A System to Evaluate Prime Farmland Reclamation Success Based on Spatial Soil Properties

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Abstract

Since the passage of Public Law 95-87, the Surface Mining Control and Reclamation Act (SMCRA) in 1977, reclamation success of prime farmland after coal mining has been determined by long-term crop yield testing. States such as Illinois and Indiana require that reclamation success be based on crop production of mined-land. This process often can continue for many years, especially for lands failing to meet production standards in a specified time period. Needs have been expressed by landowners, mine operators, and regulators for methods to expediate this process. A soil property based model could relieve this burden and ensure the most efficient process for returning the soil resource to the landowner. The objective of our work was to develop a soil-based model to replace the current crop yield-based system and to evaluate mined-land for diagnostic purposes. Georeferenced corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and wheat (*Triticum aestivum* L.) yield, cone penetrometer test (CPT), VIS-NIR spectrophotometer, apparent electrical conductivity (EC_a), elevation and terrain derivatives, fertility, and other site characteristic data were collected on fields at the Lewis Mine site in southwestern IN, the Cedar Creek Mine site in western IL, and the Wildcat Hills Mine site in southern IL. Soil-based productivity models were developed using regression and multivariate techniques to assign probabilities of meeting crop yield standards at the partial-field level. Our research indicates that soil compaction and water availability primarily influence a field's ability (bonding area) to meet crop yield standards across time. Model validation between fields and among sites has been encouraging, thus we propose modeling soil variability as a diagnostic tool to identify problematic field areas and to complement yield-based requirements.

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, 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 the 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 re-vegetation 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 100% 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 croplands after mining, on the basis of their physical and chemical soil characteristics. Hammer (1992) proposed 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 relatable to environments found on mined land would provide an alternative to yield measurement systems.

Preliminary Work

Barnhisel et al. (1992) 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 will 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 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 will be 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: success and failure from long-term test plots. Soil attributes measured include % organic matter, topsoil depth, tillage depth, soil strength, bulk density, texture, and coarse fragments.

Research studies (Dunker et al., 1993) have shown that poor soil physical condition 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., 1995). Soil strength measurements taken with a cone penetrometer has 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, 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 natric 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 natric 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 in 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 Mg m3 and very low hydraulic conductivity.

Response to soil horizon replacement in southern Illinois has been less dramatic than has been observed at the western Illinois sites. This is understandable considering that A horizons are more highly weathered and average 8-10 in. in depth compared to 14-18 in. in the highly productive western Illinois soils. At River King, in southern Illinois, topsoil replaced by scrapers over wheel spoil 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 in. 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 the 24-32 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 1985-91 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 8 in. of topsoil replaced on the rooting media. Significant differences in soil strength, a measure of soil compaction, and rowcrop 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 were 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., 1995) 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, R. E. and I. J. Jansen. 1987a, Dunker, R. E. and I. J. Jansen. 1987b, Dunker, R. E., I. J. Jansen, and W. L. Pedersen. 1988, Dunker, R. E., C. L. Hooks, S. L. Vance and R. G. Darmody. 1992, Hooks, C. L. and I. J. Jansen. 1986, Hooks, C. L., R. E. Dunker, S. L. Vance, and R. G. Darmody. 1992, Jansen, I. J., and W. S. Dancer. 1981, Jansen, I. J., R. E. Dunker, C. W. Boast, and C. L. Hooks. 1985 Jansen, I. J. and C. L. Hooks. 1988, McSweeney, K. and I. J. Jansen. 1984, McSweeney, K., I. J. Jansen, C. W. Boast, and R. E. Dunker, Snarski, R. R., J. B. Fehrenbacher, and I. J. Jansen. 1981, Dunker, R.E., C.L. Hooks, S.L. Vance, and R.G. Darmody. 1993, Dunker, R.E., S.L. Vance, C.L. Hooks, and R.G. Darmody. 1994, Dunker, R.E., C.L. Hooks, S.L. Vance, and R.G. Darmody. 1995, Dunker, R. E. and R. I. Barnhisel. 2000, Darmody, R. G., R. E. Dunker and R. I. Barnhisel. 2001, Darmody, R. G., R. E. Dunker and R. I. Barnhisel 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 % 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.

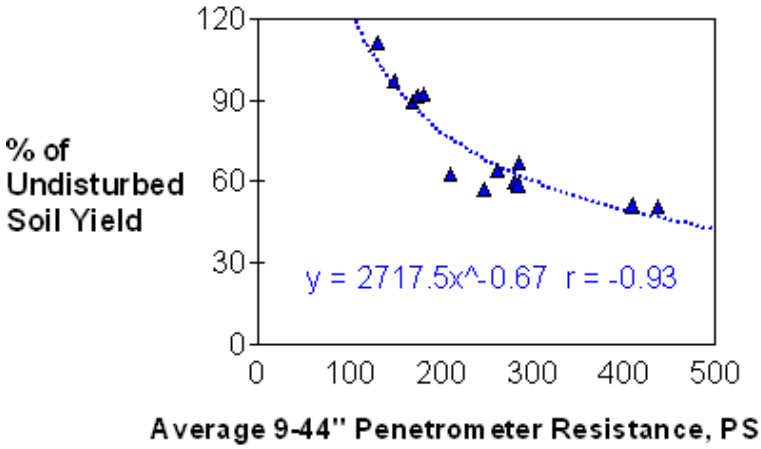

Fig. 1. Relationship of 9-44" Average Soil Strength and Yield Expressed as Percent of Undisturbed Nearby Soils with Similar Management

Depth of tillage, depth to a densic 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.

Project Description

The objective of this work was to develop a soil-based approach that could eventually replace the current yield-based approach for bond release. This soil-based approach uses 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.

Specific Objectives

- Expediate bond release process
- Save time and money required by bond release process and yield testing
- Increase precision over yield testing
- Provide detailed maps of reclamation efforts
- Provide recommendations for problematic field areas

Data Collection

Data was collected on coal-mined fields in reclamation at the Lewis Mine site (39°28'N, 87°24'W) and Cannelburg Mine site (38°64'N, 87°03'W) in southwestern Indiana, the Wildcat Hills Mine site (37°75'N, 88°35'W) in southern Illinois, and the Cedar Creek Mine site (40°13'N, 90°85'W) in western Illinois (Table 1, Fig. 2). Two adjacent 18 and 13 ha fields were sampled at the Lewis Mine site (Lewis and Lewis West fields). Similarly, two adjacent 9 and 11 ha fields were sampled at the Cedar Creek Mine site (Cedar and Cedar West fields). One 9 and 16 ha field was sampled at the Cannelburg and Wildcat Hills Mine sites, respectively. A 6 ha undisturbed reference field (Lewis Undisturbed) was also sampled at the Lewis Mine site.

