ABSTRACT

Since the passage of Public Law 95-87, the Surface Mining Control and Reclamation Act (SMCRA) in 1979, reclamation success on agricultural lands has been determined by long-term yield testing. This has required a long bond release period lasting ten years or more. Landowners, mine operators, and regulators have voiced the need for methods to expedite the bond release process. Financial burdens of annual cropping and field maintenance by mine operators and monitoring by regulators are of major concern. Landowners need reclaimed land returned to their production operations instead of being locked in the bond release process for a decade or more. A soil property based formula could relieve these financial burdens and ensure the most efficient process to return the productive soil resource to the landowner. In addition, this method will also identify problem fields immediately after reclamation.

Time required for productivity validation with yield tests over time may be ten times that required for extraction and reclamation. A soil based method of productivity validation will provide the shortest period of time that the land will be out of normal production. Twenty years ago, the Illinois Agricultural Land Productivity Formula and the Indiana Yield Performance Standards were the best measure possible for productivity over time. Reclamation research was in its infancy and relationships between minesoils and crop productivity were not known. Now, following 25 years of reclamation research, the idea of a soils based productivity model for bond release is realistic because of the large database on yield response to minesoil reclamation and new technology to accurately measure soil parameters on a spatial scale. If successful, it would result in reduced time and effort from all involved while not compromising the accuracy of productivity testing. The mine database continues to grow with new sampled fields and additional data collected at previously sampled fields. Soil based models to predict yield on coal-mined lands are being developed and tested along with recommendations (number of samples, time of sampling) for sampling mined lands. Results have shown to date that our penetrometer and water related (electrical conductivity, elevation) variables describe yield variability well across years, especially where compacted field areas are present. We conclude thus far that our soil modeling based approach is successful in delineating field areas with yield limiting problems, and thus may be used as a tool to address problems early in the bond release process and potentially speed up this process.
EXECUTIVE SUMMARY

The Surface Mining Control and Reclamation Act (SMCRA) of 1979 requires state regulatory authorities to find in writing that a mine operator has the technological capability to restore mined prime farmland, and in many states, cropland capable soils that are not classified as prime farmland. Restoration must occur in reasonable time, and crop yields and other productivity standards must meet or exceed levels of non-mined soils. The Federal Office of Surface Mining Reclamation and Enforcement periodically reviews permits as part of its oversight responsibilities for each state program. Most states require that success in revegetation of cropped land be determined on the basis of crop production from the mined land area as compared to either an approved reference area or to other technical guidance procedures. Statistical procedures may be utilized to determine productivity success. If a statistical approach is used, productivity of a mined area shall not be considered equal (successful) if it is less than 90% of the production of the approved standard with 90% statistical confidence when planted to crops commonly grown, such as corn, soybeans, hay, sorghum, wheat, oats, barley, or other crops found on surrounding prime farmland. To demonstrate prime farmland productivity, standards must be met in at least three crop years within a specified time period.

Individual states have enacted their own legislation to administer SMCRA. Illinois Public Act 81-1015 (1981) enabled Illinois to develop, submit for approval, and receive conditional approval of a Permanent Regulatory Program and received primacy for regulation of the coal mining industry. In 1986, Illinois promulgated its productivity measurement technique, called the Agricultural Land Productivity Formula (ALPF). ALPF utilizes the computation of estimated soil productivity indices at high levels of management and provides for seasonal adjustment in yield standard, based on the use of USDA Agricultural Statistics Service county estimated yield per acre. The fact that ALPF integrates both county weather and management practices during a given year, as well as the use of expected high management yields, may make it a more accurate yield standard for a given growing season than some alternative choices (i.e. published yield equivalents, published on-farm yields, etc.).

When they were developed, the Illinois ALPF and the Indiana Yield Performance Standards were the best measure possible for productivity over time. Reclamation research was in its infancy, and relationships between minesoils and crop productivity were not known. Today, after 25 years of reclamation research, researchers, coal operators and regulators feel a need exists for a method to evaluate reclamation in the absence of either test plots or actual measured yields. This would involve the development of indices to predict productivity of crop lands after mining, on the basis of their physical and chemical soil characteristics. A soils based productivity model for bond release is realistic because of the large database on yield response to minesoil reclamation and new technology to accurately measure soil parameters on a spatial scale.

The concept of the productivity index is that the soil environment affects root growth, and that plant yield will be proportional to root growth. In a model developed at the University of Missouri-Columbia, five easily measured soil properties - aeration, pH, bulk density, potential available water-holding capacity, and salinity - were chosen to
represent the soil environment. Development of a model to simulate environments found on mined land would provide an alternative to yield measurement systems. The objective of this work was to develop a soil based approach that will eventually replace the current yield based approach for bond release. The soil based approach uses measurable soil characteristics to determine if a given reclaimed field meets requirements of restoration of field productivity as outlined in existing federal and state regulations.

Because considerable time and effort is required of regulatory agencies and mine operators to implement and monitor current reclamation programs, landowners, mine operators, and regulators have all voiced the need for a method to expedite the bond release process. Time required for productivity validation with yield tests over time may be ten times that required for extraction and reclamation. A soil based method of productivity validation will provide the shortest period of time that the land will be out of normal production. In addition, such a method would identify problem fields soon after reclamation. Currently, fields undergo ten years of yield testing before a problem becomes evident. Then, after remediation, another period of testing is required.

