Moisture regime	Udic	Aquic				
3. Rooting depth	shallow	deep				
4. Reaction	acid	nonacid	calcareous			
5. Texture family	fine	fine silty	fine loamy	loamy-skeletal	clayey	loamy
6. Base saturation, surface	<50%	≥50%				
7. Base saturation, subsurface	<35%	≥35%				

[1]See text for definition of classes.

colors. Accessory field evidence such as landscape position or water table records may be necessary to support the Aquic classification. Soils that do not have gley colors within 150 cm are not wet and are classified as Udic.

Soil depth has two classes. Shallow soils have a root restricting layer within 50 cm of the surface. This can be identified by a bulk density greater than 1.6 g/cc and a lack of roots under deep rooted crops. An additional identification technique is the penetrometer. Penetrometer values greater than 2 MPa when the soil is at or near field capacity is considered root restricting, values of 1-2 MPa are considered root limiting (USDA, 1990).

Reaction class is an evaluation of the pH of a soil. Mine soils that have free carbonates which react to dilute HCl are calcareous. Nonacid soils have a pH of 5.0 or more in 0.01 M Ca Cl2(2:1). Acid soils have a pH of less than 5.0 in 0.01 M CaCl2(2:1).

Texture families are defined in Soil Taxonomy (SCS 1975) and refer to the fine-earth fraction (<2mm) of the upper 100 cm. If there is a root restricting layer, the texture of the material above the layer is included in assessing the family texture class.

Table 4 gives some properties of existing and proposed soil series for mine soils. Because of the lack of good alternatives, the existing soils series have been used in a very broad sense. They would have to be redefined and restricted to a narrower range of soil properties. Their definitions and descriptions would have to include consideration of properties imparted upon the soils by modern reclamation techniques. The tentative classification of the proposed new series, as well as revisions of the existing series are given in Table 5.

As knowledge of mine soils is gained, the need to better manage and evaluate these soils becomes both possible and necessary. A classification system for mine soils will enable the reclaimed soils to assume their rightful place in the landscape.

CONCLUSION

The view of mining and reclamation has changed dramatically over the years. What was once considered a by-product of surface mining is now considered a soil resource to be studied, characterized, mapped, classified, and interpreted. This change in viewpoint reflects society's concern for the environment, and emphasizes the main objective of reclamation which is to construct a land resource of maximum feasible utility and versatility for future generations (Jansen, 1982). Accurate and precise description of soil properties and, spatial and temporal variability are critical to understanding the impact of reclamation practices and the optimum use of the constructed land resource. As reclamation technology and practices continue to change to meet the demands of producing a quality land resource, so must our ability to accurately describe, map, and classify this resource.

Table 3. Suggested minesoil series and phase placement criteria for central part of interior coal minning region.

	Class				
Criteria[1]	A	B	C	D	E
1. Topsoil thickness (in.)	<2	2-6	6-12	>12	
2. Topsoil texture	silt	silty clay loam	silty clay loam	clay loam	loam
3. Rooting media thickness (in.)	0	1-30	30-42	>42	
4. Soil drainage	well	moderately well	somewhat poorly	poorly	
5. Depth to compaction	0-10 (in.)	10-20	20-40	40-60	>60
6. Penetrometer resistance[2] (Avg. 9-48 in.)	<1 MPa	1-2 MPa	>2MPa		
7. Slope (%)	0-5	5-10	10-25	25-50	>50
8. Surface stonyness	<15	15-35	>35		
9. Subsurface stonyness (vol%)	<15	15-35	>35		

[1] Criteria adapted from draft of USDA soil survey manual and are presented for discussion.
[2] Penetrometer resistance is measured when soils are at or near field capacity.

Table 4. Properties of revised existing and proposed new soil series for mine soils in the central portion of the interior coal mining region.[1]

Soil Series	Surface Texture	Soil Color	Drainage	Permeability Surface	Sub-Surface
Lenzburg 871	SiL,SiCL,CL,L	light	well	mod slow	mod slow
Morristown 821	SiL,SiCL,CL,L	light	well	mod slow	mod slow
Schuline 823	SiL, SiCL, CL,L	light	well	mod	m slo-slo
Swanwick 824	Sil,SiCL	light	m-well	mod slow	m slo-v slo
Rapatee 872	SiL,SiCL	dark	well	mod slow	m slo-v slo
Galum*	SiL,SiCL,CL,L	light	well	mod	m slo-slo
Fairview*	SiL,SiCL	dark	well	mod slow	m slo-slo
Pyatts*	SiL,SiCL	light	m-well	mod slow	m slo-v slo
Tablegrove*	SiL,SiCL	dark	m-well	mod slow	m slo-v slo
Captain*	SiL,SiCL	light	well	mod	mod slow
Industry*	SiL,SiCL	dark	well	mod	mod slow
Burningstar*	SiL,SiCL,CL,L	light	well	mod	mod slow
Riverking*	SiCL,SiC,C	dark	s-w poor	m slo-v slo	m slo-v slow
Dupo*	SiCL,SiC,C	dark	s-w poor	m slo-v slo	v slo
Du Quoin*	SiL,SiCL,CL,L	light	s-w poor	mod	m slow

(Continued)

Soil Series	Coarse Fragments(%)+ Surface	Subsoil	Soil Slope(%)	Rooting Depth	Soil Replaced (in.) Top Soil	Root Media
Lenzburg 871	0-35	10-35	0-70	deep	0	0
Morristown 821	15-50	35-80	0-70	deep	0-12	0
Schuline 823	0-15	0-15	0-15	deep§	6-10	0
Swanwick 824	0-10	0-15	0-10	deep§	6-12	36-42
Rapatee 872	0-20	0-20	1-15	deep§	6-18	36-42
Galum*	0-15	0-15	0-15	deep	6-10	0
Fairview*	0-15	0-15	1-15	deep	6-18	0
Pyatts*	0-15	0-15	0-12	shallow	6-12	36-42
Tablegrove*	0-15	0-15	0-12	shallow	6-18	30-42
Captain*	0-15	0-15	0-12	deep	6-12	36-42
Industry*	0-15	0-15	0-12	deep	6-18	30-42
Burningstar*	0-15	0-15	0-12	deep	6-12	36-42
Riverking*	0-15	0-15	0-5	deep	6-12	30-42
Dupo*	0-15	0-15	0-5	shallow	6-18	30-42
Du Quoin*	0-15	0-15	0-5	deep	6-12	36-42

[1] Adapted from Darmody, R.G., R.E. Dunker and D.L. Spindler. Classification and mapping of reclaimed mine soils. Prime Farmland Reclamation After Surface Mining, Fourth Annual Report 1991. Dept. of Agronomy, University of Illinois, Urbana, IL.

* Proposed series: There may be need for additional series with different texture families etc. Research is needed to establish proposed series properties and to verify existing series properties. Galum is essentially a deep (>40 in.) tilled Schuline. Fairview is essentially a deep (>40 in.) tilled Rapatee. Captain is a deep tilled Swanwick.

§ Compaction: soils with a layer ≥4 in. thick with an upper surface within 40 in. of the soil surface with a penetrometer resistance > 2MPa and an average penetrometer resistance >1.8 MPa in the 10-40 in. depth are considered compacted. Compacted layers also have high bulk density (>1.6g/cc) and should be designated as Cd. The compaction also stops roots and should be considered a paralithic contact. If the paralithic contact is within 50 cm of the soil surface the soil should be classified as shallow. Values for penetrometer resistance and bulk density are provisional and subject to change.

+ Coarse (2- 25mm) fragments by volume.

ACKNOWLEDGMENTS

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Table 5. Classification of revised existing and proposed new soil series for mine soils in the central portion of the interior coal mining region.[1]

Soil Series	Proposed Classification[¤]
Lenzburg 871	fine-loamy, (calcareous), mixed, mesic, Typic Udorthent
Morristown 821	loamy-skeletal, (calcareous), mixed, mesic, Typic Udorthent
Schuline 823	loamy, (calcareous), shallow, mixed, mesic, Typic Udorthent
Swanwick 824	loamy, nonacid, shallow, mixed, mesic, Typic Udorthent
Rapatee 872	loamy, nonacid, shallow, mixed, mesic, Mollic Udorthent
Galum*	fine-loamy, (calcareous), mixed, mesic, Typic Udorthent
Fairview*	fine-silty, nonacid, mixed, mesic, Mollic Udorthent
Pyatts*	loamy, nonacid, shallow, mixed, mesic, Alfic Udorthent
Tablegrove*	loamy, nonacid, shallow, mixed, mesic, Mollic Udorthent
Captain*	fine-silty, nonacid, mixed, mesic, Alfic Udorthent
Industry*	fine-silty, nonacid, mixed, mesic, Mollic Udorthent
Burningstar*	fine-loamy, nonacid, mixed, mesic, Alfic Udorthent
Riverking*	fine, nonacid, mixed, mesic, Mollic Haplaquent
Dupo*	clayey, nonacid, shallow, mixed, mesic, Mollic Haplaquent
Du Quoin*	fine-loamy, (calcareous), mixed, mesic, Aeric Haplaquent

[1] Adapted from Darmody, R.G., R.E. Dunker and D.L. Spindler. Classification and mapping of reclaimed mine soils. Prime Farmland Reclamation After Surface Mining, Fourth Annual Report 1991. Dept. of Agronomy, University of Illinois, Urbana, IL.

[¤] The existing soil series are currently classified as mixed, mesic, Typic Udorthents. Some of the proposed as well as the existing series may be Udarents. Schuline, Swanwick, and Rapatee need to be redefined as shallow and loamy.

* Proposed.

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Evaluation of Grain Crops on Reconstructed Prime Farmland

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Abstract. An ongoing project to determine the yield potential of several grain crops on reconstructed prime farmland is being conducted in western Kentucky. Crops being evaluated include: grain sorghum, wheat, and soybeans. In some cases, yields for non-mined land are also reported. Significant differences between varieties for each crop were obtained. It would appear that selection of certain varieties for each crop would be to the advantage of coal companies in their use of these crops in proving performance standards for Phase III bond release of prime farmland. However, since the ranking is not consistent from year to year, caution should be exercised in making specific variety recommendations.

INTRODUCTION

Proof for the restoration of the productivity of prime farmland is currently based on crop yields for three years. Coal mine operators have some latitude in selecting which crop they may grow in order to determine productivity. In addition to forage or hay crops, grain crops such as corn, wheat, soybeans, and grain sorghum are commonly planted in mid-western states. In Kentucky, as well as most all of these states, corn must be grown and the target yields equaled or exceeded one of three years under consideration for Phase III bond release. The overall objective of this research was the evaluation of grain sorghum, wheat, and soybean varieties over a five-year period on restored prime farmland. However, to date only the collection of grain sorghum yield data has been completed. Variety evaluation of corn is the subject of other papers (Powell et al., 1988 and Poneleit et al., 1992).

MATERIALS AND METHODS

Reconstruction Procedures

All data reported in this paper were collected on the River Queen and Alston Surface Mines operated by Peabody Coal Co. in Muhlenberg Co. and Ohio Co., respectively. The prime farmland soils were reconstructed using scraper pans. The dominant soil types that occurred on these mines were the Sadler silt loam (fine-silty, mixed, mesic Glossic Fragidulfs) and the Belknap silt loam (coarse-silty, mixed, acid, mesic Aeric Fluvaquents).

The two soil types were mixed together in a temporary stockpile in the process of surface mining. At the River Queen Site approximately 75% of this mixture was Sadler, with the remainder being Belknap. At the Alston mine, the two soils were approximately in the same proportion. At both sites, the mixture of subsoil was placed over graded spoils to a depth of 36 inches, leveled with a dozer, and approximately 8 inches of topsoil was placed on this graded subsoil.

Soil Fertility

The soil was limed to 6.4 by incorporating 2-4 tons/acre into the leveled topsoil with a heavy-duty disk. Lime rates were based on Kentucky Cooperative Extension Service Recommendations in AGR-1 (Anonymous, 1985*). Lime was needed only the first year of the experiment.

Rates for P and K for each grain crop were based on the same publication, AGR-1. These recommendations were made from randomly collected soil samples taken each year, and generally recommendations decreased as the soil test level slowly increased from very low and

* Although a few changes have occurred over the years with respect to recommendations of lime, nitrogen, phosphorus, and potash, all recommendations were taken from this same publication for each crop, i.e. grain sorghum, wheat, and soybeans.

medium for P and K, respectively. The rates of P_2O_5 initially applied were 120, 120, and 150 lbs/acre for soybeans, wheat, and grain sorghum, respectively. For K_2O, rates were 50, 40, and 100 lbs/acre for soybeans, wheat, and grain sorghum.

RESULTS AND DISCUSSION

Grain Sorghum

Grain sorghum has several traits that may reduce the risks for crop failure on reconstructed prime farmlands. It withstands drought stress better than corn or soybeans by becoming semi-dormant. This has been attributed to its fibrous root system which tends to increase its efficiency in extracting water. The evapotranspiration tends to be lower than corn, and pollination does not seem to be as severely affected by high temperatures. When moisture and nutrients are adequate, grain sorghum produces tillers or extra seed heads that will contribute to higher grain yield, but during drought periods only the primary tiller will produce a seed head. Grain sorghum also withstands excessive moisture conditions better than either corn or soybeans.

The grain sorghum varieties were planted in 30-inch rows at 7 lbs of seed per acre. Each plot or variety consisted of 2 rows, 38 feet in length. Five replications were used in a randomized complete block experimental design. In general, plots were planted the second week of May and harvested when the grain was dry enough to be thrashed with a MF plot combine. Yields were adjusted to 14% moisture.

Grain sorghum yield data are given in Table 1. The varieties planted each year varied somewhat during the 5-year period due to availability from seed suppliers and availability of plot space. The target yield for grain sorghum has not been established by the USDA-SCS, however subtracting the long-term (20-year) state aver-

Table 1. Grain sorghum hybrid test results on reconstructed soil, Peabody Coal Company—River Queen Mine.

Brand-Hybrid*	Maturity Group	Yield** 1985	1986	1987	1988	1989
		bu/a				
Pioneer 8333	3	53	60	65	39	102
Asgrow GS712	4	—	61	46	76	94
Funks G1711	4	63	55	51	58	94
TE Y75	2	—	43	43	81	94
Pioneer 8515	3	53	60	66	28	92
DeKalb DK424	2	57	—	51	40	87
NK S9740Y	2	—	—	—	54	86
TE Y101G	3	77	48	57	45	86
Asgrow Mustang	3	—	57	71	42	86
TE Dinero	3	68	44	40	41	85
NK 2778	3	81	62	70	—	83
NK 2660	3	64	53	31	53	80
Asgrow Topaz	3	63	37	50	45	78
NK 734G	3	—	—	—	33	69
Funks G522DR	3	69	42	39	51	67
Funks RA787	2	—	—	—	57	65
DeKalb M565	2	—	—	38	50	58
NK 2779	3	—	—	48	39	55
TE Y35	1	—	—	—	—	31
Garst 5521	3	—	—	—	51	—
Garst 5511	3	—	—	—	46	—
Pioneer 8226	3	—	—	49	38	—
SS SS1313	4	—	—	37	—	—
SS FFR321	3	—	—	36	—	—
TE Y45G	1	62	64	—	—	—
SS SS174	3	53	58	—	—	—
Funks G1602	3	71	50	—	—	—
TE Dinero-E	3	—	42	—	—	—
NK 2244	2	60	—	—	—	—
TE Y77	2	52	—	—	—	—
L.S.D. (.10)		14.5	14.6	14.4	12.0	17.0

* NK, TE, and SS corresponds to Northrup-King, Taylor-Evans, and Southern States, respectively.

** Yields ranked according to 1989 values. Entries with no values were not planted the respective years.

age yield for grain sorghum from corn, a yield difference of 22 bu/a was determined. The pro-rated target yield for the reconstructed prime farmland at River Queen was calculated to be 83 bu/a. An adjusted statistical value may be determined by subtracting the L.S.D.(.10) value from this target yield, which equals 69, 69, 69, 71, and 66 bu/a for 1985 through 1989, respectively.

In 1985, only 4 of 15 varieties equaled or exceeded the target yield, whereas in 1986, none of the varieties produced enough grain to exceed the target value. In 1987, 2 of the 18 varieties exceeded the target. Prior to 1987 yields were reduced due to compacted subsoil, poor weed control, and perhaps low soil fertility. In 1987, the combine was not available for a timely harvest and considerable losses occurred due to birds. Some varieties experienced as much as 25% loss.

In 1988, much of Kentucky was affected by drought. At this experimental site, the effect of drought diminished after July 10 due to scattered thundershowers. Only 2 of the 20 varieties exceeded the adjusted target yield in 1988.

In 1989, all but 4 varieties exceeded the adjusted target yield and 11 of these had a yield greater than the actual target of 83 bu/a.

Five years of data may not be enough to support conclusive recommendations on which varieties are best suited for reconstructed prime farmland soils, however, it is apparent that some varieties consistently yielded higher than others. There did not appear to be a strong relationship between maturity group and yield.

Wheat

Wheat has some characteristics that may be considered advantageous as a grain crop for Phase III bond release. It avoids summer drought by reaching maturity in late June. Winter wheat also provides reduction in erosion by protecting the soil during its growing period. The straw following harvest may be used as a mulch on steeper non-prime farmland soils.

Soft red winter (SRW) wheat has been used extensively in reclamation as a temporary cover crop, nurse crop, and to a limited extent as a cash crop on mine spoils. Soil depth, ripping, and cultivar selection have been shown to be important to wheat production (Barnhisel et al. 1988). In that study, wheat yields increased with topsoil depth between 10 and 20 inches but not much increase in yield resulted between 20 and 30 inches of soil. Ripping significantly increased yields 2 out of 3 years. Wheat yields ranged from excellent (56 bu/a) to poor (18 bu/a) depending on the year and cultivar selected.