Georeferenced corn, soybean, and wheat yield were obtained for the above fields, depending upon year and location. Yield data were recorded on 1-s intervals using a yield monitor (Ag Leader Technology, Ames, IA) equipped with a global positioning system (GPS) receiver. Yield data were cleaned for technical errors such as grain flow delay, pass delay, velocity and flow issues, manual border row corrections, and moisture adjustment when needed using the Yield Editor program (Sudduth and Drummond, 2007). After crop harvest of the first year of data collection, field borders of all sampled fields were mapped using a GPS Trimble unit (Trimble Navigation, Sunnyvale, CA) mounted on a tractor. Cone penetrometer test data (Applied Research Associates, Inc., Randolph, VT) was collected for all fields including multiple sets at the Lewis and Cedar Creek Mine sites, using an evenly spaced grid as a reference sampling guide. The cone penetrometer used in this research is mounted on a tractor and pushes a 3.57-cm diameter, 60˚ cone in to the ground at a rate of 2 cm sec^{-1} (Fig. 3). The penetrometer push system consists of a soil probe (Giddings Machine Company, Colorado Springs, CO) equipped with a sub-meter GPS receiver (Raven Industries Inc., Sioux Falls, SD). The probe is equipped with soil volume moisture (VM), cone tip strength (TS), and sleeve strength (SS) measurement sensors. One measurement, up to 1.2 m deep, was collected at each sampled point. Histograms of CPT data were reviewed and sample data was cleaned for errors resulting from the probe hitting rocks and electronic problems.

Elevation data was obtained in 1-s intervals for the Cedar, Cedar West, Lewis, Lewis West and Wildcat Hills fields in 2007 using a 4-wheeler equipped with a Geo XH unit (Fig. 3) and a Zephyr antenna (Trimble Navigation, Sunnyvale, CA). Approximately 1500 to 4000 elevation measurements were taken across these fields depending on field size, respectively, with an average distance between swaths of 15 to 30 m depending on diversity of topography (Kravchenko et al., 2000). ArcView Spatial Analyst (Environmental Systems Research Institute, 2002) was used to construct a digital elevation model (DEM) from the elevation data and to derive primary topographical features such as slope, aspect, plan and profile curvature (Ruffo et al., 2006). Elevation data were acquired for the Cannelburg and Lewis Undisturbed fields using the GPS receiver on the penetrometer.

Apparent soil electrical conductivity (EC_a) data were collected for all sampled fields, except Cannelburg and Lewis Undisturbed, at the same time and density as elevation measurements using an EM-38 electromagnetic induction EC meter (Geonics, Mississauga, ON, Canada) on a polyvinyl chloride (PVC) pipe sled pulled behind a 4-wheeler. The EM-38 was used in the vertical dipole position which is effective at soil depths of near 1.5 m (McNeill,

1992). Before data collection, the EM-38 was calibrated to specified levels as noted in the EM-38 instruction manual (Geonics Limited, 1998).

Spectrophotometer data was collected for the Lewis, Lewis West, Cedar, and Cedar West fields in the spring and summer of 2010 using a VIS-NIR Spectrophotometer probe (Veris Technologies, Salina, KS, USA). The probe acquires visible and near infrared absorbance, force (penetration resistance), and EC_a measurements in the soil to a depth of 1 m. Absorbance measurements have shown to be related to soil nutrients such as C, N, P, and K (Veris Technologies Research). Fifteen 1 m soil cores divided into 15 cm increments were collected for each sampled field for spectral calibrations. Calibrations were then used map soil properties according to procedures developed by Veris Technologies.

Table 1. Data collection for most frequently sampled fields.

	Cedar Site		Lewis Site		
	East Field	West Field	East Field	West Field	Undisturbed
Crop Yield	Corn 2006 Soybean 2007 Wheat 2008 Soybean 2009	Corn 2006 Soybean 2007 Wheat 2008 Soybean 2009	Soybean 2005 Corn 2006 Soybean 2007 Corn 2008 Soybean 2009	Soybean 2005 Corn 2006 Soybean 2007 Corn 2008 Soybean 2009	Soybean 2005 Corn 2006 Soybean 2007 Corn 2008 Soybean 2009
Soil Penetrometer	April 2006 Sept 2008	Oct 2006 Sept 2008	Oct 2005 June 2006 Sept 2007	June 2006 Sept 2007	Oct 2005
Spectrophotometer	June 2010	June 2010	May 2010	May 2010	None
Elevation	June 2007	June 2007	April 2007	April 2007	Probe Points
EM38 (ECa)	June 2007	June 2007	April 2007	April 2007	None
Fertility	None	None	April 2008	April 2008	April 2008
Weather	Yes	Yes	Yes	Yes	Yes

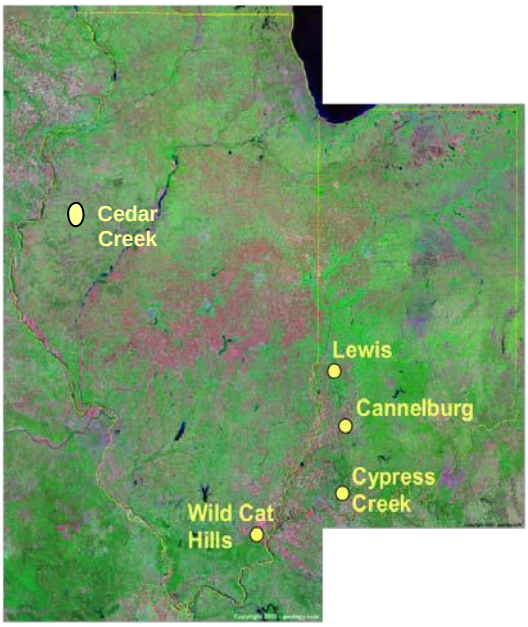

Fig. 2. Mine site sampling locations in Indiana and Illinois.

Fig. 3. Cone penetrometer (left) and elevation/EC_a (right) sampling equipment.

Model Development

Processing of Data

Cone penetrometer test data from each year and field combination were imported into SAS (SAS, 2002). Each dataset was then broken up into several soil depths (23-46, 46-69, 69-91, and 91-114 cm) corresponding to depth of penetration. Resulting penetrometer data sets consisted of 12 predictor variables and a differing number of observations depending on the field.

Crop yield, elevation, and EC_a estimates were obtained for each penetrometer point using kriging techniques. Estimates of primary topographical features such as slope, aspect, plan and profile curvature were made using a digital elevation model (DEM) developed for each field in ArcView 3.x (Environmental Systems Research Institute, 2002). In order to facilitate analysis, DEM cell sizes for deriving topographical variables were chosen to avoid unrealistic small cells in relation to collected elevation points. Estimates of secondary topographical features such as the topographic-wetness-index (TWI) (Beven and Kirkby, 1979) and the stream-power-index (SPI) (Moore et al., 1991) were made using the TOPOCROP-extension (downloaded from the ESRI website at http://arcscripts.esri.com) using ArcView 3.x (Schmidt and Persson, 2003). Specific calculations for these indices are found in their corresponding papers and also noted in recent literature (Zirlewagen et al., 2007). The TWI has shown to be related to soil water content (Chamran et al., 2002) and organic matter (Moore et al., 1993) while SPI has shown to be related to soil erosion (Moore et al., 1988). Estimates of soil nutrient properties, based on spectral calibrations, were selected for each penetrometer point and included into each field-by-field data set.

A depth to compacted soil layer variable was created by manually looking at TS as a function of soil depth in each penetrometer log file. A cutoff value of 450 psi was used to determine the presence of a compacted soil layer with each penetrometer reading. Starting at the soil surface and moving downward in the soil, once a TS value of 450 psi was reached, the soil depth that corresponds to this value was recorded. This procedure was used for all field penetrometer data sets and values were added to corresponding data sets.

