Lonwall Mine Subsidence of Farmland in Southern Illinois: Near-surface Fracturing and Associated Hydrogeological Effects

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Abstract. The Illinois Mine Subsidence Research Program (IMSRP) coordinated a study to document near-surface fracturing and hydrogeological changes caused by subsidence above an active longwall coal mine in southern Illinois. Using seismic refraction and electrical resistivity, a saturated zone was identified below a depth of 15 ft (4.5 m). There were no widespread subsidence-induced changes to the level or character of this zone. Observations of surface fracturing over the tensile zone of the panel were correlated with strain determinations to estimate a surface strain at incipient cracking of 0.006 to 0.009. Displacement measurements suggested a linear strain profile with depth; therefore, the maximum surface strain and the strain at incipient cracking were used to estimate a maximum depth of surface-fracture penetration of 27 to 31 ft (8-10 m). Resistivity soundings and pseudo-depth profiles over the margins of panel 2 revealed post-subsidence resistivity changes, apparently attributed to fracturing, to an approximate depth of 20 ft (6 m). Resistivity soundings at the centerline of panel 2 revealed major resistivity increases, which are consistent with air-filled fractures extending to a depth of 13 ft (4 m). Repeated soundings after subsidence indicate that these fractures closed to a depth of 3 ft (1 m) about one week after passage of the mine face.

INTRODUCTION

Subsidence associated with high-extraction coal mining causes complex ground displacements and strains that produce tensile fractures at the ground surface. These cracks can alter the hydrologic properties of the soil and bedrock overburden and provide a pathway for contaminant migration into shallow groundwater aquifers.

The advance of the longwall mine face and the development of the subsidence trough on the ground surface is typically revealed by the pattern of open tensile cracks behind the mine face and along the sides of the panel, which is shown schematically in figure 1. Open surface cracks form in the dynamic tensile zone, which follows behind the advancing mine face, and in the static tensile zone along the sides of the panel. Fractures associated with the dynamic subsidence wave are parallel to the mine face in the center of the panel. Near the sides of the panel, however, these cracks turn through a 90 degree arc until they become parallel with the static tension cracks that are aligned with the side of the panel.

Characterization of the distribution, extent, and effects of subsidence-induced fractures is a goal of the Illinois Mine Subsidence Research Program (IMSRP). Therefore, the IMSRP coordinated a study to document ground displacements, fracturing and hydrogeological changes caused by subsidence above an active longwall panel in southern Illinois. This study involved researchers from the Illinois State Geological Survey and Northern Illinois University.

During subsidence, surface displacements were measured within a closely-spaced grid of survey monuments located near the side of the longwall panel. Principal strains were calculated within the grid and correlated with the formation of surface fractures. Inclinometers recorded horizontal displacements and strains as a function of depth; the data were used to estimate the maximum depth of surface-fracture penetration. The electrical resistivity method was used to document near-surface fracturing at different locations over the longwall panel. Pre- and post-subsidence resistivity and seismic refraction profiles were compared to estimate a depth of closure of these surface fractures and document changes in the groundwater table.

SITE

The longwall mine is located in the gently rolling farmland of northwestern Saline County, Illinois, where the local topographic relief is 40 ft (12 m). The mine is

producing coal from the 6-ft (1.8 m) thick Herrin Coal at a depth of 400 ft (122 m). Pennsylvanian-age shales and siltstones comprise the bulk of the bedrock overburden (figure 2). Eighty to 90 ft (24 to 27 m) of glacially deposited soils, consisting of loess over clay loam and sandy clay loam with some sand and gravel lenses, overlie the Pennsylvanian-age rocks.

The panel layout is shown in figure 3. Longwall panels 1 and 2 are approximately 2 miles (3.2 km) long, and 668 and 618 ft (204 and 188 m) wide, respectively. The panels are 132 ft (40 m) apart. The mine face of panel 2 advanced to the west at an average rate of 55 ft (17 m) per day during the study.

MONITORING PROGRAM

Deformation Measurements and Observations

A square grid of 16 survey monuments was located to straddle the anticipated zone of maximum-tensile strain near the edge of panel 2 (figure 3) and a transverse line of survey monuments extended across the longwall panel. The location of the tensile zone on panel 2 was predicted from transverse strain measurements of panel 1 (Van Roosendaal et al., 1990). Monuments were spaced 20 ft (6 m) apart (5 percent of the mine depth). Control monuments were placed 320 ft (98 m) south of panel 2. Four inclinometer casings, each 20 ft (6 m) long, were installed in boreholes at the corners of the grid.

Monument positions were surveyed using a Lietz SET 3 total station from a position 180 ft (55 m) south of the panel (figure 3). Prior to each coordinate survey, the position of the instrument station was confirmed by shooting a resection to the control monuments. Baseline

Figure 2. Lithologic column for subsidence research site, Saline County, Illinois.

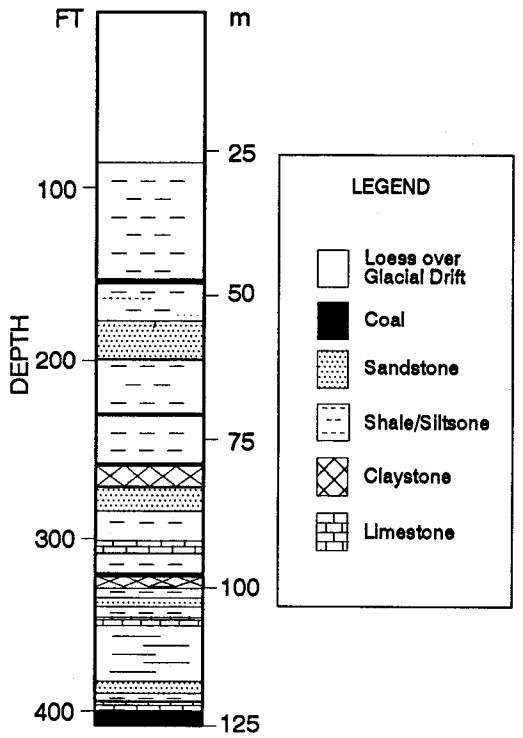
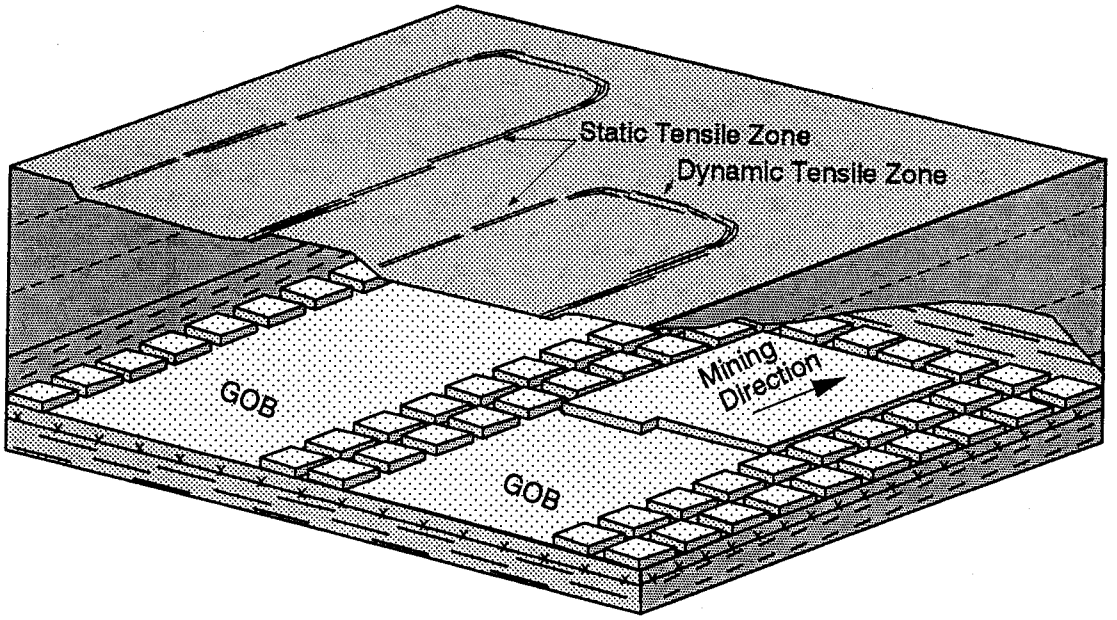


Figure 1. Schematic block diagram of longwall panels showing development of surface trough and typical crack patterns.



surveys of the monuments and instruments were conducted on September 18, 1990. The grid monuments and the tops of the inclinometer casings were surveyed 10 times between September 22 and October 2, 1990, as the longwall face advanced beneath the grid. The seven surveys that best documented the dynamic progression of ground-surface movements were chosen for subsequent data analysis. The positions of the longwall face at the time of these surveys are labeled A through G on figure 3. A final survey (survey H) was conducted two months after the grid was undermined. The transverse monument line was surveyed once during active subsidence (survey C) and again 6 weeks after the line was undermined. The inclinometers were read each time the grid was surveyed.

Electrical Resistivity

Earth resistivity was measured by inserting into the ground 4 stainless steel electrodes in a line, equally spaced, with the outer electrodes carrying the current and the inner electrodes measuring voltage. Earth resistivity was computed from the measured voltage, current, and electrode spacing. With this configuration (Wenner array) the spacing between individual electrodes was expanded to allow current to penetrate deeper into the earth and respond to deeper layers. This procedure is called sounding and the subsurface resistivities were interpreted in terms of a layered resistivity model.

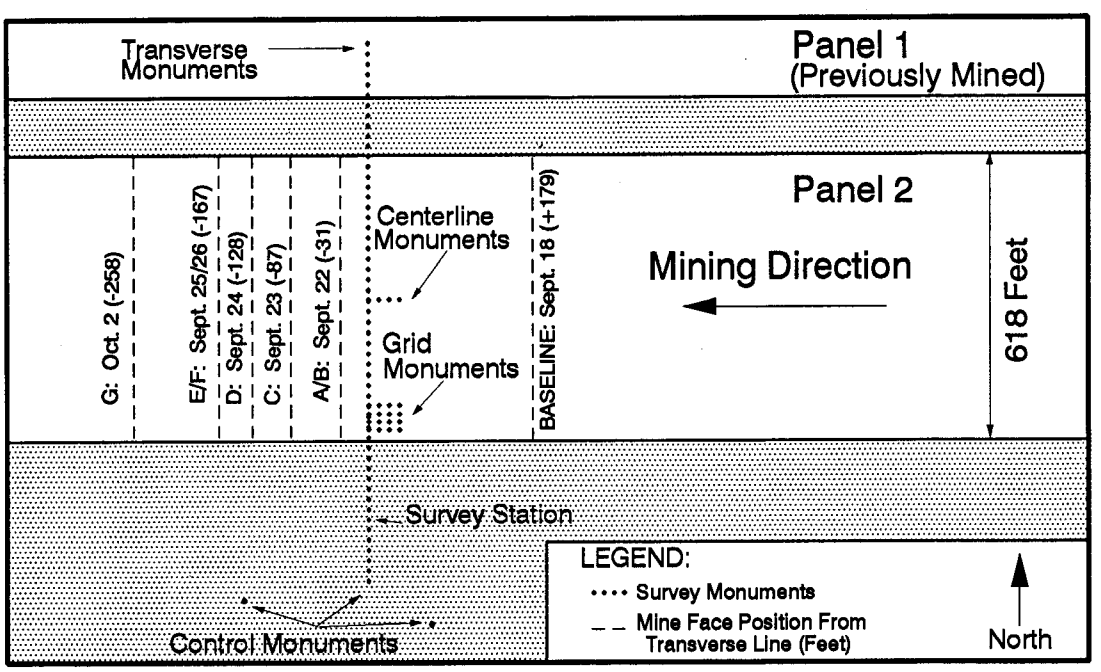
Lateral changes in resistivity were identified by moving Wenner arrays along the earth's surface with a constant electrode spacing (profiling). Soundings were also made at different points along a profile line and a pseudo-depth section was created which, in some ways, resembled a geological cross-section.

As of December, 1991, 25 resistivity soundings have been made over panels 1 and 2, most oriented north-south along the monument line over panel 2. Two north-south pre- and post-subsidence resistivity profiles spanning panel 2 (and parts of panel 1) have also been completed.

Seismic Exploration

Forty seismic refraction lines have been recorded over the center and margins of panels 1 and 2. The seismic refraction method employs a line of motion sensors (geophones) at the earth's surface. At each end of the line a sledgehammer blow on a metal plate sends sound waves into the earth. These sound waves are bent (refracted) by soil and rock layers in the earth and directed back to the surface where they are detected by the geophones. The arrival times of these waves at the geophones are then recorded and interpreted in terms of a layered earth model.

Figure 3. Schematic map of site showing monument locations and longwall mine face position relative to transverse line at times of grid surveys (1 ft = 0.31 m).



RESULTS OF DEFORMATION MEASUREMENTS AND OBSERVATIONS

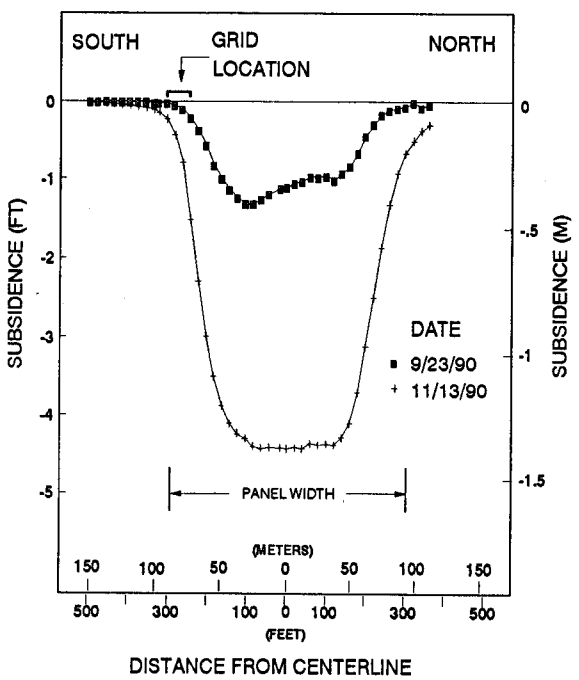
Vertical and Horizontal Displacements

The transverse subsidence profile across panel 2 is displayed in figure 4. The bracket near the south edge marks the location of the grid and the tensile zone. This profile exhibits the flat-bottomed trough typical of supercritical longwall panels (Whittaker and Reddish, 1989). Maximum subsidence was 4.2 ft (1.28 m) after 6 weeks.

The development of subsidence within the grid is shown by a series of three-dimensional surface plots in figure 5. The surface is constructed of vertical-displacement contours with each contour line representing 1 inch (2.54 cm) of subsidence. The 3-D plots are viewed from the northeast.

Figure 6 exhibits the evolution of horizontal displacements of the 16 grid monuments. Initial displacements of the grid monuments were small in magnitude and toward the northeast. As the mine face advanced away from the grid, incremental displacements shifted to the north and northwest and increased in magnitude. The resultant horizontal displacement of the northernmost grid monuments exceeded 15 inches (38 cm). Figure 6 also displays the decrease in the magnitude of displacements between the northern and southern edges of the grid. These displacement gradients cause the tensile strains commonly associated with the tensile zone of the static subsidence profile.

Figure 4. Transverse subsidence profile across panel 2.



Surface Strains and Cracks

The grid was divided into nine square elements with a survey monument located at each corner. Strain analysis followed the "surface element approach" of van der Merwe (1989), which determines principal strains within each element of a grid of surface points. Thus, it was possible to document changes in the direction, magnitude, and sign (tensile or compressive) of the maximum and minimum principal strains on the ground surface and correlate principal strains with observed surface fractures. Using formulae for a three-element rectangular strain rosette (Dally and Riley, 1978, p. 321), the magnitude and direction of the principal strains were calculated for each corner point of the element. Four values were averaged to estimate the magnitude and direction of principal strains within each element.

Principal strains within each element are plotted for surveys A through H in figure 7. Maximum principal strains were all tensile and initially aligned in a northeast-southwest direction (surveys A and B). As the face advanced from east to west and the tensile zone developed, maximum strains increased and rotated to the north. The largest tensile strains (0.027) were measured in the center row of elements in the grid, which confirms that the grid straddles the maximum tensile zone.

The actual open crack patterns recorded within the grid at the times of surveys B, C, E, and H are illustrated in figure 8. These fracture patterns show the progression from the northwest-trending, arcuate cracks of the dynamic wave to the west-northwest trending cracks that eventually developed in the static tension zone as the mine face moved away from the grid.

Subsurface Displacement Profiles

The north-south and east-west profiles of horizontal displacement versus depth for the inclinometer at the northeast corner of the grid are displayed in figure 9. The displacements of the top of each inclinometer were obtained from survey data. These profiles show a linear decrease in horizontal displacement as a function of depth. If the northward displacement profile (transverse to panel) is extrapolated, horizontal displacements reduce to zero at a depth of approximately 40 ft (12 m).

RESULTS OF GEOPHYSICAL METHODS

Stratigraphy from Resistivity Soundings

Resistivity soundings were inverted for a layered geoelectrical model in which layers represent different units observed in a boring made at the center of panel 1

Figure 5. Three-dimensional surface plots showing development of subsidence in the grid. Each contour equals 1 inch (2.54 cm) of vertical displacement. View to southwest.

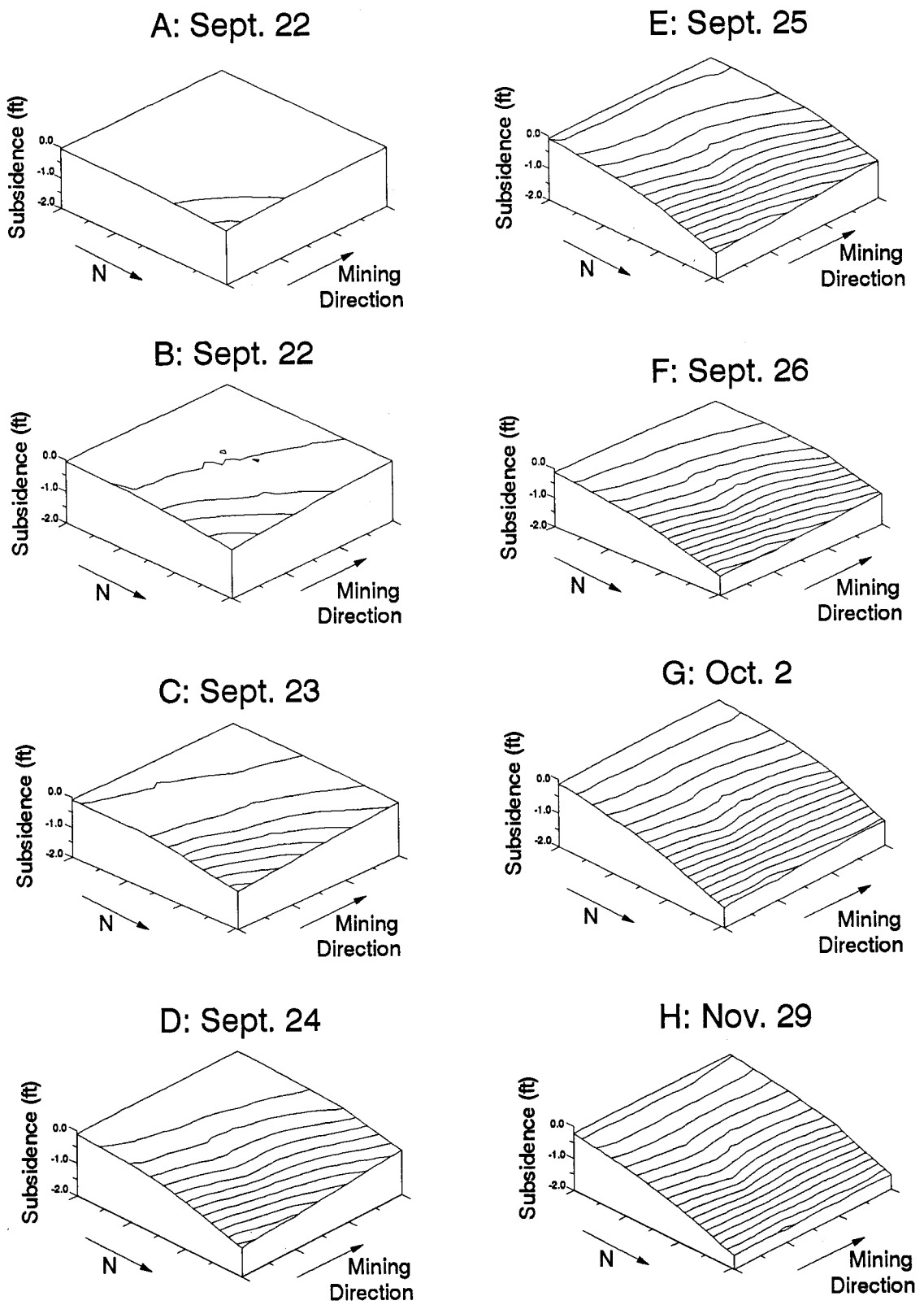


Figure 6. Horizontal displacements of grid and centerline monuments.