The objective of this five-year study is to evaluate wheat varietal performance on reconstructed prime farmland soils and determine whether varietal rankings can be predicted from conventional variety trials grown on non-mined soils. Data given here are for the first full scale trial, although a few varieties were planted in 1989.

Fifteen SRW wheat varieties were seeded in mid-October 1990 in 7-inch row spacings at a seeding rate of 1.5 bu/a. Each variety was sown in 250 foot strips that were 28 feet wide. Each strip was divided into four blocks or replications. Plots were harvested with a MF plot combine by cutting two 2-meter wide strips from each of the four plot areas, 100 feet in length. All yields were adjusted to 12% moisture.

An intensive management system was employed which consisted of split applications of nitrogen. One was applied at planting and three in the spring with a total of 120 N lbs/a. Three applications of foliar

Table 2. Yields (bu/a) and rankings (in parentheses) of soft red winter wheat varieties grown in mine and non-mine soils in 1991.

	Mine	Non-Mine		
Variety	River Queen	Ohio Valley	W. Coal Field	S. Tier
Saluda	42 (1)	31 (6)	8 (13)	33 (8)
Coker 9803	35 (2)	34 (4)	2 (9)	49 (1)
Pioneer Brand 2555	33 (3)	27 (8)	8 (2)	38 (6)
Verne	31 (4)	37 (1)	1 (1)	47 (2)
Coker 916	30 (5)	35 (2)	3 (8)	34 (7)
Coker 833	30 (6)	34 (3)	6 (4)	41 (5)
Becker	27 (7)	22 (10)	11 (10)	25 (12)
Pioneer Brand 2548	27 (8)	23 (9)	7 (3)	43 (4)
Howell	25 (9)	28 (7)	6 (5)	30 (9)
Clark	24 (10)	31 (5)	6 (6)	46 (3)
Excel	22 (11)	12 (14)	9 (12)	25 (13)
Dynasty	21 (12)	21 (12)	14 (7)	26 (11)
Caldwell	20 (13)	20 (13)	6 (14)	20 (14)
Cardinal	18 (14)	21 (11)	11 (11)	30 (10)

fungicides were also applied, two with the last two nitrogen applications and one additional, as diseases were excessive in 1991.

Yield data for 1991 are presented in Table 2. This table includes data for the fourteen varieties planted at River Queen and for these same varieties planted at three locations in the conventional variety trials. Across Kentucky, and in the state variety trials, wheat yields in 1990 easily surpassed those of 1991 (Van Sanford et al., 1991). This same trend was observed at River Queen for the few varieties planted for the 1990 harvest. Yields for varieties planted at River Queen, Saluda, Pioneer 2555, Becker, Howell, Clark, Dynasty, Caldwell, and Cardinal were 40, 44, 35, 36, 34, 39, 45, and 38, respectively. In 1991, spike disease, such as scab and glume blotch, severely limited yields and were generally not amenable to chemical control.

In spite of the similarity between the mine study and conventional variety trials, there are differences which require comment. It is notable that the top variety in the 1990 River Queen test, Caldwell, and the top variety in 1991, Saluda, are both viewed as varieties that have passed their peak performance. The popularity of each has dwindled, and neither has fared very well in variety trials in the past two years. For example, Caldwell received the lowest ranking of any variety evaluated in 1990-91 in the state trials, and Saluda was ranked in the lowest one-third of that group (Van Sanford et al., 1991).

The 1991 mine data are compared with data from three variety trial locations in Table 2. As a measure of correspondence between mine and non-mine sites, one can look at rank correlation coefficients for varieties. The rank correlation coefficients for the River Queen and the Western Coal Field, Ohio Valley, and Southern Tier sites were r = 0.24, 0.69, and 0.60, respectively. One can attribute a lack of correspondence to simple genotype x environment interaction which is common among all locations in the state variety trial. It is not possible, at this point, to identify the factors unique to the mine soil environment which would inflate the genotype x environment interaction. The other issue that must be considered is the management regime for each of the trials. In the state variety trial, diseases are not controlled with fungicides. This clearly can have a dramatic impact on varietal performance.

Soybeans

Since the soybean is a legume, it will supply nitrogen for its growth provided the needed bacteria are supplied through seed inoculation. Soybeans may also be used in a double-crop management system that could provide data for two grain crops in a single year. However, reconstructed prime farmland that has marginal soil available water holding capacity due to a heavier texture or compaction, may not produce high enough yields for Phase III bond release unless an adequate rainfall distribution occurs.

The soybean varieties were planted in four, 30-inch rows at a rate of 1 bu/acre. The length of each plot was 38 feet and organized in a randomized complete block experimental design with four replications. In general, plots were planted the third week in May and harvested with a MF plot combine. Only three of the four rows were harvested for yield determination. All grain moistures were adjusted to 13% moisture.

Data for soybean yields which have been collected in 1990 and 1991 are given in Table 3. Prior to 1990, yields were collected from several varieties at the River Queen site, but this research had to be discontinued temporarily after one year (1985). Only two of the 14 varieties planted in 1985 have been included in the current project, these were Essex and FFR 516. In 1985, yields for these varieties were 33.7 and 31.9 bu/a, respectively and ranked 2 and 4 of those tested. These earlier data have been published (Barnhisel et al., 1986).

Yields were low at both sites. Both years weeds, especially fall panicum, foxtail, and yellow nutsedge, were not controlled. Weeds were so heavy at River Queen in 1990, plots were not harvested. However, since there did not appear to be any significant difference in weed populations among varieties, values may be considered as relative.

The target yield for Phase III bond release for soybeans (34 bu/a) was not exceeded at either location. Only one variety in 1990 (Pioneer 9531) approached the adjusted target value of 28.3 bu/a. Since these data are preliminary, few conclusions may be drawn with respect to variety selection. Group IV and V maturity ranking has been observed in the earlier study (Barnhisel et al., 1985) to be superior to group III. This is largely expected since our site falls on the general line separating maturity groups.

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Table 3. Soybean yields at two locations on restored prime farmland.

Variety[1]	River Queen	Alston	
	1991	1990	1991
	bu/a		
Asgrow 4595	24.8 (1)*	16.0 (12)	11.0 (20)
Jacques J499	24.4 (2)	23.2 (5)	16.1 (12)
TN 5-85 (R)	24.0 (3)	14.3 (17)	16.0 (13)
So. States 516 (R)	24.0 (4)	16.0 (12)	18.6 (5)
Essex	23.2 (5)	17.2 (10)	17.7 (9)
Stafford	24.0 (6)	24.5 (4)	17.6 (10)
Asgrow 5403 (R)	22.5 (7)	23.0 (7)	19.8 (3)
Pharaoh (R)	21.8 (8)	—	18.6 (5)
FFR 561	21.5 (9)	20.2 (9)	21.5 (1)
DeKalb cx458	21.0 (10)	15.4 (14)	13.3 (16)
Pioneer 9531 (R)	20.8 (11)	23.1 (6)	17.1 (11)
So. States 487	20.8 (12)	17.1 (11)	15.5 (14)
Pioneer 9501	20.7 (13)	27.0 (1)	7.9 (8)
Coker 425	20.6 (14)	21.4 (8)	18.9 (4)
TN 4-86 (R)	18.2 (15)	15.2 (15)	15.3 (15)
FFR 565 (R)	16.8 (16)	25.4 (3)	18.3 (7)
Pioneer 9461	15.3 (17)	12.5 (19)	11.8 (19)
Pennyrile	15.2 (18)	13.2 (18)	12.2 (18)
NK 42-40	14.3 (19)	14.5 (16)	9.6 (21)
Spencer	13.1 (20)	9.8 (20)	13.2 (17)
Hutcheson	11.8 (21)	25.5 (2)	20.9 (2)
L.S.D. (10)	4.3	5.7	3.8

*Rank of yield in parentheses

[1] Varieties with R indicates resistance to cyst nematode

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Ecological Succession - - Its Effects on Soil Properties and Implications for Surface Mine Reclamation

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Abstract. Natural succession, which has been studied for nearly a century, has provided important insight into rates and pathways of soil development and clues about ecosystem dynamics necessary to reconstruct damaged ecosystems. Soil chemical and physical properties are improved under primary and secondary succession. Research has shown that soil properties degrade under agricultural practices, and degradation is accelerated under continuous row cropping. Public Law 95-87 requires that reclaimed prime farmland meet or exceed productivity of unmined similar soils. The economic pressure to release the bond mandated by law has resulted in a focus upon achieving crop yield at the expense of reassembling the disturbed ecosystem. This manuscript examines some of the progress made and lessons learned since enactment of Public Law 95-87 and suggests examples of how a change in perspectives would benefit the reclamation process and those engaged in its implementation.

INTRODUCTION

Fifteen years after enactment of Public Law 95-87 (The Federal Surface Mining Control and Reclamation Act of 1977 (SMCRA)), we have gathered at this symposium to discuss progress, problems, and perspectives resulting from reclamation and research in response to the federal mandate. Among the speakers are research scientists with specialties including crops, soils, engineering, and statistics; administrators from state and federal agencies; and representatives of the coal mining and electrical power industries. In attendance are managers, regulators, miners, reclamation specialists, and environmentalists. Other interests and perspectives undoubtedly are represented. Hopefully, among the consequences of the symposium will be: increased awareness of progress made and of remaining challenges; a renewed willingness to work together to build upon what we have learned; and willingness to integrate that which we know, but have not used.

The many individual reclamation perspectives represented here probably have undergone modification with time. A benefit of SMCRA has been the forced focus upon productive reclamation. Many resources have been invested in attempting to find ways to meet bond release on prime farmland. Much of the effort has been in measuring crop response to treatment impacts, with particular emphasis on ameliorating compaction, evaluating crop varieties, and measuring yield response to fertilizer applications. Among the manuscripts at this symposium are 16 which directly address crop yield responses. Six papers address modification of compaction by tillage. Unless titles are deceiving, only this paper addresses soil ecology or alternative uses of reclaimed land. The objectives of this presentation are: 1) to review effects of natural succession on soil properties, 2) to discuss a few aspects from natural succession which are potentially important to reclamation, and 3) to review SMCRA from the perspectives of time and succession.

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NATURAL SUCCESSION

Definition of succession

Plant succession has been studied for nearly a century. North American ecology has its roots in the investigations of ecological succession (Colinveaux,

1986). Consequently, succession has received much attention, various perspectives exist among ecologists (Horn, 1974), and much of the attention has focused upon dynamics of plant communities (Keever, 1983). Time and space limit our depth of treatment. The references we have cited will provide quick access to the important literature.

Primary succession colonizes freshly exposed, unweathered sites and results in the first occupation of the habitat by the climax community. Examples are successions on sand dunes, volcanic mud flows, glacial till, and marshes (Colinvaux, 1986). Abandoned, unreclaimed mine spoils fall into this category. Secondary succession replaces a climax community following a catastrophic disturbance (Colinvaux, 1986). Old field succession following abandonment is the example most commonly investigated and reported (Keever, 1983). Reclaimed surface mine sites would qualify as secondary succession if the topsoil were replaced and nature were allowed to take its course.

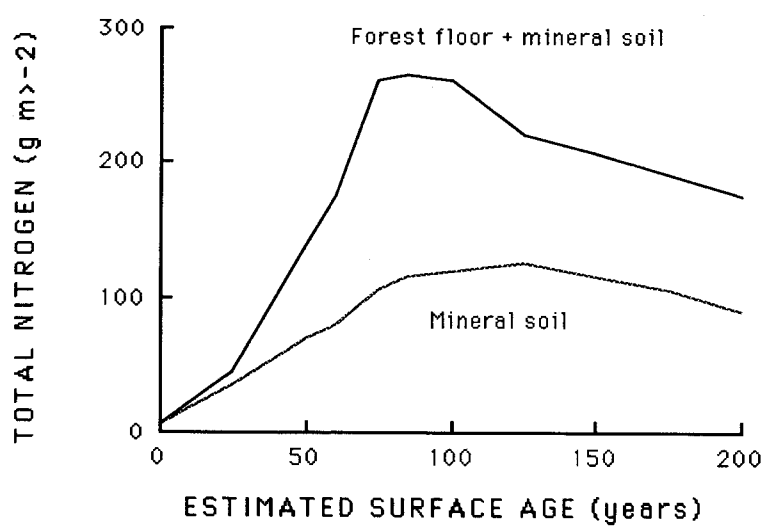
Succession is an organizing process, with some predictable consequences. Early site and habitat improvement by the first colonizers modify conditions and pave the way for later successional species (Colinvaux, 1986). Ultimately, according to Clements (the founder of the "climax theory"), a climax community is established and is noted for the complexity and biomass accumulation (Clements, 1936). Climax species have the unique ability to reestablish themselves on the sites they occupy. Recent ecological concepts recognize the role of soil and nutrients in affecting the rates and directions of successional patterns. Nutrient additions can prolong site occupancy by some species and favor the presence of some over others (Bush and Van Auken, 1986). Cause and effect relationships among individual plant species and soil development often are difficult to demonstrate (Bush and Van Auken, 1986), although investigators commonly credit some plant species as being "soil builders" or "site degraders" (Miles, 1985). Stone's (1975) eloquent treatise of this topic should be required reading for all who are interested in soil development.

Effects of succession on soil development

A few investigations of effects of succession on soil development have become classics among ecologists and pedologists (Birkeland, 1984). Crocker and Major (1955) studied soil development related to plant succession on Alaskan glacial moraines. Knowledge of glacial retreat rates allowed them to estimate surface ages, thus determining nitrogen accumulation as a function of time. Figure 1 reveals that N levels in the forest floor (the organic debris overlying mineral soil) reached a maximum in the first 50-60 years, then began to decline. Mineral soil N continued to increase for several decades. The early N accumulation was attributed to legumes such as *Dryas drummondii* and *Sheperdia canadensis* in the understory and *Alnus crispa*—a nonleguminous N-fixing species in the overstory. The N-fixers ultimately were replaced by successors, and the N level reached a dynamic equilibrium between 150 and 200 years.

Leisman (1957) investigated successional dynamic of an iron mine spoil bank in Minnesota. His results (Figure 2) show a rapid surface accumulation of N, with a delayed accumulation at depth. Leisman also noted the presence of legumes in the early stages of succession, and reported that N levels eventually reached a steady-state level.

Figure 1. Accumulation of N in the mineral soil and forest floor during primary succession of glacial moraines in Alaska (adapted from Crocker and Major, 1955).



Mud flows near Mt. Shasta, California, provided a site for Dickson and Crocker (1953) to study primary succession. Organic matter (OM) accumulated rapidly in the soil surface, reaching a steady-state in about 560 years in a pattern similar to Leisman's (Figure 3).

The cited examples of primary succession indicate that steady-state soil OM levels are reached in periods of centuries. However, OM accumulation in secondary succession proceeds more rapidly. The best known early report of secondary succession is Billings (1938) observation of abandoned fields in North Carolina (Figure 4), where organic matter in the soil surface accumulated rapidly, and reached steady state, at a level three times the initial amount, in about 80 years. Old field succession in this region is characterized by a forest climax. Time to establishment of climax is a

Figure 2. Accumulation of total nitrogen with depth and age in Minnesota iron mine spoil banks (adapted from Leisman, 1957).

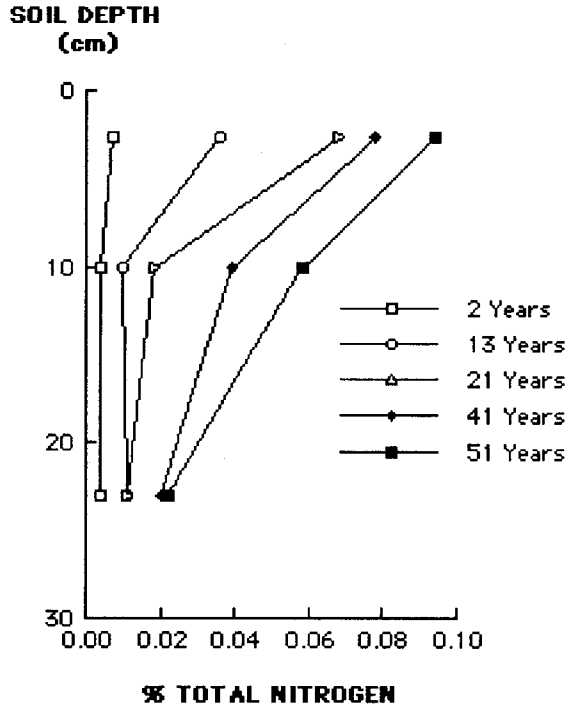


Figure 3. Accumulation or organic carbon as a function of surface age and soil depth near Mt. Shasta, California (adapted from Dickson and Crocker, 1953).