Weather data was obtained for the Lewis and Cedar Creek mine sites over the years of which they were sampled. Monthly temperature and precipitation data were obtained from the nearest weather station to the research sites. Data were then pooled into four categories such as spring, summer, fall, and winter temperature and precipitation. These values were added to each corresponding research site data sets.

Model Building

Data sets were developed in SAS (SAS, 2002) and statistical analysis was performed using multivariate techniques. Because of the binomial nature of the bond release question (meet/fail to meet), the LOGISTIC procedure of SAS (SAS, 2002) was used to assign probabilities of meeting bond release for each sampled point. The logistic regression model compared to the simple linear regression model is as follows:

$$E(Y_i) = \pi_i = \frac{\exp(\beta_0 + \beta_1 X_i)}{1 + \exp(\beta_0 + \beta_1 X_i)}, \quad Y_i = 0,1 \qquad [4]$$

$$E(Y_i) = \beta_0 + \beta_1 X_i, \qquad [5]$$

Logistic regression is a more favorable alternative compared to simple linear regression when the response variable has only two possible outcomes. A major difference between models is that the simple linear regression model is linear in its parameters (no parameter is raised to an exponent or multiplied by other parameters), however the logistic regression model in is non-linear in its parameters. Because the response variable has only two outcomes, problems arise when applying a simple linear regression model (with the frequent assumption of normal error terms) to such data (Kutner et al., 2004). Because of these problems, analyzing binomial data using a normal error regression model with ordinary least squares is not appropriate (Kutner et al., 2004).

Because of overlapping information that many of the mine soil predictor variables contain (especially penetrometer variables), the variables are said to be highly correlated or exhibit high multicollinearity. That is, if two variables are highly correlated, they essentially describe the same phenomenon. One approach to reducing multicollinearity is to remove highly correlated variables and maintain variables that do not contain redundant information. This approach, however, disregards information contained in correlated variables. Another approach that accounts for this structure is to use multivariate techniques such as principal component analysis (PCA), factor analysis (FA), or canonical discriminant analysis (CDA) to determine the actual dimensionality of the correlated data set without eliminating variables (Johnson, 1998; Johnson and Wichern, 1998). These newly created variables can further be used in analyses like logistic regression without the previous issues associated with correlated variables. Figure 4 illistrates the use of PCA for variables measured on the Lewis East field. In Factor 1, soil related tend to group together as indicated by the (*) while in Factor 2, water related variables tend to group together.

Variable selection procedures exist in many statistical software packages that can solve the problem of correlated variables or utilize new variables developed by multivariate techniques. The STEPWISE variable selection method was used in the LOGISTIC procedure of SAS (SAS, 2002) to construct soil and weather based models for each field, along with a robust model containing information from all researched fields. Crop yield was standardized for all years within each field to put corn, soybean, and wheat yield on the same scale. Models were constructed taking into account yearly variation in crop yield, in reference to target crop yields needed to meet bond release standards for each field. These models were built using Indiana regulation in which crop yield targets are fixed across years and Illinois regulation in which crop yield changes thus accounting for yearly variation.

Initial Factor Method: Principal Components

Factor Pattern

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
SS46_69_07	92 *	12	-2	15	-10
SS69_91_07	88 *	-7	12	22	-3
TS46_69_07	88 *	10	-22	-11	-15
TS69_91_07	86 *	-9	22	8	-8
TS23_46_07	83 *	33	-16	10	-2
SS23_46_07	68 *	16	23	24	-20
SS91_114_07	66 *	-37	55 *	1	8
TS91_114_07	62 *	-36	58 *	-9	8
VM23_46_07	-51 *	-8	51 *	0	-19
aspect	-54 *	-26	29	6	0
elevation	8	80 *	25	-14	3
slope	-33	71 *	21	27	-40 *
plancurv	-5	57 *	41 *	-39 *	42 *
procurv	-9	-50 *	0	32	-1
twi	10	-81 *	-30	8	13
ec	-17	-8	52 *	51 *	-15
VM91_114_07	27	21	-38	66 *	22
VM46_69_07	-42 *	-6	49 *	57 *	34
stream	-42 *	6	-19	55 *	-45 *
VM69_91_07	2	37	-20	55 *	59 *

Fig. 4. Principal component analysis (PCA) using our measured data for the Lewis field in Indiana.

Significant variables in discriminating bond release outcomes were selected based on a model entry probability level of 0.10 and an exit probability level of 0.15 (Kutner et al., 2004). Once a reasonable subset of predictor variables was obtained, probabilities of meeting bond release were calculated for a given field. These probabilities (which correspond to a GPS logged penetrometer point) were then exported out of SAS and back into ArcView 3.x in order to develop a probability map for a given field. Probability maps were constructed for fields using their own data, between fields within a mine site, and validated among mine sites. A general flow chart of this process is seen in Fig. 5 below.

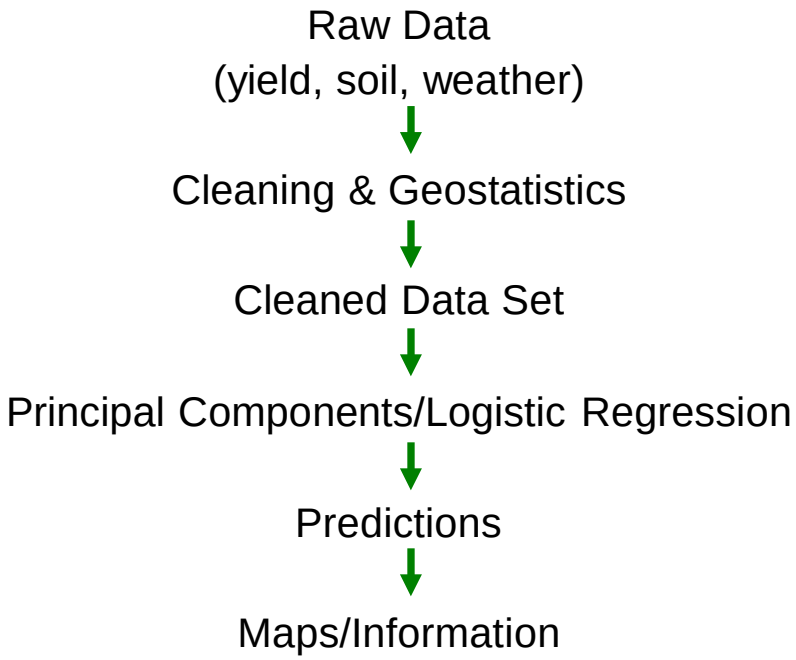

Fig. 5. Flow chart of model-building process.

Results

From our work, we have been able to construct statistical models which predict future yield potential (meeting a bond release standard) on mine fields in reclamation using only soil properties and weather information. Our models work very well for individual fields in which they were built upon. We have seen that certain measurements like compaction related variables (i.e. CTP tip strength, sleeve strength) consistently describe yield variation spatially and temporally. Thus, we believe an important next step is to sufficiently generalize our models to be robust across mine sites. Developing a model then validating it with independent data (such as another field or site) is the best way to assess a model's performance. An example of our work is shown below at the Lewis Mine site in Indiana using the Lewis East and Lewis West fields.and the Cedar Creek Mine site in Illinois using the Cedar and Cedar West fields (Fig. 6).

