EFFECTS OF SOIL PROPERTIES, CLIMATIC FACTORS, AND LANDSCAPE FEATURES OF PRIME FARMLAND SOILS ON VEGETATIVE GROWTH USING PRODUCIVITY INDICES ON RECLAIMED COAL SURFACE MINED SOILS[1]

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Abstract: Selected soil chemical and physical properties, climatic factors, and landscape features can be used as indicators of potential vegetative growth for commodity crops on reclaimed soil after coal surface mining. The logic for evaluating vegetative growth is similar to the "Storie Index for Soil Rating." The Storie Index, manipulating selected soil properties, is used to calculate soil productivity indices. Some elements have more impact on plant growth than others. Typically, selected soil properties, e.g., proportion of sand, silt, and clay, pH, bulk density, root limiting earthy soil layer, salinity, sodicity, root limiting non-earthy layers, landscape position, amount of precipitation, organic matter, rock fragments, etc. will determine the root zone available water capacity (RZAWC) of a soil. In normal precipitation years, the RZAWC of prime farmland soils determines the vegetative growth. RZAWC becomes a surrogate for many other soil properties and features. Knowing the RZAWC relationship allows soil scientists to make relatively accurate vegetative growth predictions. The significance of these properties determines the commodity crop vegetative growth using productivity indices of reclaimed soil compared to the pre-mined soil. The question being addressed in this paper, are the relationships of soil properties, climate (both soil and climatic atmospheric), and landscape features understood well enough to guarantee that soils reclaimed after surface mining for coal will be as productive as the pre-mined soil?

Additional Key Words: NASIS, soil climate, soil parent material, prime farmland, and soil profile development.

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Introduction

The United States Department of Agriculture (USDA) is responsible for all phases of agriculture programs on rural lands that are important for producing food, feed, fiber, forage, oil seed crops, and crops for fuel for the nation. These responsibilities include the parts of P.L. 95-87, Title V that address land areas that are to be surfaced mined for coal. P.L. 95-87, Title V (1977) outlines the steps in the reconstruction of a soil similar to that which existed before surface mining for coal, at least from the standpoint of the productivity of the reconstructed soil. Thirty Code of Federal Regulations (30CFR, 2005) explains USDA-Natural Resources Conservation Service (NRCS) activities with prime farmland historically used as cropland. After surface mining, P.L. 95-87 specifies that prime farmland will be reclaimed to its original productivity (30CFR823, 2005).

Smith (1983) proposed an alternative that would use the soil properties as a measure of prime farmland reclamation success. A large amount of research has been done during the twentieth century on soil properties, climate (both soil and atmospheric), and landscape features as they relate to production of commodity crops. The question being addressed in this paper, are the relationships of soil properties, climate (both soil and atmospheric), and landscape features understood well enough to guarantee that soils reclaimed after surface mining for coal will be as productive as the pre-mined soil? For example, what role, if any, does root zone available water capacity (RZAWC) have with soil productivity?

Selected soil chemical and physical properties, climatic factors, and landscape features can be used as indicators of potential vegetative growth for commodity crops on reclaimed soil after surface mining for coal (Wilson et al., 1991). The logic for evaluating vegetative growth is similar to the "Storie Index for Soil Rating" (Storie, 1933 and 1978, and Storie et al., 1948). Scrivner et al. (1985) stated that the model for converting soil property data into estimates of productivity is based upon the assumption that soil is a determinant of crop yield because it provides the environment for root growth. Ulmer and Patterson (1988) made statistical comparison of wheat yields within management units by county, year, and soil. They stated that results from sequential sampling support the use of the procedure as a viable means of obtaining yield data for developing productivity indexes and quantifying crop yield interpretations. However, results may not reflect long-term climatic variability and the relative rather than the absolute yield differences among soils should be emphasized. Ulmer et al. (1988) used climate, landscape features, and selected soil properties to quantify soil productivity indices for wheat and sunflower in North Dakota. Plant-available water at seeding has long been recognized as an important production factor in North Dakota. Olson and Lang (2004) developed equations for predicting grain crop yields and productivity indices for soils in Illinois using soil properties. Sopher and McCracken (1973) showed the relationship between soil properties, management practices, and corn yields on the South Atlantic Coastal Plain. Rust and Hanson (1975) developed a crop equivalent Rating Guide for Soils of Minnesota. Ulmer et al. (1988) developed crop yield interpretation using long term empirical models that included climate, landscape features, and selected soil properties to quantify soil productivity indices for wheat and sunflower for North Dakota. Persinger and Vogt (1995) published work detailing the productivity of soils in Missouri. Iowa State University (2005) developed Corn Suitability Ratings (CSR) that are based on soil properties, average weather, and the inherent potential of each kind of soil for corn production. Soil Survey Staff (2000) developed Soil Rating for Plant Growth (SRPG) - A System for Arraying Soils According to Their Inherent Productivity and

Suitability for Crops that was used for federal programs. Brown and Carlson (1990) states that under dryland farming, water is the most limiting factor for crop production in Montana and the Northern Great Plains. They developed equations to relate grain yields related to stored soil water and growing season rainfall for winter and spring wheat, barley, oats, and safflower. Gross and Rust (1972) determined that relating soil moisture to temperature, precipitation, and water holding capacity provides a more realistic available moisture value for commodity crops. They documented that one of the variables most highly correlated with yield was soil moisture during the growing season. Mitchell (1940) determined that despite variations in yields on the same soil due to managerial or other factors it appears possible to express with some degree of uniformity the comparative productivity value of the soil based on profile characteristics and chemical properties.

Soil and climate properties have different interactions for plant growth. Some elements have a greater impact on plant growth than others. Typically, selected soil properties, e.g., proportion of sand, silt, and clay, pH, bulk density, salinity, sodicity, root limiting (earthy and non-earthy) layers, landscape position, amount of precipitation, organic matter, and rock fragments, etc. will determine the root zone available water capacity (RZAWC) of a soil (Dale, 1968). In years of normal precipitation, the RZAWC of prime farmland soils to a large extent determines the vegetative growth and crop yield (Shaw and Felch, 1972 and Voss et al., 1970). RZAWC is a surrogate for many other soil properties and features. Knowing the RZAWC relationship allows soil scientists to make relatively accurate vegetative growth predictions (Whitney et al., 1897). The significance of these properties determines the commodity crop vegetative growth of reclaimed soil compared to the pre-mined soil (Sinclair et al., 2004 and 2005a).