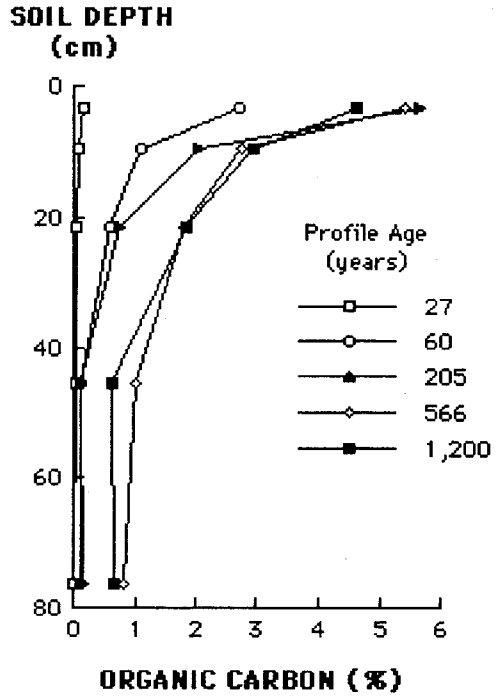
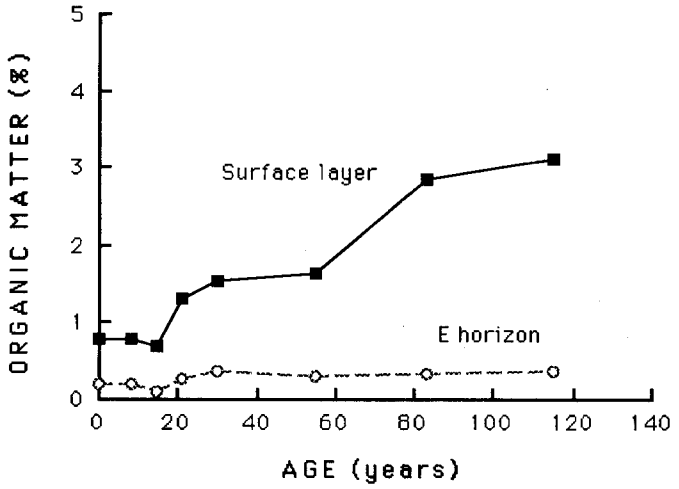


Figure 4. Accumulation of organic matter in the surface soil and E horizon of a forest soil during old field succession in North Carolina (adapted from Billings, 1938).



function, among other factors, of proximity and abundance of seed source (Keever, 1983). The final soil conditions, including O.M. levels and forms and stability of N reserves are a function of climate and parent materials as well as vegetation.

Hammer and Koenig (1988) compared total carbon levels in cultivated soils and adjacent warm season grass stands planted as wildlife habitat in west-central Missouri (Figure 5). Within five years, 0.6 % total C had been added to the surface 5 cm of soil, and total C had increased at all depth increments in the upper 30 cm. Similar OM increases were found in seven and 10-year-old grass stands. Additionally, large earthworm populations were established in the rooting mats of the grasses, and agricultural plow pans, still present in soils between grass clumps, were absent in the root columns beneath individual grass clumps. A thesis project in progress is comparing aggregate stability and water-holding capacities of these soils. Preliminary indications are that soils under the grasses have increased structural aggregation and aggregate stability, decreased bulk density, and higher water-holding capacities. Other investigators have reported rapid OM accumulations under grasses (Dormaar et al., 1990; Stevenson, 1982; Jenkinson, 1971; White et al., 1976). The positive effects of soil OM on structure, porosity, aeration, water-holding capacity, aggregate stability, and cation exchange capacity are well documented (Stevenson, 1982; Birkeland, 1984; Clement and Williams, 1958).

We have briefly established the positive attributes of succession on soil OM, and have concluded by inference that other positive attributes occur as OM levels rise. Bradshaw (1987) said the accumulation of organic matter into the surface soil is probably the most important aspect of succession because it ameliorates the soil physical condition, is the energy source for soil fauna, and is a nutrient- and water-holding source for soil flora. In another setting, Bradshaw (1983) proposed that the greatest hope in ecosystem restoration is "creative ecology which learns from nature's examples."

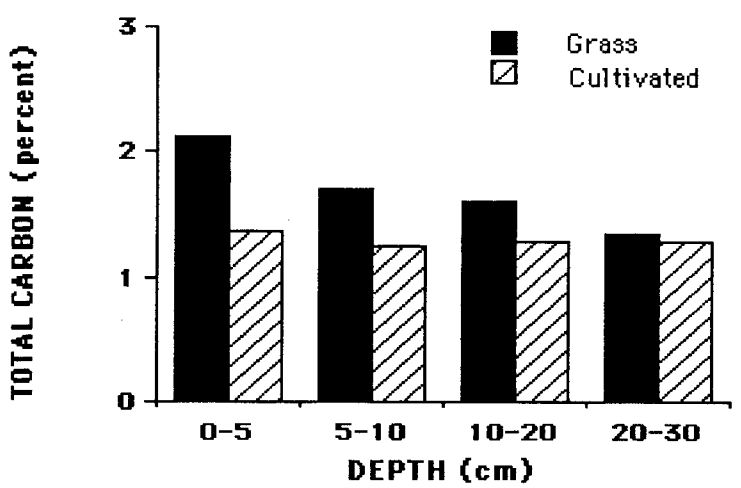
EFFECTS OF CULTIVATION ON SOILS

Research has established that many soil properties are negatively impacted by cultivation. A detailed review is beyond the scope of this paper, but a few key points will be illustrated. For example, McCoy (1987), reviewing past progress and future challenges in soil conservation, lamented the rapidly growing problem of increased compaction in agricultural soils. He cited the demonstrated effects of aggregate destruction on reduced aeration, reduced infiltration, and increased resistance to root penetration. One who reads McCoy's comments cannot help but feel that we who deal with soil compaction in reclamation will soon be joined by agronomists studying related problems created by tillage of agricultural soils.

One of the first reported impacts of cultivation, and one which profoundly affects a host of other soil properties, is loss of O.M. (Jenny, 1941). Jenny observed (Figure 6) a rapid initial loss of soil O.M. with cultivation, with a new, lower, steady-state level being reached in 50 to 60 years. Stevenson (1982) reviewed the subsequent work verifying Jenny's observation.

The loss of soil O.M. with cultivation is accelerated by continuous row-cropping. Larson et al. (1972) found that additions of six t ha^{-1} $year^{-1}$ of plant residue were required to maintain O.M. levels in a Typic Hapludoll in Iowa. When legumes and fibrous-rooted small grains are included in crop rotations, O.M. losses are minimized. Hammer and Brown (1989) reported that 100 years of cultivation on Sanborn Field had not

Figure 5. Total carbon content of cultivated soil and adjacent five-year-old established warm season grass plot. (adapted from Hammer and Koenig, 1988).



destroyed surface or subsoil structure or greatly reduced O.M. levels on plots which had received annual additions of manure in a corn, oats, wheat, red clover rotation. Plots receiving no O.M. and continuously cropped to corn or soybeans were severely eroded, contained only trace amounts of O.M., and were structureless in the plow layer. Barnhisel et al. (1988) reported measurable improvement of soil structure in reclaimed minesoils planted to forage crops. Minesoils in continuous row cropping exhibited very poor surface soil structure and developed platy structure at the base of the plow layer. Unfortunately, the time frame (10 years) allowed by SMCRA for operators on prime farmlands to demonstrate crop productivity results in continuous cropping, with expensive mechanical means often being used to modify compacted soils.

LESSONS FROM SUCCESSION

The role of microorganisms in the nitrogen cycle

Stevenson (1982) observed that microorganisms are necessary in all phases of the soil N cycle, including biological fixation, mineralization, assimilation by soil flora and plants, immobilization, and denitrification. Further, he stated that "... the ability of a few bacteria and blue-green algae to fix molecular N_2 can be regarded as being second in important only to photosynthesis for the maintenance of life on this planet. Soil fauna are necessary precursors, through breakdown of macro debris, for the soil microorganisms (Kevan, 1968). A diverse, robust population of soil organisms and annual returns of O.M. to the soil appear necessary to maintain soil O.M.

Much remains to be learned about the abilities of ecosystems to produce O.M. In addition to N, P and S are essential for O.M. production. Both the quantity and quality of stable humus appear to be affected by these nutrients (Stevenson, 1982).

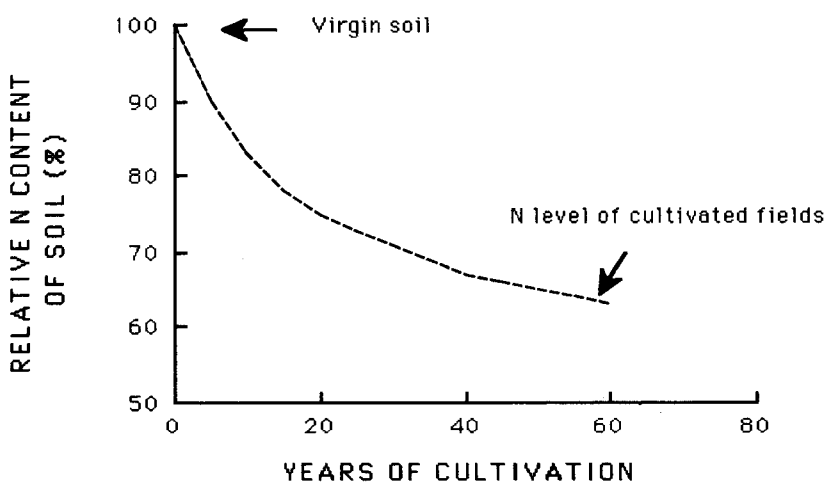
Until recently, microbiologists were limited in their abilities to study soil microorganisms. Schmidt's (1987) review is succinct. He reminded that the majority of soil-born bacteria remain "... unknown to nature, unknown as to function, and inaccessible to isolation." He lamented that the role of soil biota other than fungi an bacteria in generalized interaction including organic matter reduction, biomass accumulation, and grazing, remains largely unknown. However, the International Biological Program (IBP) demonstrated that most of the flow of energy and nutrients in ecosystems is regulated by below-ground events through the activities of soil microorganisms. The soil, to a great extent, has been regarded by ecologists and agronomists as a "black box," into which materials flow and from which different or modified products emerge. Until the internal processes of the "black box" are more clearly understood, our abilities to predict the effects of our activities will remain low.

Recent progress

Jeffries et al. (1981) demonstrated dramatically increased forage production on reclaimed minesoils when legumes were incorporated into the forage mix. The benefits of legumes were observed even when N fertilizers were added to the minespoils. Legumes have been repeatedly observed to be site colonizers in early primary and secondary succession. Much remains to be learned about their role with soil microorganisms in the fixation of atmospheric N and its subsequent conversion to stable forms of humus (Stevenson, 1982).

Some recent progress offers hope that the role of soil microorganisms will receive more attention. Most progress has been in the arena of ecosystem restoration.

Figure 6. Soil nitrogen reduction with time as a result of cultivation (adapted from Jenny, 1941).



Perhaps the subtle difference in perspective resulting from use of the term "restore" rather than "reclaim" has prompted a more holistic approach in the restoration arena. While we may appear overly critical, it is important to note that no papers in this symposium address soil microbiology or soil ecology, and only one of 34 papers addressed the topic at a recent symposium addressing "innovative approaches" to reclamation (Schaller and Sutton, 1987).

Miller (1984) reported that carbon-to-nitrogen and carbon-to-phosphorus ratios affect the establishment and maintenance of mycorrhizal populations in topsoil placed over reclaimed subsoils. Miller also noticed that stockpiling topsoil seriously impeded the mutually dependent processes of seed germination and mycorrhizae activity. This information, when compared with Keever's (1983) observations reminds us that we know very little of the important interactions between plant roots and their environments. In fact, Miller (1987) later stated that the discovery of the prevalence of mycorrhizal fungi in plant communities and the growing awareness of the roles played by mycorrhizae in the lives of plants was ". . . one of the most significant ecological events of the decade."

Among the observations about the role of mycorrhizae in reclaimed minesoils are Schramm's (1966) discovery that early ectomycorrhizal development was essential for seedling establishment of tree species on anthracite wastes in Pennsylvania. Only mycorrhizae inoculated seedlings survived. Later, Marx (1975) observed higher survival rates of inoculated pine seedlings than uninoculated seedlings planted on acid mine spoils. Indigenous mycorrhizae were more beneficial than introduced species.

Sopper and Seaker (1987) amended minesoils with sewage sludge as supplemental O.M. and planted tall fescue (*Festuca arundinacea*), orchardgrass (*Dactylis glomerata*), and birdsfoot trefoil *Lotus coniculatus*). The sludge-amended soils produced higher percentages of forage cover and greater forage biomass than untreated controls. Large, diverse microbial populations accompanied the sludge treatments, but were absent in the controls. Soil organic matter levels generally increased with site age, but at a faster rate on sludge-treated sites. Earthworms were found only on five-year-old sludge treated sites, which were the sites with the greatest CO_2 evolution and the highest O.M. levels. Sopper and Seaker (1987) concluded that sludge application contributed to rapid revegetation and enhanced rejuvenation of microbial populations.

Very little research has investigated the role of earthworms, another important soil builder (Buntley and Papendick, 1960: Buol et al., 1980; Hole, 1981), in reclaimed soils. However, Vimmerstedt and Finney (1973) reported that on minespoil banks, earthworms buried or consumed the equivalent of 5 metric tons leaf litter ha^{-1}. In a 174 day greenhouse study, earthworms buried or consumed the equivalent of 9.5 metric tons of litter and 52.5 metric tons of humus while depositing on the soil surface the equivalent of 16.7 metric tons of castings. Infiltration and air permeability were significantly improved as a result (Vimmerstedt and Finney, 1973).

The holistic approach to the study of soil systems

The tendency of scientists to focus upon the parts of the system most closely related to their interests is not new. Only recently, with the growing awareness of global environmental issues has a systems approach to environmental issues been advocated. Wilding and Drees (1983) noted in their discussion of soil spatial variability that for several decades the focus of agricultural experimental designs was

> ". . . to interpret the significance of main treatment effects (yield or fertility response) with little or no effort to understand the results in terms of soil conditions. Variance due to soil parameters was extracted as blocking or replication. . ."

The perspective is shared by others, including Daniels and Hammer (1992) and Hammer (1991) who warned that any investigations of soils will be incomplete or unsatisfactory if the soils are not considered as parts of a dynamic system which includes an understanding of the abiotic factors causing coevolution of the soil-landscape and the adapted biota. Rowe (1984) noted that pedologists at some time became interested in soils as entities unto themselves, a problem whose solution he could not foresee until pedologists again recognize that soils are the "rooting medium and detritus component of ecosystems." Rowe was careful to state that the problem (of narrow vision) was not limited to pedologists. He explained that most earth-related sciences experienced their beginnings before ecology was defined. He said that

> ". . . because of that historical mistake, pedologists, phytosociologists, climatologists, animal ecologists and geomorphologists work diligently today in their separate fields, occasionally bumping into one another in the landscape ecosystems where periodically they go alone to get more material."

Rowe went on to say that the emerging discipline of landscape ecology offers the conceptual framework within which the disciplines can integrate with a common focus. However, existing landscape ecology treatises greatly understate the role of soils in the flow of energy, nutrients, and water in ecosystems (Naveh and Lieberman, 1984; Forman and Godron, 1986).

It should be noted that this symposium contains numerous examples of multidisciplinary approaches to obtaining higher crop yields from reclaimed minesoils. The magnitude of the mandated reclamation challenge has forced multidisciplinary work. The related realm of ecosystem restoration is also characterized by multidisciplinary approaches, although focus on ecological concepts is more strongly emphasized than is practiced by those responding to the agricultural challenges of prime farmland reclamation. Prime farmland reclamation will move closer to success when the reclaimed minesoil is approached from the perspective that it is a dynamic biological and physical system whose interface occurs where the plant root contacts the soil.

There are lessons to be learned from our colleagues in ecosystem restoration and in systematic ecology. Some key issues relating to restoring the soil have been addressed here. Bradshaw's comments are germane. He noted that to many people, particularly engineers, reclamation is not a biological issue, but is a technical, resource problem of finding permanent, economical ways to stabilize land surfaces and control pollution (Bradshaw, 1987). Bradshaw is correct that this is an incomplete perspective, because land reclamation should strive to model the achievements of nature, and therefore must be based upon the lessons and examples nature has provided.

RECLAMATION CONSIDERATIONS FROM AN ECOLOGICAL PERSPECTIVE

Perspective one: Agronomic and soils rejuvenation vs. bond release

A paradox exists. The SMCRA requires that prime farmland be reclaimed to productive levels equal or greater to similar, unmined soils. The operator wants, for economic reasons, to obtain complete bond release as soon as possible. The ecological and pedological literature reveals that certain soil-building processes are accomplished in decades or centuries, and that traditional agricultural practices degrade rather than build soils. Is it realistic to expect that all soil systems can be restored to former levels of productivity within the six to 12 year window provided by the law? Clearly this is an issue that should be reviewed and evaluated. Soils vary regionally and locally. Is it reasonable to expect one law to pertain to all soil and climatic systems? Is it not reasonable to suggest that some soil systems should be restored to a condition compatible with local climate and parent materials, then be allowed to naturally regenerate prior to resuming cultivation? Another alternative could be to require that reclaimed minesoils be farmed with crop rotations shown to build or maintain soil O.M. levels. It would seem that any reclamation alternative which promotes soil improvement would be desirable.

Secondly, the regulations governing soil replacement are not flexible and may actually result in some less than desirable reclamation. For example, the subsoils across much of Missouri are acidic, but are underlain by unoxidized glacial till high in weatherable minerals. The till is better soil material than the subsoil. However, the review process required for each reclamation plan is lengthy and exhaustive. The operator is therefore encouraged by law to replace the soil as it was rather than to improve it by using the glacial till. The solution would be to review the soil replacement requirements for each site on an individual basis.

Perspective two: Is the concept of land use valid as perceived through the law?

The first example is alternative uses of reclaimed minesoils. Klimstra and Nawrot (1987) addressed this issue with vigor and an creativity. They lamented the legal pressure to return the land to its premined condition when other environmental concerns are of equal or greater importance. Wetlands construction as a part of surface mine reclamation was their focal point. Soil compaction, which impedes vertical water movement and root growth, is a primary reclamation problem. The reclamation process, by creating compaction, favors the development of water catchments (wetlands) in certain parts of the landscape. The potential benefits of wetlands are numerous, with obvious benefits for wildlife and recreation. At the same time that one federal government program encourages the maintenance and restoration of wetlands, a federal law restricts their construction on well-suited sites.

Much of Missouri is a natural ecotone between the eastern deciduous forest and the tall grass prairie biomes (Braun, 1950) and rainfall often is limiting in timing and abundance to create maximum crop yields. Why should law restrict the wetlands construction as a part of reclamation? Most farms in the area have farm ponds. Water for irrigation would improve the productivity of the reclaimed land in dry years. Irrigation is becoming a more common management practice in much of Missouri. We submit that wetlands, with the proper design, planning, and cooperation among agencies, would be economically effective, environmentally sound reclamation alternatives which would improve the agricultural production of reclaimed lands while providing additional, desirable alternative land uses.