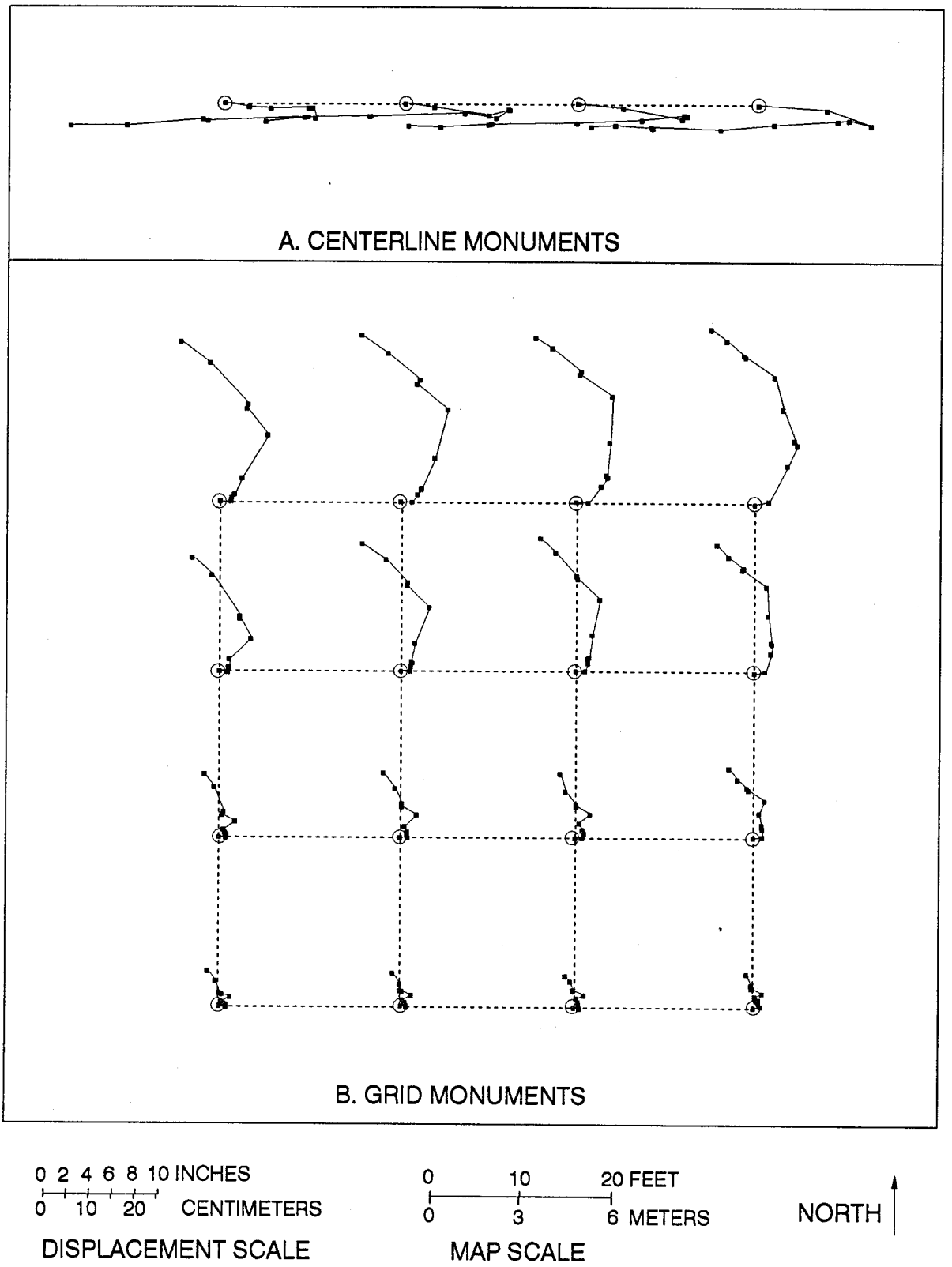


Figure 7. Principal strains calculated within each element. C denotes compressive minimum principal strain.

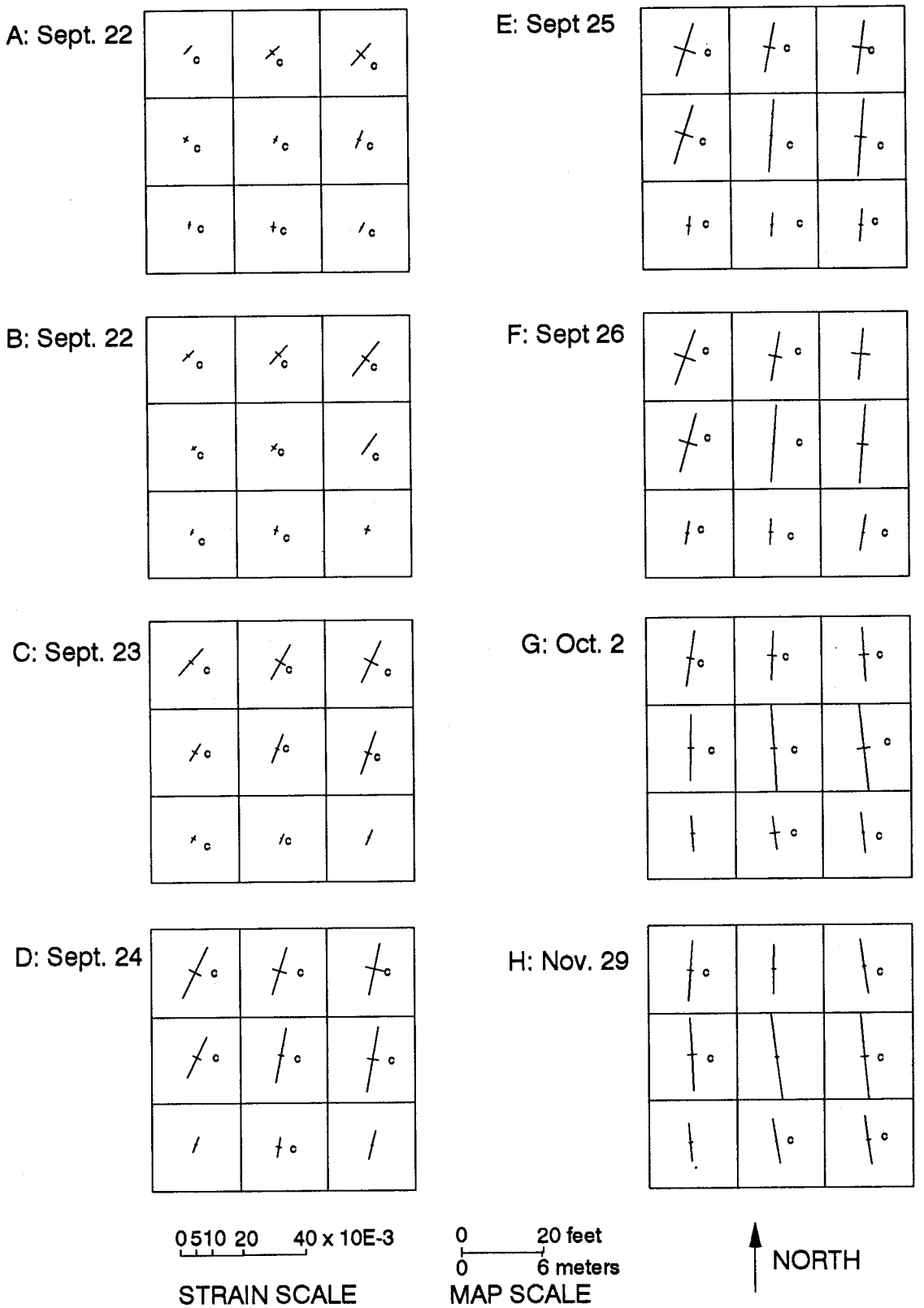
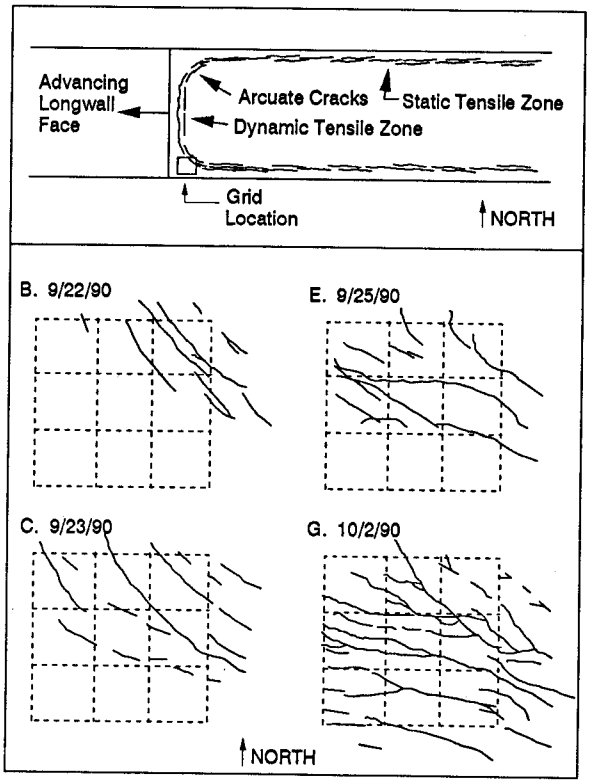


Figure 8. Schematic diagram showing typical pattern of open tension cracks over a longwall panel and the actual crack patterns observed within the grid.



(figure 10). The inversion routine employed the linear filter method to generate model sounding curves for the forward problem and inverted the data using a least-squares algorithm and an equivalence analysis (Interpex, 1988). The geoelectrical layers may be approximately correlated with the boring log as follows: at the surface a 3 ft (1 m) thick, high-resistivity topsoil and loess layer (averaging 75 ohm-m) overlies a 9 ft (2.7 m) thick, clayey, unsaturated layer (46 ohm-m). This lies above a relatively conductive layer (20 ohm-m), which includes saturated clayey and gravelly till overlying bedrock (40-70 ohm-m).

Water-level Fluctuations

A saturated zone at a depth of approximately 15 ft (4.5 m) was identified from seismic refraction surveys made over panel 1 post-subsidence and panel 2 prior to subsidence (figure 11). This saturated zone correlated closely with water levels measured in shallow drift piezometers (Darmody, 1992). Seismic refraction and electrical resistivity soundings over panel 1 (post-subsidence) and panel 2 (pre-, syn- and post-subsidence) show no widespread long-term changes in the level or character of this saturated zone. It is assumed that materials beneath 15 ft (4.5 m) are also saturated.

Figure 9. Horizontal displacement profiles for inclinometer at the northeast corner of the grid.

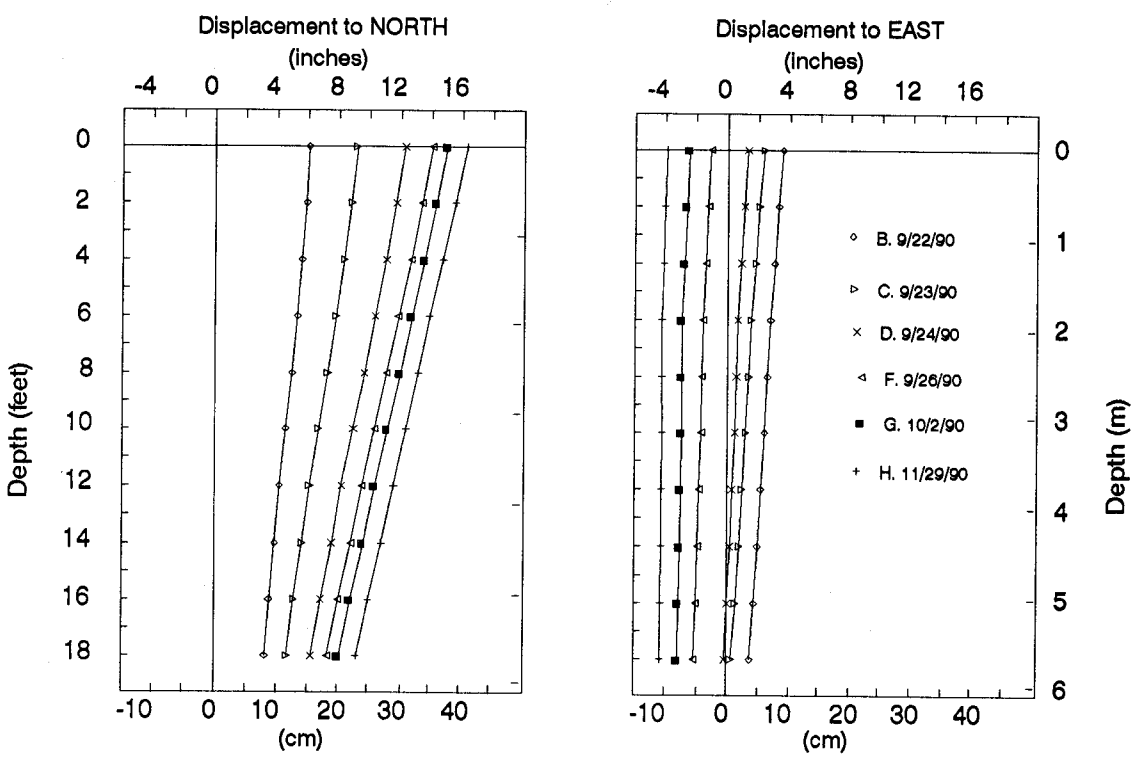


Figure 10. Inverted Wenner array resistivity sounding curve and layered resistivity model with interpreted lithologies (along transverse monument line at north edge of panel 1).

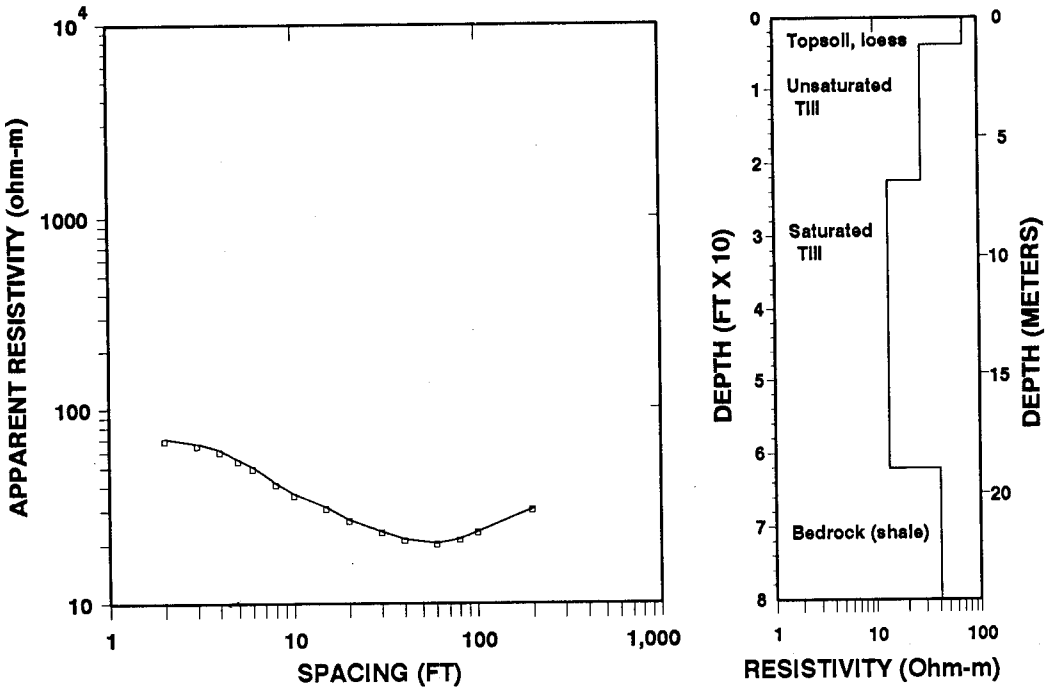
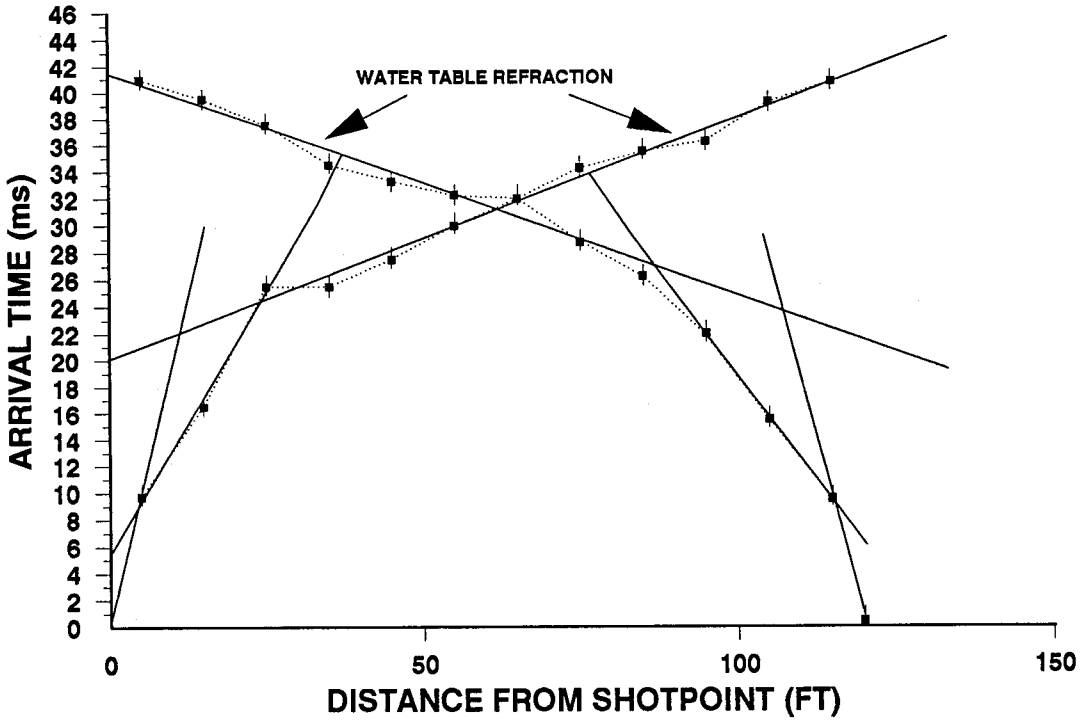


Figure 11. Presubsidence water table seismic refraction travel-time curve from south portion of panel 2. Line segments through data points indicate separate layers. The first layer (topsoil, loess) is about 3 ft (1 m) thick and the water table lies at a depth of 13 ft (4 m).



DISCUSSION: CHARACTERIZATION OF SURFACE FRACTURES

Deformation Measurements

The evolution of surface strain and fracturing reflected the advance of the dynamic subsidence wave through the grid followed by the development of the static tensile zone near the side of the longwall panel. Principal strains were initially directed to the northeast, which was perpendicular to the dynamic wave front. As the dynamic wave passed and the static tensile zone developed, major principal strains rotated to the north and increased in magnitude.

The development of cracks is consistent with the progression of principal strains shown in figure 7. As expected, the orientation of tensile fractures is generally perpendicular to the major principal strain. The initiation of tensile cracks within any given element consistently corresponded to a maximum principal strain within the range of 0.006 to 0.009. This strain at incipient cracking agrees with values published by Kratzsch (1983).

The linear displacement profiles observed with the inclinometers support a neutral-axis bending model for surface subsidence (Kratzsch, 1983). The location of the neutral axis corresponds to the depth at which horizontal displacements reduce to zero. Neutral-axis bending implies a linear strain profile, where strain is a maximum at the surface and decreases to zero at the depth of the neutral axis. The maximum strain at the ground surface (e_{max}) is 0.027 and the estimated depth of the neutral axis is 40 ft (12 m). Assuming that fractures penetrate to a depth where strains are equal to the observed principal strains at incipient cracking (e_i), the depth of penetration is expressed as:

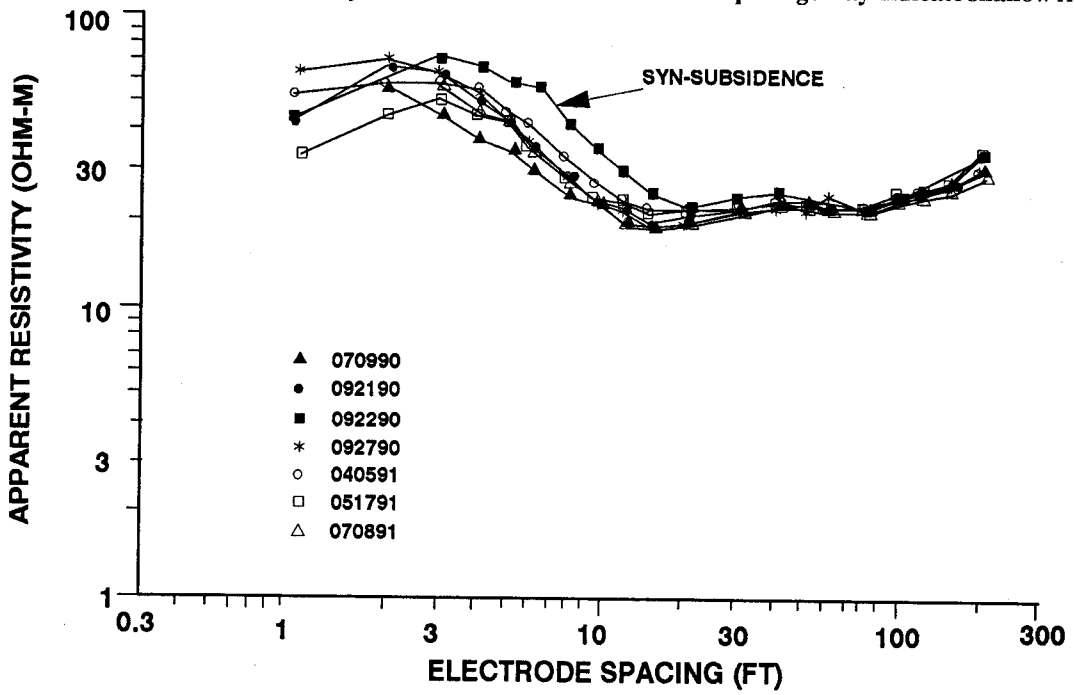
$$D_f = 40 - 40(e_i/e_{max}) \quad [ft](1)$$

The observed strains at incipient cracking range from 0.006 to 0.009. Consequently, the maximum depth of surface-fracture penetration ranges from about 27 to 31 ft (8-10m). This simple estimate is based on strains and fractures observed at the surface only, and does not consider the actual stress-strain behavior of the soil or the change in stress with depth.

Bulk Resistivity Changes

Open air-filled fractures in the vadose zone may increase the bulk electrical resistivity of unsaturated tills by providing barriers to electrical current flow (Taylor and Fleming, 1988; Carpenter et al., 1990). Increases in fracturing in the glacial materials overlying bedrock were identified through the use of resistivity soundings. Soundings made at the centerline of panel 2 exhibited major resistivity increases at short spacings, which are probably due to air-filled fractures in glacial deposits above the saturated zone (figure 12). The observed resistivities are consistent with fractures ex-

Figure 12. Multiple Wenner array resistivity soundings over the center of panel 2 before, during and after subsidence. Elevated syn-subsidence resistivities at short spacings may indicate shallow fracturing.



tending to a depth of at least 13 ft (4 m). If this interpretation is correct, these fractures may provide pathways to the water table for chemicals used in surface agricultural activities. However, repeated soundings suggest the deeper portion of these fractures have closed up within about 1 week of passage of the mine face; shallow fractures (3 ft [1 m] deep) may have remained open up to 9 months after subsidence.

Resistivity Profiles

Pseudo-depth sections are constructed by plotting apparent resistivity at different stations as a function of electrode spacings. The section is only a general guide to resistivity changes along the profile. While larger spacings are influenced by deeper structure, the conversion between depth and spacing is nonlinear (in places a 40 ft [12 m] spacing equates roughly to structure at 15-20 ft [4.5-6 m] depth). Wenner array resistivity soundings were made every 20 ft (6 m) to construct a pseudo-depth section along the profile line. Profiles made across panel 2 one month after subsidence (figure 13) showed increased resistivity along the margins of the panel, possibly reflecting air-filled fractures in the upper unsaturated zone. Resistivity decreases, however, extended below this along both margins of panel 2 and over the north barrier pillar between panels 1 and 2. Moisture percolating downward along fractures in this interval of the drift to a depth of about 13-20 ft (4-6 m) may have led to the resistivity decreases.