The scope of this project includes evaluating a method of collecting point source data using commercially available sensor technology. Digital cones provide simple, easy-to-use Cone Penetration Test (CPT) measurements in a compact and rugged system. Data collected down hole is transmitted in ASCII format providing complete compatibility with commercially available laptops as well as data acquisition systems. A fully loaded probe configuration might include tip load (penetration resistance), sleeve friction (texture relationship), pore pressure, soil moisture, resistivity (electrical conductivity), temperature, inclination, and video. The video cone penetrometer permits a unique “look” at texture, grain size, color, and other subsurface soil features. A soil moisture and resistivity (SMR) probe provides real-time, in-situ volumetric soil moisture data as well as resistivity data without costly and time consuming soil sampling that has been done in the past. The SMR module takes advantage of a relationship between the soil dielectric constant and moisture, widely known as Topp’s Equation.

Field productivity is very complex and involves not only characteristics of the field itself, but also management decisions and stochastic variables (i.e. weather), which bring statistical estimation methods into play. An inability to account for spatial structure is largely responsible for the poor performance of models developed in the past. Fortunately, much faster computers and new spatial and geo-statistical techniques now exist. With this technology, it was expedient that modeling move beyond the small plot work that makes up existing baseline data. Thus, this work characterizes whole fields and develops a probabilistic model that estimates the probability of a given field, or portions of a field, meeting the requirements of a soil based bond release approach.

Characterization work involved four tasks. In Task 1, soil characterization and terrain, weather, current and historical crop management, and yield data were acquired, as suggested in the literature, with a minimum of 100 probe locations per field. In Task 2, Task 1 data was used to build electroconductivity maps, digital elevation models (DEM), associated terrain derivatives and detailed maps for each field of compaction (a first order
variable), water holding capacity and root limiting depth (second order variables). These maps are produced using variography and kriging, tools of spatial statistics. Error assumptions are checked by taking independent validation points at random field locations. The product is a large set of maps characterizing physical soil characteristics in the field with a known accuracy level. In Task 3, yield data was acquired from each field with a calibrated GPS equipped yield monitor at 1-second intervals to determine which soil field characteristics are responsible for unacceptably low yielding areas or fields. This produces data sets showing yield and characteristics for small subsections of each field. Finally, in Task 4, all data is compiled into statistical field productivity and soil characterization models used to identify groups of soil characteristics responsible for yield variability and what effect changes will have on reclamation compliance.

CPT data was collected at five sites in Indiana and Illinois from 2005 through 2008. These sites are the Lewis Mine and the Cannelburg Mine operated by Solar Sources, Inc. in Vigo County Indiana and Daviess County Indiana, respectively; the Cypress Creek Mine operated by Vigo Coal Company in Warrick County Indiana; the Wildcat Hills Mine and the Cedar Creek Mine operated by Black Beauty Coal Company in Gallatin County Illinois and Schuyler County Illinois, respectively. At each location, systematic sampling grids were generated along with additional randomly spaced points within the field boundary using GPS mapping software. GPS navigational software guided the tractor/penetrometer to selected points on the grid for sampling.

Data analyses indicate that yield limiting factors are associated with soil structure and not soil fertility and that spatial correlation for the probe data does exist and, not surprisingly, it is complex. The data also suggests that there is a need to increase the number of samples taken at each location with 200 to 300 points per field estimated to be an adequate number for describing yield clusters. The first year data was used to develop preliminary statistical yield prediction models for two fields based on a selection of the variables sampled. Prediction variables were selected using the PROC STEPDISC procedure of SAS, a leading business analytics software company. For example, two significant variables were tip strength, representing differences in how compacted layers influence crop yield, and elevation, which impacts water flow and accumulation and subsequent crop yield. The predictive models show the ability to predict yield on points that were not used to develop model parameter estimates meaning that future algorithms could be used to predict yield clusters in fields that have never been sampled for yields.

Work continues to increase the mine database with new sampled fields and additional data collected at previously sampled fields. Soil based models to predict yield on coal-mined lands continue to be developed and tested. Additionally, recommendations (number of samples, time of sampling) for sampling mined lands are being established. Results have shown to date that penetrometer and water related (electrical conductivity, elevation) variables describe yield variability well across years, especially where compacted field areas are present. We conclude thus far that our soil modeling based approach is successful in delineating field areas with yield limiting problems, and thus may be used as a tool to address problems early in the bond release process and potentially speed up this process.
OBJECTIVES

The objective of this work is to develop a soil based approach that could eventually replace the current yield based approach for bond release. The soil based approach will use measurable soil characteristics to determine if a given reclaimed field meets the requirements of restoration of field productivity as outlined in existing federal and state regulations.

INTRODUCTION AND BACKGROUND

SMCRA requires the regulatory authority to find in writing that the operator has the technological capability to restore mined prime farmland, and in many states, crop land capable soils that are not classified as prime farmland. Restoration must occur in reasonable time, and crop yields and other productivity standards must meet or exceed levels of non-mined soils. The Office of Surface Mining Reclamation and Enforcement periodically reviews permits as part of its oversight responsibilities for each state program (Allen, 1992).

Most states require that success in revegetation of crop land be determined on the basis of crop production from the mined land area as compared to either an approved reference area or to other technical guidance procedures. Statistical procedures may be utilized to determine productivity success. If a statistical approach is used, productivity of the mined area shall not be considered equal (successful) if it is less than 90% of the production of the approved standard with 90 percent statistical confidence when planted to crops commonly grown, such as corn, soybeans, hay, sorghum, wheat, oats, barley, or other crops found on surrounding prime farmland. To demonstrate prime farmland productivity, the standards must be met in at least three crop years within the specified time period.

Some researchers, coal operators and regulators feel a need exists for a method to evaluate reclamation in the absence of either test plots or actual measured yields. This would involve the development of indices to predict productivity of crop lands after mining on the basis of their physical and chemical soil characteristics. Hammer (1992) proposes that a soil-based productivity index developed at the University of Missouri-Columbia may provide a conceptual framework useful for developing a productivity index suitable for reclaimed mine soils. The concept of the productivity index is that the soil environment affects root growth, and that plant yield will be proportional to root growth. In the Missouri model, five easily measured soil properties – aeration, pH, bulk density, potential available water-holding capacity, and salinity – were chosen to represent the soil environment. Development of a model to relate to environments found on mined land would provide an alternative to yield measurement systems.