A second issue is land use on minesites. Rather than reclassify each area of a permit as a particular land use, we submit that a better method would be to regulate the maximum slope of the entire minesite and allow an

overall reclamation plan which recognizes that in unmined landscapes, soil properties vary among geomorphic surfaces. The concept of "land uses" requires the operator to submit volumnous amounts of paperwork when requesting changes. Region-specific landscape reclamation models are suggested to eliminate individual permits for each requested land use on a mine site. This would greatly reduce the volumes of paperwork required of the operator, hours of review by regulators, and would permit long-range planning based on landscape ecology concepts.

Perspective three: Ambiguous experimental practices regulations

Currently, variances may be submitted for the purposes of conducting experiments, for new research, and for creating alternative land uses. The applicable regulations are general, allowing the operator and the regulatory staff different interpretations of the same passages. Examples of such ambiguity are "... logically planned, implemented and monitored." Regulations require the operator to "conduct monitoring" and to "ensure the collection, analysis, and reporting of reliable data." Proposals generally require many iterations between regulator and operator, with much consumed time and energy. The result is that few experimental practices have been approved since Public Law 95-87. Although rapid advances are being made in many scientific disciplines, including soil microbiology, plant genetics, Geographic Information Systems, rhizosphere chemistry, and spatial statistics, current inertia prohibits or unnecessarily delays application of new knowledge. The experimental practices regulations are valuable and serve an important purpose. However, some streamlining is necessary to ensure timely, cost-effective application of new concepts.

A possible solution could be to require the operator to assume differing levels of liability for different experimental practices. The degree of liability could be correlated to degree of environmental risk. For example, a "Type I" experimental practice might require lengthy review and a high bond, while a "Type II" experimental practice might require little liability and brief review. If published, peer-reviewed research shows that power plant by-products are low-risk, potentially beneficial soil amendments in minesoil reclamation, the experimental practices review should allow rapid, controlled field verification.

SUMMARY

Growing public concern and awareness of the role of man in his environment will likely ensure that surface mining and other resource utilization activities will continue to be regulated by law. Existing laws have endured and probably will continue to do so. Surface mine reclamation has provided society with a unique situation. The theorist (research scientist), the agronomist, the engineer, the reclamation specialist, and the regulator have met at the mutual interface of their disciplines. All of the participants have learned much and experienced related, if not different frustrations. All share a common goal—learning to wisely and economically utilize our finite resources in such a way that the land we bequeath to our children and grandchildren will sustain them in health and happiness. We must work together to apply what we know in environmentally and economically sound ways. The keys to our successes lie in recognizing our mutually shared objectives and in approaching the reclaimed landscape as an ecological system in which the soil is the dynamic interface between the biotic and the abiotic components.

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Vegatation Productivity Equations: An Overview

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Abstract. Vegetation productivity equations are being reported by reclamation investigators. Present equations have been devised for predicting plant growth (woody plants, crops and rangeland) on reclaimed soils. Equations have been derived for Juniperus virginiana, Picea glauca densata, Picea pungens, Pinus ponderosa scopulorum, Celtis occidentalis, Fraxinus pennsylvanica, Populus deltoides, Salix alba tristis, Ulmus pumila, Caragana arborescens, Cornus sericea, Prunus americana, Prunus virginiana, Syringa vulgaris, sugarbeets (Beta vulgaris), spring wheat (Triticum aestivum, spring sown cultivars), oats (Avena sativa), barley (Hordeum vulgare), sunflowers (Helianthus annus), soybeans (Glycine max), and grasses-legumes. The equations employ soil hydraulic conductivity, percent slope, topographic position, bulk density, percent rock fragments, electrical conductivity, percent clay, and percent organic matter as predictors. The equations have R-square values ranging from 0.6 to 0.8, a p-value less than 0.0001 for the total regression, p-values of less than or equal to 0.0101 (Type II sums of squares) for each regressor.

Currently, the reported equations are limited to reclamation applications within Clay County, Minnesota and limited to soils derived from the same parent material as employed in the studies. Another study is currently developing equations for the coal fields of North Dakota. Unfortunately, the equations lack a theoretical/ecological framework to explain them; however, the equation approach is practical and applicable to reclaiming soils from a wide variety of disturbances including surface mining, construction activities, and landfills. In contrast to reference area reclamation verification methods, the equations can provide a quick, defensible, and statistical analysis of the suitability and capability of a soil profile to support plant growth. In some states, reclamation laws may require amendment to accommodate productivity equations as a legal method to verify soil ability to support plant growth.

Individuals can construct similar equations for their region or county providing there exists a suitable Soil Conservation Service soil survey(s).

INTRODUCTION

Reclamation research has led to the formative development of empirical prediction models to forecast the suitability of reconstructed soils (neo-sols) on reclaimed surface mines and other post-disturbance landscape conditions including reclaiming the landscape for prime farmland. This approach can aid in creating the optimum post-disturbance landscape configuration during the pre-site development and governmental permitting stages to generate usable landscapes for agriculture, forested lands, transportation corridors, naturalized vegetation associations, and urban vegetation applications. These equations may cause the current time consuming and expensive reclamation assessment methods such as reference evaluation procedures to become obsolete (Doll and Wollenhaupt 1985 describe the problems associated with reference areas). This paper describes the current body of knowledge associated with reclamation productivity equations and suggests future investigatory directions necessary to develop an increased understanding in predicting vegetation response to neo-sols.

LITERATURE REVIEW AND CURRENT RECLAMATION MODELS

Burley (1988) reviewed the historical development leading to the rise of predictive reclamation modeling as a tool to assist in pre/post-mining landscape planning and design. Significant early contributions leading to the development and issues concerning predictive reclamation equations include works by Neill (1979), Pierce, et al., (1983), Lohse, et al., (1985), Walsh (1985), Vories (1985), Doll and Wollenhaupt (1985) and Plotkin (1986).

Burley and Thomsen (1987) described a methodology to produce a quantitative reclamation productivity equation. The basis for this methodology originated with multivariate statistical concepts presented by

Kendall (1939), requiring computationally complex matrix algebra (see Johnson and Wichern 1988). With the advent of the computer to perform matrix algebra for dimensions greater than three, multivariate statistical techniques made reclamation productivity development possible. By computing eigenvalues and eigenvectors for all possible dependent variables such as crops and woody plants, an investigator could determine the extent of multi-variable covariance and develop an equation to represent a linear combination of variables to generate a single dependent variable. In other words, if the first eigenvalue was relatively large and the eigenvectors for the first eigenvalue were relatively similar, a simple equation derived from the eigenvectors (providing numerical weights for each crop type or woody plant type) would suggest a linear combination to combine the dependent variables into one value per soil type. With one dependent variable value per soil type, it was possible to perform multiple regression analysis upon one single dependent variable. Table 1 lists the vegetation types that have been employed by Burley and colleagues to generate dependent variables.

In the multiple regression analysis, a single independent variable value for each soil parameter was generated by applying a weighting formula suggested by Doll and Wollenhapt (1985), where the soil parameters in the first foot contributes 40% of a plant's vegetation production, the second foot in a soil profile contributes 30%, the third foot contributes 20%, the fourth foot contributes 10% and the remaining layers do not contribute to vegetation growth. With this formula, any soil parameter for a specific soil profile can be measured on a foot by foot basis (even inch by inch) and the investigator can generate a single value for each soil profile, such as a single weighted pH value or a single weighted bulk density value (see Burley and Thomsen 1987). Table 2 lists the variables employed by Burley and colleagues to generate independent variables.

It is also important to recall that most land-use disturbances do not typically affect some plant growth variables such as climate. Instead, disturbances associated with reclamation activities usually affect the soil. Thus in an equation, the analytic tool required is a measure to predict soil suitability. Some investigators have confused "real time crop-yield indexes" with reclamation productivity equations. While real time crop-yield equations can compute the predicted level of vegetation production for a particular year under specific field conditions experienced over the growing season, a reclamation productivity equation predicts the

Table 1. Dependent variables and units of measurement as recorded and published by the U.S. Soil Conservation Service (Jacobson 1982).

Abbreviation	CROP-WOODY PLANT	Measured Average Yield
JV	Juniperus virginiana	feet/20 years
PG	Picea glauca densata	feet/20 years
PP	Picea pungens	feet/20 years
PS	Pinus ponderosa scopulorum	feet/20 years
CO	Celtis occidentalis	feet/20 years
FP	Fraxinus pennsylvanica	feet/20 years
PD	Populus deltoides	feet/20 years
ST	Salix alba tristis	feet/20 years
UP	Ulmus pumila	feet/20 years
CA	Caragana arborescens	feet/20 years
CR	Cornus sericea	feet/20 years
PA	Prunus americana	feet/20 years
PV	Prunus virginiana	feet/20 years
SV	Syringa vulgaris	feet/20 years
SW	Spring Wheat	bushels/acre
BA	Barley	bushels/acre
OA	Oats	bushels/acre
SF	Sunflowers	pounds/acre
SB	Sugarbeets	tons/acre
SN	Soybeans	bushels/acre
GE	Grasses/Legumes	tons/acre

1 meter = 3.281 feet; 1 foot = 0.3048 meter
1 hectoliter = 2.837 U.S. bushels; 1 U.S. bushel = 0.363 hectoliter
1 hectare = 2.471 acres; 1 acre = 0.405 hectare
1 kilogram = 2.2046 pounds avoirdupois; 1 pound = 0.4536 kilogram

average expected yield across many years of cultivation. This average yield is produced by employing crop yield values that were measured over many years including drought years, wet years, warm growing seasons, and cold growing seasons. This averaging effect thereby negates the yearly variances upon crop yields produced by climate, allowing an investigator to study more closely the influences of soils upon vegetation growth over many growing seasons (see Burley and Thomsen 1987 for further elaboration).

Burley, Thomsen and Kenkel (1989) applied this mathematical approach to produce a productivity equation for seven agricultural crops: spring wheat, barley, oats, soybeans, sunflowers, sugarbeets, and grasses/legumes. The data base for this investigation was the Clay County soil survey (Jacobson 1982). The result was a reclamation productivity equation, Equation 1 (coefficient of multiple determination, 0.740).

Equation 1

PLANTS=.6206+(-1.1805*(HC-3.9296)/4.0030)+
(-0.3575*((SL-3.0000)/4.6810)**2)+
(-1.9375*((BD-1.3584)/0.2644)((FR-0.9075)/3.4929))+
(-2.3420*((EC-2.526)/1.0947)((FR-0.9075)/3.4929))+
(1.2424*((OM-3.9512)/0.6638)((EC-2.5269)/1.0947))

Where

PLANTS = Predicted Productivity Score

HC = Hydraulic Conductivity (inches/hour, 1 inch=2.54 cm)

BD = Moist Bulk Density (g/cm cubed)

FR = % Rock Fragments (percentage weight of particles > 7.62 cm)

EC = Electrical Conductivity (Mmhos/cm)

OM = % Organic Matter (percentage weight)

SL = % Slope

** Denotes raised to the exponent power.

Equation 1 does not consider woody plants and thus is not an all inclusive vegetation productivity model. Since reclamation often includes woody vegetation for the development of housing or commercial/industrial sites, wildlife habitat, agricultural shelterbelts, and forestry post-mining land-use applications, the development of a productivity model which includes woody plants would be more universally applicable in reclamation planning and design, including the development of prime farmland where woody plants composed of shelterbelts and windrows can be intricate components of an agricultural landscape.

Equation 2 is the selected best universal (universal in Clay County, Minnesota) reclamation equation derived from Burley's and Thomsen's (1987) methodology. The development of this equation was published by Burley (1991). The coefficient of multiple determi-

Equation 2

ALLPLANTS=.8916+(-1.4366*((HC-3.9296)/4.0030))+
(-1.1419*((SL-3.0000)/4.6810)((TP-2.575/0.9682)+
(-2.3041*((EC-2.526)/1.0947)((FR-0.9075)/3.4929))+
(-0.5887*((EC-2.526)/1.0947)((CL-22.843/14.3063))+
(-1.9375*((EC-2.526)/1.0947)((BD-1.3584)/0.2644))+
(1.2424*((OM-3.9512)/0.6638)((FR-0.9075)/3.4929))

Where

ALLPLANTS = Predicted Productivity Score

HC = Hydraulic Conductivity

SL = % Slope

TP = Topographic Position

BD = Bulk Density

FR = % Rock Fragments

EC = Electrical Conductivity

CL = % Clay

OM = % Organic Matter

Table 2. Main effect independent variables and units of measurements from the U.S. Soil Conservation Service (Jacobson 1982).

Abbreviation	Factor	Unit of Measurement
FR	% Rock Fragments	Proportion by weight of particles > 7.62 cm
CL	% Clay	Proportion by weight
BD	Bulk Density	Moist Bulk Density g/cm^3
HC	Hydraulic Conductivity	Inches/hour (1 inch=2.54 cm)
PH	Soil Reaction	pH
EC	Electrical Conductivity	Mmhos/cm
OM	% Organic Matter	Proportion by weight
AW	Available Water Holding Capacity	Inches/inch, cm/cm
TP	Topographic Position	Scale 1 to 5 Where: 1=Low (Bottomland) 2.5=Mid-slope 5=High(Ridgelines)
SL	% Slope	(Rise/Run)*100

nation in the equation is 0.795. In other words, the regressors explain approximately 80% of the variation in the regression model.

Burley (1990) also reported an equation (Equation 3) that described a sugarbeet model, because the eigenvalue and eigenvector interpretation reported by Burley (1988) suggested that although sugarbeets covaried with other crops, they may be significantly different to the extent that a "sugarbeet only model" merited investigation. The coefficient of multiple determination in the sugarbeet equation is 0.63.

Currently, Burley is reviewing soil reclamation assessment methods for several selected states in the United States of America (North Dakota, South Dakota, Minnesota, Wyoming, Indiana, and Michigan). Numerous states require quantitative reclamation assessment procedures (primarily for coal surface mining reclamation on prime farmlands), meaning that soil productivity equations are potentially compatible with these quantitative assessment demands and could make a contribution in evaluating the post-disturbance soil environment. Burley and Thomsen (1990) have described an approach employing a soil productivity equation for reclaiming surface mines.

While some soil scientists, foresters, agronomists, ecologists, and reclamation specialists may consider these formative equations noteworthy, the development of these equations is not without indirect criticism. For example, Power and Kareiva (1990:312-313) note, "All too often, researchers report significant effects but ignore the processes that lead to these effects." They also state that, "Such models are often so lacking in theoretical content that they do little to advance our understanding of how systems work."

Williams and Schuman (1987) provide one of the few attempts to integrate reclamation soil parameters with empirical equations and biological processes. Yet Power and Kareiva (1990:312) might counter that too many of these investigations are single factor studies or studies that consider the interactions of only a few variables.

Equation 3

$$SBP=-0.342+(0.339*(CL-22.84)/14.3)+(0.425*(pH-7.50)/0.43)+(0.182*((CL-22.84)*(CL-22.84)/14.31))+(-0.816*((AW-0.259)/0.69)*((CL-22.84)/14.31))+(0.363*((pH-7.50)/0.43)*((EC-2.53)/1.09))$$

Where

SBP = Sugarbeet Productivity (unitless)

CL = Percent Clay, by weight

pH = pH

AW = Available Water Holding Capacity, cm cm-1

EC = Electrical Conductivity, Mmhos cm-1

In addition to lacking a theoretical basis, including processes, to explain reclamation productivity equations, there seems to be a host of other fundamental criticisms applicable towards reclamation productivity equations (see Burley 1991). While no scholar has directly attacked these equations, the primary investigator who developed these productivity equations has compiled a list of shortcomings associated with reclamation productivity equations, meriting further investigation, including:

A. the need for self-validation analysis (bootstrap and jackknife statistical techniques),
B. inclusion of empirical data from reclaimed sites into the models,
C. the study of neo-sol long term productivity rates,
D. inclusion of toxic parameters into the models,
E. theoretical/biological/ecological basis for the equations.

Figure 1 illustrates these concerns and their relationship to reclamation productivity equations. The remaining text presented in this paper addresses each of these associated concerns separately.

DISCUSSION

Theoretical Basis

Developing a theoretical basis for explaining empirical results can be a difficult task. In scientific methodology approaches often presented in academia, few if any discussions, seminars, or coursework address, "how one might develop a theory from empirical information."

The equations developed by Burley et al appear to reflect the idea that vegetation responds to a multiplicity of soil parameters for a given agroecosystem. In addition, a broad spectrum of vegetation types covaried around a specific set of ideal environmental conditions, at least for vegetation grown in Clay County, Minnesota agroecosytems. In the future, these vegetation responses may lead to a theory that explains the equations and empirical observations.

Validation Modeling

The current productivity equations are comprised of small data sets with 80 cases, representing the eighty soil types found in Clay county, Minnesota. The equations derived from this small data set could be skewed by selected soil cases. Three techniques useful in examining these small data sets include "Jackknife Estimates," "Bootstrap Estimates," and "Subsampling Estimates" (Mathsoft 1988:73-80).

Jackknife estimates remove one case from the data

set, then calculate the variables of interest (in this case the coefficients of the regressors, the p-values of the regressors, and the coefficient of determination for the equation) termed the jth pseudo-values. Then the case is returned to the data set and the j+1 case is removed. The means and the variance of the pseudo-values can be inspected for large differences. Small differences are interpreted to indicate that no one specific case (soil type) drastically affects the outcomes from the data set.