The criteria on how to evaluate prime farmland reclamation success are based on crop productivity (Howard, 1980; Mavrolas, 1980; Reybold and McCormack, 1980; USDA-NRCS, 1999). Crop production as a measure of the success in the reclamation of prime farmland is explained in 30 CFR. 2006. Research by Dunker et al. (1992), Dunker and Barnhisel (2000), Hooks et al. (1992), Underwood and Sutton (1992), Vance et al. (1992), and Caldwell et al. (1992) explained the specifications and conditions for deep tillage result in a positive response in crop yield. Dunker et al. (1991) explained methods for the alleviation of compaction and how reducing compaction in the subsurface horizons increases crop yields. Dunker and Barnhisel (2000) and Hooks (1998) showed the relationship of bulk density to average root length density and crop yield. Hooks et al. (1992) determined that rooting media for plant growth using shovel-truck placement is typically less compacted and usually results in higher crop yields than soils placed by scrapers.

Dunker and Barnhisel (2000) show penetrometer resistance and mean yields for various deep tillage treatments on reclaimed mine soils placed by scrapers. Corn yields were reduced from about 8 Mg/ha with about 1 MPa of penetrometer resistance to about 4 Mg/ha with about 3 MPa of penetrometer resistance. Soybean yields were reduced from about 2 Mg/ha with about 1 MPa of penetrometer resistance to about 0.8 Mg/ha with about 3 MPa of penetrometer resistance.

Several studies have demonstrated that corn roots will penetrate to a depth of 5 feet or more in rooting media that is friable and fertile (Fehrenbacher and Snider, 1954, Fehrenbacher and Rust, 1956, Fehrenbacher et al., 1960, and Illinois Agricultural Experiment Station, 1967). Yield prediction was explained by Odell, (1958). Other documents used peer reviewed papers and field experiments to explain the relationship between soil properties and soil management (Soil Survey Staff, 1993 and 1999).

Additional research was done by Agricultural Research Service (ARS), Cooperative State Research, Education, and Extension Service (CSREES), and Economic Research Service (ERS) that are agencies in the United States Department of Agriculture after Pub. L. 95-87 was passed. The additional research complemented research that had been accomplished before and after Pub. L. 95-87 (Dunker and Barnhisel, 2000). The replacement and mixing of topsoil was a controversial issue that needed research to support its value (Carter and Doll, 1983). Field studies compared selected soil properties before the soils were mined and after they were reconstructed (Barnhisel et al., 1979).

Favorable subsoil rooting media means the difference between successful crop production and crop failure (Fehrenbacher et al., 1982). Barnhisel et al. (1992) conducted a study to determine whether a calculatable index based on the physical and chemical characteristics of the reconstructed soil after surface mining for coal could be used to accurately predict soil productivity based on corn yield. One of the many properties used in the model was potential available water capacity. The Soil Survey Staff (2000) developed a system for arraying soils according to their inherent productivity and suitability for crops. Root zone available water capacity was one of the soil properties used in the system. Fanning et al. (2002) explained that special soil manipulation and reclamation strategies are needed where sulfide bearing soil materials are exposed by land disturbance activities because high soil acidity can reduce the volume of soil that roots can explore. Schroeder (1992) stated that small grain yields on downslope positions of the landscape produce 30 to 80 percent higher yields than upslope positions when averaged over years. This indicated that landscape position played an important role in yields of small grains. Thus, a methodology to maximize available water by adjusting topographic effects during reclamation will be a key to meeting the regulatory requirements of “equal to better than” pre-mining productivity levels. Olson (1992) worked on assessment of reclaimed farmland disturbed by surface mining in Illinois. Olson and Lang (2000) developed publications showing optimum and average crop productivity ratings for Illinois soils. Their information indicates that corn yields can differ as much as 42 to 48 bushel per acre following soil mining reclamation.

Methods

Soil scientists used guidelines established by the National Cooperative Soil Survey (NCSS, 2005) to complete the Soil Survey of Fulton County, Illinois. The NCSS is a nationwide partnership of federal, regional, state, and local agencies and institutions. This partnership works closely with universities to cooperatively investigate, inventory, document, classify, and interpret soils and to disseminate, publish, and promote the use of information about the soils of the United States and its trust territories. The activities of the NCSS are carried out on national, regional, and state levels. Populating soil property data, climatic factors, and landscape features in the National Soils Information System (NASIS) followed the NCSS guidelines. The information in Tables 1 through 3d was extracted directly from NASIS or generated using interpretative models with data elements in NASIS.

Soil productivity is strongly influenced by the capacity of a soil to supply the nutrients and soil-stored water needs of a growing crop in a given climate (Olson and Lang, 2002). For soil constraints or qualities, Tables 4a-4d use the soil interpretations module of the soil survey database system (Soil Survey Staff, 2005b) to assess the impact of 35 data elements on plant growth to compute a soil productivity or inherent soil quality index for components of soil map units (Soil Survey Staff, 2005a). The calculations in Tables 4a-4d followed the "Stories Index Soil Rating" (Storie and Weir, 1958; Storie, 1933 and 1978) which was based on soil characteristics that govern the land's potential utilization and productive capacity. The Storie Index was originally adapted to semiarid and arid regions and included profile characteristics that influenced effective rooting depth and the quality of the root zone, subsurface properties (permeability, available water-holding capacity, drainage class, soluble salts), and landscape properties. However, information in Tables 4a-4d also consider climate as an additional factor in calculating the index, which is a particularly significant parameter, given the range of soil climate across regions. Therefore, the information in Tables 4a-4d provides a reasonable semi-quantitative index (from 0.01 to 1) of soil productivity applicable to map unit components of the soil survey database. Table 3a shows the productivity indices generated using the soil survey database and the soil interpretations module.

The conceptual model of the soil interpretations module consists of five basic parts: "main rules" (also called "interpretations"), "base rules" (also called "subrules"), "evaluations", and "properties." The property in this context is a Structured Query Language (SQL) script that retrieves the desired soil attribute data, such as the pH of the surface horizon. This piece of data is placed into the evaluation, which is a graph that indicates the degree of membership of that attribute in the set of soils that are productive. For example, a soil component having a pH of 6.5 would receive a score of 1, while a pH of 5.0 would receive a score less than 1 and may approach zero (0). The shape of the curve depends on the soil attribute being modeled. The base rule is a logical diagram depicting the relationship between the soil attribute and the land use being modeled. It uses the rating from the evaluation to make a statement about the impact of the soil attribute in question on the land use. Main rules can consist of one or more levels of base rules, depending on the complexity of the land use situation being considered (Soil Survey Staff, 2001).