Preliminary Studies: Barnhisel et al. (1992b) and Barnhisel and Hower (1994) looked at the development of a soil productivity index (PI) for use in prime farmland reclamation in the Midwestern cornbelt and collected data in Kentucky, Indiana, and Illinois. Soil parameters measured in this study included bulk density, cone penetrometer resistance,
water-holding capacity, P, K, exchangeable Al, particle size distribution, and pH. A four-year study was conducted to determine if corn yields could be predicted with the PI concept. Results were highly variable. Correlation coefficients between PI and yield ranged from near 0 to 0.76 from one field or mining method to another. Further refinement or weighting of components within the PI equation would be necessary to rely on a formula-based system to be used for bond release. However, the authors were not optimistic that this would result in a workable PI that would be able to consistently predict corn yield based on soil properties for disturbed prime farmland, as the data was site specific.

**University of Illinois Existing Baseline Data:** The basic approach to the soils based productivity concept is a comparison of soil attributes with known sufficiency levels. This determination considers controllable management factors such as fertility, pH, tillage practices, etc., since they are considered to be part of a sound, high level, crop management program. In order to establish a soil based approach, soil attributes were correlated with long-term yields from tests plots and field studies from previous research and with newly collected data in a large field scale scenario. The database for this study includes yields in a period from 1979 to 2004 at various research plots and field tests in Illinois and Indiana. Periods of time for individual test sites varies from 3 to 10 years. Reclamation methods included are scraper haul, shovel/truck, cross pit wheel, and wheel beltline, with and without various deep tillage methods. It is unique in that it contains a wide range of productivity – both success and failure – from long-term test plots. Soil attributes measured include percent organic matter, topsoil depth, tillage depth, soil strength, bulk density, texture, and coarse fragments.

**Existing Database Findings:** Research studies (Dunker et al., 1993) have shown that poor physical condition of the soil is the most limiting factor to successful row crop production on mined land. Critical to success are selection of the best available soil materials used in soil construction and a material handling method which will minimize compaction. Excellent corn and soybean yields have been achieved on low soil strength soils in high stress as well as low stress years. Total crop failures have occurred on high strength soils in years of weather stress. Some deep tillage practices have been successful in improving compacted soils, but it is preferable to avoid compaction when the soil materials are handled (Dunker et al., 1995a). Soil strength measurements taken with a cone penetrometer have proven to be a useful tool in evaluating rooting media and reclamation practices.

Segregation and replacement of horizons from the pre-mine soils is a practice that is required by law under many conditions. Early reclamation research was focused on the evaluation and characterization of selected soil materials to be used for soil horizon replacement or substitution to determine if the substituted soil material could be shown to be as productive as the natural soil horizon it replaced. Construction of minesoils with good quality soil materials and desirable physical properties is essential to attaining productivity levels necessary for bond release.
Greenhouse evaluation revealed that replacement or alteration of the claypan subsoils of southern Illinois would increase crop growth by enhancing the chemical and physical properties of mined land (Dancer and Jansen, 1981; McSweeney et al., 1981). Topsoil materials generally produced somewhat greater plant growth than did mixtures of B and C horizons, but the B and C horizon mixtures were commonly equal to or better than the B horizon materials alone. The natural subsoils of this region are quite strongly weathered and acid, or are natic and alkaline (Snarski et al., 1981). The alternative material mixed in or substituted was generally much higher in bases than the acid soils and lower in sodium than the natic soils. Liming and fertilizing of the soil horizon material produced a good yield response and reduced the need for material substitution. McSweeney et al. (1981) also got a favorable greenhouse response to blending of substratum materials with B horizon materials from the high quality Sable soils (Typic Haplaquolls) in western Illinois. This response to blending was less pronounced than that observed with materials from southern Illinois.

Topsoil replacement has generally been beneficial for seedbed preparation, stand establishment, and early season growth when compared to graded spoil materials (Jansen and Dancer, 1981). Yield response to topsoil replacement has ranged from strongly positive to strongly negative. At the Norris mine in western Illinois, replacement of 18 inches of dark prairie topsoil over graded wheel spoil resulted in a significant positive corn yield response in three of four years with irrigation and two of four when not irrigated. Soybeans responded favorably to topsoil in one of the two years studied (Dunker and Jansen, 1987a). Significant negative yield responses to topsoil occurred in years of weather stress. Year-to-year variation in corn yield was considerably greater on the unirrigated topsoil than the unirrigated wheel spoil. Compaction caused by the use of scrapers to replace topsoil is assumed to be the reason for low topsoil yields in years of weather stress. The zone directly below the topsoil has a bulk density of 1.7 to 1.9 g/cm³ and very low hydraulic conductivity.

Response to soil horizon replacement in southern Illinois has been less dramatic than has been observed at western Illinois sites. This is understandable considering that A horizons are more highly weathered and average 8 to 10 inches in depth compared to 14 to 18 inches in the highly productive western Illinois soils. At River King, in southern Illinois, topsoil replaced by scrapers over wheel spoils significantly increased corn yields in only one of eight years and soybeans in three of six. The River King site does have good quality spoil and rather mediocre topsoil.