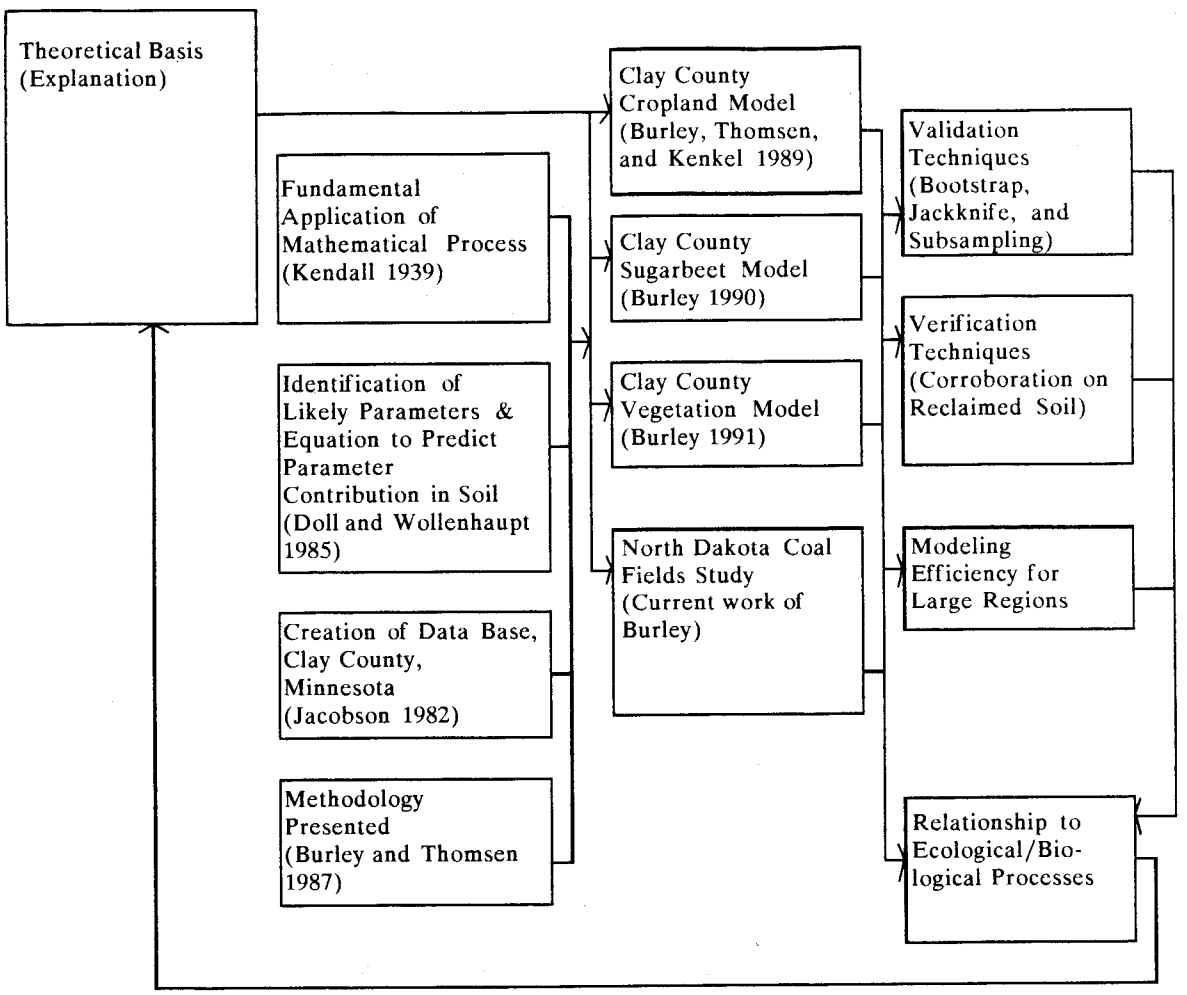
Bootstrap estimates randomly select a specified number of cases (such as 80) with replacement from the data set. Then the variables of interest are calculated. The random sample case selection is repeated a specified number of times (such as 100 or 200 times), generating a pseudo-sampling data set. The means and the variance of the pseudo-sampling data set are then computed. Again, small differences are interpreted to indicate that no one specific case (soil type) drastically affects the outcomes from the data set.

A third procedure would be to randomly select a subset of the cases, without replacement, then follow the equation procedures described by Burley and Thomsen (1987) with this subsample. The cases that were not selected would then be employed in the derived equation to examine existing productivity values with predicted productivity values. Comparisons with high correlations would indicate that the data set is not affected by selected cases (soil types). If there is not a high correlation, the data set is subject to strong influences by particular cases (soil types), indicating that the equation may not be as robust as previously suspected.

Post-disturbance Data Sets

Presently, the reclamation productivity equations presented by Burley and colleagues have been generated strictly from pre-mining soils. None of the soils employed in the studies have been from soils reclaimed

Figure 1. Flow-diagram illustrating the connections to existing work and related issues requiring further investigation.



in surface mining operations. The data sets have been derived from "pristine" soils. Thus, the claim that these equations are applicable to post-mining soils is without direct empirical evidence. The authors of these equations suggest that, providing that one uses the same overburden material derived from the eighty soil types, the equations may be a reasonable predictor. However, this claim is purely speculation. Until reclamation productivity equations use data supplied from post-mining soils (soil parameters and crop yield data), the reliability of these equations is still in doubt.

Long Term Reclamation Productivity

Reclamation productivity equations and long-term landscape neo-sol stability should be investigated to verify the suitability of various soil treatments suggested by the model. Burley (1988) notes that the stability of chemical and physical parameters in neo-sols has not yet been firmly verified. Neo-sols could remain stable, slowly become less productive, or actually improve over time. Predictive integral equations where time is introduced as a variable may be used as an approach to generate long term descriptions of soil productivity rates.

Toxic Conditions

There are numerous soil parameters that have not been introduced into the reclamation productivity modeling process. Soil parameters that encounter abnormal levels of selenium, boron, or sodium adsorption ratio (SAR) may be pertinent to the equation modeling process. The soils studied for Clay County, Minnesota were not necessarily toxic, meaning that no toxic variable was entered into the equation modeling process, as discussions with soil scientists for the region suggested that Clay county did not have any pertinent soil toxicity conditions for the eighty soils studied (see Jacobson 1982 for a description and classifcation of the soil profiles and series).

Ecological Processes

Ties to ecological processes through the reclamation productivity process have not been conducted. Although there may be numerous speculative arguments concerning the ties between ecological processes and reclamation productivity equations, little or no substantive work has been initiated. Some ecologists believe that connecting empirical equations to ecological processes is an important aspect in the development of scientific understanding.

SUMMARY REMARKS

Reclamation productivity equations are presently being reported (Burley, Thomsen, and Kenkel 1989, Burley 1990, and Burley 1991) for a particular county in Minnesota (Clay County), with a new investigation being conducted in North Dakota to test the methodology on a larger region. The North Dakota investigation will examine self-validation issues, reclaimed soil verification, and modeling efficiency for an area larger than one county.

Burley and colleagues suggest that the Minnesota equations are able to predict soil vegetation productivity values and compare means between predicted soil productivity values with 95 % confidence levels (Burley 1991). However, unless one is intending to reclaim sites in Clay County, Minnesota, the current equations are of only modest immediate and practical significance.

The equations may require further internal validity testing, the incorporation of cases from reclaimed soils, the addition of toxic soil parameters, and may eventually contain an integration function to predict changes in soil productivity over time.

Eventually, other investigators may adopt Burley and Thomsen's (1987) methodology to study the development of vegetation productivity equations for other regions.

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Evaluation of Small Grains on Minesoils

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Abstract. Yield response and tillering capacity of several soft red winter wheat cultivars grown on reclaimed surface mined lands to various seeding rates were evaluated over a two year period in southern Illinois. Two mine soils, one consisting of scraper placed rooting medium plus topsoil, and the other consisting of cross-pit wheel spoil plus topsoil were studied. Seeding rates were 60, 90, and 120 lb/a. An undisturbed tract of Stoy silt loam (Aquic Hapludalf) was used as an unmined comparison. Seeding rate significantly affected tiller numbers and grain yields on both mine soil treatments. No response to seeding rate was observed on the undisturbed Stoy soil. Results from this study indicate that higher seeding rates of soft red winter wheat are necessary on mined land to maximize productivity. Cultivars significantly affected grain yields on both the mined and unmined soils.

INTRODUCTION

Grain yield for wheat is a function of three parameters: i) the number of heads per unit area, ii) the number of seeds per head, and iii) the weight of the seeds. The number of heads per unit area can be affected by tillering capacity, seeding rate, row spacing, and environment. The tillering capacity of a specific cultivar can be extremely dependant upon environmental conditions and fertility levels. Since seeding rate and row spacing can be adjusted, several researchers in different locations have studied their effect on yield and yield parameters (Baker, 1982; Faris and DePauw, 1981; Guitard, et al., 1961; Johnson, et al. 1988; Joseph, et al., 1985; Marshall and Ohm, 1987; Roth, et al. 1984; and Tompkins, et al., 1991).

Approximately 1.5 million acres of soft red winter wheat is grown in Illinois annually. Most of the wheat is grown in the southern half of the state and a large percentage of the acres are double cropped with soybeans. Standard agronomic practices, cultivar selection, date of planting, seeding rate, row spacing, and fertility levels, have been developed for this geographical area; however, no information was available for mined soils in Illinois. Therefore, this study was designed to evaluate several soft red winter wheat cultivars planted at different seeding rates on mine soils in southern Illinois.

MATERIALS AND METHODS

Research was done on the Denmark Mine, Horse Creek Mine and a nonmined control site. All sites were located in Perry County, southwestern Illinois. The Denmark mine soil consisted of an area of scraped placed rooting media with 9 inches of topsoil replaced. The area had been tilled with the Kaeble-Gmeinder TLG-12 deep ripper. The Horse Creek mine soil consisted of cross-pit wheel spoil. A nearby tract of Stoy silt loam (Aquic Hapludalf) was used as the nonmined comparison in both years. The undisturbed soils of this region are formed on 4 to 6 feet of Peorian loess overlying Illinoian glacial till. Most of these soils have highly weathered acidic subsoils which are high in clay, highly plastic, and poorly aerated when wet. The C horizon consists of clacareous loess and calcareous glacial till and is chemically favorable for plant growth.

1988-89 Study: In the fall of 1988, three soft red winter wheat cultivars (Cardinal, Caldwell, and Dynasty) were planted on the Denmark mine and the nonmined control site. Plots were six-rows-wide with 7.0 inch row spacing and 25 feet long. Treatments were arranged in a randomized complete block design with six replications on the mined site and four replications on the nonmined site. Seeding rates were 60, 90 and 120 pounds/acre. All plots received 45 lbs/a of nitrogen fertilizer at planting and 45 lbs/a in the spring. The number of tillers/meter were determined at harvest on

one of the center rows of each plot. Plots were machine harvested and grain weights were expressed as bu/a at 13.5% moisture.

1989-90 Study: In the fall of 1989, five cultivars (Cardinal, Dynasty, and Pioneer Brand 2550, 2548, and 2555) of soft red winter wheat were planted on the Horse Creek Mine, and on the nonmined Stoy site. Seeding rates were 90 lbs/acre and 180 lbs/acre for each cultivar. Plots were 21 feet wide and 200 feet long and treatments were arranged in a randomized complete block design with four replications. As in 1988-89, plots received 45 lbs/a of nitrogen at planting and again in the spring. Two subplots, 7.5 feet wide and 50 feet long, were harvested for each plot. Plots were machine harvested and grain weights were expressed as bu/a.

RESULTS AND DISCUSSION

1988-89 Study: Seeding rate significantly affected grain yields on the mine soil but no response to seeding rate occurred on the undisturbed Stoy soil (Table 1). Six replications were harvested on the mine soil in 1989 and four replications on the Stoy soil. Cultivars form the main treatment factor with seeding rate being a split effect. Cultivars significantly affected grain yields on both soils. Mean yields for cultivars and seeding rates are presented in Table 2. Yields for the Dynasty cultivar were the highest on both soil treat-

Table 2. Mean treatment yields of cultivars and seeding rates for the 1989 Denmark wheat experiment.

Treatment	Mine soil	Stoy soil
	----- Yield, bu/ac -----	
Cultivars:		
Dynasty	32.2 a	64.0 a
Cardinal	25.4 b	63.4 a
Caldwell	24.3 b	46.6 b
LSD (0.05)	2.2	7.3
Seeding Rates:		
1.0 bu/ac	23.2 c	57.7 a
1.5 bu/ac	27.7 b	58.5 a
2.0 bu/ac	31.0 a	57.7 a
LSD (0.05)	1.1	4.6
Target Yield-HCL[1]	41.8	

[1/] Base target yields of high capability lands (HCL) for Denmark permit area calculated by IL Dep of Agric. This base target yield is adjusted annually by a county success factor to adjust for weather variation.

Table 1. Error mean squares and F ratios for cultivars and seeding rates on tillers/meter and grain yield at the Denmark mine and nonmined control site in 1988-89.

Source of Variation	df	Mine Soil Tillers	Mine Soil Yield	Stoy Soil Tillers	Stoy Soil Yield
		---------- Mean Squares ----------			
Cultivar (C)	2	33.40**	125.37**	21.43**	40.30**
Error a	15,9	3.76	9.37	4.41	6.25
Seed Rate(R)	2	11.33**	104.18**	1.17	0.10
R x C	4	2.31	1.70	0.99	0.04
Error b	53,35	2.25	2.61	5.22	29.20

**, Statistically significant at the 0.01 level.

Table 3. Tiller number and grain yields for seeding rates within cultivars for the three wheat cultivars in 1988-89 at Denmark mine and nonmined control sites.

Cultivar	Seeding Rate	Mine Soil Tillers	Mine Soil Yield	Stoy Soil Tillers	Stoy Soil Yield
	(lbs/a)	(no./m)	(bu/a)	(no./m)	(bu/a)
Caldwell	60	42.0	18.9	87.3	46.3
	90	58.3	24.6	82.0	46.5
	120	58.3	28.0	85.8	46.6
Cardinal	60	41.3	21.3	100.3	63.0
	90	59.3	25.0	102.0	64.5
	120	65.5	29.3	105.3	62.5
Dynasty	60	55.5	29.0	120.5	64.0
	90	64.8	30.9	118.8	63.6
	120	71.8	36.1	115.3	62.0
LSD (0.05)		5.3	2.7	6.8	9.3
Target Yield-HCL[1/]			41.8		

[1/] Base target yields of high capability lands (HCL) for Denmark permit area calculated by Illinois Department of Agriculture. This base is adjusted annually by a county factor to adjust for weather variation.

ments. Caldwell cultivar yielded the lowest on both soil treatments. Cardinal yielded very well on the undisturbed Stoy soil but was significantly lower than Dynasty on the mine soil. Seeding rate had no effect on the Stoy in 1989, while seeding rate on the reclaimed soils did effect yield, and there appears to be a linear relationship that needs to be tested beyond the 2.0 bushel/acre rate. This response is probably due to reduced number of tillers produced on the mine soil treatment. In addition, the average number of heads per meter of row ranged from 40-75 for the reclaimed plots, while the number of heads on the Stoy soil ranged from 80-120 per meter of row. Response for seeding rates within cultivars are presented in Table 3.

1989-90 Study: There was a significant difference among the five cultivars on the Horse Creek mine soil and the nonmined Stoy soil in 1990 (Table 4). There also was a significant seeding rate effect at the Horse Creek location, and a significant R x C interaction at the nonmined site. This response is similar to the 1988-89 sudiies at the Denmark Mine, indicating a higher seeding rate is recommended on mined lands. Pioneer 2548 had the highest yields on both soil treatments when seeding rates were combined (Table 5). Pioneer 2550 had the second highest yield at Horse Creek, but it produced the lowest yields on the undisturbed Stoy site. This cultivar is an older cultivar that is reported to have "drought tolerance". Based on its performance in the mined plots, this appears to be correct. All five cultivars had higher yields at the 180 lb/a seeding rate than the 90 lb/a rate (Table 6 and Figure 1); however, the difference was not significant for individual cultivars. The significant seeding rate effect for the mined soils in Table 4 resulted when the two seeding rates were compared over all five cultivars. The mean grain yield over cultivars at the 90 and 180 lb/a seeding rates was 38.6 and 41.5 bu/a, respectively, with a LSD value (0.05) of 2.2 bu/a. There was a significant reduction in yield associated with the 180 lb/a seeding rate on the nonmined soils for Dynasty and Pioneer Brand 2550. Conversely, Cardinal had a significantly higher yield at the 180 lb/a seeding rate and Pioneer Brands 2548 and 2555 were not affected.

SUMMARY AND CONCLUSION

Small grain yields on mined soils were significantly lower than the nonmined soils in both years. None of the cultivars equalled the target yield for Perry county in 1989. The lower yield on the mined soil was associated with fewer tillers compared with the nonmined soil and to increased sensitivity to weather stress on mined land.. In 1990, Pioneer Brand 2550 exceeded target yields at the 180 lb/a seeding rate. Pioneer Brand

Table 4. Error mean squares for the effect of cultivar and seeding rate on grain yield in 1990 at Horse Creek mined and a nonmined control site.

Treatment	df	Mine Soil	Stoy Soil
Cultivars (C)	4	503.3**	1289.8**
Error a	12	175.6	42.3
Seeding Rate (R)	1	171.7**	26.1
R x C	4	10.5	48.6**
Error b	52	24.1	8.9

**, Statistically significant at the 0.01 level.

Table 5. Mean treatment yields of cultivars and seeding rates for the 1990 wheat experiment.

Treatment	Mine Soil	Stoy Soil
	(bu/a)	(bu/a)
Cultivars:		
Pioneer 2548	48.6	66.6
Pioneer 2550	41.6	42.2
Cardinal	38.9	48.5
Dynasty	37.6	51.3
Pioneer 2555	33.5	52.3
LSD(0.05)	10.2	5.0
Seeding Rate:		
90 lb/acre	38.6	52.7
180 lb/acre	41.5	51.6
LSD(0.05)	2.2	1.4
Target Yield-HCL[1/]	41.8	

[1/] Base target yields of high capability lands (HCL) for Denmark permit area calculated by IL Dep of Agric. This base target yield is adjusted annually by a county success factor to adjust for weather variation.