Soil attribute data can be manipulated is a variety of ways to arrive at a value that is meaningful in terms of soil productivity. For example, roots are sensitive to the bulk density of a soil layer, since penetration resistance is partially a function of bulk density. At some point, a soil layer becomes too dense for root ramification. The values for nonlimiting, critical, and root-limiting bulk densities for each family particle-size class were determined by Pierce et al. (1983). The depth to the first layer with a bulk density of more than the value shown in the Table 1 is either a critical bulk density or root-limiting (Pierce et al., 1983). Root restrictive layers are critical in determining soil productivity, since roots cannot enter these layers, thus any soil moisture and plant nutrients in these layers cannot by used by the plants commonly grown in the area (Soil Survey Division Staff, 1993). The relationship between particle size and optimal bulk density data is compared to populated bulk density and is used in the model to estimate the resistance to root penetration by horizon in a soil component. Water Retention Difference (WRD) is the volume of water that is measured in the laboratory, inclusive of rock fragments. The Available Water Capacity (AWC) is the volume of water that should be available to plants if the soil, inclusive of rock fragments, were at field capacity. Reductions in AWC are made in the water difference for incomplete root ramification that is associated with certain soil features such as fragipans, bulk density, and other chemical and physical soil properties that are indicative of root restrictions. The amount of available water (root zone available water capacity, RZAWC) to the expected maximum depth of root penetration, commonly either 1 or 1.5m, or a physical or chemical root limitation, whichever is shallower (Soil Survey Division Staff, 1993).

Table 1. Nonlimiting, critical, and root limiting bulk densities for each family texture class (Pierce et al., 1983).

Family Texture Class	Nonlimiting Bulk Density $g\ cm^{-3}$	Critical Bulk Density $g\ cm^{-3}$	Root-Limiting Bulk Density $g\ cm^{-3}$
Sandy	1.60	1.69	1.85
Coarse loamy	1.50	1.63	1.80
Fine loamy	1.46	1.67	1.78
Coarse silty	1.43	1.67	1.79
Fine silty	1.34	1.54	1.65
Clayey: 35-45%	1.40	1.49	1.58
Clayey: 45-100%	1.30	1.39	1.47

Discussion

Table 2 shows that Fulton County, Illinois has about 18,996 hectares (46,939 acres, about 73 square miles, or two townships) of land strip mined for coal (Suhl, 2003). The types of soil reclamation in Fulton County depend on the time period – prior to 1971, 1971 to 1977, and 1977 to the current. The 62ilac, Chapter I, Sec. 1825 (2002) entitled “High Capability Land” was passed in 1971 and amended in 1976 by the Illinois legislature to reclaim certain mined land to arable soils. Currently the State of Illinois uses the federal reclamation law to require the reclamation of soils that are prime farmland and uses the “High Capability Land” law to reclaim many prime and non-prime farmland soils to arable soils. The Lenzburg, Lenzwheel, and Rapatee series are soils forming in reclaimed soil materials replaced after surface mining for coal in Fulton County, Illinois. The pre-mined soils were dominantly the Rozetta (62.2 square kilometers), Ipava (41.5 square kilometers), Osco (25.9 square kilometers), Hickory (20.6 square kilometers), Keomah (15.5 square kilometers), Clarksdale (7.8 square kilometers), Sable (7.7 square kilometers), Beaucoup (2.6 square kilometers), Tice (2.6 square kilometers), and Titus (2.6 square kilometers) or very similar soils. Figure 1 depicts a cross section showing the relationship of parent materials and the soils in Fulton County, Illinois (Suhl, 2003). Figure 2 shows the typical pattern of soils and parent material in the Lenzburg-Lenzwheel landscape (Suhl, 2003).

Tables 3a and 3b assign non-irrigated land capability subclasses (Klingebiel, 1958; Klingebiel and Montgomery, 1961; Sinclair and Dobos, 2006), important farmland designation (7CFR 2004), classification, and productivity indices for the soils selected for this study. The land capability subclass indicates one or more limitations or hazards that must be managed to sustainably cultivate a soil. The limitations or hazards for soils are excessive wetness, soil erosion, droughtiness/stoniness/etc., and climate. Typically, as number or severity of hazards or limitations increase, land use alternatives decrease (Sinclair and Dobos, 2006), cost of farming the land increases, and typically return on investment decreases. The Ipava soil is class I land, but the reclaimed Rapatee soil is subclass IIe land. Table 3a also indicates the soils and their extent that probably existed before mining for coal. Tables 4a-4d contain the soil properties, climatic elements, and landscape characteristics used to determine the soil productivity indices for soil map units. Dobos and Sinclair (2006) and Sinclair et al. (2005b) describe a methodology for deriving the numerical ratings for the elements considered in calculating productivity indices. This data for selected soils in Fulton County is given in Tables 4a-4d. The model (National Commodity Crop Productivity Index)) that generates the soil productivity indices is in the National Cooperative Soil Survey Interpretations Module (Soil Survey Staff, 2006a). The data used to generate the soil productivity indices are stored by the National Cooperative Soil Survey in the National Soil Information System (NASIS). The NASIS data is available for use by the public at the Soil Data Mart Web site (Soil Survey Staff, 2006b).

Table 2. Acreage of Soils in Fulton County, Illinois that was Surfaced Mined for Coal (Suhl, 2003).

Soil Map Symbol	Soil Map Unit Name	Soil Series Name	Hectares
871B	Lenzburg silty loam, 1 to 7 percent slopes	Lenzburg	5,609
871D	Lenzburg silty clay loam, 7 to 20 percent slopes	Lenzburg	2,905
871G	Lenzburg silty clay loam, 20 to 60 percent slopes	Lenzburg	5,467
872B	Rapatee silty clay loam, 2 to 5 percent slopes	Rapatee	716
876B	Lenzwheel silt loam, 1 to 7 percent slopes	Lenzwheel	1,975
876D	Lenzwheel silty clay loam, 7 to 20 percent slopes, eroded	Lenzwheel	1,290
876G	Lenzwheel silty clay loam, 20 to 60 percent slopes	Lenzwheel	1,027
		Total acres	18,996