CONCLUSIONS

1. Using seismic refraction and electrical resistivity, a saturated zone was identified below a depth of 15 ft (4.5 m). There were no widespread subsidence-induced changes to the level or character of this zone.
2. Deformation measurements and resistivity soundings both predicted a shallow depth of closure (20 to 30 ft [6-9 m]) for subsidence-induced surface fractures. Subsurface profiles of horizontal displacement versus depth, principal-strain determinations and observations of surface fractures within a monument grid, were used to estimate a maximum penetration depth for surface fractures of 27 to 31 ft (8-10 m) over the maximum tensile zone on the southern edge of panel 2. Resistivity soundings and pseudo-depth profiles over the margins of panel 2 revealed post-subsidence resistivity changes, apparently attributed to fracturing, extending to an approximate depth of 20 ft (6 m).
3. Resistivity soundings at the centerline of panel 2 revealed major resistivity increases, which are consistent with air-filled fractures extending to a depth of 13 ft (4 m). Repeated soundings after subsidence indicate that these fractures closed to a depth of 3 ft (1 m) about one week after passage of the mine face.

ACKNOWLEDGMENTS

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REFERENCES

Carpenter, P.J., R.S. Kaufmann, and B. Price. 1990. Use of resistivity soundings to determine landfill structure, Ground Water. v. 28, no. 4, pp. 569-575.

Dally, J.W. and W.F. Riley. 1978. Experimental Stress Analysis, 2nd Edition, New York: McGraw-Hill Inc., 571 pp.

Darmody, R.G. 1992. Personal communication, Department of Agronomy, University of Illinois, Urbana, Illinois.

Interpex, Ltd. 1988. ResisPlus (Trademark), Software and Users Manual, Interpex, Ltd., Golden, CO.

Kratzsch, H. 1983. Mining Subsidence Engineering, New York: Springer-Verlag, 543 pp.

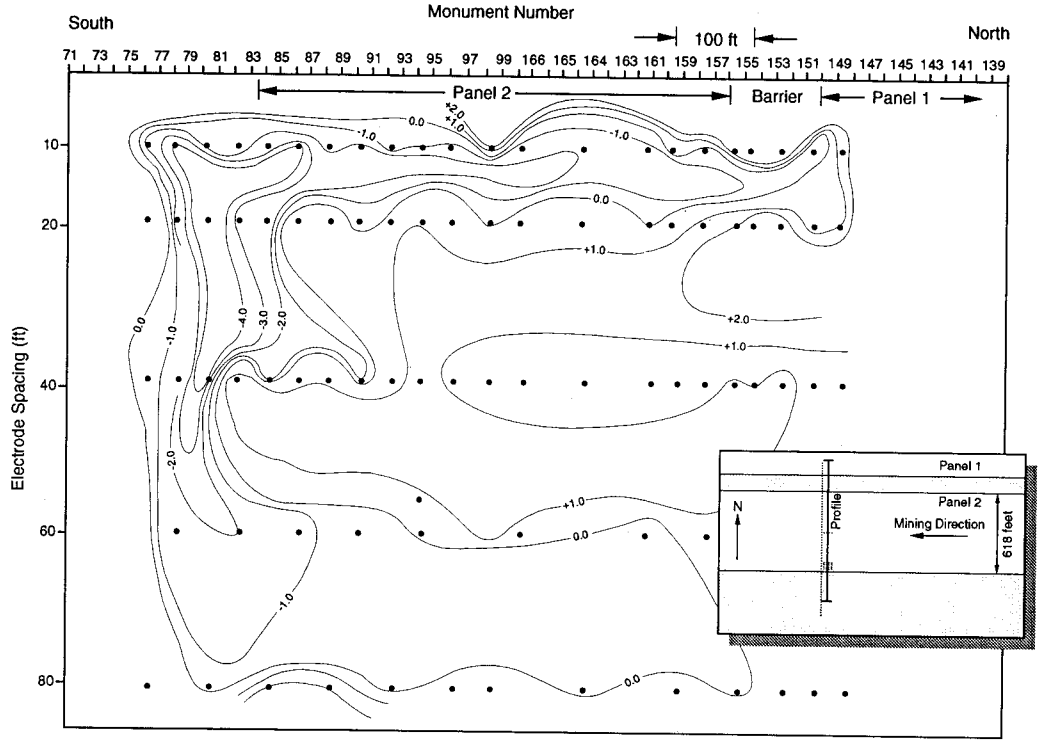
Taylor, R.W. and A.H. Fleming. 1988. Characterizing jointed systems by azimuthal resistivity surveys. Ground Water. v. 26, pp. 464-474.

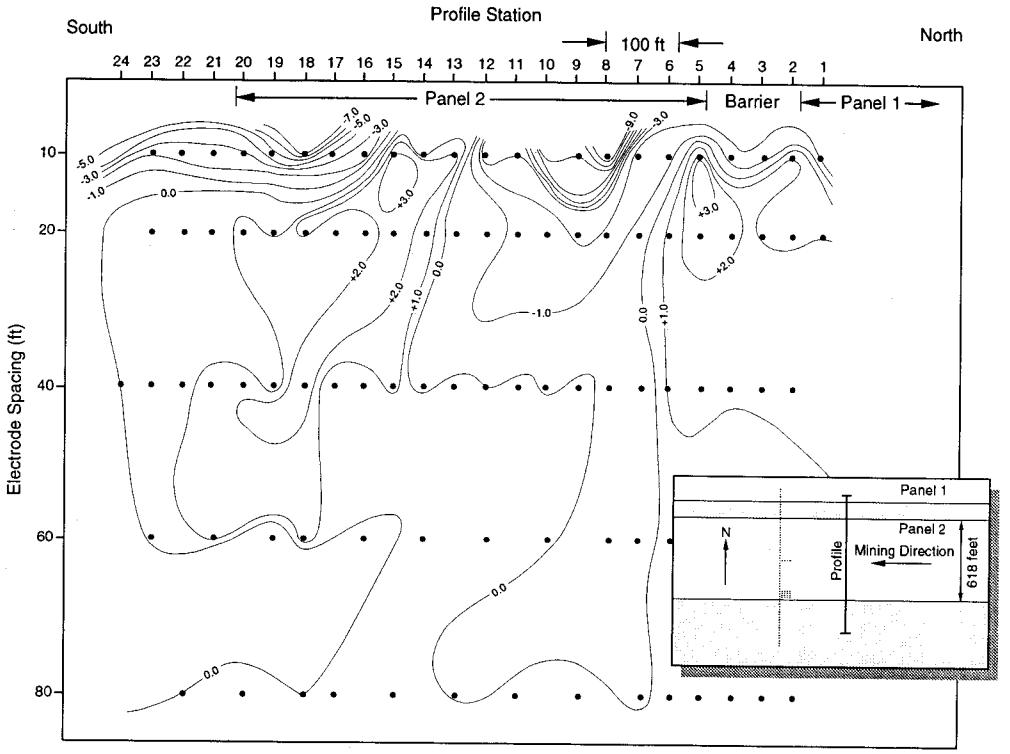
van der Merwe, J.N. 1989. The surface element approach to the analysis of surface subsidence, Proceedings of the South African National Group of the International Society for Rock Mechanics, Witbank, South Africa, p. 59-69.

Van Roosendaal, D.J., D.F. Brutcher, B.B. Mehnert, J.T. Kelleher, and R.A. Bauer. 1990. Overburden deformation and hydrologic changes due to longwall mine subsidence in Illinois, In Y.P. Chugh. (ed.). Proceedings of the Third Conference on Ground Control Problems in the Illinois Coal Basin, Southern Illinois University, Carbondale, Illinois, p. 73-82.

Whittaker, B.N. and D.J. Reddish. 1989. Subsidence: Occurrence, Prediction and Control, Developments in Geotechnical Engineering, 56, New York: Elsevier, 528 pp.

Figure 13. Pseudo-depth sections depicting pre - postsubsidence apparent resistivity differences across panel 2 (contoured in ohm-m).





Implementation of the Agricultural Lands Productivity Formula: Practical Application

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Abstract. Under the Surface Mining Control and Reclamation Act of 1977, the mining industry was required to replace prime farmland to its pre-mining level of productivity. In Illinois, the Illinois Department of Agriculture was charged with the responsibility of developing a method of assessing the productivity capability of reclaimed mined land. The Agricultural Lands Productivity Formula was adopted in 1986, but not without considerable effort being given to the development of a carefully detailed sampling. The implementation of this program required developing field sampling procedures, assessing manpower requirements, providing intensive training and office support for sample enumerators, and integrating two federal agencies into the program.

INTRODUCTION

Illinois coal falls within the sequence of rocks commonly called the Pennsylvanian System which was developed 280 to 315 million years ago. These coal bearing rocks underlie 65% of the 56,400 square miles of Illinois and contain a coal resource of approximately 181 billion tons (Treworgy and Bargh, 1982). These figures made by the Illinois State Geological Survey are an estimate of total coal in the ground, much of which is not recoverable under present economics or present engineering technology.

LEGISLATIVE HISTORY

On August 3, 1977, President Carter signed into law the "Surface Mining Control and Reclamation Act", Public Law 95-87. This Federal Act required most states to pass legislation that would comply with the federal statutes in order to receive primacy for enforcement of the federal law.

In 1979, Illinois passed Public Act 81-1015, "The Surface Coal Mining Land Conservation and Reclamation Act," which enabled Illinois to develop, submit for approval, and receive conditional approval of the Permanent Program on June 1, 1982. With that approval, Illinois received primacy under the Federal Act for regulation of the coal mining industry.

LITERATURE REVIEW

The Federal Act in Sections 510(d)(1), 515(b)(19), and 519(c)(2) and the Federal Rules and Regulations (Federal Register 1979) concerned with reclamation of mined prime farmland indicate that success in revegetation shall be determined on the basis of crop production from mined areas compared to that of approved reference areas or other technical guidance procedures. State Rules and Regulations in Section 1785.17e(3), 1816.116a(3)c, 1817.116a(3)c, and 1823.15b(2) (62 Illinois Administrative Code) requiring proof of soil productivity has led to the initiation of considerable research to determine and evaluate methods of reclaiming mined prime farmland.

Hoffman et al. (1981) studied both vegetative production and animal performance on mined land and obtained results similar to those from undisturbed soil. However, Nielsen and Miller (1980) reported that corn yields on mined soil were 4 to 90 percent less than adjacent native soils, depending upon topsoil applications and age. Grandt (1978) found that corn yields decreased over a 3-year period when corn was grown on a graded spoil, but yields were relatively constant where topsoil had been replaced. Most of the published research has addressed the methodology of reclaiming mined soils for crop productivity, with research results often reflected in rules and regulations concerning mined land reclamation.

A major difficulty in predicting crop yield at either a reclaimed or unmined site is the variability in weather and its effects on crop yield. Considerable research has been conducted evaluating relationships between crop yield and weather variables (Runge and Odell, 1958; Runge, 1968; and Thompson, 1975), and crop yields, weather variables, and soil parameters (Robbins and Domingo, 1953; Leeper, et al., 1974; and Nelson and McCracken, 1962). However, applications of specific parameters in this research to individual sites for pur-

poses of calculating a yield standard would not be appropriate since agronomic management factors are likely to be different from those used in the cited studies. For example, recommended crop varieties, plant populations, herbicides and fertilizer rates change over time and these factors would affect crop yield based on current management practices. Variable weather conditions affect crop productivity as well as affecting parameters used to predict crop yield. Thus, yield equations developed from research data would have limited value in predicting individual site yields.

The Federal Act (PL 95-87) required that prime farmland must be reclaimed to equivalent or higher yield levels compared to non-mined prime farmland in the surrounding area (Jansen, 1981). Researchers indicate that reconstruction of mine soils is site specific (Schuman and Power, 1981) and, thus, productivity comparisons therefore might be expected to be site specific. This would minimize differences in yields that might be attributed to factors other than those studied.

It is apparent that the research methodology for evaluation of the productivity of reconstructed soil is to make comparisons with unmined adjacent soil at specific sites. Federal and State rules and regulations suggest similar methodology or other technical guidance procedures. The methodology proposed in the Agricultural Lands Productivity Formula (ALPF) developed by the Illinois Department of Agriculture (IDOA) evidently would be categorized as "other technical guidance procedures" as the number of sites to be evaluated and the limited resources available for site evaluation make it prohibitive to use the research approach for evaluation of reconstructed soil productivity at each site. Therefore, the purpose of the Agricultural Lands Productivity Formula is to provide a calculated standard yield to be used for comparison to determine if productivity has been restored to mined land.

The Agricultural Lands Productivity Formula (ALPF) has advantages as a method for determining a yield standard. Calculating a yield standard is much less expensive than managing a comparable research plot on undisturbed soil, and it also provides for seasonal adjustment in the yield standard based on the use of the USDA Agricultural Statistics Service county estimated average yield per acre. The ALPF also utilizes the computation of estimated soil productivity at a high level of management (Fehrenbacher et al., 1978) as well as the "average" management of crops reflected by the county yield that is reported.

The calculated yield standard produced by the Agricultural Lands Productivity Formula (ALPF) is not site specific, the importance of which was emphasized by Schuman and Power (1981). Variations in weather during the growing season such as drought, rain, or hail storms can be site specific and quite detrimental to site yield even though the county average is not greatly affected. It appears that some adjustment in yield at a specific site may be necessary when "abnormal" weather occurs at specific sites within a county.

Little or no research has been published that provides suitable methodology or parameters for predicting yields from constructed soils or even unmined soils at a specific site at some future point in time. As has been suggested previously, agronomic management factors change over time and published research showing yield prediction equations are generally not suitable beyond the conditions specific in the research.

Computations in the Agricultural Lands Productivity Formula integrate both county weather and management practices during a given year, as well as the use of expected high management yields (Fehrenbacher et al., 1978) by soil type to reflect recognized productivity differences in soils. Thus, it might be concluded that the yield standard calculated by the Department of Agriculture's productivity formula is more current relative to weather and county management practices than some alternative choices (i.e., published yield equations, published farm yields, etc.).

LOSS ADJUSTMENT

The problem of major weather disasters at a given site relative to a standard yield will need adjustment. For example, corn is relatively sensitive to moisture stress at flowering (Denmead and Shaw, 1963; Robbins and Domingo, 1953) and differences in moisture stress at flowering may result in relatively large differences in yield at harvest. It is entirely possible that one part of a county can be severely deficient in moisture while the remainder of the county has a relatively normal growing season. A provision has been made to make adjustments for "largely abnormal" growing conditions at a test site where yields are to be compared against a county-wide standard. An abnormal growing condition might include drought, flood, hail, etc.

Crop adjusters certified to perform adjustments by the Federal Crop Insurance Corporation (FCIC) are utilized on a site specific basis to evaluate reported crop losses. FCIC adjusters are provided with field delineation maps by the Illinois Department of Agriculture (IDOA) and are assigned, on an as requested basis, to perform loss adjustments. Due to the lack of historical crop data, it is necessary to perform crop appraisals during the growing season. Loss adjustments requested by industry are determined by a comparison to the appraisals previously made. The use of loss adjusters is optional because it is an added cost that must be born by industry. The IDOA program allows for the mining

company to cancel requested appraisals any time during the crop season. Cancellation may be appropriate should the site specific instance of loss not materialize.

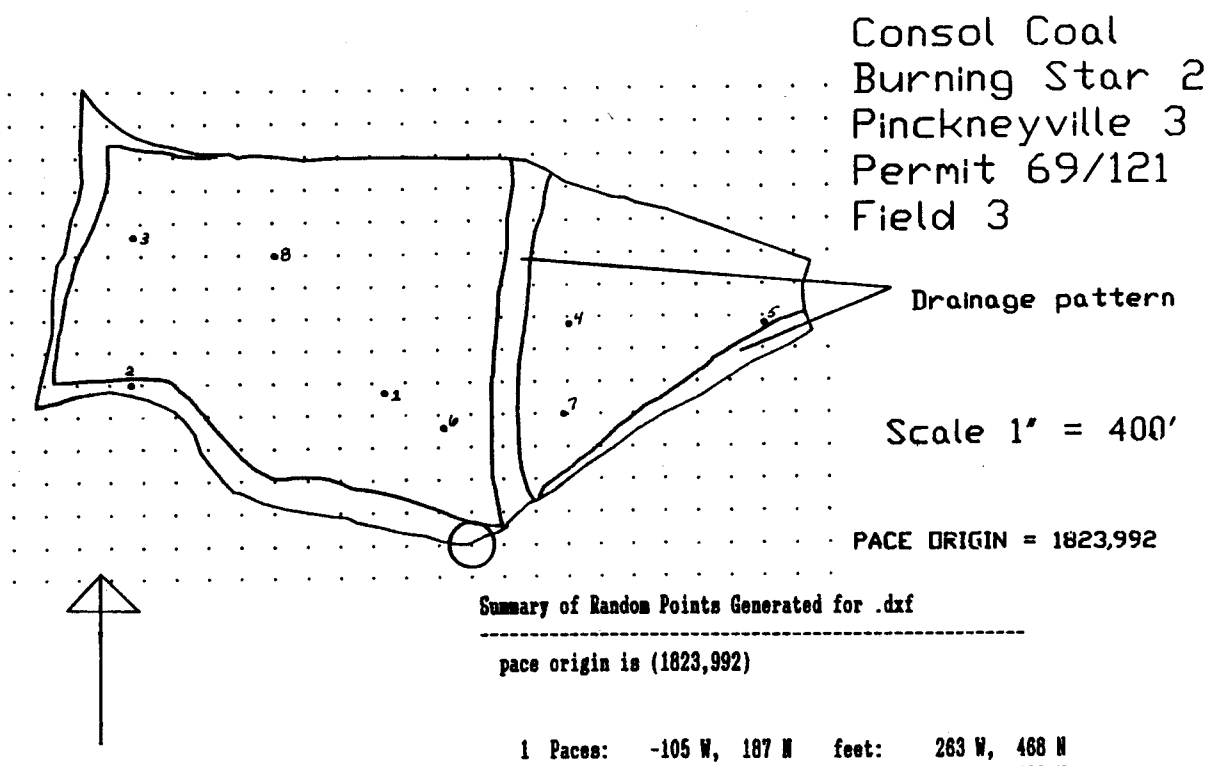
SAMPLING

An important section of the productivity formula is the sampling procedure, and an integral part of that is the location of the sample points. The Department looked at many procedures used by various groups or agencies involved in field sampling. Everything considered was based on statistical sampling procedures that involved only partial field representation. Due to the very nature of the reconstructed soils, we could assume there was no homogeneity in the soils that would lead to consistent crop production.

In an effort to account for the variability that we encountered, it was decided to impose a whole field sampling procedure, using complete randomization of sample points. A customized computer program was created by a private contractor to generate random samples points by computer. Once sampling points are generated, the program creates a script file which works interactively in the Auto-Cad computer aided drafting environment. The final product is a single sheet of paper with field boundaries delineated and all sampling points located from a single point of origin by pace count (see attached Figure 1). The use of this sheet makes it simple for the field enumerator to locate and take samples. Although the coefficient of variation remains high for the individual sample points, the correlation of the mean to the actual harvest remains within five percent. Provisions were also made in the Illinois rules that in every case a certified whole field weight would take precedent over sample weights.

In preparing to implement the formula, a number of crop sampling procedures that could be adapted to our needs were reviewed. Ultimately, the procedures of the USDA Agricultural Statistics Service were chosen to be incorporated in to the Productivity Formula. USDA hand sampling procedures have evolved over many decades of actual field sampling and have proved to be

Figure 1. Illinois Department of Agriculture sample enumerator field sheet.



Summary of Random Points Generated for .dxf

pace origin is (1823,992)

1	Paces:	-105 W,	187 N	feet:	263 W,	468 N
2	Paces:	-413 W,	199 N	feet:	1033 W,	498 N
3	Paces:	-409 W,	383 N	feet:	1023 W,	958 N
4	Paces:	123 E,	271 N	feet:	307 E,	678 N
5	Paces:	363 E,	271 N	feet:	907 E,	678 N
6	Paces:	-33 W,	143 N	feet:	83 W,	358 N
7	Paces:	115 E,	159 N	feet:	287 E,	398 N
8	Paces:	-237 W,	359 N	feet:	593 W,	898 N

the most reliable. The only exception to USDA procedures was for hay. There was no hand sampling procedure developed for hay which would meet our needs. The IDOA began a long literature search which resulted in the adaptation of a formula provided to us by Fenn & Company of Cottage Grove, Oregon.

A major problem of hand sampling hay is its rapid decomposition after it is cut. Annual tonnage figures for hay, produced by the Agricultural Statistics Service, and used almost universally are in dry matter content. Within an hour after sampling, decomposition of the mixed hay substantially alters the dry matter content. The number of samples to be taken in a day and their total volume made transportation to a lab for moisture content determination impractical.

An extensive review of available field moisture meters was undertaken, only to determine that the variability of readings made reliability unacceptable for our purposes. The company which was ultimately chosen (Dickey-John Corp), worked directly with the Illinois Department of Agriculture to improve useability of the meter of choice. The Agency undertook an intensive sampling program whereby we provided carefully sealed and iced samples which were laboratory tested and correlated for the specific machines.

Feeling that the field moisture problem had been overcome, field sample correlations were begun only to find that field scales were not sufficiently accurate. We needed accuracy within one tenth of a pound or greater. This involved the purchase of some very expensive platform scales which were difficult to transport and set up. When all was said and done, a very accurate hay plot sampling method determining dry matter tonnage in the field had been developed. When the first requests for hay sampling came in, logistics and volume made the initial field sampling plan unworkable. It was quicker, cheaper and more responsive to industry needs to simply weigh a representative sample of bales. Using bales for weights still required moisture testing, which introduced still another round of problems with taking moisture samples. The decision was made to displace the variability in countering the inherent problem with determining field moisture content with any degree of accuracy. In developing yield calculations, an administrative decision was made to establish a 15% moisture standard to replace the dry matter standard. All dry matter calculations are adjusted to 15% moisture, thus eliminating the variability problems of the sampling equipment.

In developing the appropriate sampling technique, a few rough edges had to be smoothed out. One such problem was the exact location of the sample in relation to the last pace count. In the process of sampling wheat, it was observed that enumerators had a tendency to lay the sample frame down and push it up against the closest wheat row. This would increase the yield by one row which generally was about 33 per cent. The enumerator had to make sure that the sample frame laid perpendicular to the toe of his/her shoe on the last pace count.

Another problem had to do with thin or bare spots in a field. As an enumerator proceeds ahead with the pace count, he/she may observe a thin or bare spot in the field. When approaching this spot, the brain automatically adjusted the length of their pace to either end short of the bare area or pass over it. This is easily compensated for by having the enumerator stop the pace count short by 5 paces and measuring the remaining distance with a tape measure.

MANPOWER

Implementing a new program posed a challenge with regard to budgeting for the correct number of man-hours to collect and process field samples. The Department of Agriculture was able to start with some basic values that were obtained in early field trials. Approximately 20 minutes were allocated per sample for collection with up to another 15 minutes allowed for paperwork and preparation for mailing the samples. Once the samples are received in the lab for moisture testing, another 30 to 40 minutes can be added per sample for processing. A starting figure of approximately 1 to 1.25 hours per sample may be used for cost estimates for grain sampling. In addition to the man-hours involved, a postage fee should be assessed for mailing to a laboratory facility (see Table 1 for sample densities).