Soil horizon replacement and thickness of soil materials from southern Illinois has been studied at the Captain mine where the natural soils have chemical and physical problems which limit productivity. The Captain wedge experiment was used to evaluate corn and soybean yield response to thickness of scraper placed rooting medium (0 to 48 inches thick) over graded cast overburden, with and without topsoil replaced. Yields of both corn and soybeans increased with increasing thickness of hauled material to about 24 to 32 inches in depth. Meyer (1983) found very few roots below the 60-cm depth and found that roots in the subsoil were largely confined to desiccation cracks. The subsoil physical condition can best be described as compact and massive with very high bulk density.
levels and poor water infiltration. These scraper built soils lack the macropore network needed to conduct water and to provide avenues for root growth. Corn yields achieved on these plots were equal to the permit target yield in only one of the twelve years studied (Dunker et al., 1992). Soybean response was similar with only one year in ten achieving target yield levels.

Corn and soybean response to mine soil construction with rear-dump trucks and scraper pans were studied from 1985 to 1991 in southern Illinois (Hooks et al., 1992). Two truck-hauled treatments, one which limited truck traffic to the spoil base only, and one which allowed truck traffic on the rooting media as it was placed, were evaluated. A third treatment consisting of entirely scraper hauled rooting media was included. The rooting media was comprised primarily of the B horizon of the natural unmined soil and all treatments had eight inches of topsoil replaced on the rooting media. Significant differences in soil strength, a measure of soil compaction, and row crop yields were observed among treatments over the seven-year period. The truck without traffic treatment produced the highest corn yields of any of the mine soil treatments and was comparable to the undisturbed tract in every year of the study. Yields from this study using the rear-dump truck system without surface traffic indicate restoration of productivity to pre-mine levels. Any traffic on the surface of the rooting media can significantly reduce productivity, and may require some level of augmentation to improve the physical condition of the soil. Yields of the scraper built rooting media were below acceptable levels needed for bond release. A thorough augmentation of the physical condition of the soil profile will be required to restore productivity.

Previous research (Dunker et al., 1995b) has indicated that handling topsoil and subsoil simultaneously with rear-dump trucks may be superior to using scrapers to place topsoil over truck-hauled rooting media. The truck placed topsoil/root media system yielded significantly higher than the topsoil replaced by scraper system and showed a 21% increase when averaged over a three-year period. Results from this experiment were highly variable, however, due to abnormal weather patterns over the three-year study.

The field research database includes 21 years of yield and soil properties data from research plots in Illinois and Indiana (Dunker and Jansen, 1987a; Dunker and Jansen, 1987b; Dunker et al., 1988; Dunker et al., 1992; Hooks and Jansen, 1986; Hooks et al., 1992; Jansen and Dancer, 1981; Jansen et al., 1985; Jansen and Hooks, 1988; McSweeney and Jansen, 1984; McSweeney et al., 1987; Snarski et al., 1981; Dunker et al., 1993; Dunker et al., 1994; Dunker et al., 1995; Dunker and Barnhisel, 2000; Darmody et al., 2001; Darmody et al., 2002). Initial results clearly confirm that subsoil soil strength and depth of tillage (or depth to a root restrictive contact) are the dominant independent variables over the wide range of productivity. Figure 1 is the correlation of mean soil strength in psi (9- to 44-inch depth) and percent long term undisturbed soil mean yields. This illustrates the same relationship discovered in earlier small plot research: yield decreases as soil strength increases. Soil strengths above 300-psi are limiting to root growth. In this area of the relationship, soil strength is the dominant factor determining yield. As soil strength decreases below that level, the soil becomes more favorable to root growth to the point where maximum rooting volume is available
and soil strength is less important. In areas where soil strength is favorable to root growth, other factors such as texture, water holding capacity, and porosity, begin to play a significant role in productivity.

Figure 1. Relationship of 9-44” Average Soil Strength and Yield Expressed as Percent of Undisturbed Nearby Soils with Similar Management

Depth of tillage, depth to a dense contact or root limiting zone plays a significant role in the minesoil evaluation. It relates to the available soil depth or soil volume favorable to support plant growth. Mean subsoil soil strength below 300-psi may indicate a uniform but marginal subsoil environment. It could also indicate a very favorable upper profile over a high strength lower profile, which could have superior productivity. While both values can be measured with the penetrometer, subsoil soil strength alone may not be adequate for the productivity formula across a wide range of minesoils.

Although this applied science project is focused on row crops, a soil based approach to reclamation success of prime farmland could be used to develop systems to evaluate other species and systems. Woolery et al. (2002) evaluated soil properties to predict forest productivity in Illinois and develop a site index. While that study did not involve spatial relationships, the technology and methodology used in this project could be applied in a forest situation to develop a site index for a particular tract based on spatial data.

The purpose of the study by Woolery and colleagues was to help explain and extrapolate expert site index value estimates for important tree species of southern Illinois soils. Statistical models were used to quantify the relationship between soil properties and expert-derived values for tree growth. Sixteen physical and chemical soil properties of 68 soils found in southern Illinois were used, along with published site index values, in a multivariate stepwise multiple regression analysis. The tree species selected for estimated site index regression were white oak (Quercus alba L.), yellow
poplar (Liriodendron tulipifera L.), and northern red oak (Quercus rubra L.). These tree species were chosen based on availability of site index data, site conditions required by the species, and ability to allow the prediction of tree growth for all soil series in the area. Stepwise regression procedures were used to select the most important soil parameters for each species productivity estimate from 16 original physical and chemical soil properties. The most important soil parameters in models to extrapolate site index predictions were total rooting depth, thickness of the A horizon, bulk density of the A and E horizon, bulk density of the subsoil, and percentage clay found in the B horizon. Parameter estimates were used to construct site index prediction equations. Soil property equations explained 61% of the variation in white oak site index estimates, 70% of northern red oak site index estimates, and 80% of the variation in site index estimates of yellow poplar. The projected productivity estimates will be useful to land managers who wish to allocate time and other resources to land based on the potential productivity of the site. Use of this method resulted in tree height growth projections for many soils published in regional soil surveys, including soils that currently lack forest cover and have high seasonal water tables or are subject to flooding.