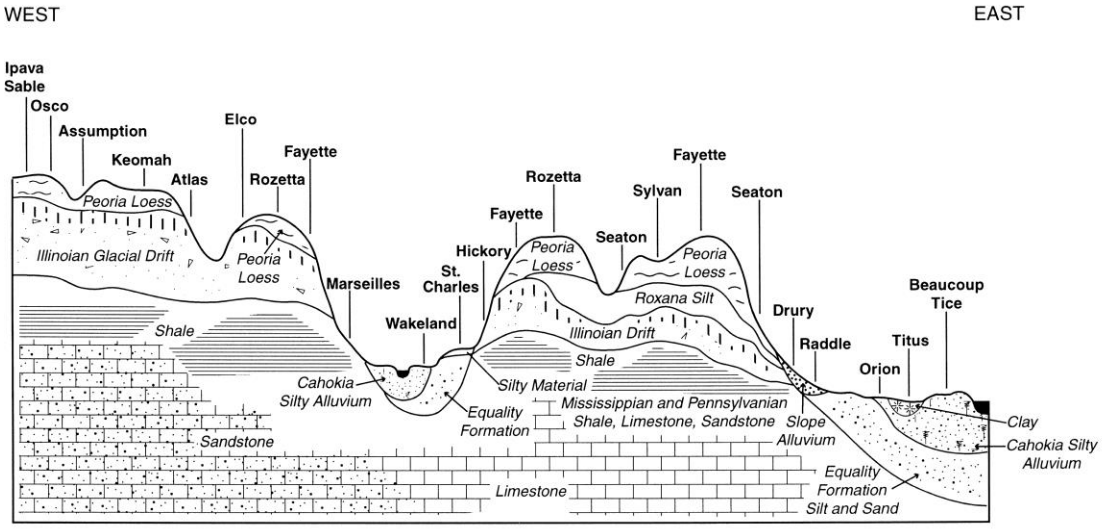

Figure 1. Depicts a cross section showing the relationship of parent materials and the soils in Fulton County, Illinois (Suhl, 2003).

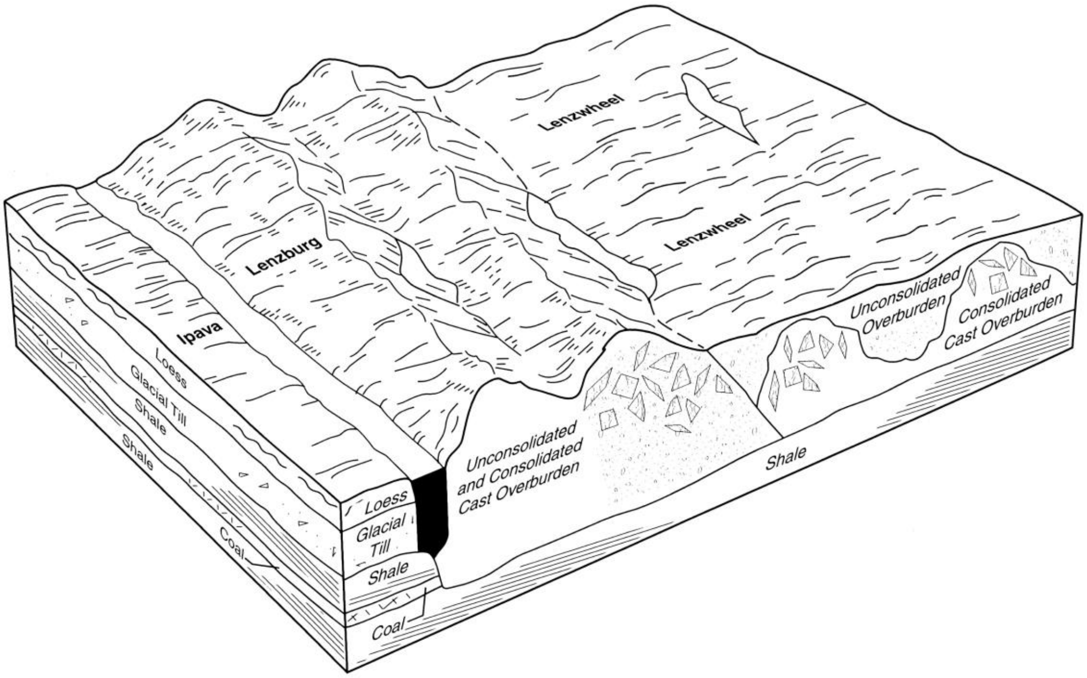

Figure 2. Depicts the typical pattern of soils and parent material in the Lenzburg-Lenzwheel landscape (Suhl, 2003).

The upland soils disturbed by mining are dominantly fine-silty – 95.8 square kilometers (37 square miles). Whiteside (1953) showed loess as the only very porous parent material that has a very high available water capacity for growing commodity crops. His comments are very relevant since the most productive soils in Fulton County are the fine-silty ones having no root limiting layer within five feet of the soil surface. The very porous fabric allows roots to readily explore more of the rooting media so more moisture is available to the plant especially during the growing season. This stored soil available moisture for plant growth is like a savings account when precipitation is needed, but Mother Nature is not forthcoming with the needed rain. Another 49.2 square kilometers (19 square miles) of soils formed in loess with no root limiting layer within a depth of five feet of the soil surface classify in the fine particle size class. These soils are also very productive for growing commodity crops. The fine-loamy soils forming in reclaimed soil materials have substantially lower soil productivity indices than the fine and fine-silty soils.

Table 3a. Land Capability Subclass, Important Farmland, and Probable Extent of Mined Areas of Soils in Fulton County Illinois (Suhl, 2003).

Soil Map Unit Symbol	Soil Map Unit Name	Land Capability Subclass	Farmland	square hectares
3070A	Beaucoup silty clay loam, 0 to 2 percent slopes, frequently flooded	3w	Prime	2.6
257A	Clarksdale silt loam, 0 to 2 percent slopes	1---	Prime	7.8
280B2	Fayette silt loam, 2 to 5 percent slopes, eroded	2e	Prime	
280C2	Fayette silt loam, 5 to 10 percent slopes, eroded	3e	State	
8G	Hickory silt loam, 35 to 60 percent slopes	7e	Not Prime	20.6
43A	Ipava silt loam, 0 to 2 percent slopes	1---	Prime	41.5
17A	Keomah silt loam, 0 to 2 percent slopes	2w	Prime	
17B	Keomah silt loam, 2 to 5 percent slopes	2e	Prime	15.5
871B	Lenzburg silty loam, 1 to 7 percent slopes	2e	Prime	
871D	Lenzburg silty clay loam, 7 to 20 percent slopes	6e	Not Prime	
871G	Lenzburg silty clay loam, 20 to 60 percent slopes	7e	Not Prime	
876B	Lenzwheel silt loam, 1 to 7 percent slopes	2e	Prime	
876D	Lenzwheel silty clay loam, 7 to 20 percent slopes, eroded	4e	Not Prime	
876G	Lenzwheel silty clay loam, 20 to 60 percent slopes	6e	Not Prime	
86B	Osco silt loam, 2 to 5 percent slopes	2e	Prime	25.9
86C2	Osco silt loam, 5 to 10 percent slopes, eroded	2e	State	
872B	Rapatee silty clay loam, 2 to 5 percent slopes	2e	Prime	
279B	Rozetta silt loam, 2 to 5 percent slopes	2e	Prime	62.2
279C2	Rozetta silt loam, 5 to 10 percent slopes, eroded	3e	State	
68A	Sable silty clay loam, 0 to 2 percent slopes	2w	Prime	7.7
8284A	Tice silty clay loam, 0 to 2 percent slopes, occasionally flooded	2w	Prime	2.6
3404A	Titus silty clay, 0 to 2 percent slopes, frequently flooded	3w	Prime	2.6
3333A	Wakeland silt loam, 0 to 2 percent slopes, frequently flooded	2w	Prime	

Table 3b. Soil Classification and Productivity indices of Soils in Fulton County Illinois.