The cost of sampling baled hay becomes more difficult to estimate because of multiple cuttings, different bale sizes, and whether the bales are stacked or left in the field. For the first year, it would be safer to appraise the cost of field sampling baled hay by projecting the cost as if the hand sampling method was being used. If this procedure is used, remember to reduce the single sample time value by the estimated lab time, as hay samples would not be processed in a lab. Hay samples used for calculation purposes would also reflect the total number of cuttings for a season.

CONCLUSION

The Illinois Department of Agriculture spent several years developing and implementing the Agricultural Lands Productivity Formula. This method of reclamation productivity assessment has allowed Illinois to proceed with the release of bond on prime farmland while satisfying the agricultural and environmental interests. The industry has shared our problems and has been understanding as we matured into a fully

functioning program. Now, working together, we can be assured that the agricultural resources of Illinois will remain for future generations.

LITERATURE CITED

Denmead, O. T., and R. H. Shaw. 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron. J. 52:272-274.

Fehrenbacher, J. B., R. A. Pope, I. J. Jansen, J. D. Alexander, and B. W. Ray. 1978. Soil Productivity in Illinois. University of Illinois at Urbana-Champaign. Cooperative Extension Service. Circular 1156.

Table 1. Illinois agricultual lands productivity formula.

Size of Bond Release Field	Minimum Number Of Samples
COR N	
4 - 39 acres	10
40 - 279 acres	14
280 - 639 acres	18
640 acres or more	30
SOYBEANS	
4 - 39 acres	10
40 - 279 acres	12
280 - 639 acres	16
640 acres or more	26
WHEAT - OATS	
4 - 39 acres	6
40 - 279 acres	8
280 - 639 acres	10
640 acres or more	14
SORGHUM	
4 - 39 acres	10
40 - 279 acres	16
280 - 639 acres	28
640 acres or more	40
MIXED HAY	
4 - 39 acres	5
40 - 279 acres	10
280 - 639 acres	20
640 acres or more	(1) additional per 35 acres

Grandt, Alten F. 1978. Reclaiming mined land in Illinois for row crop production. J. Soil Water Conser. 33:242-244.

Hoffman, L., R. E. Ries, and R. J. Lorenz. 1981. Livestock and vegetative performance on reclaimed and non-mined rangeland in North Dakota. J. Soil Water Conser. 36(1):41-44.

Jansen, I. J. 1981. Reconstructing soils after surface mining of prime agricultural land. Mining Eng. 33:312-314.

Leeper, R. A., E. C. A. Runge, and W. M. Walker. 1974. Effect of plant available stored soil moisture on corn yield: II. Variable climatic conditions. Agron. J. 66:728-733.

Nelson, L. A., and R. J. McCracken. 1962. Properties of Norfolk and Portsmouth soils: Statistical summarization and influence on corn yields. Soil Sci. Soc. Am. Proc. 26:497-502.

Nielson, Gerald A., and Eilif V. Miller. 1980. Crop yields on native soils and strip mine soils: A comparison. J. Soil Water Conserv. 36:44-46.

Public Act 81-1015. The Surface Coal Mining Land Conservation and Reclamation Act. Eighty-first Illinois General Assembly. June 1, 1980. Public Law 95-87. Surface Mining Control and Reclamation Act of 1977. 95th U.S. Congress. August 3, 1977.

Robbins, J. S., and C. E. Domingo. 1953. Some effects of severe soil moisture deficits at specific growth stages in corn. Agron. J. 45:618-621.

Runge, E. C. A. 1968. Effects of rainfall and temperature interactions during the growing season on corn yield. Agron. J. 60:503-507.

Runge, E. C. A., and R. T. Odell. 1958. The relationship between precipitation, temperature, and the yield of corn on the Agronomy South Farm, Urbana, Illinois. Agron. J. 50:448-454.

Schuman, Gerald E., and James F. Power. 1981. Topsoil management on mined lands. J. Soil Water Conser. 36:77-78.

Thompson, Louis M. 1975. Weather variability, climatic change, and grain productivity. Science 188:535-541.

Treworgy and Bargh. 1982. Deep minable coal resources of Illinois. Illinois Department of Energy and Natural Resources. State Geol. Survey Circ. 527.

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Cropland and Hayland Productivity Restoration on Mined Land in Illinois

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Abstract. The Surface Mining Control and Reclamation Act (PL 95-87) introduced many new controls on the coal industry. One of these was the requirement to re-establish cropland and hayland productivity. Each state has been required to establish measuring techniques for evaluating productivity restoration. In 1986 the Agricultural Land Productivity Formula (ALPF) became an approved regulation to assess productivity restoration on both cropland and hayland in Illinois. Since that time several hundred field-years have been tested at 23 mines around the state. Initial results indicate that wheat and hay crops have been tested the most. Wheat crops have met or exceeded the required target yields a greater percentage of the time than soybeans, corn or hay. These results are attributed to the poor physical conditions (compaction) at the time of testing and its effect on the individual crops. Compaction alleviation (deep tillage) is having positive results relative to those fields that have not been augmented.

INTRODUCTION

Cropland reclamation does not have a long history in the art of reclamation. Illinois created its first cropland reclamation standard with the passage of the Surface-Mined Land Conservation and Reclamation Act of 1971. This regulation, commonly known as Rule 1104, established a rooting medium quality with defined limits of clay, rock size and quantity. Major changes were added in 1976 to include topsoil replacement and further limit the rock content. Rule 1104 includes all soils capable of producing crops which is a broader definition than prime farmland soils. In 1977, with the passage of the Surface Mining Control and Reclamation Act, specific provisions for prime farmland restoration and actual measurements of restored cropland productivity became effective. Illinois also retained its Rule 1104, which is now known as high capability land.

It is virtually impossible to operate a large or medium size surface or underground mine in Illinois without affecting prime farmland or high capability land (1). This results in a significant acreage of land, primarily from surface mines, being returned to a post mining land use of cropland. The concept of the productivity regulations is to measure the yields of the reclaimed fields to either 90% or 100% of their premining yields.

The regulations allow this to be done by determining a soils premining yield potential and comparing it to a reference area or to established values in the literature. Adjustments are made for seasonal weather influences. Numerous problems were anticipated in Illinois for reference areas near the mine site. These included finding representative sites and equivalent management monitoring. In 1986, Illinois promulgated its measurement technique called the Agricultural Land Productivity Formula (ALPF)(2). This technique is a blend of both methods. The basic concept is direct comparison of the yield potential of the soils in the permit with the yield potential of the soils that are cropped in the county. Each year the changes in county average yields proportionately alter the required yield targets for the permit area for corn, wheat, soybeans and hay.

MATERIALS AND METHODS

Under the ALPF operators must submit requests for field testing. Requests must include the crop to be grown and maps of the fields. The current crops which are approved for use are corn, soybeans, wheat and hay. All cropland must have one successful year of corn and is limited to one successful year of hay or wheat. During the harvest season random samples are taken to determine if the field meets or exceeds the success standards.

A statistical comparison, one-sided t test with 90% confidence, is used to compare the sample yields with the target yields established for that year. Current regulations set a 90% and 100% of target standard for high capability and prime farmland, respectively. A total of 646 field sample success results from 1985 through 1990 were compiled from 23 mines and evaluated for the differences between crops, the effects of subsoil replacement technology and deep tillage (>18 inches). Subsoil replacement has been placed into four categories which include: bucket wheel excavator (BWE); truck shovel (TS); scraper, which includes combinations with trucks (S); and direct cast by dragline (D). The deep tillage technology includes the TLG 12 vibrating ripper, the DMI static shank plow, the slip plow, Jones vibrating ripper and Sahara static ripper. For the purpose of this paper, only information on interactions between tillage, crops and soil replacement methods with at least 5 individual field-year tests will be interpreted.

RESULTS AND DISCUSSION

Of the 646 field-years of crop productivity tested under ALPF, approximately 200 field-years of each corn, hay, and wheat have been tested; 48 field-years of soybeans have also been tested for productivity. Scraper replaced rooting media has been the most commonly tested (326 field-years), followed by bucket wheel excavator (215 field-years), dragline (77 field-years) and truck shovel (28 field-years). Two hundred field-years of the 646 tested have been deep tilled to greater than 18 inches; 446 field-years have not been augmented. When looking at individual crops independent of soil replacement technology or deep tillage, the data compiled indicated that wheat was the most successful crop in meeting the requirements of ALPF (Figure 1).

Seventy (70) percent of the wheat field-year tested met production requirements, followed by soybeans (62.5%), corn (59%) and hay (48%). Presumably, any poor soil physical conditions after reclamation (compaction) would affect wheat yields the least of the four crops tested. Typical fall and spring weather provide adequate moisture for the wheat crop, and any compaction related moisture stress would be less likely, relative to those crops with growing seasons extending over drier summer months. The low rate of successful hay production is likely attributed to both management problems, especially timely cutting and soil physical conditions. Lack of root proliferation, caused by compact rooting zones, as well as decreased water recharge potential and reduced water uptake, hinder hay production, especially during dry periods. Little difference was evident between three of the four root medium replacement methods (Figure 2) when looking at all crops and all tillage. Dragline soil replacement appears to be lower in crop success for an undetermined reason. Because the coal industry anticipates more compaction to occur on scraper placed soils, this soil replacement method is the method where most deep tillage has been done. Over one-half of the scraper field-years tested were deep tilled; however, less than one-tenth of the bucket wheel excavator fields tested have been deep tilled. No truck shovel replaced fields tested for production have been augmented.

Yields from non-augmented fields appear to be negatively impacted by subsoil replacement methods generally recognized as resulting in the most amount of compaction; i.e., scraper, or by crops most susceptible to water stress (Figure 4 & 6). In those field-years tested that have not received augmentation, 55% meet production requirements. Augmented fields met production 70% of field-years tested (Figure 3). These results seem

Figure 1. Overall Crop Success - All Soil Replacement Methods and Tillage.

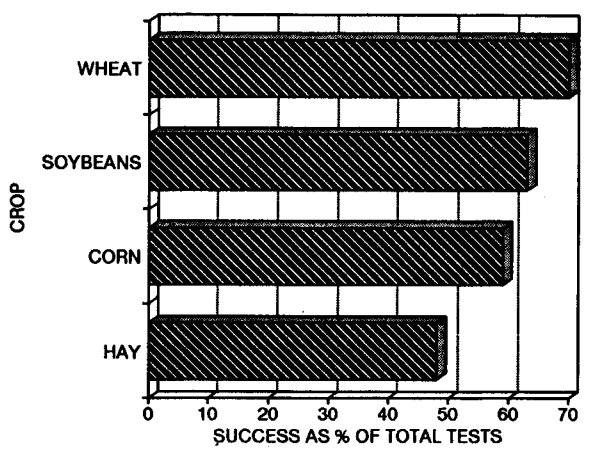
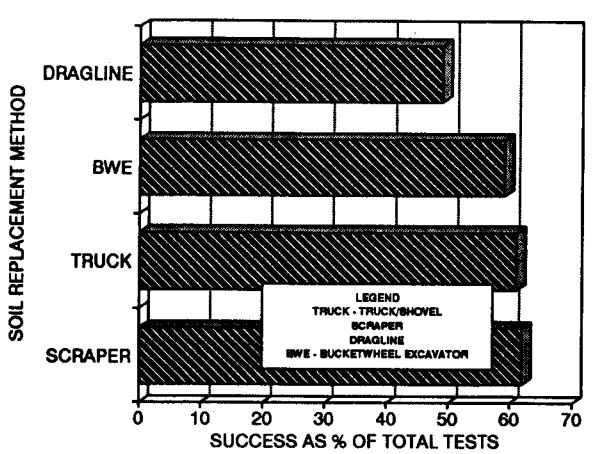


Figure 2. Soil Replacement Methods - All Crops and Tillages.



to support the premise that deep tillage increases the likelihood of fields meeting productivity.

Across the crops examined, those grown on subsoil replaced by the bucket wheel excavator (BWE) had the least variability between crops of field-years meeting production requirements (Figure 4).

One may speculate that the BWE replaces a relatively consistent rooting material, possibly explaining the consistent crop production results. While the production success of all crops is relatively consistent, a review of Figures 4 and 5, reveals that deep tillage of bucket wheel material appears to increase yields for corn. Wide variations of production success across the crop tested under the other subsoil replacement methods without deep tillage are evident (Figure 4).

Various physical conditions of the rooting media, the response of the crops to the rooting media, and weather variations are all potential causes for the variable crop success. Another possible source of variability may be limited numbers of sample points. The largest number of field-years for any crop grown in dragline rooting media was 34 and the largest for truck shovel was 17. One point worth mentioning regarding Figure 4, concerns the low percentage of field-years of wheat that met productivity requirements in truck shovel material. This data was collected from one mine which, due to wet weather conditions near harvest, had reduced crop yields as a result of disease. Figure 6 shows the effect of augmentation to rooting media replaced by the bucket wheel excavator, dragline and scrapers. No augmentation data is available for truck shovel rooting media. Augmentation effects were most noticeable in bucket wheel and scraper replaced subsoil materials. Augmented subsoil replaced by a bucket wheel passed in 100% of the field-years tested for corn and in only 55% of the field-years that were not augmented. One must be careful however, to note that only 8 field-years of bucket wheel data have been deep tilled, but the trend does appear favorable. Scraper replaced subsoil appears to have enough data to draw solid conclusions. Of

Figure 3. Effect of Deep Tillage - All Crops.

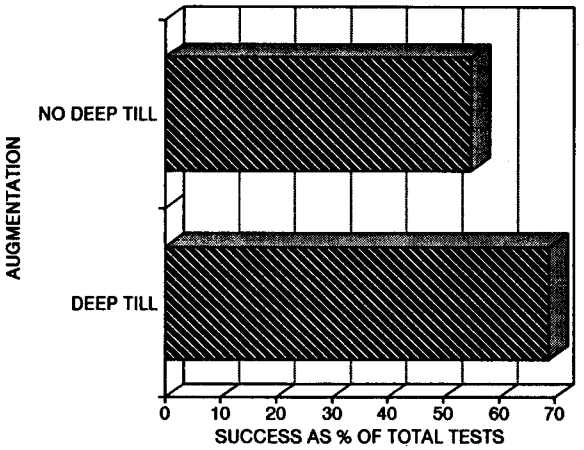


Figure 4. Non-Deep Tilled Crop Successes - Wheat - Hay - Corn - Beans.

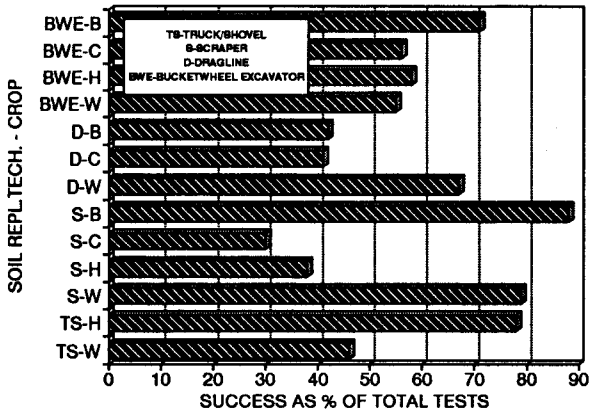


Figure 5. Deep Tilled Crop Successes - Wheat - Hay - Corn - Beans.

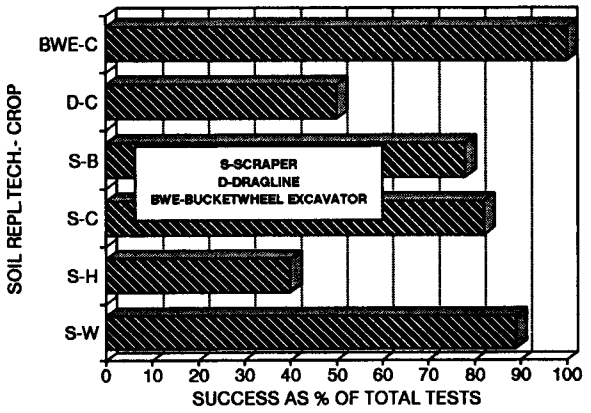
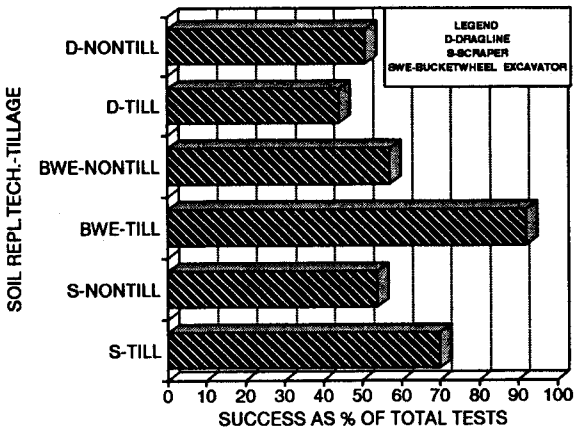


Figure 6. Soil Replacement Methods - All Crops.



the 155 non-augmented subsoil field-years tested an average of 57% met crop production requirements, while an average of 70% of the 171 augmented subsoil field-years made crop productivity. Dragline rooting media had less deep-tilled field-years passing relative to non-deep tilled field years. Again, limited data for deep tilled field-years (only 16 samples) make the conclusions speculative in nature.

In examining trends of all three variables (crop, subsoil replacement method, and augmentation), several prove to be very interesting. Soybeans grown in non-augmented scraper replaced rooting media met productivity requirements in 88% of field-years tested (Figure 4) compared to only 78% of field-years tested for augmented scraper material. However, due to the limited number of data (8 field-years, no augmentation; 15 field-years augmentation) the results are far from conclusive. Scraper replaced hay showed a slight increase in field years meeting requirements after deep tillage (40% to 38%), but such a small difference is likely inconsequential. As stated earlier, the low percentage of hay meeting productivity requirements may be the result in part of limited experience in hay management. Wheat production in scraper replaced subsoil was slightly more successful in augmented field-years relative to non-augmented field-years (87 to 79%).

As previously discussed, weather conditions may influence these results and the success of non-augmented wheat ground may be misleading as to the adequacy of the subsoil physical conditions. As expected, corn field-year success after deep tillage showed dramatic increases in success of production. Both bucket wheel excavator and scraper replaced subsoil appears to have sufficient data to draw such conclusions. Experience with deep tillage of bucket wheel excavator materials and corn productions is much less than on scraper placed materials, but similar positive results for corn were shown by Dunker, et.al.(3) Corn production on dragline replaced rooting media showed a modest increase in percentage of field-years passing after augmentation; however, data is limited. A review of the many fields which passed after deep tillage indicated a history of prior crop failures.

CONCLUSIONS

Approximately 200 field-years of each corn, hay and wheat have been tested for productivity of the 646 field years sampled to date in the state. Scraper replaced rooting media was the most commonly tested root media replacement method. Of the 646 field-years tested, 200 have received some sort of augmentation. Wheat was the most successful crop, (independent of replacement method and augmentation) followed by soybeans, corn and hay. Growing season may influence the success of wheat to date, and management problems likely have contributed to the poor success of hay. Scraper placed subsoils were the most commonly augmented materials. Over all crops and soil replacement methods, deep tillage appears to be having a positive effect on meeting targets; 70% of deep tilled field-years tested met target yields compared to 55% of non-augmented field-years. When looking at crops across root-media replacement methods, bucket wheel excavator material produced relatively consistent success ratios. Crops grown on the other replacement methods showed much more variable success. These results may be due to consistency of rooting materials, effects of weather, reactions of crops, limited number of sample points or interactions of any or all of the above. The low percentage of truck shovel wheat field-years meeting production requirements is in part related to crop disease. Augmentation had the most noticeable positive effects in bucket wheel excavator and scraper replaced materials, but limited number of bucket wheel field-years do not allow concrete conclusions. Dragline subsoils showed variable success and failure in augmented soils, but again sample numbers are small. This also holds true for soybeans grown on scraper replaced augmented soils which was less successful compared to non-augmented soils. Corn fields have definitely tended toward more success in augmented bucket wheel and scraper material, but bucket wheel subsoil is again inconclusive due to limited data. A review of individual fields reveals many of the fields which passed after deep tillage had repeatedly failed prior to the tillage. Over all, data appears very positive for deep tillage effects. Further evaluation is planned to assess the impact of yearly weather stress on individual treatments to refine the conclusions.

REFERENCES

1. Ill. Dept. Mines and Minerals. 1991. Permitting statistics. p.22. 1990 Annual Report.
2. Ill. Dept. Mines and Minerals. 1992. 62 Ill. Adm. Code 1816.116.
3. Dunker, R.E., I.J. Jansen and S.L. Vance. 1989. Corn response to deep tillage on surface-mined prime farmland. ASSMR-CLRA Symposium: Reclamation, A Global Perspective, Aug. 1989.

A Review of Procedures OSM Uses to Evaluate and Improve State Regulatory Programs Regarding Prime Farmland Reclamation of Mined Soils

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Abstract. Coal operators and regulatory agencies have the responsibility for insuring that prime farmlands are restored to their premining productivity. The coal operators must demonstrate in permit applications that they have the technological capability to mine and reclaim prime farmland. State regulatory authorities review and then approve these permit applications, if they determine that the applicant can satisfactorily mine and restore the land according to the approved state regulations. The Office of Surface Mining Reclamation and Enforcement periodically reviews permits as part of its oversight responsibilities for each state program. The purpose of the detailed permit approval process and the performance standards placed on the mine operator is to insure that prime farmlands keep their premining productive capability. The number one cause of productivity failures in prime farmland reclamation is excessive soil compaction. Mechanical loosening and incorporation of organic materials into the soil are traditional treatments for compaction.

INTRODUCTION

The Office of Surface Mining Reclamation and Enforcement (OSM) is required to evaluate state regulatory programs to determine their effectiveness. OSM Field Offices often request topic or issue-specific assistance from the Eastern Support Center (ESC) in Pittsburgh or the Western Support Center (WSC) in Denver to implement this responsibility. One topic which has been evaluated by ESC is prime farmland (PFL) reclamation in the states of Illinois, Indiana, Ohio, Pennsylvania, Kentucky, and Alabama. In addition to program oversight reviews, ESC has conducted special PFL studies in Ohio and Illinois. Special studies differ from evaluations by the extensive field testing and statistical evaluation which often occur in a special study.

Background

Public Law 95-87, the Surface Mining Reclamation and Enforcement Act of 1977 (SMCRA), requires the regulatory authority to find in writing that the operator has the technological capability to restore mined PFL. Restoration must occur within a reasonable time, productivity must meet or exceed the levels of yield from non-mined PFL in the surrounding area under equivalent levels of management, and the operator must meet the established soil reconstruction standards. Specifically, state regulations promulgated to comply with SMCRA require the operator to prove he can achieve this performance standard before a permit is issued (30 CFR Part 700, 1991).