Significance of Project: Since the passage of Public Law 95-87, the Surface Mining Control and Reclamation Act (SMCRA) in 1979, reclamation success on agricultural lands has been determined by long-term yield testing. This has required a long bond release period lasting ten years or more. Needs have been voiced by landowners, mine operators, and regulators for methods to expedite the bond release process. The financial burdens of annual cropping and field maintenance by mine operators and monitoring by regulators are of major concern. Landowners need to have the land returned to their production operations instead of being locked in the bond release process for a decade or more. A soil property based formula could relieve these financial burdens and ensure the most efficient process to return the productive soil resource to the landowner. In addition, this method also will identify problem fields immediately after reclamation. Currently, some reclaimed fields undergo several years of yield testing before a problem becomes evident. Then, after further remediation, an additional period of testing is required.

Time required for productivity validation with yield tests over time may be ten times that required for extraction and reclamation. A soil based method of productivity validation will provide the shortest period of time that the land will be out of normal production. When they were developed, the Illinois ALPF and the Indiana Yield Performance Standards were the best measure possible for productivity over time. Reclamation research was in its infancy, and the relationships of minesoils and crop productivity were not known. Today, after 25 years of reclamation research, the idea of a soils based productivity model for bond release could be a reality because of the large database on yield response to minesoil reclamation and new technology to accurately measure soil parameters on a spatial scale. If successful, this would result in reduced time and effort from all involved while not compromising the accuracy of productivity testing.
EXPERIMENTAL PROCEDURES

The scope of the project includes evaluating a method of collecting point source data using sensor technology. Such systems are available commercially. Digital cones provide simple, easy-to-use CPT measurement in a compact and rugged system. Data collected down hole is transmitted in ASCII format providing complete compatibility with commercially available laptops as well as data acquisition systems. Sensor specific data (calibration factors, serial numbers, and sensor type) are stored in each sensor module in the cone, and are automatically transmitted to the laptop or data acquisition system with each penetration. The digital design allows configuration of multiple digital sensors in a single cone with only four conductors, leaving six conductors for other special sensors. A fully loaded probe configuration could include: tip load (penetration resistance), sleeve friction (texture relationship), pore pressure, soil moisture, resistivity and soil conductivity.

Soil moisture, or the volumetric percentage of water in soil, has become an important consideration in the design of environmental remediation processes and agricultural planning, and it is one of the most fundamental factors influencing soil strength. Traditionally, soil moisture has been determined by time consuming and expensive soil sampling and desiccation. At best, these methods generate discrete points of information and require many days of field and lab work. A soil moisture and resistivity (SMR) probe will provide real-time, in-situ volumetric soil moisture data as well as resistivity data without costly and time consuming soil sampling. The SMR module takes advantage of a relationship between the soil dielectric constant and moisture, widely known as Topp’s Equation. This relationship is not strongly influenced by soil type and resistivity if the dielectric measurement is made above a critical frequency of approximately 30 MHz. The inner two electrode rings of the SMR module determine the soil’s moisture content by measuring the frequency shift of a high frequency excitation signal as it passes through the soil near the surface of the module.

A complete analysis of the existing baseline data from small plots was described earlier in this report. This effort indicated which soil characteristics describe yield differences. This was a very important and valuable first step since it indicated roughly the characteristics which should be concentrated on. It was assumed that while soil strength would account for a large part of the problem, other factors would also be found that are responsible and as a group provide a much clearer picture of what is going on in restored fields. Unfortunately, the vast majority of these baseline data is from small plots and was not recorded spatially. That is a common problem in much of the work that preceded the availability of high accuracy GPS. The lack of an ability to account for spatial structure is largely responsible for the poor performance of models developed in the past. In defense of those researchers, it should be noted that many of them were aware of the limitations of their models and analysis, but they could not do any better since they lacked not only location equipment (i.e. GPS and GIS), but they also lacked appropriate statistical methodology, computers, and software to address the problem. Fortunately, much faster computers and new spatial and geo-statistical techniques are now available. It is interesting to note that the geo-statistical techniques were developed by statisticians.
working with mining operations in which classical statistical methodology simply did not work. These statisticians developed the very earliest statistical theory behind these techniques in the mid 1970s through early 1980s and the combination of computer power and software to implement the theory has just become available for widespread use in the last five years.

In order to achieve the goal of developing a technique to determine if a given restored field meets the restoration requirements, it was absolutely essential that we move beyond the small plot work that makes up the existing baseline data base. This required the characterization of whole fields and the development of a probabilistic model that estimates the probability of a given field, or portions of a field, meeting the requirements of a soil based bond release approach. In the past, such models could not be developed since it was prohibitively difficult and expensive to collect the necessary characterization data. That has also now changed. With the advent of new technology, new statistical techniques and software, and improved computer accessibility, we now have the opportunity to produce and utilize probabilistic models. Even with soil characterization sensors we do not have the ability to actually measure every square inch of soil and therefore we must make the best use of what we do measure in order to estimate non-sampled areas. Soil scientists, environmental and mining engineers, and geologists have long used their understanding of the systems and processes they work with to supplement actual measures in order to estimate non-sampled areas. Good examples of this include the production of soil type maps or the estimation of soil fertility for a given field.