Soil Map Unit Symbol	Soil Series Name	Soil Classification	Particle Size Class (family)	Productivity Indices
3070A	Beaucoup	Fine-silty, mixed, superactive, mesic Fluvaquentic Endoaquolls	fine-silty	0.5952
257A	Clarksdale	Fine, smectitic, mesic Udollic Endoaqualfs	fine	0.6188
280B2	Fayette	Fine-silty, mixed, superactive, mesic Typic Hapludalfs	fine-silty	0.7934
280C2	Fayette	Fine-silty, mixed, superactive, mesic Typic Hapludalfs	fine-silty	0.787
8G	Hickory	Fine-loamy, mixed, active, mesic Typic Hapludalfs	fine-loamy	0.5553
43A	Ipava	Fine, smectitic, mesic Aquic Argiudolls	fine	0.6787
17A	Keomah	Fine, smectitic, mesic Aeric Endoaqualfs	fine	0.6005
17B	Keomah	Fine, smectitic, mesic Aeric Endoaqualfs	fine	0.5609
871B	Lenzburg	Fine-loamy, mixed, active, calcareous, mesic Haplic Udarents	fine-loamy	0.4782
871D	Lenzburg	Fine-loamy, mixed, active, calcareous, mesic Haplic Udarents	fine-loamy	0.4896
871G	Lenzburg	Fine-loamy, mixed, active, calcareous, mesic Haplic Udarents	fine-loamy	0.319
876B	Lenzwheel	Fine-loamy, mixed, active, calcareous, mesic Alfic Udarents	fine-loamy	0.2675
876D	Lenzwheel	Fine-loamy, mixed, active, calcareous, mesic Alfic Udarents	fine-loamy	0.3022
876G	Lenzwheel	Fine-loamy, mixed, active, calcareous, mesic Alfic Udarents	fine-loamy	0.1196
86B	Osco	Fine-silty, mixed, superactive, mesic Typic Argiudolls	fine-silty	0.9487
86C2	Osco	Fine-silty, mixed, superactive, mesic Typic Argiudolls	fine-silty	0.8345
872B	Rapatee	Fine-silty, mixed, superactive, nonacid, mesic Alfic Udarents	fine-silty	0.3406
279B	Rozetta	Fine-silty, mixed, superactive, mesic Typic Hapludalfs	fine-silty	0.9122
279C2	Rozetta	Fine-silty, mixed, superactive, mesic Typic Hapludalfs	fine-silty	0.8235
68A	Sable	Fine-silty, mixed, superactive, mesic Typic Endoaquolls	fine-silty	0.9713
8284A	Tice	Fine-silty, mixed, superactive, mesic Fluvaquentic Hapludolls	fine-silty	0.9379
3404A	Titus	Fine, smectitic, mesic Vertic Endoaquolls	fine	0.4048
3333A	Wakeland	Coarse-silty, mixed, superactive, nonacid, mesic Aeric Fluvaquents	coarse-silty	0.8442

Tables 4a-4d demonstrate the importance of interaction of soil properties and landscape elements on determining soil productivity indices. Climatic elements are not significant since the area consists of a few square miles and the elevation differences are only a few feet. Hydraulic conductivity (Ksat), linear extensibility percent, bulk density, depth to water table, flooding, ponding, root zone available water capacity, and water table recharge seem to be the elements determining differences in the soil productivity indices for these soils (U.S. Department of Agriculture, Natural Resources Conservation Service, 2006). The model also includes EC, gypsum, and SAR, but these factors were not limiting in these soils. The relationships in Tables 4a-4d for soil properties, soil climate, and landscape features seem to be understood well enough to evaluate and compare soils reclaimed after surface mining to soils before being mined.

Table 4a. Productivity Indices and results for soil chemical properties (Soil Survey Staff, 2006a).

Soil Map Unit Symbol	Soil Series Name	Productivity Index	Soil Chemical Properties	RZ CEC Subrule	RZ pH Optimal Subrule	RZ Calcium Carbonate Subrule
3070A	Beaucoup	0.5952	0.9659	0.9167	0.9999	0.9935
257A	Clarksdale	0.6188	0.9683	0.9278	0.9932	0.9825
280B2	Fayette	0.7934	0.959	0.9413	0.8283	0.9968
280C2	Fayette	0.787	0.961	0.9378	0.8593	1
8G	Hickory	0.5553	0.9616	0.9285	0.9235	0.9825
43A	Ipava	0.6787	0.9387	0.8605	0.9571	0.9907
17A	Keomah	0.6005	0.9451	0.9026	0.8406	1
17B	Keomah	0.5609	0.9191	0.8545	0.7733	1
871B	Lenzburg	0.4782	0.9159	0.9012	0.85	0.763
871D	Lenzburg	0.4896	0.9157	0.9191	0.7769	0.763
871G	Lenzburg	0.319	0.9149	0.9151	0.7851	0.763
876B	Lenzwheel	0.2675	0.9045	0.8016	0.98	0.8867
876D	Lenzwheel	0.3022	0.9504	0.9127	0.98	0.8987
876G	Lenzwheel	0.1196	0.8556	0.7096	0.9775	0.792
86B	Osco	0.9487	0.9733	0.944	0.9567	1
86C2	Osco	0.8345	0.9714	0.9337	0.9789	1
872B	Rapatee	0.3406	0.9423	0.9257	0.9194	0.8404
279B	Rozetta	0.9122	0.9615	0.9444	0.8426	0.9959
279C2	Rozetta	0.8235	0.9629	0.9416	0.8629	1
68A	Sable	0.9713	0.9623	0.9097	0.9948	0.9919
8284A	Tice	0.9379	0.9717	0.9378	0.9936	0.9782
3404A	Titus	0.4048	0.932	0.8323	0.9905	1
3333A	Wakeland	0.8442	0.9163	0.7909	0.9995	1

Table 4b. Results for soil physical properties for determining Productivity Indices (Soil Survey Staff, 2006a).