OBJECTIVE

The overall objective of this paper is to describe OSM's procedures for evaluating how well state regulatory authorities comply with PFL restoration provisions of their approved programs. In addition, some methods for improving the chances for successful reclamation of PFL soils will be explored.

Evaluation Techniques

OSM uses a three-step approach to evaluate compliance with PFL reclamation requirements. An OSM permit reviewer compares the PFL restoration plan against the requirements of the approved state program. Minesite visits are made to see how well PFL restoration plans compare to actual field operations. Special field studies are undertaken to resolve issues identified in the permit or field reviews.

OSM Field Office Directors in Ohio and Illinois have requested such special studies from the ESC in Pittsburgh. Procedures used in the special studies were similar to those used in field review; but, with a specific objective. These special studies involved a complete review of all prime farmland permits issued during a specific period. A selected number of permits with restored PFL soils were then field sampled using a Giddings soil probe. The findings resulting from the evaluation process are either regulatory or technical in nature, and are discussed below.

In addition to measuring the effectiveness of state programs, existing regulations, and enforcement

procedures, OSM evaluates new technology which may help the state and the coal mining industry achieve these standards. OSM research and experimental practice programs endeavor to assess and publicize technology where there is a better or less expensive method of accomplishing successful restoration of PFL soil.

REGULATORY ISSUES

In Ohio, an OSM special study was conducted to determine whether operators were restoring PFL soils to proper thickness (OSM 1986). Several Ohio reclaimed sites were found to have thinner PFL soil than the standard thickness approved in the permit. There were two possible reasons for this shortage of material. Either the operator did not save enough PFL soil material for reclamation; or, there was never enough material on-site before mining to satisfy the PFL reclamation requirements. The latter possibility points to the need for obtaining site-specific information before mining. Published soil surveys are valuable tools for the agriculture industry; but, they are not entirely suitable for mine reclamation. If an operator bases reclamation plans on the published soil surveys, mining may reveal that insufficient PFL soil is present to reclaim to the permitted (or soil survey) thickness.

Several alternatives exist when an operator finds he has less soil than is required for reclamation. All of the alternatives are difficult and expensive. The worst case would involve re-affecting an area already reclaimed to bring the soil thickness to the required level. This would require locating a suitable borrow area on-site, or permitting a new area off-site to acquire the necessary soil for reclamation.

If the operator suspects there is not enough soil present before mining, there are ways to show that the soil is thinner in the disturbed area. The Soil Conservation Service (SCS) will work with the operator to resolve the issue. However, it is very difficult to determine after reclamation what the soil was like before mining.

Another possible solution is to obtain a variance from the thickness requirements. The spoil could be tested to see if it is suitable for use as a growth media to augment the PFL soil. If all efforts to restore the soil fail, the operator may be able to show (through yield data) that premining yields can be met on the restored PFL area. All of these techniques are risky, and there are no guarantees that any of them will work. Therefore, the operator should delineate actual PFL soil thickness before mining. The Ohio Department of Natural Resources has experience with these options, and had success with most of them; but, one site was so inadequate in PFL thickness that any solution short of total reconstruction was infeasible.

In Illinois, an OSM special study was conducted to determine whether the PFL rooting medium was in the textural and chemical range specified by the permit application (OSM, 1987). The Illinois Department of Mines and Minerals routinely approved subsoil substitute material as a growth medium for PFL permits. The department was approving these materials for final soil reclamation based on a specified range of chemical and physical characteristics listed in the permit application. During the OSM special study, a minimum of five composite soil samples were taken at each of six mine sites and sent to a laboratory for analysis. The results showed that all sampled materials were within the range of characteristics originally approved in the permit application. As a result of this study, OSM was able to affirm the Illinois regulatory practice as effective in meeting PFL reconstruction standards.

PFL reclamation techniques have improved steadily since the passage of SMCRA. Prime farmland issues that remain are the result of different interpretations of the regulations. For example, the Soil Conservation Service (SCS) is responsible for setting standards and specifications for mining and reclaiming PFL. The SCS establishes standards for the allowable soil depth to a root-inhibiting layer (such as bedrock). Disagreement, however, can and does occur about replacement depth—especially when the root-inhibiting layer is non-rock (such as fragipans). Some operators base their reclamation plan upon published soil survey data that identifies fragipans as root-inhibiting layers in the soil. However, the SCS has determined that all fragipans that supply more than 0.06inches per inch of available water are not root-inhibiting (7 CFR Part 655, 1985).

The SCS published national standards and specifications that define root-inhibiting fragipans based on their moisture-supplying capability. However, some problems exist because a court decision requires the SCS to publish state-specific standards in the Federal Register before requiring the state to use the standards. This requirement was intended to give all interested parties the opportunity for a public comment period. Unfortunately, it has also delayed instituting the new SCS standards. In order to have some guidelines until standards are published for a particular state, the SCS published a national standard. OSM recognizes the national standards and specifications published in the Federal Register as minimum standards that are more current than those found in the published county-by-county soil survey. Thus, OSM may find state programs less effective than federal requirements where states use published county soil surveys.

The coal industry and the states recognize the SCS as the responsible agency in the area of PFL reclamation. The SCS agrees with the compromise that the 48 inches

of rooting material required by the regulations is necessary to achieve PFL target crop yields on mined land. Bond release is problematic at mine sites with less than 48 inches of PFL material. Purely from an economic standpoint, it costs less to replace 29 inches of soil material over graded spoil than it does to replace 48 inches. However, this is only the initial cost, and does not account for any additional cost the operator may incur to meet productivity standards, legal costs associated with violations, and countless hours of staff time.

Generally, field evaluations show that operators are doing a good job of reclaiming PFL soils. However, diligent regulatory inspection of operations is vital in pointing out deficiencies that can be corrected before the operator completely reclaims the site. Despite differing interpretations, a good inspection program will go far towards successful PFL reclamation.

TECHNICAL ISSUES

Prime farmland restoration success is ultimately measured by crop yield. Operators are typically not farmers, and often do not want to grow crops. Therefore, mine operators want some method of predicting crop yields on restored PFL other than by actual crop production.

OSM has funded research to study reclaimed PFL yields in an attempt to develop a predictive tool. Three studies developed models for predicting crop yield based on soil characteristics. A University of Illinois study did not support the concept of predicting crop yield by soil characteristics alone (Jansen and Walker, 1985). Another study is still active at the University of Kentucky. Interim results reported by the principal investigator are encouraging. However, the selection of input variables for the model is critical (Barnhisel and Grove, 1992). Crop yield depends on so many variables being in balance.

This balancing phenomenon is known as equilibrium. All nutrients necessary for plant growth must be in solution before the plant can use them. Some nutrients will be attached to the soil particles and an equal amount will be in solution or dissolved in the soil water. Soil pH and the interrelationship of nutrients affect the availability of nutrients. For example, if nitrogen is in short supply and the plants need potassium, the operator can add potassium and plants will not produce maximum yields until he corrects the nitrogen deficiency. Drought and a host of other natural problems also affect crop yield. These are but a few of the reasons why variable selection for crop yield modeling is so difficult. Understandably, those are also some of the reasons operators do not want to grow crops. Depending on favorable weather for crop production in any particular year is a gamble for mine operators seeking bond release.

The second technical issue in restoring PFL yields is soil compaction. OSM studies of this issue involved several techniques for mitigating compaction. Two studies involved ripping the soil with deep tillage equipment and planting a deep-rooted legume (such as alfalfa) to hold the ripped zones open. Ohio State University had research data showing that alfalfa production increased within one foot on either side of the ripped zone. OSM funded a study where they moved the ripper spacing from four foot centers to two foot centers and planted alfalfa. However, it was extremely wet in Ohio for the three years of the study and the result may be more weather-related than treatment-dependent (McCoy, Barta, and Sutton, 1992). The other study by North Dakota State University involved ripping and deep-rooted plants . This project was affected by several years of drought. Results to date show that deep tillage following redistribution of both topsoil and subsoil, has been the most effective treatment in reducing compaction (Schroeder, 1992). Bulk density also decreased in the topsoil during the first three years following redistribution due to vegetative growth.

In another OSM study, organic material was pneumatically injected into the subsoil as it was deep-ripped to loosen the compacted soil (Saperstein, et al., 1992). While the study results only deal with laboratory data, OSM feels the concept of using organic material to alleviate soil compaction has merit. Organic matter is important because of the effect it has on soil consistency. It is the 'glue' that holds soil particles together, forming soil aggregates. Organic matter increases soil water-holding capacity and its decay leaves channels in the soil for the movement of air, water, and plant roots.

Injection technology is important for correcting existing soil compaction problems. Incorporation of organic material during reconstruction is probably more feasible/practical because the equipment needed for field scale injection of organic material is not available. The researchers were unable to find a manufacturer to develop a prototype field injection ripper. Although one of the injected materials showed some improvement in preventing re-compaction, the results were not statistically verifiable. However, research on non-PFL have shown significant increases in vegetative cover with the addition of organic material such as sewage sludge and wood chips. OSM believes this technology would also benefit PFL restoration.

Almost any organic material is suitable. In addition to the previously mentioned sewage sludge, other researchers have experimented with turning under cover crops into the subsoil before adding the topsoil. This

technique is called green manuring. However, known research involving this technique did not statistically prove that green manuring prevented soil compaction on mined lands.

The coal mining industry has also been investigating compaction remedies through mechanical loosening and different placement methods. Inspectors continually evaluate the success of new techniques during routine inspections of active operations. These techniques receive a critical review during OSM's field evaluation of state programs.

CONCLUSIONS

- The state regulatory authorities have rules in place that can insure successful reclamation of prime farmland.
- Coal mine operators must do a premining soil thickness examination, because some PFL soils are naturally thinner than 48 inches.
- Soil compaction is the number one cause of crop failures on restored PFL soils.
- The primary method used by coal operators to loosen compacted soil is deep-ripping.
- The technology exists to restore PFL soils to their premining productivity.
- Some techniques developed by coal operators in PFL restoration and by federally-funded research are improving reclamation.
- Sewage sludge and other organic additives used on non-PFL mine sites have resulted in a significant improvement in vegetative success.

RECOMMENDATIONS

- The use of organic amendments to combat PFL compaction should be considered.
- A cover crop should be grown on the protected PFL subsoil before restoration to add organic matter. Turning under this cover into the subsoil prior to PFL replacement would promote decay and provide channels for the movement of air, water, and roots in the restored soil.
- Additional study of organic material incorporated into both topsoil and subsoil is needed on reclaimed PFL.

LITERATURE CITED

1. Barnhisel, R. I. and J. H. Grove. In progress Schedule Completion 1993. Use of Productivity Indices to Estimate the Yield Potential of Disturbed Soils. University of Kentucky. OSM Cooperative Agreement No. GR996211.
2. Jansen, I. J. and W. M. Walker. 1985. Soil Survey VS. Crop Production as a Measure of Soil Productivity. Soil Characteristics as Predictors of Corn and Soybean Yields, NCSS Data Base.
3. McCoy, E. L., A. L. Barta, and P. Sutton. 1992. Maintenance of Compaction Alleviation in Mineland Soils. Ohio State University. OSM Cooperative Agreement No. GR896391.
4. Public Law 95-87 [H.R.2] August 3, 1977. The Surface Mining Control and Reclamation Act of 1977.
5. Saperstein, L. W., R. J. Swiegard, L. G. Wells, R. I. Barnhisel, and D. L. Simpson. 1992. Techniques to Reduce Soil Compaction in Reclaimed Soils. University of Kentucky. OSM Cooperative Agreement No. GR896211.
6. Schroeder, Stephen. 1992. Relation of Compaction/ Soil Physical Parameters to Productivity of Reclaimed Soils. North Dakota State University. OSM Cooperative Agreement No. CT896381.
7. U. S. Code of Federal Regulations. 1990. Title 30: Mineral Resources.
8. U. S. Federal Register. 1985. 7 CFR Part 655. Soil Conservation Service. General National Guidelines. Page 34491.
9. U. S. Office of Surface Mining Reclamation and Enforcement. 1986. An Evaluation of Prime Farmland Soil Restoration in Ohio. Inservice Report.
10. U. S. Office of Surface Mining Reclamation and Enforcement. 1987. Illinois Prime Farmland Soil Restoration Study. Inservice Report.

Assessment of Reclaimed Farmland Disturbed by Surface Mining in Illinois

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Abstract. Illinois procedures for the assessment of reclaimed farmland disturbed by surface mining and reclaimed under various statutes are discussed. The current interim assessment approach maintains the productivity index (PI) of a tract of land at either 90% or 100% of the PI of the soils on the original tract prior to disturbance by surface mining and reclamation. The recommended long-term approach will establish a new tract PI based on the actual soil series present after disturbance by surface mining and all reclamation and productivity restoring treatments have been applied. Before the recommended approach can be implemented, the following tasks will need to be completed: (1) the USDA, Soil Conservation Service in cooperation with the Illinois Agricultural Experiment Station will need to establish additional soil series on surface mined soils with or without reclamation and/or compaction alleviating treatments; (2) a soil scientist should be assigned to re-survey a reclaimed area after all reclamation and productivity restoring treatments have been completed and final bond release has occurred; and (3) crop yields and PI's are assigned by the Illinois Agricultural Experiment Station after an evaluation of the soil properties and plot yield data collected from University of Illinois research plots and by the Illinois Department of Agriculture, Bureau of Farmland Protection and in cooperation with the Illinois Department of Mines and Minerals.

INTRODUCTION

Illinois soils have been disturbed by surface mining for over 100 years. Various techniques for strip mining coal were developed in the last century, and these extraction methods have steadily gained importance. Much of the land surface mined in Illinois prior to 1962 was not reclaimed. The utility of the land was sometimes completely destroyed by surface mining with improper or no reclamation. Since surface mining, reclamation methods, and compaction alleviation treatments vary among companies, locations, and even over time; it has been difficult to develop sufficient soil series to reflect all of these differences.

In the last few years, landowners and other interested parties have suggested that surface mining and reclamation will result in the loss of local tax revenues. In western Illinois, the soils on many tracts have high productivity indexes (PI's); however, after surface mining and reclamation, the tracts in a few counties are shown as soil series mapped on disturbed lands with lower PI's. If county tax assessors were to assign value based on these lower productivity indexes from Circular 1156 (Productivity of Illinois Soils) by Fehrenbacher et al., (1978) as amended by Jansen (1987), the tax revenues collected from the tract would decline. The Illinois Coal Association (personal communication), as well as individual mining companies, believe the assigned PI's of some recently surface mined and reclaimed soils are too low and do not reflect the current reclamation technology in restoring soil productivity. Specifically, the recent compaction reducing treatments have been found to increase total and aeration porosity, increase rooting depth, increase soil water storage and raise crop yields[1/] (McSweeney and Jansen, 1984; Jansen and Hooks, 1988; Hooks et al., 1988). Data collected in the last few years by the Illinois Department of Agriculture, Bureau of Farmland Protection in cooperation with the Illinois Department of Mines and Minerals for bond release under provisions of the 1977 Surface Mining Control and Reclamation Act (SMCRA) law (Public Law 95-87) shows higher crop yields for areas with compaction reducing treatments. If these reclaimed surface mined lands are under-assessed, the public will perceive that reclamation was not successful even when soil productivity was sufficiently restored to meet the 1977 SMCRA law and 1981 Illinois Public Act 81-1015 standards. In Knox County (Illinois), a request for a surface mining permit was challenged by landown-

[1/] I.J. Jansen and R.E. Dunker. 1989. Reclamation for row crop production after surface mining, state of the art. Staff Paper. Department of Agronomy, University of Illinois.

ers at a public meeting held by the Illinois Department of Mines and Minerals (personal communication). One of the reasons cited for requesting that the permit not be issued indicated that reclaimed surface mined land would have lower PI's than the original soils and result in lost tax revenue for the county. In a number of western Illinois counties this has become an important public issue.

This paper outlines current interim approach and the recommended[2/] long term assessment procedures for reclaimed surface mined land in Illinois based on their current productivity.

ASSESSMENT APPROACH - SURFACE MINED LANDS (PRIOR TO 1977)

Lands which were surface mined prior to the 1977 SMCRA law may or may not have been reclaimed. Some areas may have been graded with some topsoil or subsoil material returned. Five soil series (Lenzburg (IL), Schuline (IL), Swanwick (IL), Morristown (KY), and Rapatee(IL)) were set up in the early 1980's and used for mapping surface mined areas. In many counties soil surveys preceded mining events. Rapatee and Schuyline have topsoil (A horizon or darkened surface horizon replacement) and Morristown, Swanwick and Lenzburg do not. The first cropland reclamation standard used in Illinois was Rule 1104 (Surface Mine Land Conservation and Reclamation Act of 1971) (applied in 1971) established a 48 in. rooting medium standard over graded spoil. The top 2 ft. of rooting material could have no more than 20% coarse fragments and no rocks greater than 6 in. in the longest dimension. The clay content could not exceed 40% or not greater than the original soil. Maximum sand content could not exceed 60% if the clay was less than 20%. The underlying 2 ft. could contain no more than 50% coarse fragments and no coarse fragments (rocks) greater than 10 inches. Rule 1104 (Surface Mine Land Conservation and Reclamation Act of 1971 as amended by P.A. 78-1295 effective July 1, 1975) to require that topsoil must be replaced to a depth of 8 in. for HCL and 6 in. for prime or to the depth of original A horizon to a maximum requirement of 18 in. The rooting media must be replaced to a depth of 48 in. or to the depth of original soil if less than 48 in. and must have less than 40% clay, unless original soil had more than 40% clay, and no coarse fragments (rocks) greater than 10 in. This standard existed when the Rapatee and Schuyline soil series were set up. If the soil survey was done before mining and/or reclamation, the productivity indexes (PI's) from Circular 1156 (Fehrenbacher et al., 1978) would be based on the soils present at the time of the soil survey. A re-mapping of these surface mined areas to Illinois Cooperative Soil Survey standards is needed before tract PI can be determined.

On average, county soil surveys are conducted every 30 to 35 years. The only counties which might have surface mined lands which were soil surveyed before surface mining and not reclaimed under the 1977 Reclamation Law would have been published in the late 1950's to 1970's. These areas were small in extent and limited to just a few counties. Most of the early surface mined areas were soil surveyed after mining. The surface mined areas within a county soil survey made after surface mining and/or reclamation activity have been assigned soil series names (County Soil Survey Report) and productivity indexes using Circular 1156 (Fehrenbacher et al., 1978) as amended by Jansen (1987) of the Department of Agronomy (University of Illinois) based on soil properties and limited yield data. These productivity index ratings are used by assessors to determine the agricultural land value and tax assessment.

ASSESSMENT APPROACH - SURFACE MINED LANDS (1977 TO PRESENT)

Assessment of all Illinois cropland is accomplished by local assessors using Illinois Real Property Appraisal Manual (Illinois Department of Revenues, 1988) and periodically updated. The current assessment procedure was authorized by Illinois Public Acts 82-0121 and 84-1275.

At the present time, soils which were mined under provisions of the 1977 Federal Reclamation Law (SMCRA) (Public law 95-87) and Illinois Public Act 81-1015 have been subject to specific standards for topsoil and subsoil replacement for high capability land (HCL) (90% level if grandfathered on or before August 1, 1982 or 100% after that date of original productivity level) and prime farmland restoration (100% level of original productivity level). The reclamation standard for both prime and high capability lands require a minimum of 48 inches of topsoil and rooting material. The primary difference between prime and high capability lands is the replacement requirements from the original soils for prime farmland. A mix of subsoil and substratum may be approved if equivalent to the original B horizon. High capability land has an automatic soil mix approval. Mining operations are under stringent standards for grading, vegetation, etc. The mine operator is under a 5-year liability for meeting reclamation requirements of SMCRA law and 10-year window

[2/]Recommendations do not necessarily represent the official positions of members of the Illinois Cooperative Soil Survey or the Illinois Department of Revenues.

for productivity. However, window may shift if second crop does not meet productivity requirements within 10 years. The 5-year liability for reclamation starts over if land is augmented, i.e., deep tillage greater than 18 inches. During this time he must achieve all reclamation standards including productivity. The productivity of the soils which previously existed are used as the basis for determining the productivity index (PI) from Circular 1156 (Fehrenbacher et al., 1978) for the surface mined lands. The soil survey could have been made before, during, or after the surface mining and reclamation process. The soil maps reflect the soils or materials present at the time of mapping. Soils constructed in surface mined and reclaimed areas differ from the original soils since soil materials are not put back on a tract in the same location and the soil horizons are often mixed. Disturbance disrupts original structural units creating a soil unlike the original. The land value for tax assessment purposes currently remains based on the productivity indexes from Circular 1156 (Fehrenbacher et al., 1978) of the original soils (prior to surface mining) until the soils are remapped. Bond release, however, can be requested after the productivity of the reclaimed soils meet the weather adjusted target goal assigned by the Department of Mines and Minerals and in cooperation with the Bureau of Farmland Protection (Illinois Department of Agriculture). The mining companies are required to meet this weather adjusted goal for 3-crop years (Prime), 2-crop years (High Capability) within a 10-year window after mining. The weather adjustment (Lohse et al., 1985) is made by dividing the county crop yield for the current year by the average annual crop yield for the county determined by multiplying the total acreage of all cropland soils by the long term average crop yield from Circular 1156 (Fehrenbacher et al., 1978). Since 1984, surface subsoiling to a 30 to 52 inch depth has been used by some coal mining companies to alleviate compaction problems, increase rooting depth, increase water storage capacity and raise crop yields. Productivity measurements must be initiated within 10 years after mining; however, the window may shift productivity testing to beyond 10 years (Lohse and Brakken 1987). Once the target goal has been reached for three years for Prime or 2-crop years with High Capability within a 10-year window, the mining companies can request phase II bond release. Phase III bond release occurs when all reclamation is completed, the land is stabilized, and sediment ponds have been removed (62 IL Admin. Code Section 1800.40). However, the land value and taxes would still be based on either 90% or 100% (HCL) or 100% (prime farm land) of the tract PI based on the soil's productivity. This is a current interim approach which helps to: (1) maintain the tax base within the county by assigning the PI of the land at either 90% or 100% of the original tract PI, and (2) accepts the premise that surface mined soils reclaimed under provisions of the 1977 Reclamation Law and Illinois Public Act 81-1015 are being restored to 90% or 100% after July 31, 1982 (62 Il Admin Code Section 1785.17a and 1816.111d) of the original tract PI for HCL and to 100% for the prime farmlands.

The recommended long term approach to assigning PI's to surface mined lands reclaimed under provisions of the 1977 SMCRA law will require the completion of the following tasks:

(1) The USDA, Soil Conservation Service in cooperation with the Illinois Agricultural Experiment Station will assess the need for additional soil series (5 soil series currently mapped in Illinois on surface mined soils with or without reclamation and/or deep tillage). Any new soil series should be established using diagnostic surface and subsurface horizons criteria to classify soils using Soil Taxonomy (Soil Survey Staff, 1975). These new soil series should reflect current topsoil and subsoil thicknesses as well as soil properties altered by subsoiling treatments. Soil series should be sampled for soil characterization. Both field and laboratory data is required.