Fig. 6. Lewis Mine Site (left photograph) in Indiana and Cedar Creek Mine site in Illinois (right photograph)

Lewis East Field

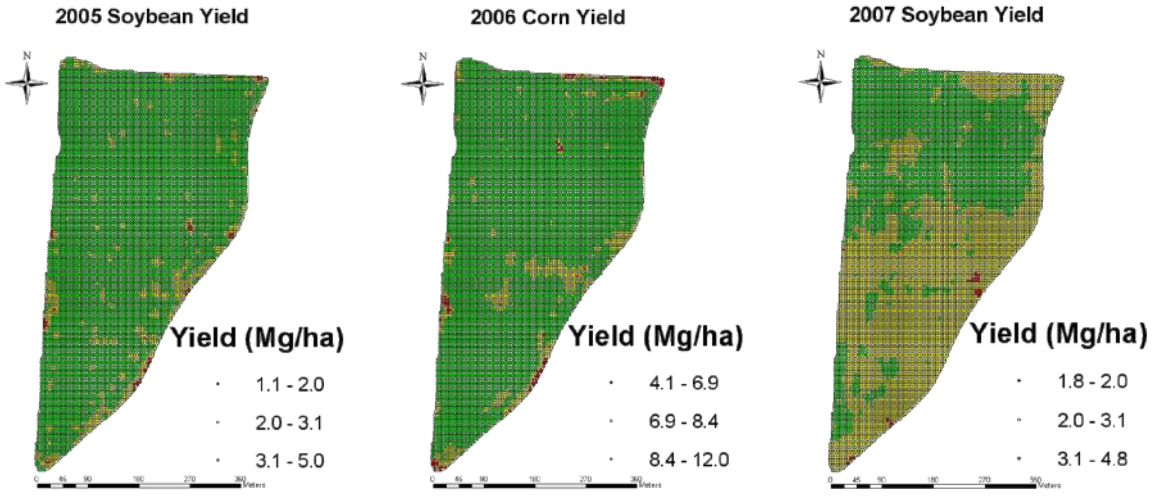

Fig. 7. Crop yield variability for 3 years on the Lewis field coded as meeting bond release standards (green portions).

Models were initially constructed on the Lewis field to account for three years of yield variability. Figure 7 shows the soybean (2005 and 2007) and corn (2006) yield. Looking at the crop yield across time, the northern half of this field consistently yields more than the southern half of this field. 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 dump trucks, however the southern half was reclaimed using the scraper pan method. Our penetrometer data (Fig. 8, 9) indicated that soil compaction is more prominent on the southern half, thus limiting crop yield potential. This trend is seen in all three years, however it is more striking in years with limited rainfall and when soybean was grown. This is in agreement with small plot data work from earlier research.

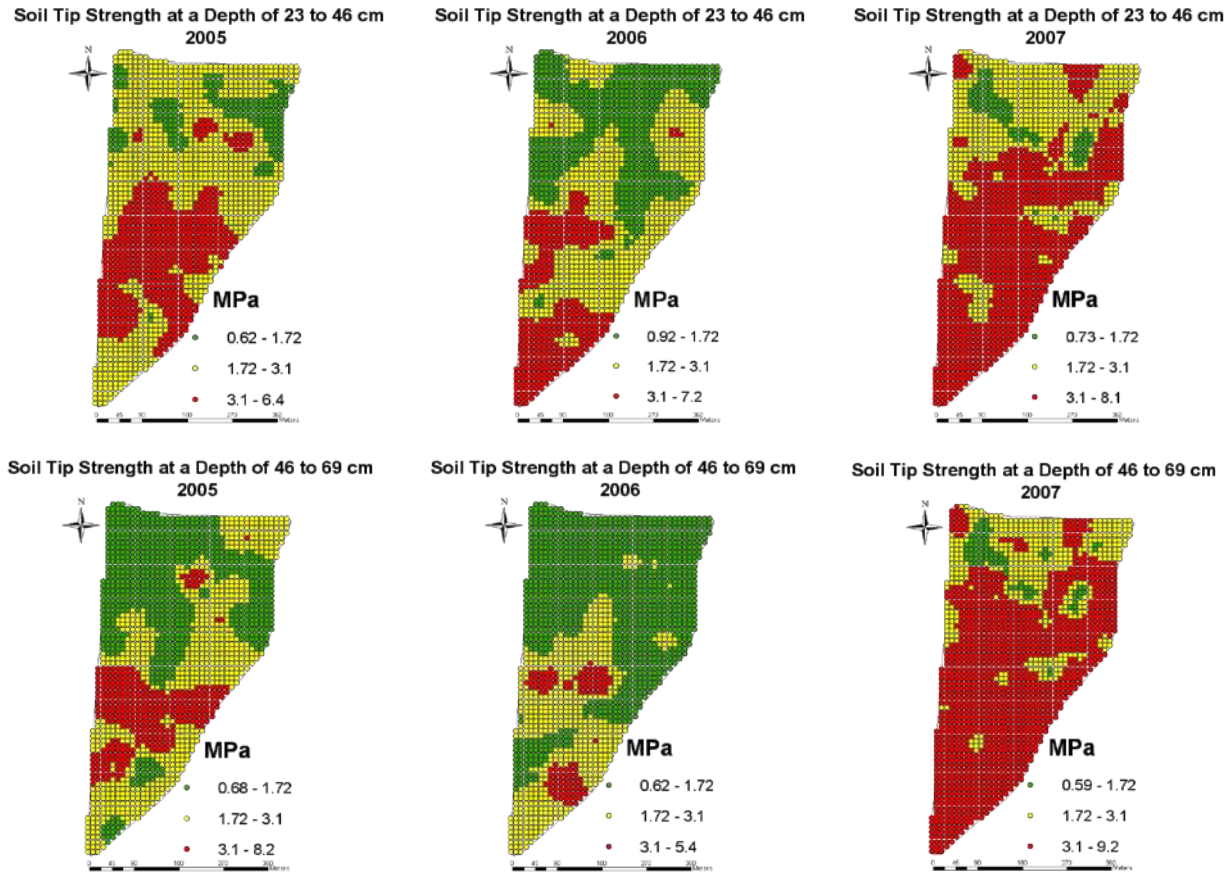

Fig. 8. Penetrometer readings organized by year (going left to right) and depth (going downward). Field areas coded in red signify compacted areas.

Figure 10 shows how the probability of bond release changes by year, crop, and weather patterns. Note that higher yielding areas each year were predicted to have higher probabilities of meeting bond release standards (darker green) although the only year in which yields were below the critical bond release levels was 2007. The areas of low yield seen in 2007 (Fig. 7) were predicted very well by the model and given less than a 1 in 4 chance of meeting bond release. We recently incorporated nutrient information into our model which has improved these predictions (Fig. 11, 12). Note the close resemblance between percent organic matter (OM), carbon (C), compaction and crop yield variability. While the southern half of this field exhibits

high compaction, it also is higher in percent OM and C. This is counterintuitive in that higher OM and C in soils are generally associated with higher crop yield potential. However, if compaction is present, crop roots cannot fully exploit such a resource, thus limiting crop yield. We can simplify the probability maps if we simply ask the question of whether or not a portion of the field met the bond release requirements (Fig. 13). Note the close agreement between the actual yield, which is the actual factor that determines meeting or not meeting, and the predicted probability generated by the model for the areas meeting the bond release standards.