Soil Map Unit Symbol	Soil Series Name Subrule	Soil Physical Properties	Ksat Minimum	RZ LEP Subrule	RZ OM Subrule	RZ Bulk Density Subrule	RZ Rock Fragment Subrule	RZ Soil Depth Subrule
3070A	Beaucoup	0.6229	0.544	1	0.9455	0.9291	1	0.8424
257A	Clarksdale	0.631	0.544	0.9092	0.8007	0.9923	0.9988	1
280B2	Fayette	0.9503	1	1	0.7517	1	1	1
280C2	Fayette	0.9503	1	1	0.7517	0.9996	1	1
8G	Hickory	0.9315	1	0.975	0.7405	0.965	0.9771	1
43A	Ipava	0.7071	0.6138	0.975	0.9019	0.994	1	1
17A	Keomah	0.6221	0.544	0.9073	0.7532	0.9978	1	1
17B	Keomah	0.6126	0.544	0.7632	0.7771	1	1	1
871B	Lenzburg	0.6167	0.544	1	0.748	0.9749	0.9615	1
871D	Lenzburg	0.612	0.544	1	0.748	0.9305	0.9554	1
871G	Lenzburg	0.6112	0.544	1	0.748	0.9426	0.9505	1
876B	Lenzwheel	0.5182	0.544	0.95	0.7442	0.8508	1	0.6112
876D	Lenzwheel	0.5551	0.544	1	0.7442	0.8813	1	0.7336
876G	Lenzwheel	0.4786	0.544	0.975	0.7442	0.7148	1	0.4792
86B	Osco	0.9742	1	1	0.8722	0.9972	1	1
86C2	Osco	0.966	1	1	0.831	0.9981	1	1
872B	Rapatee	0.5259	0.4164	1	0.8938	0.6623	0.9854	0.908
279B	Rozetta	0.9522	1	0.975	0.7784	0.9894	1	1
279C2	Rozetta	0.9491	1	0.975	0.7663	0.9822	1	1
68A	Sable	0.9906	1	1	0.9528	1	1	1
8284A	Tice	0.9686	1	1	0.8446	0.9972	1	1
3404A	Titus	0.4409	0.3122	0.51	0.8624	0.9734	1	1
3333A	Wakeland	0.9637	1	0.95	0.8437	1	1	1

Table 4c. Results for soil landscape properties for determining Productivity Indices (Soil Survey Staff, 2006a).

Soil Map Unit Symbol	Soil Series Name	Soil Land-scape Subrule	Water Table Subrule	Effective Slope Subrule	Fragments on Surface Subrule	Flooding Subrule	Ponding Subrule	Erosion Class Subrule
3070A	Beaucoup	0.9732	1	0.9942	1	0.6	0.889	1
257A	Clarksdae	0.9918	0.78	0.9883	1	1	1	1
280B2	Fayette	0.9006	1	0.9533	1	1	1	0.9
280C2	Fayette	0.8749	1	0.9125	1	1	1	0.9
8G	Hickory	0.6733	1	0.5333	1	1	1	1
43A	Ipava	0.9927	0.86	0.9895	1	1	1	1
17A	Keomah	0.9918	0.78	0.9883	1	1	1	1
17B	Keomah	0.9673	0.78	0.9533	1	1	1	1
871B	Lenzburg	0.9673	1	0.9533	1	1	1	1
871D	Lenzburg	0.8857	1	0.8367	1	1	1	1
871G	Lenzburg	0.6733	1	0.5333	1	1	1	1
876B	Lenzwhel	0.9673	1	0.9533	1	1	1	1
876D	Lenzwhel	0.8271	1	0.8367	1	1	1	0.9
876G	Lenzwhel	0.6733	1	0.5333	1	1	1	1
86B	Osco	0.9714	1	0.9592	1	1	1	1
86C2	Osco	0.8749	1	0.9125	1	1	1	0.9
872B	Rapatee	0.9673	1	0.9533	1	1	1	1
279B	Rozetta	0.9673	1	0.9533	1	1	1	1
279C2	Rozetta	0.8749	1	0.9125	1	1	1	0.9
68A	Sable	0.9892	1	0.9942	1	1	0.889	1
8284A	Tice	0.9758	0.86	0.9883	1	0.6	1	1
3404A	Titus	0.9692	0.55	0.9883	1	0.6	0.889	1
3333A	Wakeland	0.9758	0.78	0.9883	1	0.6	1	1

Table 4d. Results for soil climate and water properties for determining Productivity Indices (Soil Survey Staff, 2006a).

Soil Map Unit Symbol	Soil Series Name	Soil Climate	Frostfree Days Subrule	Precipitation Subrule	Water Subrule	RZ AWC Subrule	Precipitation Recharge Subrule	Water Table Recharge Subrule
3070A	Beaucoup	0.9869	1	0.9869	1	0.7348	0.189	1
257A	Clarksdale	0.9913	1	0.9913	1	0.941	0.176	0.6293
280B2	Fayette	1	1	1	0.9386	0.9125	0.087	0
280C2	Fayette	0.9968	1	0.9968	0.9593	0.9125	0.156	0
8G	Hickory	0.9869	1	0.9869	0.9059	0.8492	0.189	0
43A	Ipava	1	1	1	1	0.9242	0.126	0.7039
17A	Keomah	0.9999	1	0.9999	1	0.9325	0.1	0.6293
17B	Keomah	0.9999	1	0.9999	1	0.9275	0.1	0.6293
871B	Lenzburg	0.992	0.9941	0.9979	0.8567	0.8156	0.137	0
871D	Lenzburg	0.9979	1	0.9979	0.9598	0.9145	0.151	0
871G	Lenzburg	0.9979	1	0.9979	0.8243	0.779	0.151	0
876B	Lenzwheel	0.9844	1	0.9844	0.5819	0.5231	0.196	0
876D	Lenzwheel	0.9844	1	0.9844	0.6831	0.6243	0.196	0
876G	Lenzwheel	0.9844	1	0.9844	0.4278	0.369	0.196	0
86B	Osco	1	1	1	1	0.9485	0.126	0.7262
86C2	Osco	0.9869	1	0.9869	1	0.9425	0.189	0.7262
872B	Rapatee	0.9844	1	0.9844	0.7008	0.642	0.196	0
279B	Rozetta	1	1	1	1	0.9735	0.125	0.7262
279C2	Rozetta	1	1	1	1	0.965	0.14	0.7262
68A	Sable	1	1	1	1	0.9547	0.126	1
8284A	Tice	0.9913	1	0.9913	1	0.9485	0.176	0.7039
3404A	Titus	0.9869	1	0.9869	1	0.8285	0.189	0.4

Table 5 shows the RZAWC and the multi-year corn yields for reconstructed soils after surface mining for coal and the soils not disturbed for mining coal. The reclaimed soils are Rapatee (reclaimed to 100 percent original yield), lenzburg, and lenzwheel. The other soils in Table 4 have not been disturbed for mining for coal. Ipava, Osco, and Sable soils have about 164 percent more RZAWC than the Rapatee soil. Their corn yields are about 130 percent more than the Rapatee soil. Figure 3 shows the relation between RZAWC and corn yield. The RZAWC is calculated to a depth of 150 cm or to a limiting layer. The RSquare is 0.85. As expected, there seems to be a relationship between RZAWC and corn yield under both average and optimum management. The margin of profit for the same increment of input is more for soils with higher RZAWC than for soils with lower RZAWC.