(2) A soil scientist (Illinois Cooperative Soil Survey) should be assigned to re-survey a reclaimed area at or soon after the time of final bond release using the existing (5 soil series) and any new soil series established by the USDA, Soil Conservation Service such as seven new series currently being considered[3/].

(3) The crop yields and PI's would be assigned by the Illinois Agricultural Experiment Station (Department of Agronomy) after an evaluation of the soil properties (measured in field and laboratory), a review of University of Illinois research plot yields, and an evaluation of certified yield data which has been collected by the Illinois Department of Agriculture, Bureau of Farmland Protection and in cooperation with the Illinois Department of Mines and Minerals.

DISCUSSION

It is quite possible that the PI of a parcel of land reclaimed under provisions of the 1977 SMCRA law and 1981 Illinois Public Act could be lower than either 90% or 100% (HCL) or 100% (prime farmland) of the PI of the original soils on a tract. A likely reason relates

[3/]R.G. Darmody and R.E. Dunker. Classification and mapping of reclaimed mine soils, Fourth Annual Report. 1991. Prime Farmland Reclamation after surface mining, Department of Agronomy, University of Illinois, February, 1991.

to differences in the methods and procedures used to determine long term crop yields. The 1977 SMCRA law and 1981 Illinois Public Act only requires 3 years of crop yields (within a 10-year time period) to meet the 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.

Even assuming that the few years of crop and tillage treatments are applied to a reclaimed site prior to the collection of yield data, it has not been established that compaction alleviating treatments applied during the reclamation process will continue to provide lasting effects (such as increased macroposity) for 10 years or more after treatment. Only a limited data base currently exists which would address this concern since the compaction alleviating treatments have only been applied since 1982. Compaction alleviation was applied to Amax-Sunspot Ipava Fields in 1982. Nine years of crop growth are available for this mine, although not 9 years of each crop were compared to a standard. The late Dr. Ivan Jansen (1982) believed that once compaction alleviating treatments have been applied and roots have established themselves in the voids (pores and channels) of the previously compacted layers, that the roots would maintain the pore network over time. This will need to be verified with soil property measurements and actual yield data collected years after the compaction alleviating treatments are applied. The PI's, assigned to the soil series mapped on surface mined, reclaimed and treated with deep tillage tract, should predict the average yields future land owners could expect over the next 10- or 20- year period. If PI's are set too high, future landowners will not be able to pay the tax from agricultural use of the reclaimed farmland.

Utilizing this long term approach to assigning PI's to reclaimed surface mined lands, based on soil conditions as they exist, would be consistent with the method utilized on soils not disturbed by surface mining and reclamation. This approach will require a significant amount of time to establish new soil series, sample for soil characterization (laboratory and field), re-map, collect crop yield data, and calculate PI's for the new soil series assigned to the reclaimed surface mined lands with compaction alleviating treatments.

CITED LITERATURE

Fehrenbacher, J.B., R.A. Pope, I.J. Jansen, J.D. Alexander and B.W. Ray. Soil productivity in Illinois. Circular 1156. Cooperative Extension Service, College of Agriculture, University of Illinois, Urbana, IL 61801.

Hooks, C.L., I.J. Jansen, and R.W. Holloway. 1988. Deep tillage effects on mine soils and row crop yields. Proceedings of 1987 National Symposium on Mining, Sedimentology, and Reclamation, University of Kentucky, Lexington, Kentucky, December 7-11, 1987. pp. 179-182.

Illinois Department of Revenue. 1988. Illinois Real Property Appraisal Manual. Springfield, IL. with updates and revisions.

Illinois Public Act. 81-1015. The Surface Mining Land Conservation and Reclamation Act. 81st Illinois General Assembly. June 1, 1980.

Illinois Public Act. 82-0121. Farmland Assessments. 82nd Illinois General Assembly.

Illinois Public Act. 84-1275. Farmland Assessments. 84th Illinois General Assembly.

Jansen, I.J. 1982. A pedologist's perspective on reclamation, Proceedings of Illinois Mining Institute, Oct. 7-8, Springfield, IL pp. 59-65.

Jansen, I.J. 1987. Productivity of Illinois Soils. Update of Table 2 to Circular 1156. University of Illinois at Urbana-Champaign.

Jansen, I.J. and C.L. Hooks. 1988. Excellent agricultural soils after surface mining. Proceedings of Surface Mine Engineering meeting in Denver, CO, February 1987.

Lohse, J.S. and K.T. Brakken. 1987. Implementation of the Illinois Agricultural land productivity formula and other state programs. Proceedings of National Meeting of the American Society for Surface Mining and Reclamation. March 17-19, 1987. Billings, MT. pp. K-1-1 to K-1-7.

Lohse, J.S., P. Giordano, M.C. Williams and F.A. Vogel. 1985. Illinois agricultural land productivity formula. Proceedings of the American Society for Surface Mining and Reclamation, Denver, Colorado. pp. 24-39 with 1987 Addendum to Illinois agricultural land productivity.

McSweeney, K., and I.J. Jansen. 1984. Soil structure and associated rooting in minespoils. Soil Sci. Soc. Am. J. 48:607-612.

Public Law 95-87. Surface Mining Control and Reclamation Act of 1977. 95th U.S. Congress. August 3, 1977.

Soil Survey Staff. 1975. Soil Taxonomy, a basic system of soil classification for making and interpreting soil surveys. USDA, Soil Conservation Service Handbook No. 436. U.S. Gov't Printing Office. Washington, D.C.

Development of a Prime Farmland Minesoil in Selectively Cast Overburden in Northeast Texas

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Abstract. Premine overburden characterization through the use of gridded geophysical logs and analytical data from continuous cores was used to compare overburden characteristics to those of native soils at the Winfield surface lignite mine in northeast Texas. Based on the results, regulatory authorities waived replacement of the original soil horizons in favor of selected overburden materials. A postmine soil mapping program suggested that the Grayrock series, the dominant minesoil developing in these materials, qualified as a prime farmland soil. Several years of yield data supported this observation, and Grayrock soils occurring on 1 to 5 percent slopes were declared prime farmland by the U.S. Soil Conservation Service in 1991. These soils comprised 65.9 percent of the mined area, compared to 38.8 percent prime farmland soils within the permit area prior to disturbance. The study suggests that substitution of selected overburden may be a valid choice, particularly in areas where native soils have low to moderate productivity. Postmine soil mapping is recommended as a tool to assist in achieving goals of reclamation planning. A mapping program can also assist in determining the characteristics of postmine soils compared to those of native soils within a given mine permit area.

INTRODUCTION

Regulatory concern for prime farmland in surface coal mining operations rests primarily with recognizing the presence of native prime farmland soils and special requirements for permitting them. A premine soils map and historical land use study is required to identify and locate prime farmland soils and determine their use prior to mining. Mining and restoration requirements for prime farmland call for the separate removal, stockpiling, if necessary, and sequential replacement of the A and B or C horizons. Regulatory authorities in most states may approve substitute materials within the top 4 feet of graded spoil on prime farmland areas, provided this material will create a soil having as good or greater productive capacity than the native soils.

The requirement for a premine soils map has additional benefits in that it provides, prior to disturbance, a permanent record of all soils, including those that qualify as prime farmland. These maps give witness to soil resource conditions before disturbance for mining and serve as a reference base for postmine soils. Development of postmine soil mapping programs is optional for the mining industry. However, few companies choose to initiate such programs. An important benefit of postmine soil mapping in reclamation planning is to provide the location and extent of prime farmland soils after mining. Postmine soil mapping provides a valid procedure for comparing premine and postmine soil quality and, where applicable, can serve as a guide for tax assessment. In addition, a formal postmine soil mapping program recognizes the potential of proper overburden handling procedures for developing prime farmland soils in excess of what was present before mining, particularly where the production potential of native soils is limited. A case in point is the postmine Grayrock soils on the Winfield Mine in northeast Texas. This lignite surface mine, operated by the Texas Utilities Mining Company, is located near Mt. Pleasant, Texas on Interstate 30, about 120 miles northeast of Dallas. Both premine and postmine land uses are dominantly forage crops used for pasture and hay.

NATIVE SOILS AT THE WINFIELD MINE

Thirteen soil map units existed on the Winfield Mine area prior to disturbance. Of these, five dominant soils (Table 1, Part A) comprised 89.4 percent of the area. The remainder of the area consisted of water, borrow pits and eight map units of widely diverse, minor soils.

The Bernaldo (fine-loamy, siliceous, thermic Glossic Paleudalfs) and Freestone (fine-loamy, siliceous, thermic Glossaquic Paleudalfs) soils, which com-

prised 38.8 percent of the mine area (Table 1), have been designated prime farmland soils as defined by the U.S. Soil Conservation Service in Section 657.5 of the Code of Federal Regulations, dated January 1, 1980. These are very deep, well drained and moderately well drained soils on uplands. Both have a fine sandy loam surface ranging from 8 to 20 inches thick and a loam or clay loam argillic horizon. They are developing in cross-bedded sands, silts and clays from the Wilcox group of Eocene age. Typically, the Freestone soils have a more clayey layer in the lower part of the argillic horizon that moderately restricts internal drainage. Reaction in both soils ranges from strongly acid to slightly acid in the surface and upper subsoil, and very strongly acid to medium acid in the lower subsoil. Although they respond to soil amendments, these soils are not particularly productive.

Nahatche soils (fine-loamy, siliceous, nonacid, thermic Aeric Fluvaquents) in Table 1 consist of very deep, somewhat poorly drained soils on floodplains. They are moderately permeable, and are developing in loamy alluvial sediments of local streams. Strata in both surface and subsurface layers range from silty clay loam to loam. Reaction throughout is typically strongly acid to mildly alkaline, although very strongly acid layers exist in some pedons. Frequent flooding is the main deterrent to crop production.

Table 1. Dominat soils at the Winfield Mine.

SOIL SERIES	% OF AREA
A. PREMINE	
Bernaldo	2.4
Freestone	36.4
Nahatchie	9.5
Wolfpen	6.8
Woodtell	34.3
TOTAL	89.4
B. POSTMINE	
GRAYROCK:	
1-5% Slopes	65.9
>5% Slopes	13.9
TOTAL	79.8

The Wolfpen series (loamy, siliceous, thermic Arenic Paleudalfs) consists of very deep, well drained soils on uplands. The surface layer (A and E horizons) is loamy fine sand ranging from 20 to 40 inches thick that rests on an argillic horizon ranging in texture from loam to sandy clay loam. Reaction throughout ranges from very strongly acid to slightly acid. Parent materials are sandy members of the Wilcox group. The thick, coarse-textured surface is the main limitation to plant yields.

The Woodtell series (fine, montmorillonitic, thermic Vertic Hapludalfs) consists of deep, moderately well drained soils on uplands. These soils have very strongly acid to slightly acid fine sandy loam surface layers 3 to 6 inches thick. These rest abruptly on a very strongly acid to strongly acid clay or silty clay (claypan) argillic horizon. The soils are developing in clayey members of the Wilcox Group. The claypan limits productivity by restricting movement of air, water and roots within the soil.

Table 2 presents data for selected parameters on native and postmine soils at the Winfield mine. These are from the upper part of the argillic horizon (or C Horizon in Grayrock and Nahatche soils). The upland native soils are deeply weathered, as evidenced by thick, well-expressed argillic horizons, described earlier, and the acid nature of the profile. The Nahatche soils, developing in local floodplain sediments, reflect physical and chemical properties of upland soils within the area.

OVERBURDEN HANDLING

During permitting stages at the Winfield mine, topsoil salvage (A horizons) was waived by the regulatory authority in favor of more suitable substitute materials. Recent land use history on the Bernaldo and Freestone series (prime farmland soils by SCS definitions) did not meet prime farmland requirements of historical use as defined in Part 779.138 of the Texas Coal Mining Regulations. Because of this, the permit did not require removal and replacement of individual (A, B and, in places, C) soil horizons on these areas.

Table 2. Selected data from soils at the Winfield Mine*.

SOIL	HORIZON	pH	B.S %	CEC me/100g	SAND %	SILT %	CLAY %	Db g/cc
Freestone	Bt	5.7	79	9.1	39	34	27	1.52
Nahatche	C	4.6	—	13.4	31	37	32	—
Wolfpen	Bt	5.1	—	—	68	12	20	—
Woodtell	Bt	4.6	31	28.4	17	26	57	1.28
Grayrock**	C	7.1	86	33.4	30	42	28	1.40

* Data for native soils are from Soil Resources Report of Mine Permit Area; for minesoils, Cooney et al., 1991.
** Minesoil; remainder are native soils. A dash indicates data are not available.

Accordingly, postmine soils at the mine are developing in a selective overburden material at least 4 feet thick.

Selection of overburden materials for placement in the surface 4-feet of graded spoil was guided by premine studies of geological and geochemical data. Stratigraphic units were correlated and characterized through the use of gridded geophysical logs and analytical data from continuous cores. These units are defined[1] as strata within the overburden that have a distinctive textural composition, a reasonably consistent and predictable stratigraphic relationship with minable lignite seams in the Mine Permit Area, a recognizable geophysical log signature, and a mappable thickness and geographical extent. Weighted averages for significant chemical and physical parameters were calculated for each stratigraphic unit. The location of each stratigraphic unit was plotted along pit centerline cross sections during premine planning. Each unit was evaluated against Texas regulatory guidelines to determine its suitability for use as postmine soil material. These guidelines prohibit use of acid-forming or toxic-forming materials, and place limits on sand and clay content. Table 3, an example of a few of the many parameters evaluated, shows that Unit L2P is discarded due to the negative acid-base accounting value (Smith and Sobek, 1978). This unit, a minor component of the Wilcox Group, consists of partings within a mineable lignite seam. Unit OBU in Table 3, also of the Wilcox Group and a major component of the overburden, consists of reduced, thinly laminated materials that have a higher average silt content and less weathering than the oxidized materials of the native soils. Unit OBU meets requirements for substitute material. Using these procedures for all stratigraphic units within the Permit Area, mining operators are able to selectively handle the most suitable materials for postmine use. Placement of materials is normally performed during dragline operations without earth-handling vehicles, which keeps compaction to a minimum (Holland and Phelps, 1986).

Table 3. Example of overburden evaluation for postmine soil use.

		MEAN VALUES			
STRAT -UNIT	pH	ABA* t/kt	SAND %	CLAY %	SUIT-ABLE
L2P	5.3	-10	13	33	NO:ABA
OBU	7.3	5	21	28	YES

* ABA = Acid-base account in tons $CaCO_3$ /1000 tons of material (Smith and Sobek, 1978).

[1] Personal communication, Jan Sloan, Geologist, Hall Southwest Corporation, Austin, Texas.

POSTMINE SOILS

As mining proceeded at Winfield, a detailed soil survey program was initiated (DeMent & Associates, 1985), first to aid in reclamation planning, and second to determine the kinds of postmine soils being developed. The expansion of this program shows (Table 1, Part B) that, through 1991, the Grayrock series, (fine-silty, mixed, nonacid, thermic Typic Udorthents) established by the SCS in 1984, occupies almost 80 percent of the postmine area (Cooney, et al., 1991). These are very deep, well drained, moderately permeable soils that are forming in reduced overburden materials similar to that characterized by Unit OBU in Table 3. The reduced materials have low value and chroma compared to the oxidized red and yellow colors of native soils. Textures throughout the soil are typically silt loam, clay loam or silty clay loam, with considerably higher silt content than commonly found in native soils of the area. The silts contain considerable amounts of mica. Reaction throughout is near neutral, ranging from medium acid to mildly alkaline. Under forage crops, A horizons with weak to moderate structure in the surface 5 to 7 inches were noted within as little as five years after vegetative reestablishment. Others (Daniels and Amos, 1981) have noted the development of A and Cambic B horizons in Virginia minesoils within relatively short periods of time.

Estimated yield comparisons for Coastal bermudagrass (Cynadon Dactylon [L] Pers.), a major forage crop in the area, and winter wheat (Tritycum aestivum L) are presented in Table 4 for the postmine Grayrock soils and principal native soils within the area. Native soil yield estimates were made by the Soil Conservation Service (SCS) for high levels of management within the area, and are based mainly on the experience and records of farmers, conservationists and extension agents (Soil Conservation Service, 1990). These can vary for

Table 4. Premine - postmine estimated yield comparisons*.

	YIELDS	
SOIL	C. BERM.	WHEAT
	(tons/ac)	(bu/ac)
Bernaldo	7	—
Freestone	6	35
Nahatche	5	—
Wolfpen	5	—
Woodtell	5	35
Grayrock**	8	39

* Rounded to nearest whole number. A dash means not commonly grown. See text for source of estimates.

** Minesoil; Remainder are native soils.

a given year depending on weather, management practices, and the presence or absence of disease and insects. Coastal bermudagrass yields for the postmine Grayrock soils were taken from clipping averages over a period of years in compliance with regulatory reporting programs. Estimated wheat yields were summarized in 1989 by the SCS[2] following three years of study on a 10-acre plot of Grayrock silty clay loam, 1 to 5 percent slopes. Management on the study area conformed to normal farming practices within the area. Due to variances in weather and damage from migratory geese, annual yields ranged from 29 to 59 bushels per acre. The estimated wheat production shown in Table 4 is an average of the 3-year study. In addition to the above, alfalfa (Medicago sativa L) established on a 5-acre plot in 1989 continued to maintain a healthy stand through 1991, in an area where native soils are not adapted to alfalfa production. None of these studies have received statistically valid testing but support conclusions by the SCS that the yield potential of the mined soil is equal to or greater than that of native soils in the area.

Following a review of chemical and physical data and the above yield studies, Grayrock soils on 1 to 5 percent slopes (Table 1, Part B) were declared prime farmland by the SCS in March 1991. These postmine soils, the first to be recognized as prime farmland in Texas, presently occupy 65.9 percent of the disturbed area, compared to 38.8 percent prime farmland soils in the mine permit area prior to disturbance.

SUMMARY

Historically, the consensus among many was that surface coal mining usually had an adverse impact on soil quality. This may have stemmed, in part, from lack of planning during the pre-regulatory period, in which acid-forming, toxic-forming and other undesirable materials were allowed in near-surface layers of graded spoil. In remediation, current regulations might, in places, be too literally applied, especially for the removal and replacement of native soil horizons on prime farmland. Substitute material may be allowed under certain conditions, but few studies demonstrate the conditions under which this is a viable option. Smith and Sobek (1978) postulate that where the original surface layers are deep, soft, dark and neutral (Mollic), as in central Illinois, there is maximum incentive for replacement of surface and near-surface materials. In northeastern Texas, however, this incentive is minimal in the presence of Wolfpen soils (thick, droughty, infertile surfaces) or Woodtell soils (claypan subsoil), particularly where more suitable materials are present within the overburden. Removal and replacement of native soil horizons with such limited productive capacity could severely limit the potential for developing postmine prime farmland. Indeed, most of the postmine 27.1 percent increase in prime farmland soils over premine extent at the Winfield mine is due to substitution of materials more suitable than native soil horizons within the Wolfpen and Woodtell series.

Premine data collection is essential to a successful reclamation program. Planning and permitting stages of mine development should carefully consider viable alternatives for overburden handling and, where justified, allow alternatives. Some alternatives, as in the case of the Grayrock series on selected overburden, not only improve soil quality for crops common to the area, but may also open the way for new cropping systems. In addition to alfalfa, Grayrock soils should also be productive for corn (Zea mays L), grain sorghum (Sorghum bicolor [L] Moench) and soybeans (Glycine max [L] Merr), crops that are not particularly adapted to native soils in the area.

In summary, the Grayrock soils have demonstrated that, where quality overburden conditions exist, careful placement of overburden materials can provide reclaimed areas superior to native soils for crop production. Along with others (Smith and Sobek, 1978), we agree with the principle stated by Borlaug (1976) that "nature's way isn't always good enough". Many soils in the United States have limiting features that can be overcome as a consequence of drastic procedures such as properly planned surface coal mining and reclamation.

Finally, reclamation managers should consider providing for a postmine soil mapping program in their operational planning. Postmine soil maps are extremely useful for reclamation and research planning; they also provide the best means for comparing premine and postmine quality. Without such a program, reclamation personnel at the Winfield mine might never have realized the extent of prime farmland soils being developed through mining and reclamation operations.

REFERENCES

Borlaug, N. 1976. Nature's way isn't good enough. Am. For. 82:20-21, 58-63.

Cooney, S. T., J. Denman, and J. A. DeMent. 1991. Computer modeling of post-mine soil maps on an east Texas lignite mining operation. P.309, Agron. Abstracts, 1991 Ann. Meet. Am. Soc. Agron., Manuscript in prep.

Daniels, W. L., and D. F. Amos. 1981. Mapping, char-

[2] Appreciation is expressed to Norman Bade, Resource Agronomist, SCS, Temple, Texas, for participating in this study.

acterization and genesis of mine soils on a reclamation research area in Wise County, Virginia. Paper in 1981 Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation (Lexington, Ky, Dec. 7-11, 1981). Univ. Ky, Lexington, pp. 261-266.

DeMent & Associates, Inc. July 1985. Classification and mapping of soils on 1979 and 1981 extended responsibility areas at the Monticello (Winfield North) mine. Texas Utilities Mining Company, P. O. Box 800, Fairfield, Tex. 75840.

Holland, L. J. and L. B. Phelps. Topsoil compaction during reclamation field studies. In Proceedings 1986 Symposium on Mining, Hydrology, Sedimentology and Reclamation (Lexington, KY, Dec. 8-11, 1986). Univ. KY, Lexington, 1986, pp. 55-62.

Smith, R. M. and A. A. Sobek. 1978. Physical and chemical properties of overburdens, spoils, wastes and new soils. Ch. 9, Reclamation of Drastically Disturbed Lands. American Society of Agronomy, Madison, Wisc.

Soil Conservation Service. 1990. Soil survey of Camp, Franklin, Morris, and Titus Counties, Texas. U. S. Gov. Print. Office, Washington, D.C.

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The Development of Restoration Strategies for Prime Farmlands Disturbed by Mineral Sands Mining in the Coastal Plain of The Eastern USA

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Abstract. A large area of the Virginia and North Carolina Coastal Plain has been proposed for mineral sands mining. Much of the area to be mined is productive farmland, and technologies for return to row-cropping after mineral sands mining have not been developed to date. The natural soils of the area are Hapludults and Paleudults with deep sandy loam surface horizons over acidic clayey subsoils. The inherent productivity of these soils is highly dependent on subsoil water retention since summer droughts are common. Simulated tailings and slimes produced from this area appear to be quite suitable for plant growth assuming that they can be blended back together after mining and re-contoured appropriately. The reconstruction of a clay enriched subsoil will be important to long term productivity, and it may also be possible to generate productive topsoil substitutes from re-blended materials. Investigations into mine soils forming in mineral sands tailings in Florida revealed moderate to high levels of subsoil compaction. Mine soil genesis appeared to be quite rapid in these materials.