Table 6. Grain yields for seeding rates within cultivars for five soft red winter wheat cultivars in 1990 from the Horse Creek mines and the nonmined control site.

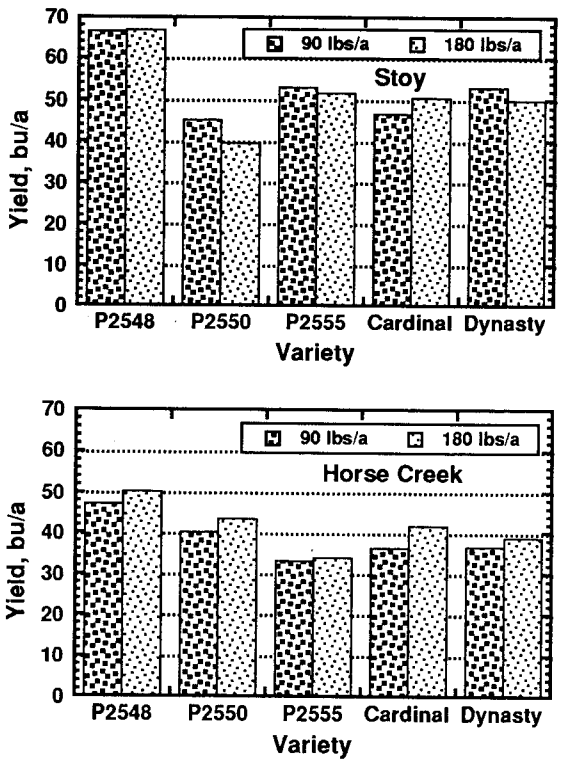
Cultivar	Seeding Rate	Mine Soil	Stoy Soil
	(lbs/a)	(bu/a)	(bu/a)
Cardinal	90	36.3	46.6
	180	41.6	50.4
Dynasty	90	36.6	53.0
	180	38.7	49.8
P2550[2]	90	40.1	44.9
	180	43.3	39.5
P2548[2]	90	47.1	66.4
	180	50.2	66.8
P2555[2]	90	33.1	53.0
	180	34.0	51.6
LSD (0.05)		9.3	2.7
Target Yield-HCL[1/]		41.8	

[1/] Base target yields of high capability lands (HCL) for Denmark permit area calculated by Illinois Department of Agriculture. This base is adjusted annually by a county factor to adjust for weather variation.

[2/] P2550, P2548, and P2555 are the designations for Pioneer Brand 2550, Pioneer Brand 2548, and Pioneer Brand 2555.

2548 exceeded the target yield at both seeding rates. The number of tillers wasn't determined in 1990. However, visual observations suggest there were fewer tillers at the lower seeding rate on the mine soil in 1990 as well. Yield data from both years indicate there are differences among the cultivars. Additional research is needed to develop recommendations for mined soils, but a seeding rate above the recommended 90 lb/a appears to increase yields on mined land.

Figure 1. Effect of seeding rate on 5 wheat varieties on mined and unmined soils in 1990.



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Corn Hybrids for Reclaimed Surface Mine Soils in Kentucky: Hybrid Performance Plus Maturity and Planting Date Evaluations

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Abstract. Agronomic performance of corn hybrids were evaluated for three years on reconstructed surface mine soil at the River Queen Mine in Kentucky. Means from the surface mine performance tests were compared to performance test results conducted on undisturbed soils. Within a year, hybrids in the two test types had similar harvest moistures but little correspondence of agronomic performance. Neither single nor multiple year data from the Kentucky Hybrid Corn Performance Test, performance evaluations conducted on undisturbed soils, were able to predict hybrid performance on reconstructed surface mine soils. Multiple year, but not single year, surface mine performance data provided a reasonable prediction of hybrid agronomic performance in a subsequent year's surface mine performance test. In a second experiment, four hybrids differing in maturity were planted at three planting dates. Full-season maturity hybrids and earlier planting date had the best agronomic performance on reconstructed surface mine soils at two Kentucky locations.

INTRODUCTION

Corn is produced in many different environments. Worldwide, corn is grown in tropical to temperate climates; from 40° south latitude to 58° north latitude; from below sea level to 13,000 feet altitude; in arid climates with as little as 8 inches of annual precipitation to areas with an excess of 100 inches of precipitation (Martin and Leonard, 1967). The extensive amount of genotypic variation available to corn breeders has been utilized to develop cultivars adapted to numerous environmental niches. Cultivars may differ in maturity, ability to withstand drought and heat, ability to resist diseases and insects, and in ability to recover nutrients from the soil. Hybrid varieties in the U.S. have been adapted to niches that are defined primarily by plant maturity relative to the growing season and to disease or insect resistances endemic to certain growing areas. In addition to specific adaptations for growing season and pest resistance, genotypic variation for productivity potential exists among hybrid varieties available from different seed companies. A corn grower in Kentucky or any other state must somehow make a choice among the tens or even hundreds of different hybrid cultivars made available to him by as many as 30 or more seed companies. The same decision faces the mine operator who plans to grow corn on reclaimed surface mine soils. A corn producer uses a number of guidelines in his selection of a hybrid(s). Information about hybrid adaptation, productivity, pest resistance, and other factors are presented by seed dealers. Recommendations based on experiences of fellow producers is often of value, but most grower decisions are made only after consultation of unbiased performance test data such as that provided by the state experiment station. The agricultural experiment station data is generally collected from numerous state environments that include different soil types and sometimes different production practices. The pertinent question for our interest is: Can the Kentucky Hybrid Corn Performance Test data (Evans and Poneleit, 1987; Poneleit and Evans, 1988, 1989, 1991a, 1991b) predict the performance of hybrids to be used on reclaimed surface-mined soils as well as it does for undisturbed Kentucky soils? Alternatively, must testing to determine hybrids suitable for reclaimed mine soils be done specifically on reclaimed surface mine soils? These questions will be examined in Experiment 1.

A second experiment will consider the time of planting and the interaction of hybrid maturity. Since both factors are known to influence corn yield potential, the influences of each will be studied in Experiment 2.

MATERIALS AND METHODS

Experiment 1

Forty - two hybrids were grown each year at the River Queen mine site in Ohio County, KY from 1987 to 1990. Most of the hybrids were selected from those grown in the Kentucky Hybrid Corn Performance Test

(KYHCPT) in the same year. Other hybrids, about 20 in 1988 and fewer in 1989 and 1990, were provided by the Illinois Prime Farmland Reclamation after Surface Mining research group as those that were expected to perform well under stress in Illinois tests. Three maturity check hybrids, FR27XLH38, FR27XMo17, and FR27XPa91, were included in both the tests on surface mined soils and in the KYHCPT. These maturity check hybrids were used to determine the environment x hybrid maturity interactions that might influence yield potential interpretations. The KYHCPT (Evans and Poneleit, 1987; Poneleit and Evans, 1988, 1989, 1991a, 1991b) were grown at seven Kentucky locations that represented most geographic areas of the state. One hundred thirty - two hybrids were grown at each test site. From 24 to 40 of the hybrids grown on the mined site were also included in the KYHCPT in any one year. The data from the state performance test in any year is the average over all seven locations. This seven site average is considered the best possible evaluation of hybrid performance potential. An attempt was also made to retain as many hybrids as possible from the prior years' surface mine test in the subsequent years' test on the surface mine site. From 26 to 30 hybrids were represented in subsequent tests and from 16 to 22 hybrids were represented in two or three year surface mine test averages.

Fertility, herbicides, insecticides, and tillage methods for the River Queen test sites were applied as per the recommendations of the Kentucky Cooperative Extension Service Recommendations in AGR-1 (Ananymous, 1990). Planting dates were as early as conveniently possible and ranged from late April to mid May. Fertility and other management inputs for the KYHCPT locations were applied for optimum production as recommended by the Kentucky Cooperative Extension Service. Planting dates ranged from late April to mid or late May. Planting of all plots was by use of a commercially available no-till planter modified with cone hoppers to facilitate plot size rows. All plots were two rows 36 inches apart and 22 feet long. All plots were planted with a set number of kernels to provide a planting density of 23,460 plants per acre. An additional 10% were planted in no-till plots. Plots were not thinned and stands at harvest were usually from 75 to 85% of the planted density. Grain harvest was completed with use of a small plot combine. Moisture content as well as grain weight was measured from each plot at harvest. All yields were calculated as bushels per acre at 15.5% moisture and 56 lb test weight.

All data were analyzed by Analysis of Variance (ANOVA) procedures for randomized complete blocks or lattices designs as appropriate. When the F test was significant, Least Significant Difference (LSD) statistics were calculated at the 0.10 level. Spearman rank correlations (SAS Institute, Inc.) were calculated for analyses of the predictive value for annual and multiple year means.

Experiment 2

Four hybrid varieties with a maturity range from 115 to 136 days were obtained from Pioneer Hybrid, Inc. The hybrids, Pioneer Brand 3475, Pioneer Brand 3378, Pioneer Brand 3320, and Pioneer Brand 3165 had harvest maturities of 115, 120, 130, and 136 days, respectively. The hybrids were planted on three dates in each year at two mine sites (Alston and River Queen) from 1989 to 1991 but only at River Queen in 1988. Planting was begun at the earliest time permitted by soil conditions and temperature. Subsequent plantings were attempted at about 10 day intervals. Planting dates were main plots and hybrid varieties were subplots. Cultural and management factors were as described above.

RESULTS AND DISCUSSION

Experiment 1

Average annual yield and moisture data for each surface mine test and KYHCPT are shown in Table 1. Within any one year, the average yield of hybrids in the surface mine test was less than the same hybrids averaged over seven locations of the KYHCPT. Harvest moisture content was about equal for the two test types in 1987 but was lower in the surface mine tests in all other years. Significant differences were found among hybrids in each test type in each year. The LSDs for the surface mine tests were always considerably higher than that of the KYHCPT because one location of data is being compared to seven locations of data.

Correlations among annual and multiple year means for yield and harvest moisture content are shown in Table 2. Several types of comparisons are made. Performance of the hybrids in the seven locations of the

Table 1. Average annual yield (bu/ac) and harvest moisture content (percent of wet weight) for surface mine and Kentucky Hybrid Corn Performance Tests grown in 1987, 1988, 1989, and 1990.

	Surface mine		Hybrid corn performance test	
Year	Yield	%moisture	Yield	%moisture
1987	83.0	15.5	156.8	15.2
1988	72.9	17.8	97.5	19.1
1989	101.7	16.1	152.5	19.8
1990	49.3	20.4	117.7	23.3

KYHCPT was compared on an annual basis with performance in surface mine tests conducted in the same year (comparisons 1-4). In only one case, in 1988, was the correlation between the two tests significant. The R^2 for this relationship was 0.17, which suggests minimal correspondence of variability in the surface mine environment with the variability arising from the average environment of tests grown in undisturbed soils. Similar comparisons for harvest moisture content show positive correlations in each year with R^2 values ranging from 0.27 to 0.55. Apparently the year environmental factors that control harvest moisture of the grain are more uniform over the growing area than are factors that influence yield.

In a predictive comparison, KYHCPT results would have been valuable to choose the top performing hybrids in the following year's surface mine test only when 1987 KYHCPT data were used to predict 1988 surface mine performance (Table 2, comparisons 5-7). Harvest moisture content from one KYHCPT year was no more accurate as a predictor of the following years' surface mine harvest moistures. Apparently both yield and moisture content can differ significantly from a year of KYHCPT to the following years' surface mine performance. Occasional correspondences may occur but our data do not indicate a consistent predictive relationship.

Two-year or three-year average data from the KYHCPT did not improve the predictive value of KYHCPT data for performance in surface mine conditions over the one year's performance test data for either yield or moisture content (Table 2, comparisons 8-10). Similar comparisons of KYHCPT data as a predictor of future performance on undisturbed soils in Kentucky are much different (Table 2, comparisons 11 and 12). In 1991, for example, the two-year yield mean of 1989 and 1990 was strongly correlated with 1991 yield ($r = 0.92$, $R^2 = 0.85$). The three-year yield mean of 1988, 1989, and 1990 was also strongly correlated with 1991 yield ($r = 0.74$, $R^2 = 0.54$). Comparable statistics for harvest moisture content are both $r = 0.83$, $R^2 = 0.69$.

Prior year surface mine performance tests also were ineffective as predictors of the following years hybrid performance for yield (Table 2, comparisons 13-15). Correlations were very low, ranging from -0.03 to 0.01. Correlations for harvest moisture were substan-

Table 2. Spearman rank correlations as indicators of predictability of hybrid performance on reclaimed surface mine soils by data collected from Kentucky Hybrid Corn Performance Tests (HCPT) on undisturbed soils and from data collected in prior year(s) surface mine performance tests (SM).

	- - - - - - - - - Data Set - - - - - - - - -			- - - - - Correlations - - - - -	
Comparison	Predictor	Predicted	N	Bu/ac	Percent Moisture
1	HCPT 1987	SM 1987	40	0.19	0.58**
2	HCPT 1988	SM 1988	25	0.42*	0.67**
3	HCPT 1989	SM 1989	27	0.12	0.52**
4	HCPT 1990	SM 1990	24	-0.04	0.74**
5	HCPT 1987	SM 1988	29	0.53**	0.25
6	HCPT 1988	SM 1989	18	0.38	0.44
7	HCPT 1989	SM 1990	30	0.03	0.60**
8	HCPT 1987-88	SM 1989	16	0.38	0.37
9	HCPT 1988-89	SM 1990	18	0.17	0.45
10	HCPT 1987-89	SM 1990	16	0.27	0.42
11	HCPT 1989-90	HCPT 1991	70	0.92**	0.83**
12	HCPT 1988-90	HCPT 1991	46	0.73**	0.83**
13	SM 1987	SM 1988	29	0.00	0.42*
14	SM 1988	SM 1989	26	0.01	0.15
15	SM 1989	SM 1990	30	-0.03	0.22
16	SM 1987-88	SM 1989	16	0.32	0.09
17	SM 1988-89	SM 1990	22	0.56**	0.15
18	SM 1987-89	SM 1990	16	0.53**	0.36

* Significant at $P \leq 0.95$

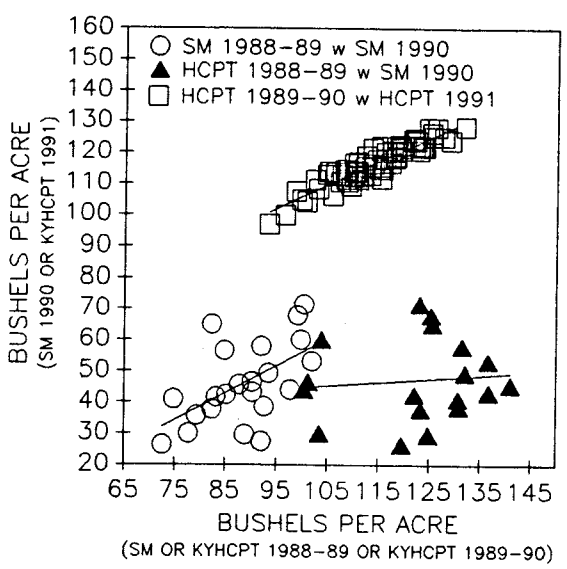
** Significant at $P \leq 0.99$

tially larger, but only one comparison, 1987 with 1988, was significant and explained only a small portion of the variation ($R^2 = 0.18$).

Predictive value of two- or three-year surface mine yield performance data was much better than for annual data (Table 2, comparisons 16-17). The correlation coefficients were significant for the two-year average, 1988 and 1989, and the three-year average, 1987, 1988, and 1989) with the 1990 surface mine yield performance. The two- and three-year variations explained a major portion of the 1990 variability; $R^2 = 0.31$ and $R^2 = 0.28$, respectively.

Although the magnitude of correlation data for the multiple year surface mine performance with a following year annual performance did not equal that for multiple year KYHCPT performance with a following year KYHCPT performance, the values were respectable considering that the surface mine data represented only one location per year while the KYHCPT data represented 7 locations per year. The use of multiple year surface mine yield performance data is, however, a better predictor of annual hybrid performance in a surface mine area than is multiple year data from undisturbed soils (Table 2 and Figure 1). The predictability of performance on reclaimed surface mine soil could be improved by including more hybrid observations per location and additional test locations. Larger numbers of hybrid observations (132 per year) averaged over seven locations for two years for KYHCPT data on undisturbed soils, provided much better predictability (Figure 1). Predictability of harvest moisture content in the surface mine tests was not improved by multiple year averages.

Figure 1. Plots of 2-year (1988 and 1989) surface mine (SM) and Hybrid Corn Performance Test (HCPT) data with 1-year (1990) SM data, plus 2-year (1989 and 1990) HCPT data with 1-year (1991) HCPT data.



In summary for Experiment 1, hybrid performance on reclaimed mine soils is quite erratic from year to year. A feasible explanation for the variability is the extreme stress imposed on the corn hybrids by the disturbed soils. The fact that reclaimed soils often have less well developed soil structures, are more compacted, and have lower soil organic matter contents, as a result of the mixing of A and B horizons during reconstruction, could contribute to low moisture retention. Droughty conditions or precipitation as thunderstorms, instead of soaking rains, could accentuate the stressful conditions. In addition, stand establishment was poor in some years. Although stand data are not reported here, low stands did contributed to erratic yields; i.e. in 1990 two of the four test replications were discarded because of poor stands. In this case, the poor stands were partially the result of poor weed, control but mice and vole feeding was believed to have caused much of the stand loss.

In each year, however, some hybrids yielded enough to exceed the level needed for bond release. The low year to year correlations suggest that the same hybrids did not always perform well in successive years. Nevertheless, multiple year averages provided a substantially better yield performance prediction. Improved hybrid selection for yield should be possible if additional years (and locations) of testing can be provided.