Table 5. Dryland corn yields for selected soils under average and optimum management with slight erosion and 0 to 2 percent slopes.

Map Symbol for Soil Survey of Fulton County, Il	Soil Component	Yield of Corn (Mg/ha)[2/]	Optimum Management Yield (Mg/ha)[3/]	Average Management Yield (Mg/ha)[4/]	RZAWC (150 cm to a limiting layer) cm
872B	Rapatee	8.41	8.88	7.87	18.54
876B	Lenzwheel	6.52	6.86	6.12	17.02
871B	Lenzburg	7.19	7.26	6.46	21.08
134E2 [1/]	Camden	---	10.02	8.88	25.15
280B2	Fayette	9.62	10.09	8.94	28.7
43A	Ipava	11.57	11.57	10.29	30.23
86B	Osco	11.43	11.57	10.29	30.23
68A	Sable	11.63	11.57	10.29	30.99

[1/] Too steep to farm.

[2/] Suhl (2003)

[3/] Olson and Lang (2000)

[4/] Olson et al. (2000)

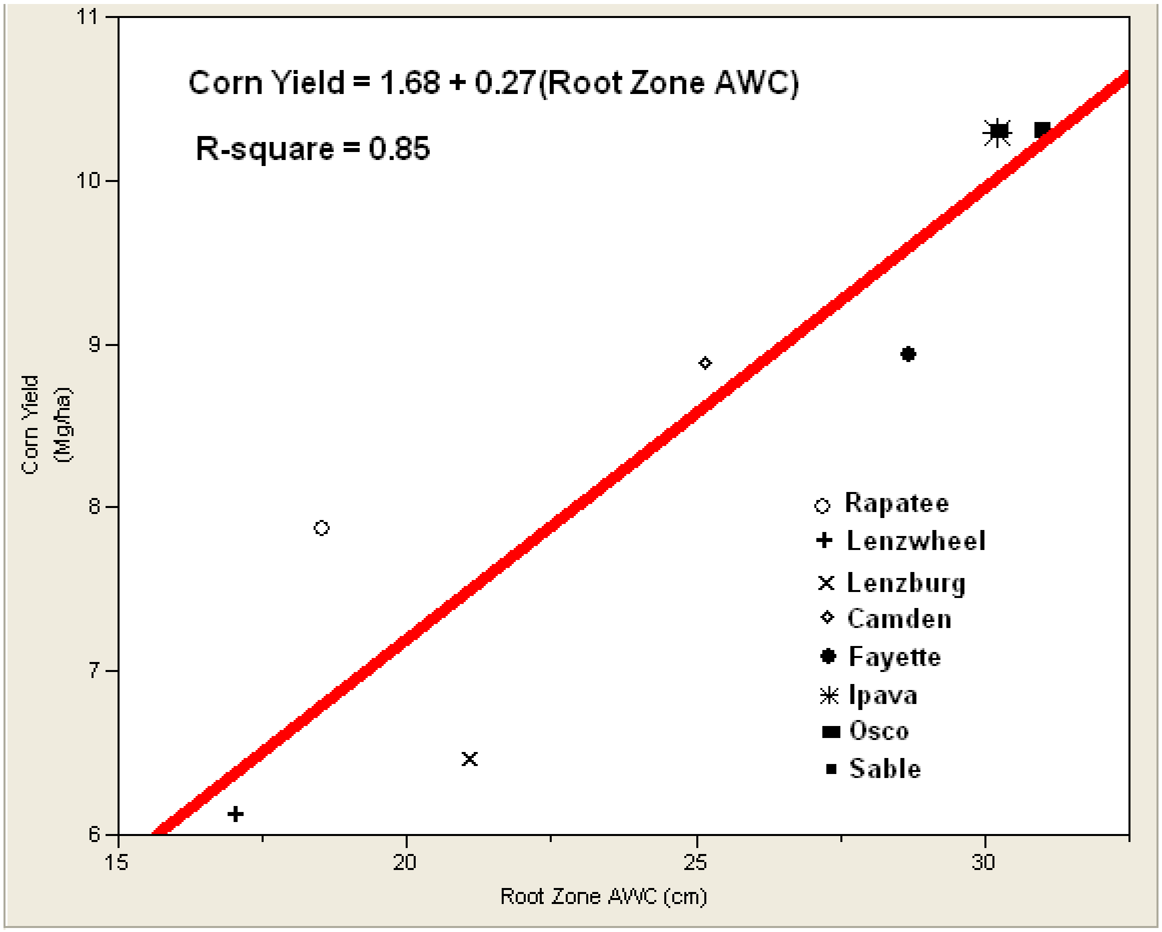

Figure 3. Bivariate fit of dryland corn yield (Olson et al., 2000) by root zone available water capacity (Suhl, 2003).

The above information about the study area has been given so now it needs to be related to scientists doing similar work and hopefully having similar results.

Burger et al. (1994) stated that tree vertical rooting patterns affect aboveground productivity. Their productivity index (PI) integrates the genetic rooting potential of a tree and its response to varying soil and topographic conditions. Sufficiency curves are used in the PI model to describe a tree's root response to individual soil/site properties, relating root growth responses to aboveground productivity. The PI can be used on forested and nonforested sites and in stands that are too young or too old for traditional site-index (SI) estimations. The profiles of sufficiencies can be used to identify layers that are limiting to root growth and productivity, as well as the magnitude of those limitations.