INTRODUCTION

In August of 1989, we entered into a research agreement with RGC Minerals, Inc. to develop effective restoration strategies for their proposed 5,000 acre mineral sands mining project in the Old Hickory area of Dinwiddie and Sussex Counties, Virginia. Additional deposits have been located in North Carolina. The development of appropriate restoration strategies and techniques for these lands will be challenging. The existing landscape contains a significant acreage of highly productive farmlands, and no research has been conducted to date regarding the return of mineral sands mining areas to rowcrop production.

SPECIFIC RESEARCH OBJECTIVES

1. To characterize the soil-landscape resource associated with the proposed heavy minerals mining operations, and to develop soil interpretations for mining operations and reclamation planning.
2. To document existing soil/crop productivity relationships to establish post-mining productivity targets.
3. To determine the optimum mixture ratio of tailings and slimes for crop productivity, with and without topsoil cover.
4. To develop an integrated materials handling/land restoration plan to maximize the productivity of the post-mining landscape.

REVIEW OF PERTINENT LITERATURE

Reclamation after Mineral Sands Mining

In Australia, heavy mineral sands containing rutile, monazite, ilmenite, and zircon have been mined for over 50 years. Although mineral sands are mined in other parts of the world, the techniques for reclaiming the mined areas were pioneered and developed in Australia (Brooks, 1986). Prior to mineral sands mining in Australia, vegetation is cleared and the A horizon of the soil is stockpiled. The subsoil is then mined with dredges or by conventional dry excavation techniques. Heavy minerals are removed from the soil/sediment matrix by gravity separation in a water slurry, and the tailings which consist of sand are recombined with the slimes (a silt/clay/humic material slurry) and replaced in such a way as to duplicate the former landforms. The topsoil is then returned to the site, and vegetation is established and stabilized (Brooks and Bell, 1984). Many mining areas are returned to native semi-arid shrub vegetation while those in more humid regions are often returned to pasture. Heavy mineral removal produces no toxic

wastes, and generally results in a volume loss of less than 5% (Brooks, 1989).

Reclamation of Prime Farmland

Prime farmland is agricultural land that possesses the optimum combination of physical and chemical factors for producing sustained high yields of feed, forage, fiber, and oil crops (Grandt, 1988). Much work has been done on methods of topsoil and subsoil replacement. Jansen and Dancer (1981) compared crop yields on soils with varying thicknesses of replaced A and B horizons to crop yields on graded overburden. They found that on some soils, blending calcareous loess and tills into acid B horizons during overburden handling operations improved their productivity. If the A horizon is replaced, soil structure tends to be better than that found in graded overburden, which results in better seed establishment. These differences in structure tend to disappear over extended periods of time as A horizons develop in the graded mine soil.

A major problem in reconstructing prime farmland after coal removal is that soil and overburden are often replaced by scrapers, which results in soil compaction. Even if topsoil is end-dumped by trucks, a compacted zone often occurs under the A horizon. Much research has focused on trying to decrease the bulk density of this compacted layer by various means.

Powell et al., (1986) found that deep ripping (to 65 cm) combined with the application of 22 to 44 Mg/ha dried sewage sludge produced target corn and sorghum yields on reclaimed prime farmland soils only one year after reconstruction. The pre-mining organic matter content of the A horizon decreases during topsoil removal and storage, and additions of organic materials can help restore the organic matter to original levels. Barnhisel et al., (1988) observed that subsoil ripping did not increase alfalfa yields on reclaimed mined land in Kentucky, and this process did not appear to affect soil bulk density. Liming of the subsoil before the replacement of the A horizon did produce higher alfalfa yields. However, other studies in Illinois have found that deep tillage can reduce soil strength and bulk density, thereby increasing soil productivity.

As mentioned before, the direct application of the results from other prime farmland research to the eastern USA Coastal Plain may be difficult, but it is obvious from the majority of studies that the subsoil conditions after mining are critical to reclamation success. Therefore, mining and materials handling strategies must be developed that insure adequate physical and chemical properties throughout the rooting zone, not just in the topsoil layers.

RESEARCH APPROACH AND METHODS

Soil Mapping and Characterization

Much of this particular landscape has little relief, and detailed mapping is essential since relatively slight changes in micro-topography have a major influence on soil drainage and profile development. The Old Hickory area was mapped in the field at 1"=1000' and was compiled to a rectified 1"=800' base which matches RGC's imagery, maps and data base. For each major soil type in the Old Hickory area, we have selected a "typical pedon" for detailed morphological description and sampling from backhoe pits.

Soil/Crop Productivity Measurements

An important part of the development of mined land restoration plans is the accurate assessment of the pre-mining productivity potential of the various soils over multiple seasons. During 1989 we took yield measurements from several different fields in the Old Hickory area utilizing a weigh wagon, and in 1990 we determined yields at similar sites by hand-harvest of random yield strips.

Florida Tailings Studies

Six representative mine soils developed in sandy tailings at the Associated Minerals mine in Green Cove Springs, Florida, were described and sampled in November 1989 in a preliminary study. An additional seven sites were studied in detail in March, 1991. The sites ranged in age from less than 1 year to approximately 20 years since reclamation. Careful descriptions were made of soil morphology and plant rooting patterns.

Simulated Tailings/Slimes Studies

The development of a set of simulated tailings and slimes was essential for future laboratory and greenhouse studies. Early in 1989, we identified five sites typical of both soils and mineralization for drilling and bulk sampling (Table 1). The entire soil plus geologic profile was drilled with a 36 in well rig, and the combined

Table 1. Soil sampling sites drilled with the well boring rig in the Old Hickory area.

Well	Soil Type	Existing Crop
1	Turbeville	Corn
2	Varina	Peanuts
3	Faceville	Corn
4	Orangeburg	Soybeans
5	Dothan	Soybeans

sample was fed through a pilot plant built on-site to simulate the mineral sands separation process. The tailings and slimes from each of the five sites were then carefully isolated and settled into separate plastic-lined impoundments.

To serve as an "undisturbed" control, Orangeburg topsoil (0-15 cm) was collected from a soybean field near site #4. Orangeburg was chosen as a control because it produced the highest corn yield the previous year. A mixture of topsoil collected from the five sites was also sampled for a second control which would be more representative of the mixture of topsoil materials that would be generated during actual mining.

DISCUSSION OF RESULTS AND PROGRESS

Soil Mapping and Site Characterization

The field delineation of soils was completed in the Old Hickory area early in 1990, and the final compilation of the maps is being completed. A detailed (200 p.) preliminary report documenting the soils, mapping units, and land-use interpretations for the area has been supplied to RGC for field use along with the preliminary field mapping sheets (Hodges et al., 1990). Specific mining related soil interpretations are being developed and include suitability for topsoil salvage operations, road building and wet-weather trafficability, dredging restrictions (pans & stoniness), and other factors.

One of our major objectives over the next year is to work closely with RGC to carefully match our surface soil map with drilling records to reconstruct the geomorphic record for this area. Analysis of these samples will allow us to determine mineral weathering sequences with depth, including clay+silt (slime) profiles, which will directly influence the materials handling and soil reconstruction operations.

The detailed laboratory characterization of the existing soils in the proposed mining areas is important for a variety of reasons. First of all, it provides us with baseline estimates of their properties before mining for comparative purposes. This will be particularly important for our understanding of soil type/crop productivity relationships. Secondly, it will allow us to accurately compare the properties of the mine soils generated by the mining process with the original undisturbed soils. The full characterization data set is given by Hodges et al. (1990) and will be summarized here.

As anticipated, the particle size distribution of the soils varies by soil type and horizon sampled. The older heavily weathered soils (Paleudults), such as Faceville and Turbeville, contain significant amounts of subsoil (Bt) clay to great depths, while those associated with the younger materials below the scarp (Hapludults, e.g. Norfolk, Suffolk) are lower in subsoil clay content. Except where strongly eroded, the thick (> 12") surface horizons (Ap+E) are loamy sands to sandy loams, and are dominated by medium and fine sand. The coarse fragment content of these soils is generally low, except for the subsoil horizons of the plinthic soils (e.g. Varina, Dothan).

Extractable Ca and Mg levels are moderate in these soils due to long term agricultural liming practices. Those soils which do exhibit fairly low levels of Ca and Mg are either extremely sandy, associated with wet or non-agricultural landscapes, or both. Extractable P levels are quite variable in the Ap horizons of these soils, but are medium to high in those which have received fertilization. Subsoil P levels are low to very low, reflecting the low native P content of these Coastal Plain soils. Extractable K content is quite variable, but generally low due to the coarse texture and highly weathered nature of the majority of these soils. The native Ph of all soils is low (< 5) due to long term leaching and weathering, and the cation exchange complex of these soils is dominated by Al.

Soil/Crop Productivity Measurements

Crop yields were taken after a very good rainfall season in 1989 and again in the fall of 1990 following a low rainfall growing season (Table 2). The fields and to some extent the soil type changed between 1989 and 1990 due to crop rotation, but the data do offer a good comparison of the productivity of these soils under good and bad climatic conditions. The influence of irrigation in 1990 was dramatic. Over the next several years it will be important for us to intensify our yield sampling program to include as many soil types and crops as possible.

Florida Tailings Studies

Our preliminary study of the mine soils forming in topsoiled tailings at Green Cove Springs was quite enlightening. Very young profiles (< 2 yr) exhibited

Table 2. Corn Yields on Various Soil Types in 1989 and 1990.

	- Corn Yield -	
Soil Type	1989	1990
	- bushels/acre -	
Varina	128	82
Dothan/Varina	120	
Varina	153	35
Dothan/Norfolk		145 (Irrig.)
Turbeville/Faceville		53
Orangeburg/Turbeville		81

little or no profile differentiation other than that resulting from topsoiling. The tailings below the topsoil layer showed obvious stratification due to wet settling, and were frequently quite compact. Mine soils between 5 and 10 years in age exhibited much stronger profile differentiation, and all contained a thin continuous band of humate within 20 inches of the surface, often accompanied by a reddish stained zone as well. These layers appear to be the result of humate+iron precipitation, presumably associated with a fluctuating water table. It seems quite remarkable that this spodic-like horizon could form within 5 years, but not totally unexpected since the pore waters of the sandy tailings contain a considerable load of humate and iron dispersed when the native spodic horizon is processed with the sands. The deeper C horizons in these soils were often well differentiated and showed prominent lamination. Several of the subsurface layers were also quite compact.

Rooting in these soils was generally limited to less than 20 inches, and quite often to less than 12 inches. This appears to be due to a combination of a high winter water table and compaction. The compaction observed high in the profile appeared to be due to final grading operations during topsoiling, while that lower in the profile appears to be simply due to wet settling and fill consolidation. In many instances, the bulk density of the subsurface tailings exceeded 1.7 g/cc, a level which may be restrictive to rooting, particularly in unstructured soils such as these. The horizontal lamination present in these subsurface layers may also pose some rooting restrictions. The soils associated with the topsoil layers and upper parts of the sandy tailings developed reasonable structural aggregation within five years, but the deeper tailings remained massive.

Simulated Tailings and Slimes Studies

As expected, the washed tailings and slimes were fairly low in organic matter, extractable P, and cations (Table 3). One very interesting property of the tailings and slimes compared with the native surface soils is that their Ph and exchangeable acidity levels are quite moderate. The only strong difference noted among the various materials was the fact that the CEC of the tailings from sites 1 and 2 were significantly higher in CEC than the others. This was an artificial difference, however, due to the fact that these analyses were run on the first-run tailings before they were re-washed a second time through the pilot plant, and these two samples still contained some slimes.

The mineralogy (Table 4) of the trace clays in the tailings and the slimes was also quite similar with the exception of site 5 (Dothan) which lies on the northern fringe of the Old Hickory deposit. The dominance of the clay fraction by kaolinite along with significant gibbsite is indicative of the highly leached and weathered nature of these materials. Only trace amounts of relatively unweathered 2:1 minerals are present.

The particle size distribution and water holding properties of the individual tailings and slimes were also quite similar (Table 5). The tailings are dominated by medium and fine sand, and show only minor differences among sites. The five slimes are also quite similar with the only major difference being a higher silt content in the Dothan sample. The measured available water holding capacity (0.1 bar minus 15 bar H_2O) was quite low for the tailings. As discussed later, we have discovered several analytical problems in measuring moisture retention in these materials.

Overall, the tailings and slimes processed from the five soil types were remarkably similar to one another in physical, chemical and mineralogical properties even

Table 3. Chemical characteristics of tailings and slimes.

Sample	O.M.	Bray P	Acid Extr. K	Acid Extr. Mg	Acid Extr. Ca	Ph	CEC
	- %-	ppm	ppm	ppm	ppm		meq/100g
			Simulated Tailings				
1	0.1	4	18	48	190	5.6	1.8
2	0.1	4	10	32	140	5.7	1.3
3	0.1	2	8	12	80	5.8	0.6
4	0.1	3	13	23	110	5.5	1.0
5	0.1	2	16	21	100	5.4	1.0
			Simulated Slimes				
1	0.6	4	73	170	550	6.0	5.1
2	0.4	2	54	122	400	5.9	3.8
3	0.4	3	89	160	500	5.7	5.1
4	0.5	5	81	144	430	5.6	4.7
5	1.2	4	102	131	460	5.8	4.5

though their surficial soils were quite different in many cases. We presume that this is due to the homogenizing effect of combining the surface profiles with considerable thicknesses of relatively less weathered deeper sediments.

Characteristics Of Mixed Tailings and Slimes Compared to Native Soils

Compared with the native topsoils, the mixture of 85% tailings with 15% slimes appears to be most similar in physical properties (Table 5). The higher slime ratio mixtures are considerably finer than native topsoils, and more similar to natural subsoil horizons. The pure tailings are extremely low in water holding capacity; water holding increases regularly with slime content, but still appears quite low.

During the initial analysis it became obvious that our lab estimates of field capacity (0.1 bar) water content were quite low, particularly for the mixtures with high tailings content. For that reason, we conducted an in-situ moisture holding experiment to estimate the actual field capacity for these various materials, which generated the data shown under the "Field Capacity" column in Table 5. Due to their coarse nature, the tailings samples apparently contained numerous large diameter packing voids which simply could not retain water against gravity at this low tension. Once the materials are wetted and dried in pots, however, they consolidate significantly and apparently change their packing. This leads to a great increase in micro-porosity and subsequent increases in water holding at field capacity. This "packing behavior" may well explain the high bulk densities observed in the Florida tailings, and may also indicate that maintaining "well drained" conditions may be difficult in the field with these materials.

The chemical characteristics of the various mixtures and native topsoils are shown in Table 6. Compared with the natural soils, the high tailings mixtures are lower in extractable nutrients and CEC, but moderate in Ph. The pH of the slimes composite was around 5.7, so the bulk pH of the original tailings:slimes mixtures decreased regularly with increasing slime content.

Table 4. Clay mineralogy of tailings and slimes from sites 1 through 5.

Site	KaO	ChV	Verm*	Mica	Qz	Gibb
	%					
			Simulated Tailings			
1	60	19	5	2	1	13
2	65	15	5	2	1	13
3	61	15	5	2	1	14
4	65	14	5	2	1	13
5	43	27	5	2	1	22
			Simulated Slimes			
1	63	20	5	2	1	9
2	65	19	5	2	2	7
3	72	12	5	2	1	8
4	64	18	5	2	2	9
5	40	37	5	2	1	15

* Smectites appear to be high charge and are reported with the vermiculite. (KaO = kaolinite; ChV = chloritized vermiculite; Verm = vermiculite; Qz = quartz; Gibb = gibbsite.)

Table 5. Physical characteristics of tailings/slimes mixes and soils. (T=Tailings, S=Slimes).

Growth Media	Moisture retention at: 0.1* bars	15* bars	Field** capacity	Sand	Silt	Clay
	%					
Tailings	1.6	0.9	10.8	97.4	1.0	1.6
85%T:15%S	6.1	3.8	12.5	84.5	7.7	7.8
70%T:30%S	11.2	7.1	13.8	77.0	9.2	13.8
55%T:45%S	16.4	10.7	14.5	59.1	13.2	27.7
Topsoil Mix	9.4	3.5	8.5	78.6	16.5	4.9
Orangeburg	7.3	2.9	7.9	79.6	14.6	5.8

*Moisture desorption method (Richards, 1965).
**In-situ equilibration method, water held in soil core after free drainage into identical material below.

Despite the relatively low pH of the slimes, they contained very low levels of total or titratable acidity. When compared with natural subsoils in the Old Hickory area, the slimes are virtually devoid of reactive Al^{3+}, the major component of exchangeable acidity. Either the Al becomes neutralized during the wet mill processing, or it is simply diluted away by mixture of the weathered acidic surface soil materials with the less weathered deeper sediments. In short, it appears that the processed tailings and slimes will be much less acidic than the existing soils.

SUMMARY AND CONCLUSIONS

The detailed soil mapping of the project area was an important first step in this project. The correlation between soil type and the paleoenvironment of deposition is very strong. Overall, the natural soils of the area are characterized by a deep sandy textured surface horizon over an acidic, clayey subsoil. The surface soils and underlying sediments have been heavily weathered and are very low in weatherable primary minerals.

Our soil/crop productivity efforts to date have shown the tremendous importance of soil water storage and availability to corn production for this region. This effort must continue for multiple seasons so that we can develop accurate site-specific productivity ranges for the dominant soils in crop production.

The tailings and slimes separated from the five major soil types processed were quite similar chemically and mineralogically. The similarity of these materials is due to the fact that they were all derived from upland soils with highly weathered Bt horizons. Other soil types with coarser textured subsurface horizons or those from poorly drained landscape positions where weathering may be less intense may yield significantly different tailings and slimes. On the other hand, if the homogenizing effect of running the entire soil profile and its underlying sediments through the wet mill will result in similar tailings and slimes regardless of original soil type, reclamation planning will be greatly simplified. It also appears that the tailings and slimes generated by the mining process will be less acidic than the natural soil materials, but will be quite low in fertility.

Our findings to date indicate that the tailings and slimes generated by the proposed mining operation will probably have suitable physical and chemical properties for crop production. However, regardless of the inherent suitability of the tailings and slimes themselves, the most important factor governing their long-term productivity for crops will be whether or not the overall mining and materials handling strategy employed will result in a deep, uncompacted, well-drained rooting zone with a moderate slimes content in the subsoil to hold water and nutrients. The Virginia deposit will be quite high in total slimes content, and an adequate method for blending slimes back with the tailings must be developed in order to rebuild productive soil profiles.

Our studies in Florida, while performed in a different soil/geologic environment, have pointed out several important facts. First, there is potential for heavy compaction in sandy tailings when they settle wet. Without significant efforts to loosen and aggregate these materials, they may not be hospitable for deep rooting crops. Distinct subsurface horizons can form in very short periods of time in these materials, indicating that it may be possible to generate differentiated mine soils in a matter of years.

LITERATURE CITED

Barnhisel, R.I., J.L. Powell, J.R. Armstrong, M.L. Ellis, and P.A. Craig. 1988. Effect of soil depth, liming and subsoilling of reconstructed prime farmland on alfalfa production In Mine Drainage and Surface Mine Reclamation. Bureau of Mines Tech. Circular 9184. pp 266-273.

Brooks, D.R. 1988. Wetlands rehabilitation following mineral sands mining in Australia. In Mine Drainage and Surface Mine Reclamation. Bureau of Mines Tech. Circular 9184. pp 146-153.

Brooks, D.R. 1989. Reclamation in Australia's heavy mineral sands industry. In D.G. Walker et al. (eds.) Proceedings of the Conference: Reclamation, a global perspective. Alberta Land Cons. and Reclam. Council Rpt. RRTAC 89-2. pp 11-26.

Brooks, D.R., and L.C. Bell. 1984. The technology of rehabilitation following mineral sands mining on

Table 6. Chemical characteristics of mixes and soils.

		Acid Extractable						
	pH	P	K	Ca	Mg	Zn	Mn	CEC
		ppm						meg/100g
Tailings	6.5	4	8	72	18	0.6	1.1	0.61
85:15 T:S	6.7	3	15	120	31	1.1	4.2	1.15
70:30 T:S	5.1	2	22	180	48	1.0	8.0	2.87
55:45 T:S	5.9	3	29	228	61	1.3	10.9	3.43
Topsoil Mix	5.9	49	64	612	84	1.7	11.5	2.71
Orangeburg	6.2	44	99	432	39	1.9	8.2	2.33

North Stradbroke Island. In R.J. Coleman et al. (eds.) Focus on Stradbroke. Boolarong Pubs., Brisbane, Australia. pp 184-194.

Grandt, A.F. 1988. Productivity of reclaimed lands - cropland. In L.R. Hossner (ed.) Reclamation of Surface Mined Lands. CRC Press, Boca Raton, FL. pp. 131-155.

Hodges, R.L., P.A. Thomas, and W.L. Daniels. Soil Maps and Interpretations for the Old Hickory Mining Project. CSES Dept., Virginia Tech, Blacksburg. 210 pp.

Jansen, I.J., and W.S. Dancer. 1981. Row crop yield response to soil horizon replacement after mining. In Proceedings of the Symposium on Surface Mining Hydrology, Sedimentology, and Reclamation. Univ. of Kentucky, Louisville, KY. pp 357-362.

Powell, J.L., R.I. Barnhisel, F.A. Craig, J.R. Armstrong, M.L. Ellis, and W.O. Thom. 1986. The use of organic amendments in the restoration of prime farmland. In Proceedings, ASSMR National Meeting, Jackson, MS. pp. 55-60.

Richards, L.A. 1965. Physical condition of water in soil. In C.A. Black (ed). Methods of soil analysis, part 1. Agronomy 9: 128-152. Amer. Soc. Agron., Madison, WI.

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Physical Root Restriction Prediction in a Mine Spoil Reclamation Protocol

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Introduction. According to Federal regulations, cropland that is prime farmland must be returned to its original productivity after disturbance by mining. For this, the potential rooting depth cannot decrease appreciably. This proposal describes comparisons between potential rooting depth of undisturbed and disturbed soil as part of a more general statement on reconstruction criteria that is under development. Field and laboratory methods are not explored in detail. The proposal has not been tested in the field.

EVALUATION CRITERIA

The criteria that will be used involves prediction of potential rooting. The criteria are based on direct root observations and on structure insofar as would seem appropriate. If rooting depth is not inferable from these observations, bulk density or penetration resistance have been employed. Criteria involving these latter measurements are based on an extensive review of laboratory root growth studies. In order to apply the laboratory data relating root restriction and penetration resistance and to provide criteria that could be applied in the field, it was necessary to obtain relationships among the kinds of tips employed for laboratory and field studies.

Root - Permissive Structure

Reference is made in several places in the criteria to root-permissive structure, defined as: Strong or moderate granular, subangular or angular blocky <10 cm, or prismatic or columnar except very coarse. Evaluation is required while moderately moist or wetter. Underlined terms here and elsewhere are defined in soil survey documents. Bodies formed by mechanical disturbance are considered structural units. Criteria for blocky are applied to fritted structure described by McSweeney and Jansen (1984).