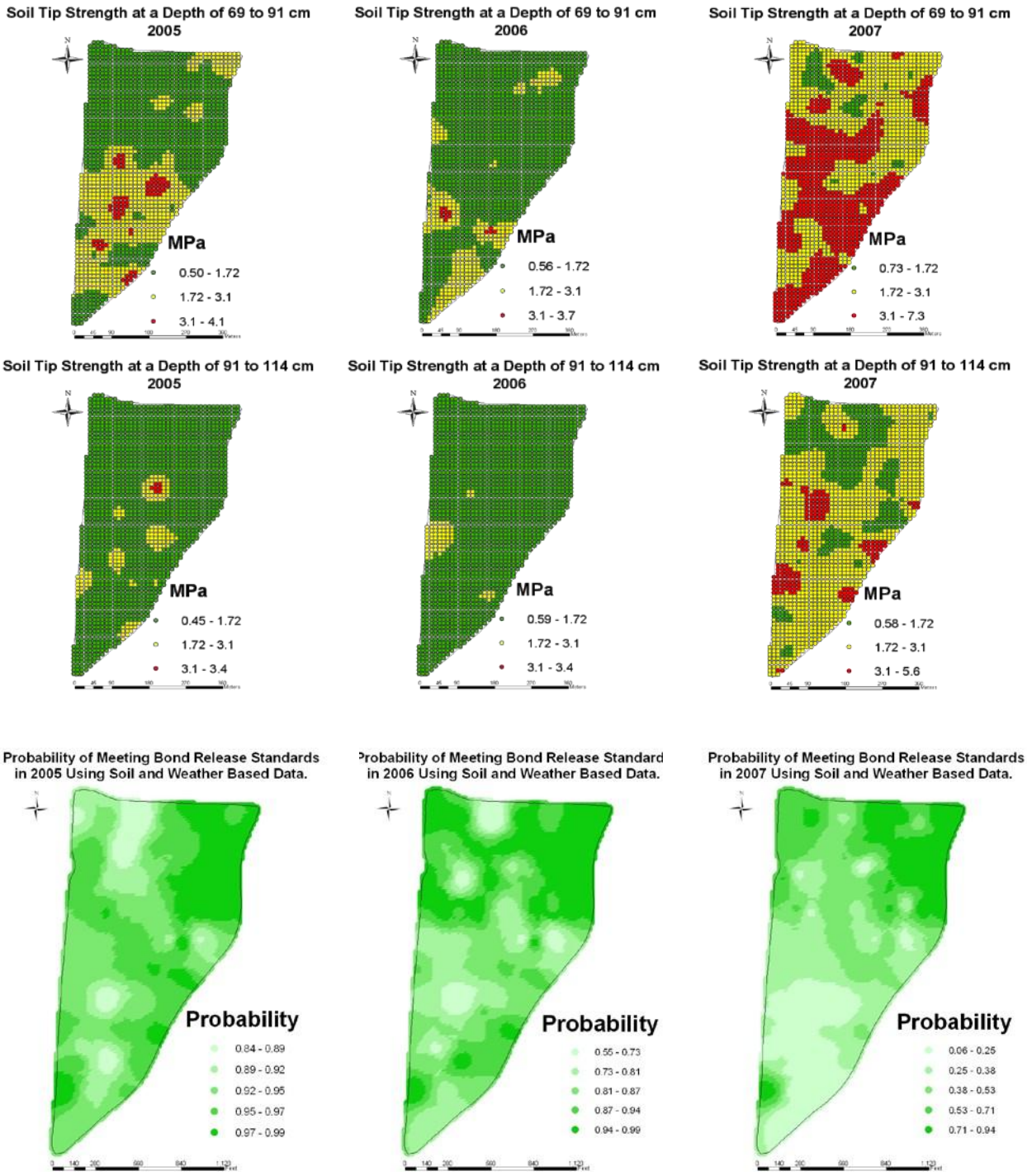

Fig. 10. Probability of meeting bond release standards across years for the Lewis field.

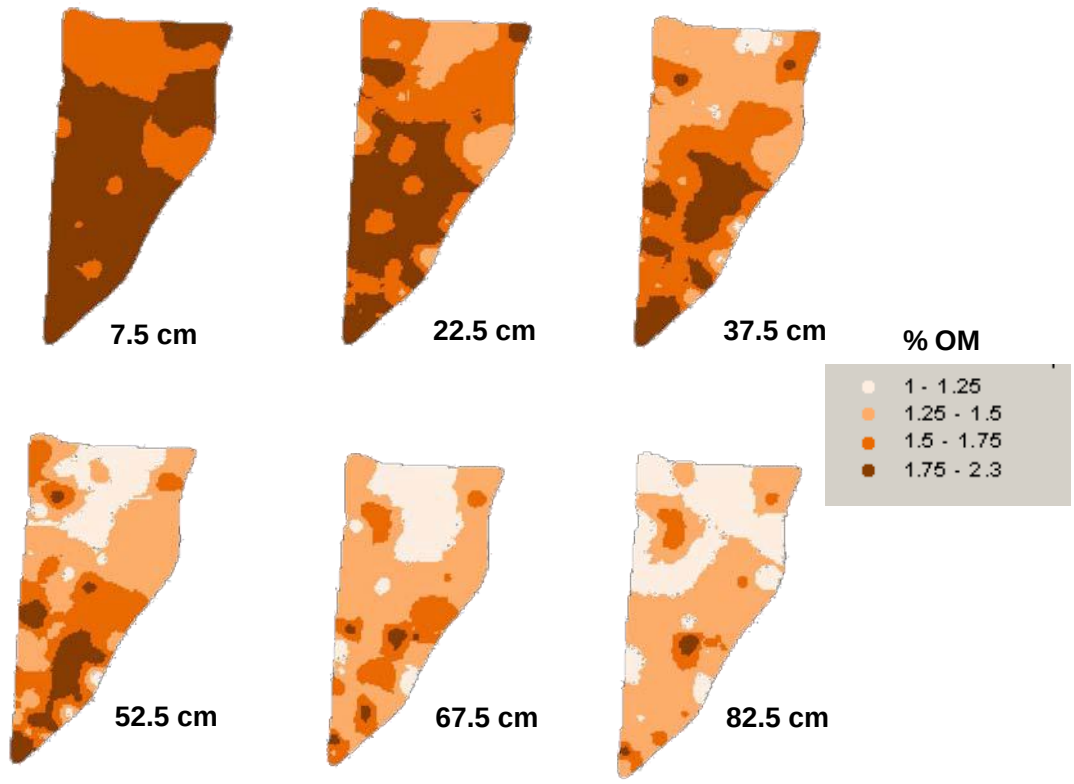

Fig. 11. Percent organic matter for the Lewis field, averaged every 15 cm in depth.