Field productivity is very complex and involves not only the characteristics of the field itself, but also management decisions and stochastic variables (i.e. the weather). Thus, while process understanding is useful and used frequently, it is incomplete and cannot produce a unique or precise answer. That is where statistical estimation methods come into play. Kitandis (1996) stated that statistics are best described as a guide to the unknown; it is an approach for utilizing observations to make inferences about an unmeasured quantity. Statistics is not a cookbook, but rather a rational methodology to solve practical problems. Proper use of statistical estimation methods complements informed process understanding and provides answers that are useful in making rational decisions. The main contribution of statistical estimation methods is that they help to determine how much weight should be given to various measures in order to compute best estimates and error bounds of these estimates, for the reality is that not all data is equally useful and can even be counter productive if not weighed appropriately. We believe that the situation we have with mine reclamation is essentially a statistical problem. The following is a brief discussion on how we intend to develop the probabilistic model.

We have the goal of a general soil based model that will work in numerous locations. We anticipate that the more general model will require additional information, but that should be reasonably straight forward since this work demonstrates the technique for model development. In each of the fields the following data will be acquired: soil characterization and terrain, weather, current and historical crop management, and yield. The soil characterization will come from a minimum of 100 sample probe locations per
field as suggested by Webster and Oliver (1992). Terrain data will be acquired and used to build electroconductivity maps, digital elevation model (DEM) and associated terrain derivatives. These ancillary terrain and electroconductivity data will be used to guide sampling in order to insure that sample data are spatially dependent and to avoid the use of a reconnaissance survey or two-phase sampling technique (Kerry and Oliver 2003). We will use the characterization data from the 100 sample points in combination with the ancillary data to produce detailed maps for each field of each of the first order variables, i.e. compaction, as well as second order variables, i.e. water holding capacity and root limiting depth. The maps will be produced with variography and kriging which are tools of spatial statistics (Webster and Oliver, 2001). Note that one of the major advantages of variography and kriging is that these techniques provide information on how confident we are about the maps. In short, we will know if the maps are doing a good job of estimating the values at the non-sampled places in the fields. Error assumptions will also be checked by taking independent validation points at random locations on the field. That is a very powerful and useful feature when making estimations. The product of this work will be a large set of maps which characterize the soil and physical characteristics of the field with a known level of accuracy.

Yield data was acquired from each field with a calibrated GPS equipped yield monitor on a 1-second interval. This produced thousands of yield points per field. Obviously yield is not constant across the field, but yield and soil property data will be at a consistent scale to provide information for the same geographic area. The goal was to determine which soil field characteristics are responsible for unacceptably low yielding areas or fields. To accomplish this we matched the yield data and characteristics data over the entire field. Thus, a data set that has the yield for a small area and the characteristics of that same area was produced.

A problem addressed at this point in the model development was that many of the things being measuring are not independent of one another. For example, the percent organic matter in a soil and the slope are related and it is accepted that one tends to find higher levels of organic matter in lower positions and depressions of the landscape and less organic matter in areas of high slope where soil erosion has occurred. The point being that if you know something about the slope at a location you also know something about the relative amount of organic matter you should expect at the location. In statistics, this is referred to as correlated data and it has been largely ignored in the past, but not without negative ramifications. It is those ramifications that have resulted in less than useful models in the past. Fortunately, statistical tools exist for this problem and they were used numerous times to address a host of problems in the general area of field productivity and soil characterization. Recent examples of our work range from soil variability effects on crop yield (Kravchenko et al., 1999; Kravchenko and Bullock, 2000a; Kravchenko et al., 2000; Martín et al., 2005), interpolation techniques of soil characterization data (Kravchenko and Bullock, 1999), economic optimality of crop inputs (Bullock and Bullock, 2000; Ruffo et al., 2005), soil mapping (Kravchenko and Bullock, 2002a), grain quality (Kravchenko and Bullock, 2002b) and water stress areas (Paz et al., 2002). The point to be noted is that these techniques have been used to solve a wide range of problems related to field productivity and plant performance. From these analyses, soil
characteristics, or more appropriately groups of soil characteristics, are identified that explain yield variability over the field. These will be the variables, or groups of variables, that need to be considered when assigning the probability of a given area of a field meeting or failing the productivity restoration requirements for any given year.

The advantage of assigning probabilities to our prediction is that it will quantify what is obvious to all involved in that a given field does not necessarily meet the requirements each year due to interactions with weather and current yield estimation techniques. Our work will also involve simulation routines that will allow us to compare different methods of validating field productivity. For example, we will be able to simulate harvesting small portions of fields versus large portions of fields and the effects of unusual weather patterns. All simulation routines will be done with actual 100-year weather data sets. The product of this work will be useful in any discussion of changing how fields are evaluated for compliance.

RESULTS AND DISCUSSION

Tasks 1 and 3: Collect Soil Property Characteristics and Yield Data from Sampled Fields

A digital probe capable of recording tip stress, sleeve stress, and soil moisture and resistivity was acquired from Applied Research Associates, Inc. of South Royalton, VT in June 2005 (see Figure 2).

Figure 2. Applied Research Associates Inc. Digital Cone Penetrometer Configuration Drawing and Photo of University of Illinois System

The penetrometer push system consists of a modified tractor mounted soil probe from Giddings Machine Company (Model GSRT, Colorado Springs, CO) equipped with a sub-meter GPS receiver from Raven Industries Inc., Sioux Falls, SD (see Figure 3).
This system incorporates the vast improvements made in penetrometer technology over the last ten years, particularly the ability to measure other soil parameters besides penetration resistance. Penetration resistance (PR) is influenced by soil and probe characteristics. The soil-to-probe friction is governed by probe factors such as cone angle, diameter, roughness, and rate of penetration. Soil factors influencing PR include matric potential (water content), bulk density, soil compressibility, soil strength parameters, and soil structure. The ARA cone used in this study meets the specifications of the American Society for Testing and Materials (ASTM) Standard D3441-98-Standard Test Method for Mechanical Cone Penetration Tests of Soil.