Bulk Density Criterion

Table 1 summarizes 18 laboratory studies of the relationship between root growth and bulk density. In these studies, measurements were made of root elongation into cores having a range in bulk density. The bulk density at maximum root growth and at 0.2 and 0.5 of the optimum is given. Maximum growth in this context is the most rapid or longest elongation of roots into the cores. Maximum growth almost always coincided with the lowest bulk density.

Figures 1 and 2 show relationships between bulk density and clay for 0.2 and 0.5 of maximum growth from laboratory studies of seedling root growth into cores with progressively higher bulk densities. The soil material passed 2 mm and only studies employing a water suction 0.03 MPa or less were included. The most frequently studied plants were those common to temperate agriculture with pea seedlings the most frequent plant material. The disaggregation limits the application of the root restriction studies to those soil horizons that lack structure with repeat distances exceeding 2 mm. The r^2 for silt plus clay was less than for clay alone. The median difference between 0.2 and 0.5 of maximum growth was 0.08 Mg/m^3. The analysis parallels that by Jones (1983) but with some differences in the studies.

The experiments commonly are for unrealistically favorable physical conditions leading to artificially high root growth rates. Since the changes in growth are on a relative basis, a small increase in bulk density may cause a large decrease in root growth. This same bulk density under natural conditions may result in less decrease in root growth. Therefore, it must be assumed that the bulk density for soils in place at 0.2 and 0.5 of maximum growth would be underestimated. The slope of the relationship may be less affected by the initial conditions.

Figure 1. Relationship between clay percentage and the bulk density at 0.2 of maximum root growth for 17 laboratory studies. (Table 1).

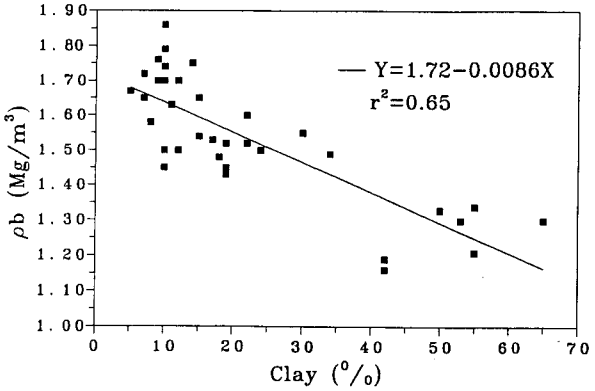

Figure 2. Relationship between clay percentage and the bulk density at 0.5 of maximum root growth for 17 laboratory studies. (Table 1).

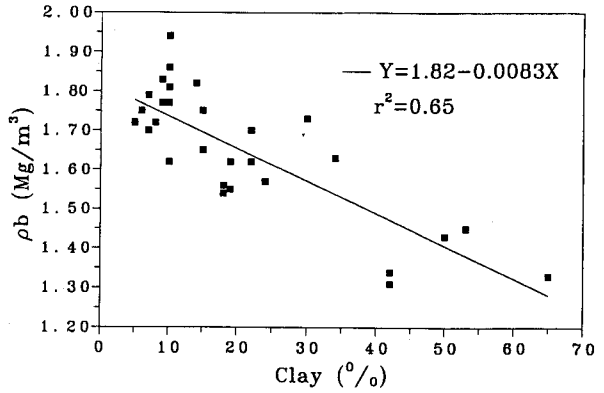

Table 1. Studies of seedling root inhibition related to bulk density arranged by ascending clay percentage and silt percentage within clay percentage.

Clay	Suction	Plant	Bulk Density at Relative Growth 1.0	0.5	0.2	Source
pct	MPa		-------	Mg/m³	-------	
5	0.02	Cotton	1.51	1.67	1.72	Bar-Yosef and Lambert(1981)
6	0.01	Cotton	1.56	——	1.75	Jones (1983)[a]
7	0.02	Cotton	1.55	1.72	1.79	Taylor et al (1966)
7	0.03	Cotton	1.55	1.65	1.70	
8	0.03	Sorghum	1.25	1.58	1.72	Hemsath and Mazurak (1974)
9	0.02	Cotton	1.55	1.76	1.83	Taylor et al (1966)
9	0.03	Cotton	1.55	1.70	1.77	
10	0.02	Cotton	1.10	1.74	1.81	
10	0.03	Cotton	1.10	1.70	1.77	
10	0.03	Soybean	1.55	1.86	1.94	Baligar et al (1981)
10	0.03	Pea	1.29	1.50	1.62	Voorhees et al (1975)
10	0.02	Cotton	1.55	1.79	1.86	Taylor and Gardner (1963)
11	0.007	Pea	1.10	1.63	——	Eavis (1972)
12	0.005	Lettuce	1.25	1.50	——	Carr and Dodds (1983)
12	0.03	Pea	1.50	1.70	——	Barley et al (1965)
14	0.03	Pea	1.55	1.75	1.82	Taylor et al (1966)
15	0.03	Sorghum	1.00	1.64	1.75	Hemsath and Mazurak (1974)
15	0.005	Sugar Cane	1.15	1.54	1.65	Monteith and Banath (1965)
17	0.02	Rye Grass	1.05	1.53	——	Cornish et al (1984)
18	0.01	Yellow Poplar	1.25	1.48	1.54	Simmons and Pope (1987)
18	0.01	Sweet Gum	1.25	1.48	1.56	
19	0.02	Cotton	1.25	1.52	1.62	Taylor et al (1966)
19	0.03	Cotton	1.25	1.45	1.55	
19	0.018-0.03	Wheat	1.17	1.41	——	Masle and Passioura (1987)
22	0.03	Cotton	1.30	1.60	1.70	Tackett and Pearson (1964a)
22	0.03	Cotton	1.30	1.52	1.62	Tackett and Pearson (1964b)
24	0.03	Pea	1.35	1.50	1.57	Blanchar et al (1978)
30	0.02	Sorghum	1.00	1.55.	1.73	Hemsath and Mazurak (1974)
34	0.005	Sugar Cane	1.33	1.49	1.63	Monteith and Banath (1965)
42	0.01	Corn	0.93	1.19	1.34	Phillips and Kirkham (1962)
42	0.001	Corn	0.93	1.16	1.31	
50	0.005	Sugar Cane	1.17	1.33	1.43	Monteith and Banath (1965)
53	0.003	Edible Bean	1.15	1.30	1.45	Asady et al (1985)
55	0.01	Pea	0.92	1.21	——	Voorhees et al (1975)
55	0.01	Pea	0.99	1.34	——	
65	0.005	Pea	1.23	1.30	1.33	Cockroft et al (1969); Greacen and Gardner (1982)

[a]Personal communication from A.T.P. Bennie in reference cited.

Penetration Resistance Criterion

Penetration resistance at 0.2 and 0.5 of maximum root growth was determined from 16 laboratory studies that used <2 mm soil material at ≤0.1 MPa water suction (Table 2). The tips used in the experiment were either flat-end rods about 6 mm in diameter or 60° cones 1.0 to 3.5 mm in diameter. Comparisons were made between the flat-end rod and both the small 60° cones used in laboratory studies and the larger 30° cones used in the field. To relate the tips, penetration resistance was measured on cores of 11 soil materials of diverse textures at 0.2 MPa water retention and 10 percentage points above. The cores were 15 cm in diameter and were formed as stipulated in the Proctor Density Determination (American Society Testing Materials. 1984). Insertion time increased from 1 to 3s with increasing tip size. The insertion was by hand; measurements are in progress using mechanical insertion. The equations in Table 3 were obtained to convert measured penetration resistance in MPa (x of equation) to the equivalent flat-end rod value (y of equation).

This approach permits the utilization of laboratory studies that employ small 60° cones to establish criteria based on the 6 mm diameter flat-end rod while also making it possible to obtain field measurements with

Table 2. Studies of seedling root inhibition related to penetration resistance arranged by ascending clay percentage and silt percentage within clay percentage.

			Penetration Resistance at Relative Growth			
Clay	Suction	Plant	1.0	0.5	0.2	Source
pct	- MPa -		- - - - - - - MPa - - - - - - -			
5	0.016	Cotton	1.8	1.3	2.6	Bar-Yosef and Lambert(1981)
7	0.02	Cotton	0.06	0.7	1.9	Taylor and Ratliff (1969)
7	0.08	Cotton	0.005	0.4	1.8	
7	0.05	Cotton	0.6	1.3	1.7	Taylor et al (1966)
7	0.02	Peanut	0.005	2.0	4.9	Taylor and Ratliff (1969)
7	0.04	Peanut	0.005	2.0	2.9	
8	0.03	Sorghum	0.2	0.8	1.0	Hemsath and Mazurak (1974)
9	0.02-0.1	Cotton	0.4	1.1	1.5	Taylor et al (1966)
10	0.02-0.07	Cotton	0.6	1.4	1.8	
10	0.03	Pea	1.0	3.3	6.4	Voorhees (1975)
10	0.1	Pea	1.0	3.4	7.3	
10	0.02	Cotton	0.5	1.4	3.3	Taylor and Gardner (1963)
10	0.03	Cotton	0.8	2.2	3.6	
10	0.05	Cotton	1.0	2.1	2.9	
12	0.03	Pea	1.5	1.7	—	Barley et al (1965)
12	0.07	Pea	1.5	3.0	3.6	Hemsath and Mazurak (1974)
15	0.02	Sorghum	0.3	0.8	—	
15	0.005	Sugar Cane	0.3	1.9	—	Monteith and Banath (1965)
17	0.02	Rye Grass	0.3	2.0	—	Cornish et al (1984)
19	0.02-0.07	Cotton	0.6	1.4	1.9	Taylor et al (1966)
19	0.02-0.1	Wheat	1.4	4.6	6.7	Masle and Passioura (1987)
19	0.03	Cotton	0.0	0.4	1.4	Pearson et al (1970)
19	0.03	Cotton	0.0	1.0	—	
19	0.03	Cotton	0.0	1.4	—	
21	0.02	Ann. Rye Grass	0.4	0.8	1.2	Shierlaw and Alston (1984)
21	0.01	Ann. Rye Grass	0.4	3.0	5.1	
21	0.02	Corn	0.4	1.0	1.5	
21	0.1	Corn	0.4	4.1	7.3	
24	0.03	Pea	—	1.2	2.2	Blanchar et al (1978)
28	0.1	Corn	1.6	1.3	—	Mirreh and Ketcheson (1973a)
30	0.015	Sorghum	0.2	0.6	1.0	Hemsath and Mazurak (1974)
30	0.03	Sorghum	0.1	0.7	1.3	
34	0.005	Sugar Cane	0.6	1.3	1.6	Monteith and Banath (1965)
50	0.005	Sugar Cane	0.4	0.6	0.7	
53	0.008	Edible Bean	0.4	3.1	4.3	Asady et al (1985)
55	0.01	Pea	0.1	1.1	—	Voorhees et al (1975)
55	0.03	Pea	0.5	2.1	—	
55	0.1	Pea	0.9	1.7	—	
65	0.005	Pea	0.6	1.4	2.0	Cockcroft et al (1969)

relatively large 30° cones. The median penetration resistance values in Table 4 are from data in Table 2. For the calculation, determinations using small cone tips were converted to the equivalent flat-end rod values with the equations in Table 3.

Locally obtained comparisons between the 6 mm diameter flat-end rod and the penetrometer tip used in the field may be substituted for those in the regulation if there are suitable safeguards that the procedure is reasonable.

As discussed for bulk density, the limiting penetration resistance values in the laboratory root growth studies are probably underestimates because maximum root growth is at unrealistically low penetration resistance.

COMPARISON OF POTENTIAL ROOTING DEPTH

The following evaluation would be applied to each soil series that occurs in the area in question. For each of these soil series, two pedons would be evaluated at locations one mile or more apart and within a five mile radius. If root depth observations or structure are employed in establishing the potential rooting depth, then the observations should be made by a soil scientist.

If rooting depth and structure together are inconclusive, then bulk density or penetration resistance is employed. The intent is to make application relatively inexpensive where possible.

Table 3. Regressions between penetration resistance using the 6 mm diameter flat-end rod (y) and various penetrometer tips (x).

Tip	Number of Comparisons	Equation	r^2
60° cone			
1.5 mm	20	y = - 0.05 + 0.61x	0.95
3.0 mm	20	y = 0.06 + 1.1x	0.95
30° cone			
13 mm	21	y = 0.4 + 0.87x	0.90
20 mm	20	y = 0.06 + 1.4x	0.72[a]
28 mm	14	y = 0.06 + 1.5x	0.92

[a] No explanation for lower r^2.

Table 4. Median penetration resistance at 0.2 and 0.5 reduction in root growth from laboratory studies.

Root Reduction	Number of Measurements	Median
		- MPa -
0.2	29	2.1
0.5	39	1.3

The bulk density is for the <2 mm. Water state is not specified. For soil materials that do not have strong structure or contain <20 percent by volume structural units exceeding 2 cm across in the smallest dimension, the bulk density of the fine earth fabric overall cannot be less than what would be obtained by methods 4A1, 4A1d (Soil Survey Staff, 1984). For other soil fabrics, the bulk density of the individual structural units should not be less than would be measured by the foregoing methods.

Each statement to follow has two parts: an informal overview and a formal proposal. The number of stipulations in the formal parts makes the statements complex. This is a reflection of the inherent difficulty in fashioning a proposal that would be regulatory if applied.

Undisturbed Soil

If available, root depth observations are used to establish the potential rooting depth. These observations must be under conditions where tillage compaction, water state, or chemistry are not limiting to root growth. Otherwise structure or bulk density is employed. Bulk density has been made less limiting at greater depth. A default value for the maximum rooting depth is provided if rooting depth is not limiting at a shallower depth. The bulk density values in the criteria are subject to adjustment.

- The potential root depth is the distance from the ground surface to the midplane of the shallowest zone of few roots for the root size class that gives the greatest depth. The plants should be annuals at physiological maturity and form an important crop. Observations must not be on a soil where sufficient compaction by tillage has reduced rooting depth appreciably. Observed rooting depth may be the basis for assignment of the potential rooting depth only if the water state above 120 cm is not restrictive during the growing season. The chemistry to 120 cm must not be more restrictive to root growth than that of the soil under relatively long-term intensive agriculture for the area.
- If observed rooting depth alone cannot be the basis, the shallower is assigned:
  - 120 cm
  - The base of a continuous zone with all parts immediately below 25 cm having one or more of the following:
    a. Root-permissive structure.
    b. Common or many roots of any size.
    c. A moist bulk density less than:
       1.77 - 0.0083 %clay for 25-75 cm
       1.82 - 0.0083 %clay for ≥75 cm

Disturbed Soil

Potential rooting depth may be based on root observations, structure, bulk density, or penetration resistance. Root depths must not be for perennials if the plants for the undisturbed condition are annuals. Criteria based on bulk density or penetration resistance are dependent on location within the rooting depth of the undisturbed soil and are more limiting if the undisturbed soil has root-permissive structure in order to penalize if this structure were obliterated in reconstruction. The soil is wetted to increase the likelihood that the structure described has some permanence. Alive roots are stipulated to exclude those present by recent burial.

- The distance from the ground surface to the midplane of the shallowest zone of few alive roots with the constraints as given for the undisturbed soil.
- If observed rooting depth cannot be the criterion, the depth of potential rooting is the base of a continuous zone from 25 cm that has in all parts one or more of the following:
  a. Many or common roots of any size.
  b. Root-permissive structure after the soil material has been subject by irrigation to the passage of at least one pore volume of water while all parts are very moist or wet. The water added must not change the soil solution chemistry from indicative of dispersion (zone A in figure 3) to non-dispersive (zone B).
  c. Flat-end rod equivalent penetration resistance and/or bulk density that does not exceed the values in Table 5. The penetration resistance cannot be determined while free water is present at the depth of measurement.

LITERATURE CITED

American Society Testing Materials. 1984. Designation D. p. 698-78. Annual Book of ASTM Standards, 1984. Vol. 04.08. Philadelphia, PA.

Asady, G.J., A.J.M. Smucker, and M.W. Adams, 1981 Seedling test for the quantitative measurements of root tolerances to compacted soil. Crop Science 25:802-806.

Baligar, V.C., V.E. Nash, F.D. Whisler, and D.L. Myhre, 1981. Sorghum and soybean growth as influenced by synthetic pans. Commun. in Soil Science and Plant Analyses 11:97-107.

Barley, K.P., D.A. Farrell, and E.L. Greacen, 1965. The influence of soil strength on the penetration of a loam by plant roots. Austral. J. Soil Sci. 3:69-79.

Bar-Yosef B. and J.R. Lambert, 1981. Root growth in response to soil impedance and water potential. Soil Sci. Soc. Am. J. 45:930-935.

Blanchar, R.W., W.R. Edmonds, and J.M. Bradford, 1978. Root growth in cores formed from fragipan and B2 horizons of Hobson soils. Soil Sci. Soc. Am. J. 42:437-440.

Carr, M.K.V. and S.M. Dodds, 1983. Some effects of soil compaction on root growth and water use of lettuce. Exp. Agric. 19:117-130.

Figure 3. The field of percent sodium and total dissolved solids, both for the saturation extract, divided into a non-dispersive part (zone A), a dispersive part (zone B), and a transitional part (zone C). From Flanagan and Holmgren, (1977).

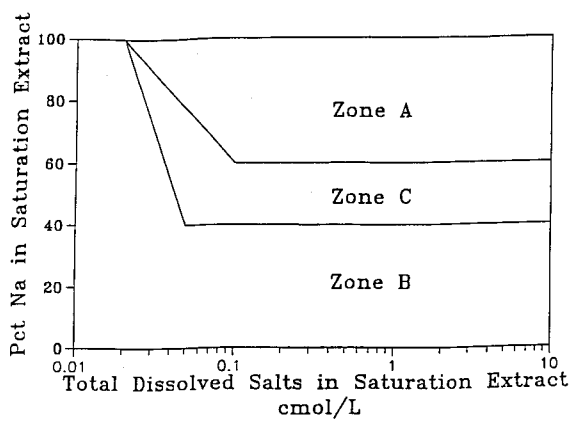

Table 5. Minimum penetration resistance and bulk density indicative of root restriction for disturbed soils. Limits are adjusted for position in the zone of rooting for the undisturbed soil and whether the zone in the undisturbed soil has root-permissive structure.

	Penetration Resistance	Bulk Density
	- - MPa - -	- - - Mg/m^2 - - -
Upper Half Depth Rooting, Undisturbed soil with root-permissive structure	1.3[b]	1.72 - 0.0086 %clay
Undisturbed soil without root-permissive structure	1.5[a]	Above plus 0.03
Lower Half Depth Rooting, Undisturbed soil with root-permissive structure	1.9[b]	Below minus 0.03
Undisturbed soil without root-permissive structure	2.1[a]	1.82 - 0.0083 %clay

[a] 25 and 50 percentile for ascending order of 0.2 root reduction for 29 laboratory measurements. (Tables 2 and 4).
[b] 50 and 75 percentile for ascending order of 0.5 root reduction for 39 laboratory measurements. (Tables 2 and 4).

Cockcroft, B., K.P. Barley, and E.L. Greacen, 1969. The penetration of clays by fine probes and root tips. Aust. J. Soil Res. 7:333-348.

Cornish, P.S., J.B. So, and J.R. McWilliam, 1984. Effect of soil density and water regimen on root growth and uptake of phosphorus by ryegrass. Austral. J. Agric. Res. 35:631-644.

Eavis, B.W., 1972. Soil physical conditions affecting seedling root growth. Part 1. Plant and Soil 36:613-622.

Flanagan, C.P. and G.G.S. Holmgren. 1977. Field methods for determination of soluble salts and percent sodium from extract for identifying dispersive soils. Am. Soc. Test Mat. STP 623.

Greacen, E.L. and E.A. Gardner, 1982. Crop behavior on clay soils. Trop Agric. (Trinidad) 59:123-132.

Hemsath, D.L. and A.P. Mazurak, 1974. Seedling growth of sorghum in clay-sand mixtures at various compactions and water contents. Soil Sci. Soc. Am. Proc. 38:387-390.

Jones, C.A., 1983. Effect of soil texture on critical bulk densities for root growth. J. Soil Sci. Soc. Am. 47:1208-1211.

Masle, J. and J.B. Passioura, 1987. The effect of soil strength on the growth of young wheat plants. Aust. J. Plant Physiol. 14:643-656.

Mirreh, H.F. and J.W. Ketcheson, 1973. Influence of soil bulk density and matrix pressure on soil resistance to penetration. Can. J. Soil Sci. 52:477-484.

Monteith, N.H. and C.L. Banath, 1965. The effect of soil strength on sugarcane root growth. Trop. Agri., (Trinidad) 42:293-296.

McSweeney, K. and I.J. Jansen, 1984. Soil structure and associated rooting behavior. Soil Sci. Soc. Am. J. 48:607-612.

Pearson, R.W., L.F. Ratliff, and H.M. Taylor, 1970. Effect of soil temperature strength and pH on cotton seedling root elongation. Agron. J. 62:243-246.

Phillips, R.E. and D. Kirkham, 1962. Mechanical impedance and corn seedling root growth. Soil Sci. Soc. Am. Proc. 26:319-322.

Shierlaw, J. and A.M. Alston, 1984. Effect of soil compaction on root growth and uptake of phosphorus. Plant and Soil 77:15-28.

Simmons, G.L. and P.E. Pope, 1987. Influence of soil compaction and vesicular-arbuscular mycorrhizae on root growth of yellow poplar and sweet gum seedlings. Can. J. For. Res. 17:970-975.

Soil Survey Staff. 1984. Procedures for collecting soil samples and methods of analysis for soil survey. USDA. SCS. Soil Survey Investigations Report No.1.

Tackett, J.L. and R.W. Pearson, 1964a. Oxygen requirements of cotton seedling roots for penetration of compacted cores. Soil Sci. Soc. Am. Proc. 28:600-605.

Tackett, J.L. and R.W. Pearson, 1964b. Effect of carbon dioxide on cotton seedling root penetration of compacted soil cores. Soil Sci. Soc. Am. Proc. 28:741-743.

Taylor, H.M. and H.R. Gardner, 1963. Penetration of cotton seedling taproots as influenced by bulk density, moisture content and strength of soil. Soil Sci. 96:153-156.

Taylor, H.M. and L.F. Ratliff, 1969. Root elongation rates of cotton and peanuts as a function of soil strength and soil water content. Soil Sci. 108:113-119.

Taylor, H.M., G.M. Roberson, and J.J. Parker, Jr., 1966. Soil strength - root penetration relations for medium- to coarse-textured soil materials. Soil Sci. 102:18-22.

Voorhees, W.B., D.A. Farrell, and W.E. Larson, 1975. Soil strength and aeration effects on root elongation. Soil Sci. Soc. Am. Proc. 39:948-953.