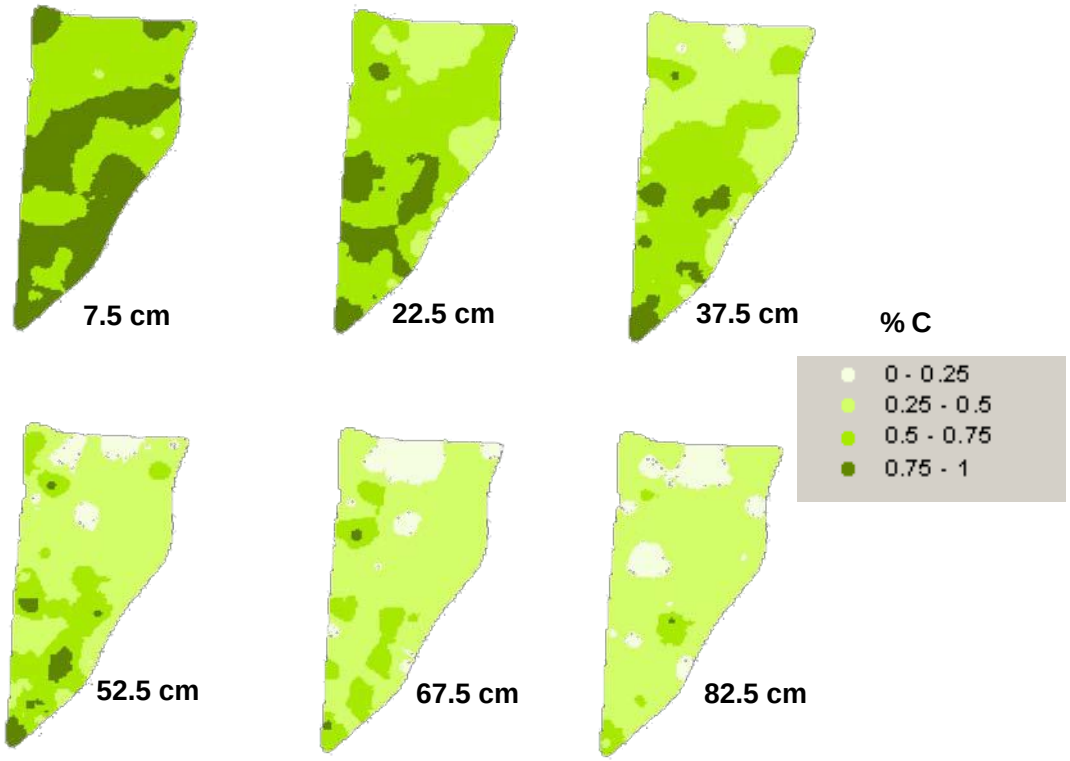

Fig. 12. Percent carbon for the Lewis field, averaged every 15 cm in depth.

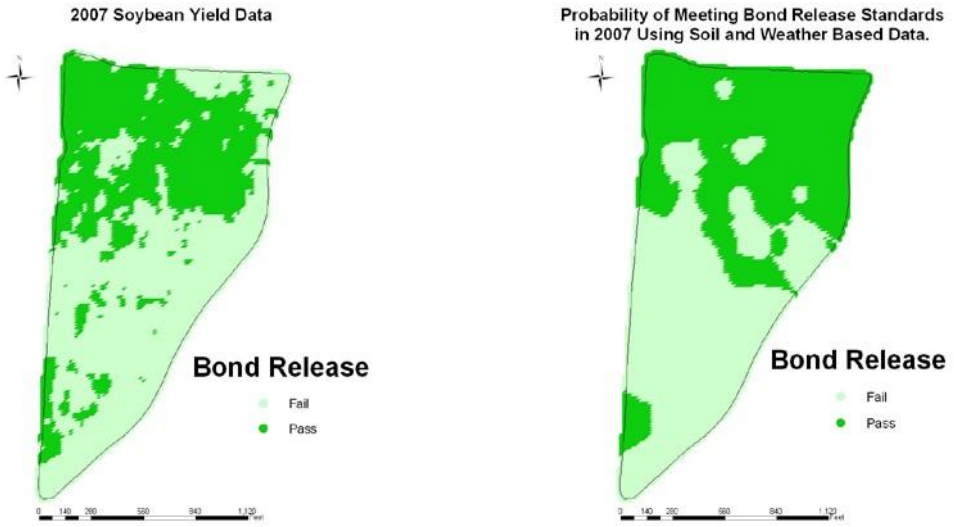

Fig. 13. Meet/Not Meet outcome for 2007 yield and model predictions of the Lewis field meeting bond release standards.

Lewis West Field

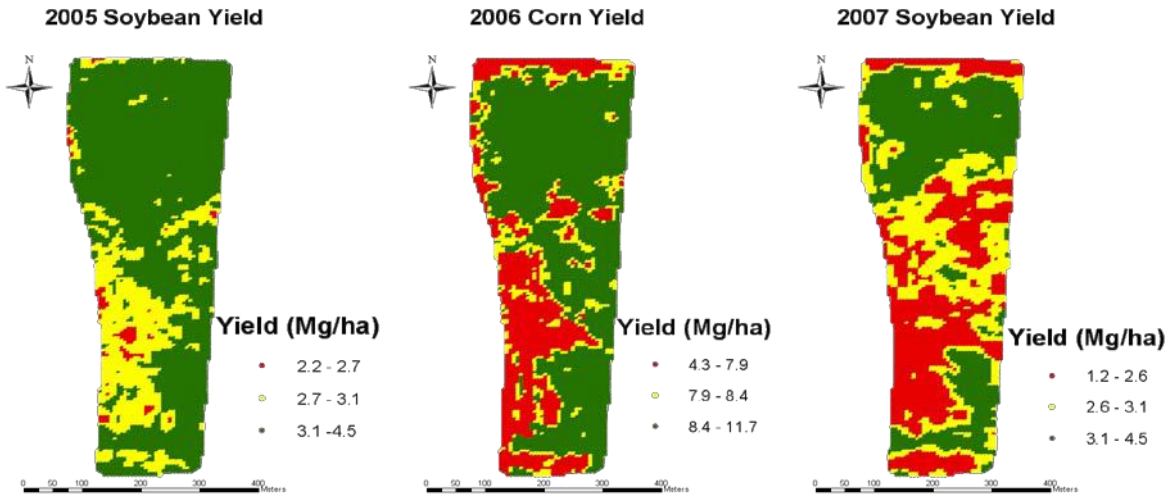

Fig. 14. Crop yield coded as meeting the bond release standard (green) across 3 years on the Lewis West Field.

Figure 14 shows how crop yield varies between 2005 and 2007 on the Lewis West field. While most of this field meets the bond release standard in 2005 and 2006 (field mostly green), in 2007 (a much drier year) the majority of the field does not meet this standard. Compaction (Fig. 15), enhanced even more by dry conditions, accounted for most of the yield variation seen

in 2007. While still present in previous years, adequate rainfall overcame compaction effects and yield reduction was not as prominent.