Fehrenbacher et al. (1960) stated that root studies of corn, soybeans, alfalfa, red clover, and timothy on Muscatune (formerly Muscatine), Flanagan, Alford (formerly Wartrace), Clarence, Cisne, Huey, and Weir soils in Illinois showed that proper fertilization increased root penetration and development and crop yields. Corn roots penetrated deeply in fertilized Muscatune (Fine-silty, mixed, superactive, mesic Aquic Argiudolls), Flanagan (Fine, smectitic, mesic Aquic

Argiudolls), and Alford ((Fine-silty, mixed, superactive, mesic Ultic Hapludalfs) soils which had thick, permeable solums, favorable structure, and medium bulk densities. Corn roots did not penetrate the fine textured C horizons which occurred at shallow depth, lacked soil structure, and had a high bulk density in the fine, illitic, mesic Aquic Argiudolls such as Clarence, even when fertilized. Shallow rooting of crops on Cisne (Fine, smectitic, mesic Mollic Albaqualfs), Huey (Fine-silty, mixed, superactive, mesic Typic Natraqualfs), and Weir (Fine, smectitic, mesic Typic Endoaqualfs) was due largely to low fertility. With proper fertilization, roots of all crops studied, except timothy, penetrated and were well developed in the "claypan" B horizon. Today, corn yields for these soils with optimum management are: Muscatune – 12.1 Mg/ha (180 bushels per acre), Flanagan – 11.8 (175), Alford – 10.1 (150), Clarence – 8.47 (126), Cisne – 9.1 (135), Huey – 6.6 (98), and Weir – 8.5 (127) (Olson and Lang, 2000). The previous corn yields estimates are for dryland conditions.

Olson (1992) stated that it is quite possible that the productivity index (PI) of a parcel of land reclaimed under provisions of the 1977 SMCRA law could be lower than 100 percent for prime farmland of the PI of the original soil on a tract. A possible reason for the difference is in the methods and procedures used to determine long term yields. The 1997 SMCRA law only requires 3 years of crop yields (within a 10-year period) to meet target yield which is adjusted for yearly weather differences. The crop yields published by Fehrenbacher et al. (1978) as amended by Jansen (1987) represent the average for all 10 years in the 10-year period and are not adjusted for yearly weather differences. The 10-year time period assumes dry and wet years as well as hot or cold years will occur within the time period that reflect "average" weather conditions.

Kiniry et al. (1983) stated that yield is assumed to be a function of root growth which is, in turn, a function of the soil environment. Other yield parameters such as climate, genetic potential of the plant genetic and levels of management were considered to be describable in terms of yield response. Thus they could be combined with the soil parameters in a more complete prediction of yield. This study was aimed at describing the soil environment in terms of the soil's sufficiency for root growth as related to five soil parameters-potential available water storage capacity, aeration, bulk density, pH, and electrical conductivity. Each of the five root response functions described the fractional sufficiency (values of 0.0 to 1.0) for values of one soil parameter. The product of all five sufficiencies was considered to describe the fractional sufficiency of any soil layer for root growth. This approach, which permits any one parameter to be limiting, was similar to that taken by Storie (1933) who related productivity to soil properties. This approach presented differs from that of Storie in that the authors attempted to describe root growth first and then relate it to productivity.

Olson et al. (2000) stated that Illinois is one of the most productive agricultural areas in the world, as a result of a favorable humid climate, deep soils with good water-holding capacity, a favorable topography, and the use of improved crop-management technology. Olson and Lang (2004) stated that crop yields are the result of environmental factors such as soil, climate, and management inputs. The effect of technology and management on crop yield is determined, in part, by the type of soil. Consequently, more specific information on the influence of soil properties on crop yields is required. Many of the soil properties considered as important for explaining crop yields have been related to moisture-holding capacity. The soil properties used by Olson and Lang (2004) in their multiple regression models result in being some of the same soil properties needed in the calculation of root-zone available water capacity (RZAWC). Soil parent material was recognized as a property in their regression models.

Stuff and Shaw (1973) stated that “soil moisture in the root zone and depth of water table on tile-drained Chalmers silt loam near Lafayette, Indiana were measured under early- and late-planted corn in the 1971-1973 growing seasons. From relations developed between available soil moisture and the drop of the water table, the amount of upward flux of water into the corn root zone was estimated. The upward flux of water from the water table was estimated to range from as little as one percent of the actual evapotranspiration from corn in the first planting in the wet season of 1972 to 11 percent in the first planting of 1973, a year with several extended dry periods. High corn yields are dependent upon an adequate supply of soil moisture. Shallow water tables which underlie much of Indiana’s cropland can furnish a significant part of the water requirement in summers with periods of insufficient rainfall.”

Brown and Carlson (1990) developed 12 yield equations for winter wheat, spring wheat, barley, oats, and safflower. Every equation uses plant-available soil water as one of the properties to determine a yield potential for a crop. Soil texture is the surrogate soil property for estimating plant-available soil water in the 12 yield equations.

Closing Comments

Restoration of soil productivity is considered achieved when the average yield during the measurement period equals or exceeds the average yield of the reference crop established for the same period for nonmined soils of the same or similar texture or slope phase of the soil series in the surrounding area under equivalent management practices. Root zone available water capacity to productivity index or restoration to an achieved level of soil productivity for a soil seems to have a relationship.

A proposed alternative for restoration of soil productivity would use soil properties as a measure of prime farmland reclamation success. A large amount of research has been done during the twentieth century on soil properties, climate (both soil and atmospheric), and landscape features as they relate to production of commodity crops. The question being addressed in this paper, are the relationships of soil properties, climate (both soil and atmospheric), and landscape features understood well enough to guarantee that soils reclaimed after surface mining for coal will be as productive as the pre-mined soil?

In a small geographic area where the soil forming factors of climate and biota are the same, the properties of the parent material largely determines the productivity of a soil. Soils formed in loess with no root limiting layer within a depth of five feet of the soil surface are typically the most productive for growing commodity crops. Ksat, bulk density, water table, rock fragments, and soil texture are some properties that help soil scientists estimate root zone available water capacity for growing commodity crops. Soil laboratory characterization data as a method of determining root zone available water capacity is limited in terms of how many sites can be sampled and how much data can be obtained. Soil characterization can be further confounded by the bias and experience of the sampling crew. Micro-topographic effects, although significant for localized areas, are difficult to describe and quantify in a database at a scale appropriate for crop growth. A salient, recurring theme of modeling soil productivity using soil properties is the volume of data required, both yield and soil property. Of the two, the soil property data is far more expensive to obtain in quantities large enough to begin to make predictions of crop productivity. As a contrast, the crop response on a landscape readily provides an integrated assessment of the spatial soil character. The best method - to determine if the productivity of the pre-mined soil is achieved in the reclaimed soil - is by growing a deep rooted commodity crop that is dominantly grown in the area, e.g., corn.

Epilog

Smith et al. (1932) stated that “loess is an excellent soil-forming material. Its texture, or size of particles, is ideal for ease of tillage, it is free from stones, and it is well supplied with all the elements of plant food. In a region like Fulton County, Illinois, where leaching has not progressed very far, the soils still contain a large proportion of the elements of plant food originally present in the loess.”

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