Harvest moisture content for corn hybrids grown on reclaimed soils seems to be strongly influenced by the yearly weather. Most of the hybrids grown in the surface mine tests, except for the three maturity checks, were of similar maturities and weather influences apparently caused random variation of harvest moisture contents. Predictability of harvest moisture content was very low. Maturity check hybrid comparisons are evaluated later.

Experiment 2

In addition to the plot data originally planned to study the hybrid maturity/planting date interaction objective of Experiment 2, data of the maturity check hybrids from Experiment 1 is also considered here. Data from four years' tests on the maturity check hybrids in Experiment 1 are shown in Table 3. The yields of the early-season, FR27xLH38; mid-season, FR27xMo17; and full-season hybrids, FR27xPa91, increase from the early to the full season hybrid. The genetic control for maturity is confounded with genetic yield potential, but the general yield trend and harvest

moisture trends were as expected. Both harvest moisture and yield increased with longer maturity (Table 3). In 1987 and 1989, the full-season hybrid yielded less than the mid-season hybrid, which is likely due to late season droughts that affected the full-season hybrid more than the mid-season hybrid in those years. The late drought effect is shown dramatically in 1989 harvest moisture data where the early- and late-season hybrids had nearly the same harvest moistures. The 1987 KYHCPT harvest moistures reflect the very early maturity in that year since each hybrid had very low harvest moisture and the difference between the late- and early-season hybrids was less than the average difference for four year data.

These data show that the full season hybrid did not express its true, higher yield potential in two of the four test years. The effect was less obvious for tests grown in undisturbed soils which would suggest less late season stresses in undisturbed soils. Extrapolating these results to the general case, later maturing hybrids may be at a disadvantage in disturbed soils in that effects of drought are more likely to occur late in the season on this soil type and in this geographic area. Alternatively, the highest possible yields will usually be associated with a full-season hybrid. The latter conclusion is derived primarily from HCPT tests on non-disturbed soils. Surface mine tests confirmed this conclusion in two years of four.

Planting date and hybrid maturity interactions were examined in Experiment 2. Four Pioneer Brand hybrids were planted at two surface mine sites in Kentucky at three dates in 1988 to 1991. Although 10 days was the intended interval between planting dates, soil or weather conditions made strict compliance impossible. Actual planting dates are shown in Table 4. Data from two locations/years were not included since deer feeding caused damage at River Queen in 1990 and poor stands reduced yield potentials at Alston in 1991.

The effect of hybrid maturity agrees with the conclusion from previous paragraphs, in that hybrids with later maturity generally outyielded earlier hybrids. This conclusion is shown in the yield average over locations and years and is statistically significant in nearly all individual location-year comparisons where significant

Table 3. Yields of maturity check hybrids from surface mine (SM) and Kentucky Hybrid Corn Performance Test (HCPT).

Year	Test	FR27 xLH38	FR27 xMo17	FR27 xPa91	Year Ave.	FR27 xLH38	FR27 xMo17	FR27 xPa91	Year Ave.
		bu ac^{-1}				% Moisture			
1987	SM	64.4b*	90.7a	66.5b	73.9	11.9c	15.4b	18.2a	15.2
	HCPT	138.0b	159.6a	165.0a	154.2	13.9b	14.4b	15.8a	14.7
1988	SM	62.6b	68.4b	97.2a	76.1	16.5b	16.8b	18.4a	17.2
	HCPT	78.5b	89.4a	97.4a	88.4	17.5b	17.6b	19.9a	18.3
1989	SM	92.8a	109.2a	89.6a	97.2	16.9a	15.7b	16.3ab	16.3
	HCPT	128.5b	160.2a	166.7a	151.8	18.0c	19.4b	21.2a	19.5
1990	SM	30.0a	29.6a	49.3a	36.3	16.1b	20.6ab	23.3a	20.0
	HCPT	102.1b	119.1a	117.3a	119.3	19.5c	21.9b	24.7a	22.0
Hybrid	SM	62.4	74.5	75.6		15.7	17.1	19.0	
Ave.	HCPT	111.8	132.1	136.6		17.2	18.3	20.4	

* Means in a row and for a variable, except for year or hybrid averages, followed by the same letter are not statistically different at $P \leq 0.10$

Table 4. Planting dates for Experiment 2 at River Queen (RQ) and Alston reclaimed surface mine sites.

1988	1989		1990		1991	
RQ	RQ	Alston	RQ	Alston	RQ	Alston
May 10	May 3	Apr 28	May 9	May 11	May 1	May 2
May 20	May 16	May 12	May 23	May 24	May 31	May 16
May 30	May 26	June 22	June 4	June 6	June 7	June 6

differences were observed (Table 5). Planting date had little influence on the relative performance of the four hybrids. Although an earlier hybrid was statistically equal to the latest hybrid in several planting date comparisons and no differences were shown among hybrids in other planting date comparisons, the average yield of the latest maturing hybrid was always highest. These data indicate that a full-season hybrid is generally the best choice for highest yield, but an earlier hybrid may, on occasion, provide an equivalent yield performance.

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SAS Institute Inc., SAS Circle, Box 8000, Cary, NC 27511.

Table 5. Grain yield (bu/ac) of four corn hybrids differing in maturity and planted at three different times at River Queen (RQ) and Alston reclaimed surface mine sites.

Pioneer Brand Hybrid	1988 RQ	1989 RQ	1989 Alston	1990 Alston	1991 RQ	Ave.
			Early planting date			
3475	29.3c*	66.3c	78.0b	71.4c	68.0	62.6
3378	43.1c	55.3c	89.2ab	88.3b	87.3	72.6
3320	77.8b	98.4a	83.9b	91.0b	70.1	84.2
3165	91.0a	89.0ab	114.0a	107.6a	68.9	94.1
			Intermediate planting date			
3475	52.7c	55.8c	116.0	75.3	71.5	74.3
3378	80.9b	59.2c	119.0	78.1	78.5	83.1
3320	90.4b	85.1b	104.0	89.8	69.4	87.7
3165	101.3a	104.0a	116.5	84.4	56.7	92.6
			Late planting date			
3475	83.3b	56.3b	86.2	72.3	80.1	75.6
3378	104.4b	36.0b	108.5	84.3	64.8	79.6
3320	118.5b	83.9a	87.2	65.0**	64.3	83.8
3165	120.5a	82.0a	112.3	95.6	46.6	90.8

* Means in a column within a planting date followed by the same letter are not significantly different at $P \leq 0.05$.
**Yield reduced by deer.

Corn Hybrid Responses to Mined Land in Illinois

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Abstract. A wide range of corn (Zea mays L.) genotypes were grown from 1988-90 at two mined land locations in western and southern Illinois. The southern Illinois site consisted of a scraper placed mine soil, while the western Illinois site was reclaimed using a cross-pit bucket wheel excavator. Nearby undisturbed soils were used as unmined comparisons. Results from these studies indicate that the potential to minimize the effects of stress exists through the selection of adapted genotypes. Hybrids with the highest yield potential on undisturbed soils did not necessarily produce the highest yields on disturbed soil plots. Weather variables were associated with yield variation more on the mine soils than on the undisturbed soil treatments. Hybrids grown on the mine soils built with scrapers, a high traffic system, yielded substantially lower than hybrids grown on the wheel spoil. This is due to differences in both the quality of pre-mine soil materials and the subsequent levels of soil compaction after reconstruction.

INTRODUCTION

Obtaining optimum row crop productivity on reconstructed mine soils requires the understanding of complex integrated soil, water, climatic, and genetic relationships. Crop varieties, plant populations, herbicides, and fertilizer rates are management factors that are generally recognized as affecting crop yields. The effects of these management factors are compounded when row crops are grown on newly constructed mine soils, which may have wide ranging physical and chemical properties, making it difficult to project productivity success. Because mine soils are fundamentally different from natural soils and have unique problems contributing to stress susceptibility of present commercial hybrids, the potential to minimize effects caused by the physical or chemical properties of mine soils should exist through hybrid selection. Corn yields of current commercial hybrids display considerable year to year variation when grown on mined land (Dunker and Jansen, 1987). There have been significant yield differences among soil reconstruction treatments in most years for an individual hybrid, but the ranking of treatments has not been consistent from year to year.

Genotype variation in response to environmental stress factors such as drought and heat stress has been observed in many fields (Blum, 1974; Boyer, 1970; Dedio, 1975; Sammons et al., 1978). Hyne and Brunson (1940) observed that corn hybrids showed less yield reduction under adverse drought and temperature stress than their inbred parents. Differences among hybrids in response to stress have been reported, with older hybrids generally affected more than newer genotypes. Russell (1977) concluded, after studying historically important hybrids, that genes for stress tolerance had been added to hybrids over years. Because the response of plants to drought, temperature, physical, and chemical stresses involves genotype X environment interactions, one needs to obtain, identify, and measure responses of various genotypes to distinguish those that respond in both favorable and unfavorable environments.

This cooperative study between the University of Illinois and University of Kentucky was initiated in 1988 to evaluate a wide range of genotypes on mined lands, compared to those growing on nearby natural soils. This study compliments work previously done in western Illinois (Dunker et al., 1988) and western Kentucky (Powell, et al., 1988).

MATERIALS AND METHODS

University of Illinois and University of Kentucky researchers managed the respective hybrid studies of their state. Common genotypes were included in each study to evaluate their performance over a wider range

of soil and climatic conditions. The Illinois experiment is being conducted at two locations. The first location is at the Denmark Mine, Arch of Illinois Inc., in Perry County in southwestern Illinois. This mined land consists of an area of scraper placed rooting medium that has had topsoil replaced. An additional treatment involved the use of a Kaeble-Gmeinder TLG-12 deep ripper, which was used on one half of the mine soil area. Two nearby undisturbed soils, a Cisne soil (Mollic Albaqualf) and a Stoy soil (Acquic Hapludalf) were used as unmined comparisons.

The second site is located at Industry Mine, Freeman United Coal Company, in McDonough County in west-central Illinois. This experiment was initiated in 1989. One mine soil treatment, consisting of cross-pit wheel spoil with topsoil, and an undisturbed Keomah (Aeric Ochraqualf) were evaluated for hybrid response. As opposed to the scraper operation which can effectively segregate the various layers of unconsolidated materials, the mining wheel blends materials from the various layers of unconsolidated materials from the geologic column. Consequently the wheel spoil at Industry is a mixture of leached loess, calcareous loess, and glacial tills from the premine soils.

Soils formed the main treatment factor, while hybrids were a split effect, with hybrids randomly blocked (four replications) within each soil treatment. A John Deere Maxi Merge planter modified with cone seeder attachments for small plot use was used to plant hybrids. The two-row hybrid plots, 30 ft in length with rows spaced 30" apart, bordered with each other within the soil blocks so little border effect would occur. Planting population was uniform across hybrids at a rate of 23,500 seeds per acre. Management practices were similar to that of a typical farming operation. Hybrids were selected for this study based on current or previous use within the geographical area. The germplasm represents a wide range of characteristics with some experimental lines supplied by plant breeders interested in the response of these hybrids when grown on mined land.

RESULTS AND DISCUSSION

Denmark Mine

1988 Results

The Denmark hybrid plots were planted on May 11 under dry soil conditions. Emergence was slow and erratic as drought conditions continued through the month of May and into June. Severe early season stress was observed on all the soil treatments, although stress was most severe on the mine soils. Total rainfall for the month of June was only 1.7 inches, and was coupled with above normal temperatures. 1988 monthly rainfall totals were below normal in May, June, and August. The average maximum temperatures for June, July, and August exceeded 90 degrees F. The hybrid plots were helped by the late July rains which occurred at anthesis. There is no doubt, however, that corn yields were significantly affected by weather stress in 1988.

Results show that there were significant yield differences for both soil treatments and hybrids in 1988 (Table 1). There was a significant soil treatment by hybrid interaction indicating that hybrids were affected differently by soil treatment effects. Mean yields for the undisturbed Cisne and Stoy were significantly higher than either mine soils in 1988. There also was a significant response to the TLG deep tillage treatment on the mine soil area. There were significant differences among hybrids within soils for all four soil treatments (Table 2).

1989 Results

The hybrid plots were planted on May 18 under favorable moisture conditions following pre-plant incorporation of fertilizer and herbicides. An early season application of Roundup on April 26 was required to control perennial weeds and migrating thistle. Subsequent rainfalls aided emergence and below normal temperatures prevailed during this period. Emergence was variable among treatments with the No TLG treatment having the slowest emergence. Below normal precipitation and above normal temperatures occurred in late June and early July. While rainfall totals for the months of June and July were above normal, rainfall came in two major events during mid-July. Stress symptoms first appeared on the No TLG treatment, followed by the TLG and Stoy soil. The Cisne soil showed stress symptoms approximately one week later than the other treatments. The rainfall in mid-July aided pollination, but high temperatures and below normal rainfall in late July to mid-August further separated treatment differences.

Table 1. Mean squares and level of significance for the various effects in the analysis of variance for 1988 hybrid yield at the Denmark Mine.

Source of variation	d f	Mean Square
Soil treatment (S)	3	65918.90**
Error (a)	12	1551.93
Hybrid (H)	19	1183.99**
S x H	57	486.48**
Error (b)	228	283.44

**, Significant at the 0.01 level of probability.

Results of the analysis of variance show there were significant yield differences for both soil treatments and hybrids in 1989 (Table 3). Yields from the Cisne soil were significantly higher than other treatments. Yields of the TLG and Stoy soil treatments were not significantly different, but yields on the No TLG treatment were significantly lower than any other soil treatment. Significant differences among hybrids within soils occurred on all four soil treatments in 1989 (Table 4).

1990 Results

Excessive spring rainfall prevented the planting of this experiment in 1990. Soils on the experimental plot areas remained in a saturated condition until late June. Most hybrids in this experiment are in a maturity range that would not respond to such a late planting date. A smaller number (5) of very early maturing hybrids were planted on the Lorsban 15G experiments on the Captain and Horse Creek mines. Results of hybrid response at these locations are discussed in that section of this report.

1988-89 Mean Yields

Two-year-mean yields for this study show the yields for the genotypes to be superior on the undisturbed Cisne soil (Table 5). Hybrid yields on the Stoy soil also were significantly higher than the two mine soils but, lower than the Cisne soil. Analysis of variance for two-year-mean yields show significant differences for both soil and hybrids. Significant hybrid by year and hybrid by soil treatment interactions indicate hybrids responded differently to year effects (environment) and for soil effects (Table 6). Two-year-mean yields for the 17

Table 3. Mean squares and level of significance for the various effects in the analysis of variance for 1989 hybrid yield at the Denamrk Mine.

Source of variation	d f	Mean Square
Soil treatment (S)	3	113622.34**
Error (a)	12	521.91
Hybrid (H)	19	660.20**
S x H	57	383.03
Error (b)	228	345.82

**, Significant at the 0.01 level of probability.

Table 2. Ranking of hybrids by yield for the 1988 Denmark Hybrid Study.

Genotype	Cisne		Stoy		Scraper-TLG		Scraper-No TLG	
	bu/a	rank	bu/a	rank	bu/a	rank	bu/a	rank
Pioneer 3165	117	1	90	1	34	18	43	3
Asgrow 2570	115	2	69	8	49	11	35	7
LH123 x LH93	114	3	86	2	65	2	46	2
FR27 x Mo17	112	4	75	4	33	19	11	19
Pioneer 3320	109	5	74	6	48	12	20	17
Zimmerman Z28	108	6	74	5	52	10	38	6
Pioneer 3295	107	7	57	17	58	6	33	10
FR303 x RSC204	105	8	79	3	58	7	5	20
LH119 x LH51	104	9	63	14	45	14	20	16
LH132 x LH123	100	10	64	12	55	9	49	1
B73 x Pa91	97	11	68	9	45	15	14	18
LH136 x LH123	96	12	68	10	61	5	41	4
B73 x LH38	95	13	69	7	74	1	34	9
Pioneer 3377	94	14	62	15	62	4	40	5
LH74 x LH123	91	15	64	13	56	8	22	14
GRE 82-10	89	16	68	11	40	17	32	11
LH119 x LH82	86	17	56	18	45	13	34	8
B73 x BS10	76	18	38	20	27	20	21	15
LH74 x LH51	73	19	59	16	45	16	24	13
LH82 x LH146	65	20	42	19	63	3	25	12
Mean	97		66		51		29	

LSD (0.05) for comparing a hybrid mean between two soils is 25.8.
LSD (0.05) for comparing two hybrid means within a soil is 23.3.
LSD (0.05) for comparing two soil means is 13.5.

common hybrids of both years are presented in Table 7. Mean yields for several of the hybrids on the TLG treatment were similar to those obtained on the undisturbed Stoy soil. Hybrid yields from either of the mine soils were not comparable to those obtained on the Cisne soil. Hybrid LH123 x LH93 had the highest 2 year yields on the No TLG and Stoy soils, and ranked second on the TLG treatment.

The low yields from the mine soils in 1988 and 1989, especially on the No TLG scraper placed treatment, are assumed to be the result of increased sensitivity to weather stress. The increased sensitivity of these hybrids to stress may be due to the root-limiting characteristics of the compacted mine soils from scraper placement. Previous researchers have documented rooting differences for selected corn hybrids between mine soils (Fehrenbacher et al., 1982; Meyer, 1983). They concluded that confinement of the root systems in constructed mine soils was due to adverse soil physical parameters. Root cores have been taken from five selected hybrids on these plots and will be evaluated to determine rooting effectiveness in mine soils.

Table 5. 1988-89 mean yields across hybrids for mined and unmined soil treatments.

Soil treatment	1988	1989	Mean
		Yield, bu/a	
Cisne	97.7	108.4	103.0
Stoy	66.3	62.2	64.2
Scraper TLG	50.9	48.7	49.8
Scraper No TLG	29.4	17.8	23.6
LSD (0.05)	13.5	7.9	7.0

Table 6. Mean squares and level of significance for the various effects in the two year analysis of variance for 1988-1989 hybrid yield.