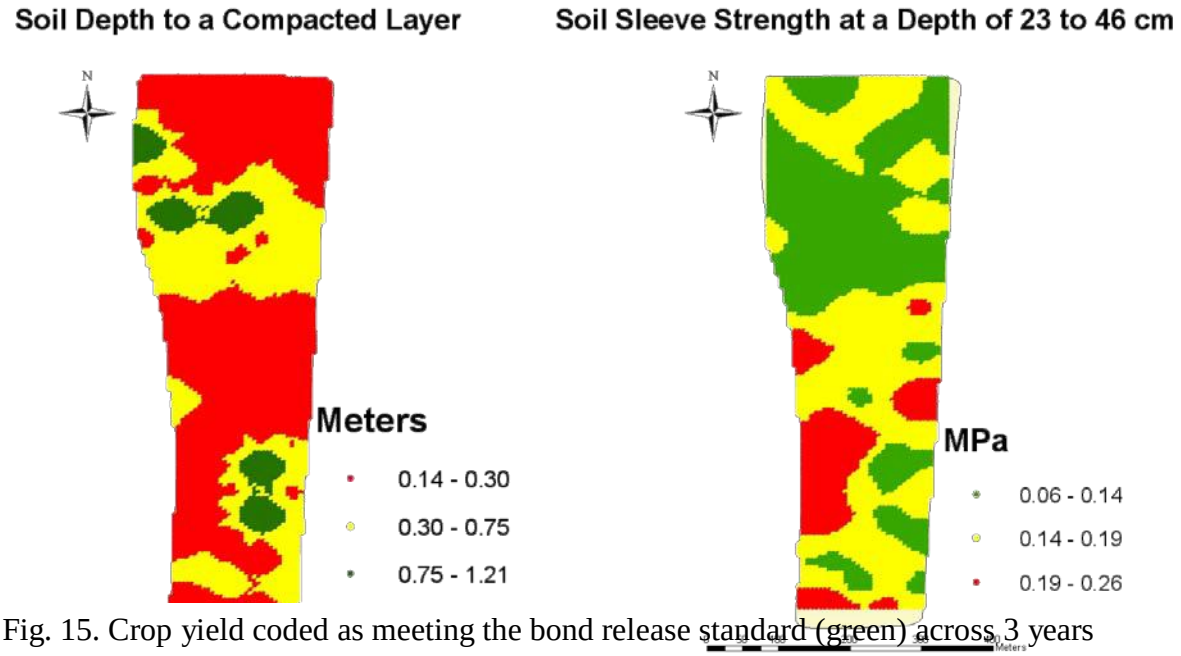

Fig. 15. Crop yield coded as meeting the bond release standard (green) across 3 years on the Lewis West Field.

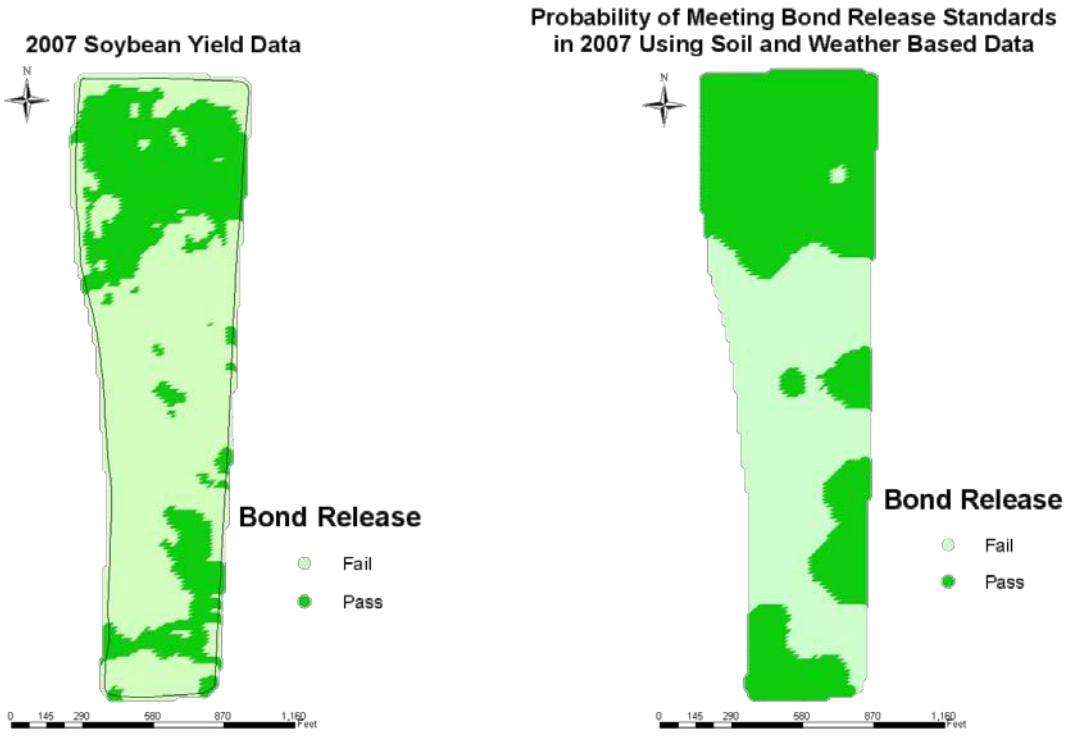

Fig. 16. Crop yield coded as meeting the bond release standard (green) across 3 years on the Lewis West Field.

Like the model constructed for the Lewis field, another model was constructed for the Lewis West field using similar variables. Again, using a simplified approach, very close agreement exists between the actual yield, which is the actual factor that determines meeting or not meeting, and the predicted probability generated by the model for the field areas meeting the bond release standards (Fig. 16).

Model Validation

The models described above were constructed individually for the Lewis and Lewis West fields, however validation of these models was not presented. Validation is defined as testing a model or models with an independent data set which was not used to construct the original model. The independent data set may be from another field on the same mine site or from a different site. The reason for testing a model with another data set is to determine how well the model works for other fields and ultimately develop a model robust enough to be used across mine sites for bond release assessment.

Validation of models between fields at the Lewis Mine site is presented in Fig. 17. The constructed model included the variables tip strength, sleeve strength, depth to compaction, elevation, and slope. A logistic regression model was developed using these variables to predict whether a given part of the Lewis West field would meet or fail to meet the bond release standard across time. The graphic on the left side of Fig. 17 is such a model constructed for the Lewis field and shows that the southern half of the field is predicted to fail in a dry environment. The graphic on the right side of Fig. 17 uses the model developed for the Lewis West field, however is applied to the Lewis field. What we notice is that these two figures are very similar visually speaking. This is very encouraging because it tells us that a model constructed for one field is generalizable to other fields with reasonable predictions.

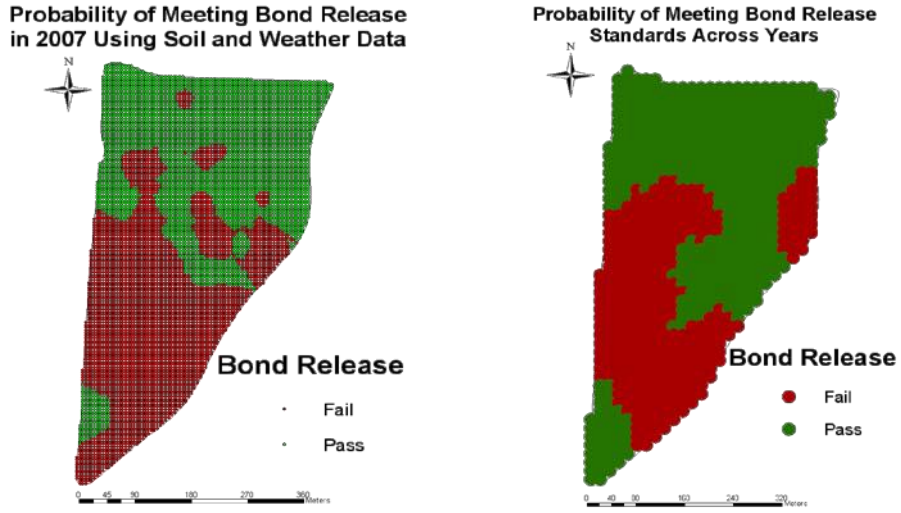

Fig. 17. Probability of the Lewis field meeting the bond release standard in 2007 using its own model (left figure) versus using a model developed for the Lewis West field (right figure).