Using this equipment, CPT data was collected at five sites in Indiana and Illinois from 2005 through 2008. These sites are the Lewis Mine operated by Solar Sources, Inc. in Vigo County Indiana; the Cannelburg Mine operated by Solar Sources in Daviess County Indiana; the Cypress Creek Mine operated by Vigo Coal Company in Warrick County Indiana; the Wildcat Hills Mine operated by Black Beauty Coal Company in Gallatin County Illinois and the Cedar Creek Mine operated by Black Beauty Coal Company in Schuyler County Illinois. The type of data collected and the time of collection at each site are identified in Table 1.
Table 1. Data Collection Status for Sampled Fields

<table>
<thead>
<tr>
<th>Data type</th>
<th>Cannelburg</th>
<th>Cedar</th>
<th>Cedar W.</th>
<th>Cedar S.</th>
<th>Cedar Wt.</th>
<th>Lewis</th>
<th>Lewis W.</th>
<th>Lewis U.</th>
<th>Wildcat</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPT data†</td>
<td>Oct. 05</td>
<td>Apr. 06</td>
<td>Nov. 06</td>
<td>Nov. 06</td>
<td>Sept. 07</td>
<td>Oct. 05</td>
<td>Jun. 06</td>
<td>Oct. 05</td>
<td>Oct. 05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sept. 08</td>
<td>Sept 08</td>
<td></td>
<td></td>
<td></td>
<td>Oct. 07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield data‡</td>
<td>Corn 05</td>
<td>Corn 06</td>
<td>Corn 06</td>
<td>Corn 06</td>
<td>Wheat 07</td>
<td>Soy 05</td>
<td>Soy 05</td>
<td>Soy 05</td>
<td>Wheat 06</td>
</tr>
<tr>
<td></td>
<td>Soy 06</td>
<td>Soy 07</td>
<td>Soy 07</td>
<td>Soy 07</td>
<td></td>
<td>Corn 06</td>
<td>Soy 05</td>
<td>Soy 07</td>
<td>Soy 07</td>
</tr>
<tr>
<td></td>
<td>Wheat 08</td>
<td>Wheat 08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Soy 06</td>
<td>Soy 07</td>
<td></td>
</tr>
<tr>
<td>Soil fertility data§</td>
<td>none</td>
<td>Yes</td>
<td>Yes</td>
<td>none</td>
<td>none</td>
<td>Yes, 08</td>
<td>Yes, 08</td>
<td>Yes, 08</td>
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<td>Elevation¶</td>
<td>Yes, 05</td>
<td>Yes, 06</td>
<td>Yes, 06</td>
<td>Yes, 06</td>
<td>Yes, 07</td>
<td>Yes, 05</td>
<td>Yes, 06</td>
<td>none</td>
<td>Sept. 07</td>
</tr>
<tr>
<td>EM 38 data#</td>
<td>none</td>
<td>Nov. 06</td>
<td>Nov. 06</td>
<td>Nov. 06</td>
<td>Sept. 07</td>
<td>Apr. 07</td>
<td>Apr. 07</td>
<td>none</td>
<td>Sept. 07</td>
</tr>
<tr>
<td>Aerial photos††</td>
<td>none</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>none</td>
</tr>
<tr>
<td>Weather data‡‡</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

† Cone penetrometer testing data.
‡ Georeferenced crop yield data.
§ Georeferenced soil fertility data.
¶ Elevation was collected using GPS software attached to an ATV.
# EM-38 electromagnetic induction EC meter (Geonics, Mississauga, ON, Canada).
†† Georeferenced, color infrared digital aerial photography.
‡‡ Weather data collected from the closest weather monitoring station to each field.
Within the Cedar Creek and Lewis Mine sites, four and three fields were sampled per site, respectively. Table 1 shows our continuous effort to increase our mine database with new sampled fields (Cedar Wt. and Cedar North) and additional data collected at previously sampled fields. For example, the number of fields with CPT measurements and yield maps has increased to accommodate a wide range of crop and soil variability. Additionally, we have focused on filling gaps in the database such as acquiring fertility data on all sampled fields at the Lewis Mine site. At each field, field boundary files were created using GPS mapping software (Trimble Navigation, Sunnyvale, CA) mounted on a tractor. The CPT data was collected by applying a systematic sampling grid to each field, then using GPS software to navigate to each sampling point. The sampling points along with their corresponding CPT readings were logged in ESRI shape file format (ESRI, 1999; 2002) for use in GIS (ArcView 3.3, ArcGIS 9.1). The following ArcView 3.3 screen shots (Figure 4) show our systematic sampling patterns for three consecutive years on the Lewis field.

![Figure 4. CPT Sampling Points for 2005, 2006, and 2007 on the Lewis Field](image)

Task 2 and 4: Map Generation, Model Development and Validation

Previously, we have identified easily measured variables that describe yield variation seen at our sampled mine sites. From our work, we have been able to construct statistical models with which to predict future yield potential on mine fields in reclamation using only soil properties. Our model building process requires sufficient data to not only account for spatial variation within a field, but also temporal variation. In the Lewis field, we have accounted for temporal variation by obtaining three separate penetrometer sets (October 2005, May 2006, and September 2007) and spatial variation by obtaining data for over 200 combined field points. In addition to developing statistical models, we believe it is important to assess the precision of CPT data and other measured variables. Previously, we were not able to do this because our data sets were too small and did not provide us with much information on temporal effects. By characterizing the precision of our CPT data, we hope to not only develop better yield prediction models, but to develop a detailed sampling protocol for use by mine regulators, landowners, and farmers.
Figure 5 shows soybean (2005 and 2007) and corn (2006) yield for the Lewis field. Looking at the crop yield across time, the northern half of this field consistently yields more than the southern half. Interestingly enough, the northern and southern halves of this field were reclaimed at different times and using different methodology. The northern half was reclaimed using rear-dump trucks; however, the southern half was reclaimed using the scraper pan method. It is apparent just from the yield figure that variability exists within the Lewis field and across time; hence, CPT measurements may act similarly.