Source of variation	d f	Mean Square
Year (Y)	1	1056.38
Soil treatment (S)	3	148609.33**
Y x S	3	3102.61
Error (a)	12	1008.76
Hybrid (H)	16	857.95**
H x Y	16	673.79**
S x H	48	496.43**
H x Y x S	48	348.08
Error (b)	228	345.82

**, Significant at the 0.01 level of probability.

Table 4. Ranking of hybrids by yield for the 1989 Denmark Hybrid Study

Genotype	Cisne		Stoy		Scraper-TLG		Scraper-No TLG	
	bu/a	rank	bu/a	rank	bu/a	rank	bu/a	rank
Dennis 642	125	1	84	1	48	10	11	15
LH119 x LH51	121	2	42	20	35	17	9	16
Pioneer 3295	120	3	53	17	40	13	5	20
LH132 x LH123	118	4	61	12	46	11	17	10
Asgrow 2570	115	5	72	4	52	8	36	2
LH74 x LH123	113	6	61	10	65	3	22	6
FR27 x Mo17	110	7	70	5	63	4	15	12
LH119 x LH82	109	8	73	3	61	6	20	7
LH74 x LH51	109	9	57	14	66	2	22	5
Pioneer 3377	108	10	79	2	50	9	9	17
Pioneer 3320	108	11	55	16	34	18	8	18
Pioneer 3165	107	12	47	18	26	20	25	4
FR1141 x FR4326	106	13	70	6	44	13	14	13
LH136 x LH123	103	14	65	8	67	1	6	19
LH123 x LH93	103	15	64	9	63	5	43	1
FR27 x LH38	103	16	68	7	59	7	15	11
Zimmerman Z14W	101	17	45	19	40	14	27	3
Zimmerman Z28	97	18	57	15	46	12	20	8
LH82 x LH146	97	19	61	11	33	19	18	9
Dekalb 689	93	20	58	13	35	16	13	14
Mean	108		62		49		18	

LSD (0.05) for comparing a hybrid mean between two soils is 25.8
LSD (0.05) for comparing two hybrid means within a soil is 25.7
LSD (0.05) for comparing two soil means is 7.9.

Industry Mine

1989 Results

Hybrid plots at Industry Mine in west-central Illinois were planted on May 17 in 1989 under favorable moisture conditions. Emergence was good to excellent on both the cross-pit wheel spoil and undisturbed Keomah soil. Rainfall in May was near normal resulting in rapid early season growth. Precipitation in June and July was significantly below normal and stress symptoms were visibly apparent on both soils by early July. Hybrids on mine soil plots were exhibiting considerably more stress than hybrids on the Keomah soil plots. Limp leaves and tight rolls were common on most hybrids. However, one hybrid (LH123 x LH93), was quite conspicuous, in that no significant stress symptoms were visible compared to the other hybrids on mine soil. This difference in visible stress expression continued through most of the growing season. Rainfall in August was near normal but rainfall in September totaled only 0.94 inches, about 1/4 of normal. This increased sensitivity to weather stress of hybrids grown on the wheel spoil treatment may be due to root-limiting physical characteristics of the wheel spoil created by grading and topsoil replacement.

Results of the analysis of variance show that yield was significantly affected by both soil treatment and hybrids in 1989 (Table 8). No significant soil treatment by hybrid interaction occurred in the 1989 experiment. Yield results from this 1989 study are presented in Table 9. Yields on the Keomah soil were significantly higher than the wheel spoil for every hybrid. The hybrid LH123 x LH93, which was duplicated twice (two different seed lots), was the number 1 and 2 ranked hybrid on the mine soil. Yields of all hybrids grown on the wheel spoil are low due to weather induced stress. Hybrid yields on the Keomah soil were very good, given the weather conditions in 1989. Rainfall when pollination occurred, June 13 to July 17, totaled only 0.74 in.

Table 8. Mean squares and level of significance for the various effects in the analysis of variance for 1989 hybrid yield at Industry Mine.

Source of variation	d f	Mean Square
Soil treatment (S)	1	156626.96**
Error (a)	6	1798.03
Hybrid (H)	24	781.89**
S x H	24	202.08
Error (b)	129	216.37

**, Significant at the 0.01 level of probability.

Table 7. Rankings of hybrids by mean yield for 1988-1989 Denmark Hybrid Study.

Genotype	Cisne		Stoy		Scraper TLG		Scraper No TLG	
	bu/a	rank	bu/a	rank	bu/a	rank	bu/a	rank
Asgrow 2570	115.4	1	70.8	3	50.8	8	35.8	2
Pioneer 3295	113.3	2	55.1	15	48.8	11	19.0	13
LH119 x LH51	112.4	3	52.6	16	40.2	16	14.7	14
Pioneer 3165	112.0	4	68.8	6	30.0	17	34.0	3
FR27 x Mo17	111.1	5	72.5	2	48.0	13	13.2	17
LH132 x LH123	109.2	6	62.9	12	50.7	9	33.4	4
LH123 x LH93	108.9	7	75.0	1	64.2	2	44.5	1
Pioneer 3320	108.6	8	64.9	10	41.3	15	14.2	16
Zimmerman Z28	102.6	9	65.6	9	49.2	10	29.1	5
LH74 x LH123	102.2	10	62.5	13	60.8	4	22.0	11
FR1141 x FR4326	102.0	11	68.9	5	44.5	14	14.2	15
Pioneer 3377	101.1	12	70.5	4	56.4	5	24.6	7
LH136 x LH123	99.6	13	66.4	8	64.1	3	23.4	9
FR27 x LH38	99.0	14	68.6	7	66.4	1	24.4	8
LH119 x LH82	98.0	15	64.5	11	53.3	7	26.8	6
LH74 x LH51	90.8	16	58.2	14	55.5	6	23.0	10
LH82 x LH146	80.8	17	51.6	17	48.1	12	21.3	12
Mean	103.0		64.2		49.8		23.6	

LSD (0.05) for comparing a hybrid mean between two soils is 25.5
LSD (0.05) for comparing two hybrid means within a soil is 25.2
LSD (0.05) for comparing two soil means is 7.0.

1990 Results

Plots were planted in 1990 on May 31. Soil moisture and seedbed conditions were very favorable to the planting operation. Emergence was excellent for all hybrids on both the mined and unmined land. Vigorous early season growth was enhanced by adequate precipitation events through June and July. Although June rainfall was 10 inches above normal rainfall was distributed into weekly events throughout the month. Little visible stress was evident at pollination in late July for any of the hybrids on either soil treatment. Below normal rainfall and above normal temperatures from mid-August to mid-September accelerated maturity and enhanced dry down of stalks and grain.

Results of the analysis of variance (Table 10) show that 1990 yield was not significantly affected by soil treatments but was significantly affected by hybrids. A significant soil treatment by hybrid interaction occurred in 1990 indicating hybrids responded differently to soil effects.

1990 yields of 23 individual hybrids on the wheel spoil treatment were not significantly different than yields on the undisturbed Keomah treatment (Table 11). The hybrid LH123 x LH93 yielded significantly higher

Table 10. Mean squares and level of significance for the various effects in the analysis of variance for 1990 hybrid yield at Industry Mine.

Source of variation	d f	Mean Square
Soil treatment (S)	1	128.71
Error (a)	6	153.37
Hybrid (H)	24	1180.73**
S x H	24	368.95*
Error (b)	129	224.49

**, Significant at the 0.01 level of probability.
*, Significant at the 0.05 level of probability.

Table 9. Ranking of hybrids by yield for the 1989 Industry Hybrid Study.

Genotype	Wheel Spoil		Keomah	
	bu/a	rank	bu/a	rank
FR27 x Mo17	48.9	13	123.6	1
FR27 x LH38	52.0	12	115.8	6
FR1141 x FR4326	58.9	9	113.5	10
LH136 x LH123	60.1	7	114.8	9
LH119 x LH51	48.3	15	121.2	3
Zimmerman Z28	34.5	20	106.5	17
Asgrow 2570	33.0	22	121.5	2
LH132 x LH123	58.4	10	115.3	7
LH74 x LH123	61.4	4	100.4	21
LH82 x LH146	48.7	14	104.7	18
LH74 x LH51	43.1	18	107.1	16
LH119 x LH82	61.3	5	110.1	14
LH123 x LH93 (1)	68.6	1	116.7	5
Pioneer 3165	31.5	23	100.0	22
Pioneer 3320	33.4	21	101.6	20
Pioneer 3377	60.5	6	120.7	4
Pioneer 3295	61.5	3	111.6	13
Dennis 642	56.5	11	109.6	15
Dekalb 689	39.4	19	96.0	23
Zimmerman Z14W	27.4	25	75.4	25
LH136 x LH82	59.6	8	113.0	12
LH74 x LH82	44.4	17	114.9	8
LH136 x LH59	48.3	16	104.3	19
LH123 x LH93 (2)	64.5	2	113.0	11
Zimmerman Z54W	27.8	24	92.7	24
Mean	49.5		108.8	

LSD (0.05) for comparing a hybrid mean between two soils is 20.6 bu/a.
LSD (0.05) for comparing two hybrid means within a soil is 16.7 bu/a.
LSD (0.05) for comparing two means of a soil is 5.1 bu/a.

Table 11. Ranking of hybrids by yield for the 1990 Industry Hybrid Study.

Genotype	Wheel Spoil		Keomah	
	bu/a	rank	bu/a	rank
Pioneer 3241	162.5	1	165.9	1
LH123 x LH93	161.3	2	132.2	17
Agrigold XA216	153.4	3	135.9	14
Agrigold XA219	149.5	4	147.6	9
Pioneer 3377	147.6	5	142.1	12
LH119 x LH51	146.4	6	145.3	10
Agrigold E3009	144.8	7	158.5	3
Pioneer 3189	141.3	8	149.7	7
Agrigold A6615	140.0	9	139.6	13
Pioneer 3295	139.5	10	158.7	2
LH136 x LH123	138.8	11	151.1	6
FR27 x FRMo17	138.3	12	154.5	4
FR1141 x FR43	137.4	13	131.7	18
Agrigold E4012	136.0	14	128.7	21
Asgrow 2570	135.6	15	144.2	11
LH74 x LH123	134.6	16	133.6	15
LH136 x LH82	133.7	17	130.9	19
LH74 x LH51	130.1	18	133.1	16
LH132 x LH123	129.2	19	148.0	8
LH119 x LH82	128.2	20	112.0	24
LH136 x LH59	126.4	21	130.6	20
FR27 x LH38	122.9	22	116.8	23
FR618 x FR600	121.9	23	153.8	5
LH74 x LH82	117.7	24	128.4	22
LH146 x LH82	115.7	25	99.6	25
Mean	137.3		138.9	

LSD (0.05) for comparing a hybrid mean between two soils is 20.7 bu/a.
LSD (0.05) for comparing two hybrid means within a soil is 20.9 bu/a.
LSD (0.05) for comparing two means of a soil is 4.3 bu/a.

on the wheel spoil treatment. The FR618 x FR600 hybrid yielded significantly higher on the Keomah soil. Mean yields of the wheel spoil treatment and the Keomah soil were not significantly different when averaged over all 25 hybrids.

1991 Results

Plots were planted on May 2 under excellent soil conditions. Emergence was good to excellent for hybrids on both soil treatments. Four inches of intense rainfall occurred 10 days after planting affecting stands on some mine soil plots. Yield sampling was not compromised however, as stand damage was avoided during harvest. Normal June rainfall allowed for vigorous early season growth . July was characterized by below normal precipitation and above normal temperatures. Mid to late July was extremely hot creating considerable stress on all hybrids during the pollination period. Ear development and grain fill was enhanced by cooler temperatures and adequate rainfall in August.

Analysis of variance of 1991 data show that yield was affected by both soil treatment and hybrids (Table 12). No significant soil treatment by hybrid interaction was observed in 1991. Yields of 11 hybrids grown on the wheel spoil were not significantly different than yields of the same hybrid grown on the undisturbed Keomah soil (Table 13). Mean yield of the 20 hybrids on Keomah soil was significantly higher (0.05 level) than mean yield of the 20 hybrids on the wheel spoil in 1991. Weather induced stress affected hybrids on the wheel spoil more than hybrids on the undisturbed Keomah.

1989-91 Mean Yields

Years, soil treatments, and hybrids significantly affected corn yields across the three year period of this study (Table 14). Year to year variation in hybrid yield is attributed to weather induced stress. Weather in 1990 was more favorable for corn production than 1989 or 1991. Significant soil by year (0.01 level) interaction indicate soil treatments responded differently to year effects (environment). Yield variation of the wheel spoil was more closely associated to weather variation than was the undisturbed treatment.

Three year mean yields for this study show the yields of the genotypes to be superior on the undisturbed Keomah soil (Table 15). Within years, mean hybrid

Table 12. Mean squares and level of significance for the various effects in the analysis of variance for 1991 hybrid yield at Industry Mine.

Source of variation	d f	Mean Square
Soil treatment (S)	1	12110.28**
Error (a)	6	891.36
Hybrid (H)	24	836.18*
S x H	24	375.16
Error (b)	129	440.85

**, Significant at the 0.01 level of probability.
*, Significant at the 0.05 level of probability.

Table 13. Ranking of hybrids by yield for the 1991 Industry Hybrid Study.

Genotype	Wheel Spoil		Keomah	
	bu/a	rank	bu/a	rank
Pioneer 3140	135.9	1	147.8	2
LH123 x LH93	129.6	2	132.6	8
Asgrow 2570	127.3	3	136.3	5
Pioneer 3165	121.8	4	150.4	1
FR27 x Mo17	121.1	5	115.7	18
Dekalb 689	117.5	6	110.7	20
Pioneer 3189	116.7	7	118.9	15
LH119 x LH51	115.4	8	130.8	9
Pioneer 3377	114.8	9	124.0	13
Dekalb 649	113.2	10	134.3	6
Dennis 642	111.5	11	130.8	10
Pioneer 3379	110.5	12	138.7	4
LH74 x LH123	108.9	13	117.6	16
Pioneer 3241	106.0	14	133.7	7
LH132 x LH123	103.0	15	116.6	17
FR1141 x FR4326	102.6	16	123.6	14
Pioneer 3180	100.3	17	140.2	3
FR618 x FR4326	97.0	18	125.0	12
FR618 x FR600	90.8	19	128.3	11
FR27 x LH38	79.3	20	115.6	19
Mean	111.2		128.6	

LSD (0.05) for comparing a hybrid mean between two soils is 24.9bu/a.
LSD (0.05) for comparing two hybrid means within a soil is 22.8 bu/a.
LSD (0.05) for comparing two means of a soil is 11.5 bu/a.

Table 14. Mean squares and level of significance for the various effects in the two year analysis of variance for 1989-1991 hybrid yield at Industry Mine.

Source of variation	d f	Mean Square
Year (Y)	1	48637.08**
Soil treatment (S)	1	31289.71**
Y x S	1	18138.57**
Error (a)	12	452.30
Hybrid (H)	16	1043.57**
H x Y	16	321.68
S x H	16	404.38
H x Y x S	16	291.51
Error (b)	181	389.41

**, Significant at the 0.01 level of probability.

yield on the Keomah soil was significantly higher than the wheel spoil in 1989 and 1991, years of greater weather stress. No yield difference among these soil treatments occurred in 1990.

Three year mean yields for the 9 common hybrids of both years are presented in Table 16. Four hybrids (LH123 x LH93; Pioneer 3377; LH74 x LH123; FR1141 x FR4326) produced three year mean yields on the wheel spoil comparable to three year mean yields on the Keomah soil.

SUMMARY AND CONCLUSIONS

Data from hybrids grown at Denmark Mine and Industry Mine support the following general conclusions: (i) The potential to minimize the effects of stress on corn grown on mine soils exists through hybrid selection of adapted genotypes. Of the 12 common hybrids between the southern and western Illinois locations, three hybrids (LH123 x LH93; LH136 x LH123; LH74 x LH123) on the mine soils were ranked in the top five hybrids over the two year period for both locations. Hybrids with the highest yield potential on undisturbed soils did not necessarily produce the highest yields on disturbed soil plots. (ii) Weather variables were associated more with yield variation on the mine soils than the undisturbed soil treatments. (iii) Over a two year period, the Cisne soil in southern Illinois, and over a three year period the Keomah soil in western Illinois were superior to the mine soils for growing corn when averaged over all hybrids. iv) The scraper placed mine soil of southern Illinois yielded substantially lower than the wheel spoil soil of western Illinois. This is due to differences in the quality of soil materials and levels of soil compaction between sites.

Table 15. 1989-91 mean yields across hybrids for mined and unmined soil treatments.

Soil treatment	1989	1990	1991	Mean
		Yield, bu/a		
Wheel Spoil	49.5	137.7	111.2	99.5
Keomah	108.8	138.9	128.5	125.4
LSD (0.05)	5.1	4.3	11.5	6.2

Table 16. Ranking of hybrids by yield for the 1989-91 Industry Hybrid Study.

Genotype	Wheel Spoil		Keomah	
	bu/a	rank	bu/a	rank
LH123 x LH93	119.8	1	127.2	5
Pioneer 3377	107.7	2	128.9	4
Asgrow 2570	104.6	3	135.1	1
LH119 x LH51	103.4	4	133.5	2
FR1141 x FR4326	103.2	5	122.9	7
FR27 x Mo17	102.8	6	132.0	3
LH74 x LH123	101.6	7	118.7	8
LH132 x LH123	96.9	8	126.6	6
FR27 x LH38	84.7	9	116.0	9
Mean	102.7		126.6	

LSD (0.05) for comparing a hybrid mean between two soils is 21.8 bu/a.

LSD (0.05) for comparing two hybrid means within a soil is 21.3 bu/a.

LSD (0.05) for comparing two means of a soil is 4.4 bu/a.

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