In order to facilitate analysis of CPT data sets, data was distinguished by year and by depth segment. Depth segments include 9 to 18 inches, 18 to 27 inches, 27 to 36 inches, and 36 to 45 inches. In this analysis, the only focus was on the tip stress (TS) variable which has previously shown to be related to crop yield. Figure 6 shows that CPT data, in particular the variable TS, varies by year and depth segment. While the time of data collection for these TS data sets varied (2005 and 2007 were taken in the fall, 2006 was taken in the spring), so did weather patterns (see Table 2). During CPT sampling, soil conditions were much drier in 2005 and 2007 when compared to 2006. It is also of note that higher precipitation occurred in spring 2006 when compared to 2005, 2007, or normal precipitation. When looking at Figure 6, it appears that drier environments in 2005 and 2007 during sampling may have led to an increased detection of compacted areas in the Lewis field when compared to 2006.
Table 2. Mean Monthly Precipitation and Temperature at the Lewis Mine Site in Indiana

<table>
<thead>
<tr>
<th>Month</th>
<th>Normal†</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Precip‡</td>
<td>Temp§</td>
<td>Precip</td>
<td>Temp</td>
</tr>
<tr>
<td>Mar</td>
<td>3.68</td>
<td>42.7</td>
<td>1.25</td>
<td>39.2</td>
</tr>
<tr>
<td>Apr</td>
<td>4.14</td>
<td>53</td>
<td>3.3</td>
<td>57.4</td>
</tr>
<tr>
<td>May</td>
<td>4.43</td>
<td>63.6</td>
<td>2.75</td>
<td>62.1</td>
</tr>
<tr>
<td>Jun</td>
<td>4.18</td>
<td>72.3</td>
<td>2.74</td>
<td>75.7</td>
</tr>
<tr>
<td>Jul</td>
<td>4.53</td>
<td>76.4</td>
<td>4.25</td>
<td>77.3</td>
</tr>
<tr>
<td>Aug</td>
<td>3.89</td>
<td>74.1</td>
<td>3.9</td>
<td>76.8</td>
</tr>
<tr>
<td>Sep</td>
<td>3.11</td>
<td>67.5</td>
<td>3.33</td>
<td>71</td>
</tr>
<tr>
<td>Oct</td>
<td>2.83</td>
<td>55.6</td>
<td>1.25</td>
<td>55.9</td>
</tr>
</tbody>
</table>

† Normal precipitation and temperature values are based on 30 yr averages.
‡ Precipitation values are measured in inches.
§ Temperature values are measured in degrees Fahrenheit.
Figure 6. Variability of Soil Tip Strength by Year and Depth on the Lewis Field
Figure 6 also shows a decline in what can be identified as compacted areas of the field as soil depth increases. This may be due to the presence of a hard soil layer, which when broken through does not exhibit compaction qualities. For instance, note in 2005 and 2006 that, at moderate soil depth (18 to 27 inches), we are detecting compaction in the southern half of the Lewis field while at a deeper soil depth (36 to 45 inches), we are not detecting such a clear pattern.

Figures 5 and 6 have very close agreement between them, especially within a given year. In a non-moisture stressed year such as 2006, most of the northern half and even some of the southern half of the Lewis field achieved good corn yield. On the other hand, in a dry environment like 2007, soybean yield was much lower on the southern half and some of the northern half compared to 2005, which had more stable rainfall events. Combining information from the above figures suggests that areas of the Lewis field identified as compacted match yield patterns very well and have much greater influence on yield in dry seasons. Hence, in growing seasons with sufficient rainfall, a field with compaction problems is more likely to pass bond release than in dry growing seasons. This is due to the inability of plant roots to proliferate deeper into the soil profile and extract water in dry growing seasons.

While CPT sampling (in particular TS), seems to be dependent on the year in which it was sampled, clear trends exist in what we are calling compacted areas. For instance, we noted that the southern half of this field was reclaimed differently than the northern half and is potentially more susceptible to compaction. Across all years of collecting data, we see that the southern half of this field is identified as compacted and potentially yield limiting at moderate soil depths. In drier years we see that this pattern extends to a greater proportion of the field. In model building, we are able to account for this sort of yearly influence and identify potential underlying problems across seasons.
CONCLUSIONS AND RECOMMENDATIONS

In summary, we are continuing to increase our data set and are now able to assess the yearly effect on our CPT (TS in this report) data. We are currently developing and testing soil based models to predict yield on coal-mined lands and additionally developing recommendations (number of samples, time of sampling) for sampling these mine sites. We are encouraged by the close agreement of the TS data and yield in this report over time, and will use our other measured variables to enhance the predictive ability of our models. This work will also continue for our other sampled locations.

At this point, the models we have developed work very well for the Lewis field. Prior to wide spread use, each model needs to be generalized through more extensive validation, which is essentially testing the current model at more locations and under different weather conditions to better understand and predict interactions between weather and soil properties. This will not require that we develop any new methodology, for the current model attempt was successful. We propose that we expand this work by selecting new locations and repeating the work that we have accomplished at the Lewis site. The final product of the work will be models that are sufficiently general that they will be able to predict if a field will pass bond release standards.

REFERENCES


Jansen, I.J. and W.S. Dancer. 1981. Row Crop Response to Soil Horizon Replacement after Surface Mining. Symposium on Surface Mining Hydrology, Sedimentology and Reclamation, 7-11 December, University of Kentucky, Lexington KY.


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