Because the above model predictions show potential for predicting bond release within a mine site, we decided to further test our models using the Cedar Creek Mine site database in Illinois. Figure 18 shows an infrared aerial photo taken in spring 2004 and an aerial photo during mining and reclamation at the Cedar Creek Mine site. The two major fields from which we have sampled are overlaid as polygons. We will refer to the polygon on the right hand side as the Cedar field and the polygon to the left of that the Cedar West field. The small additional field on the far left is referred to as Cedar Slope, however it will not be included in this report.

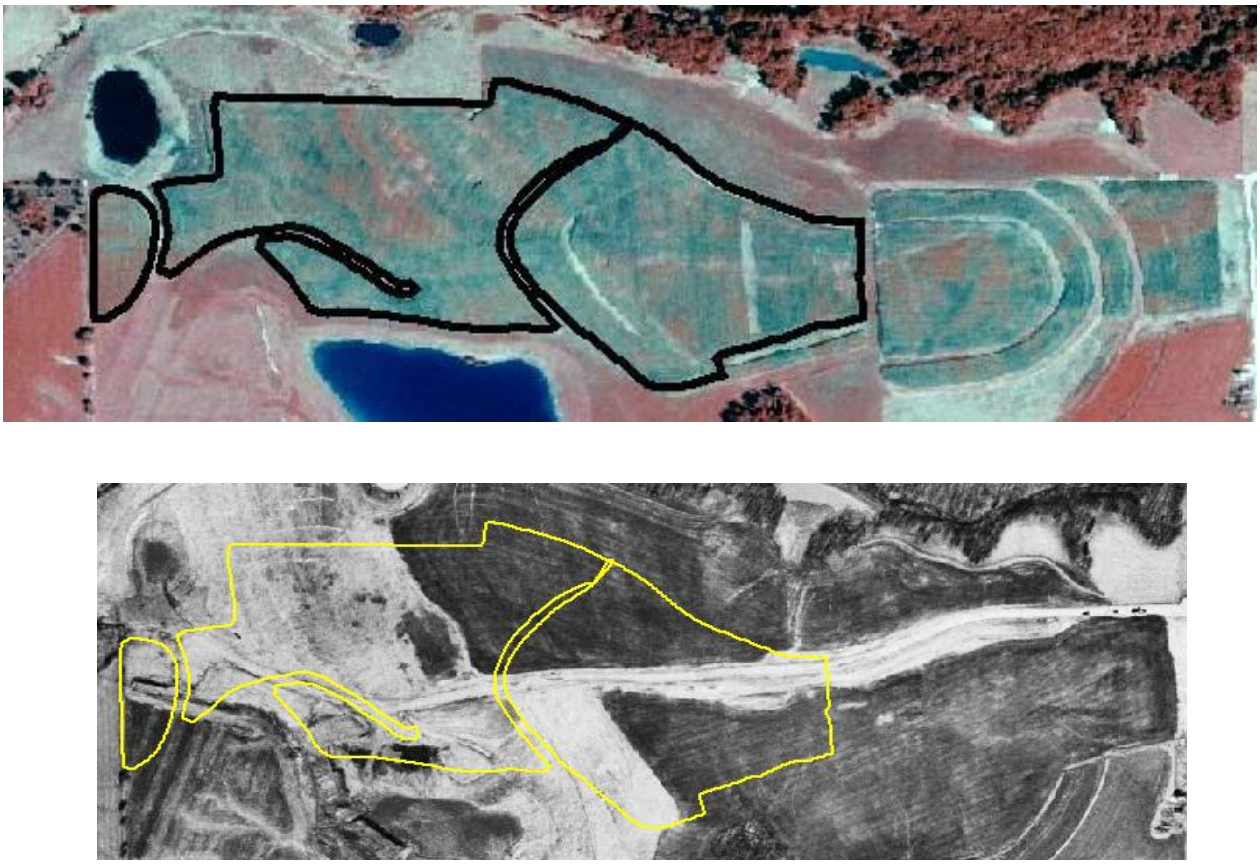

Fig. 18. Infrared aerial photo taken on April 2004 (top photo) and an aerial photo taken during mining and reclamation (bottom photo).

An example of corn yield variability across the Cedar Creek Mine site is shown in Fig.19. Interestingly enough, corn yield variability for the Cedar field seems to correspond well to the old haul road seen in Fig. 18. The highest yielding areas of this mine site are the south-central portion of the Cedar field and the middle portion of the Cedar West field as indicated by the darker green color.

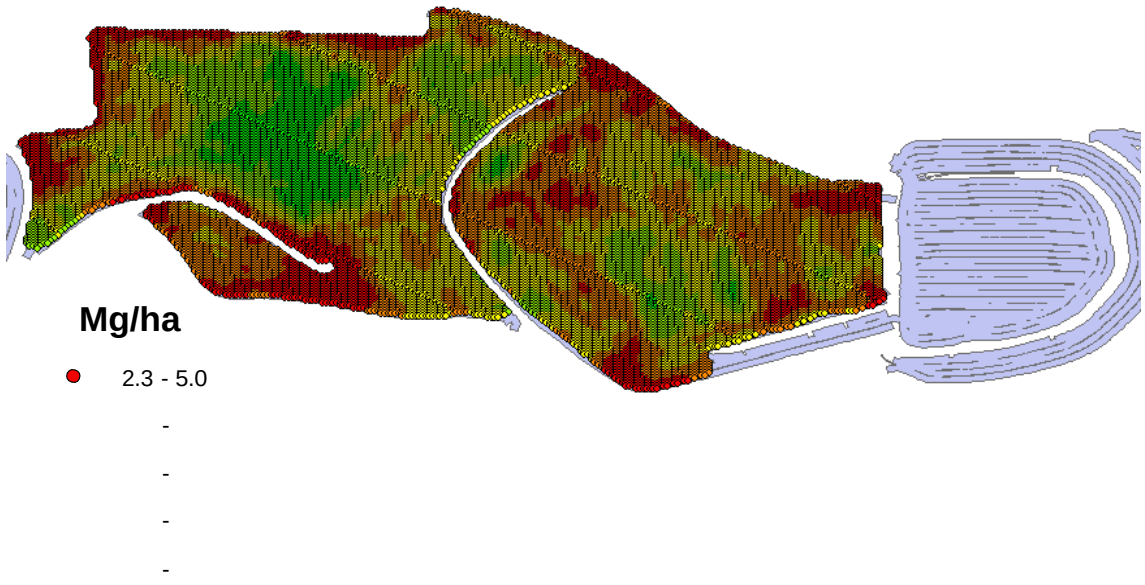

Fig. 19. Cedar Creek corn yield variability in 2006.

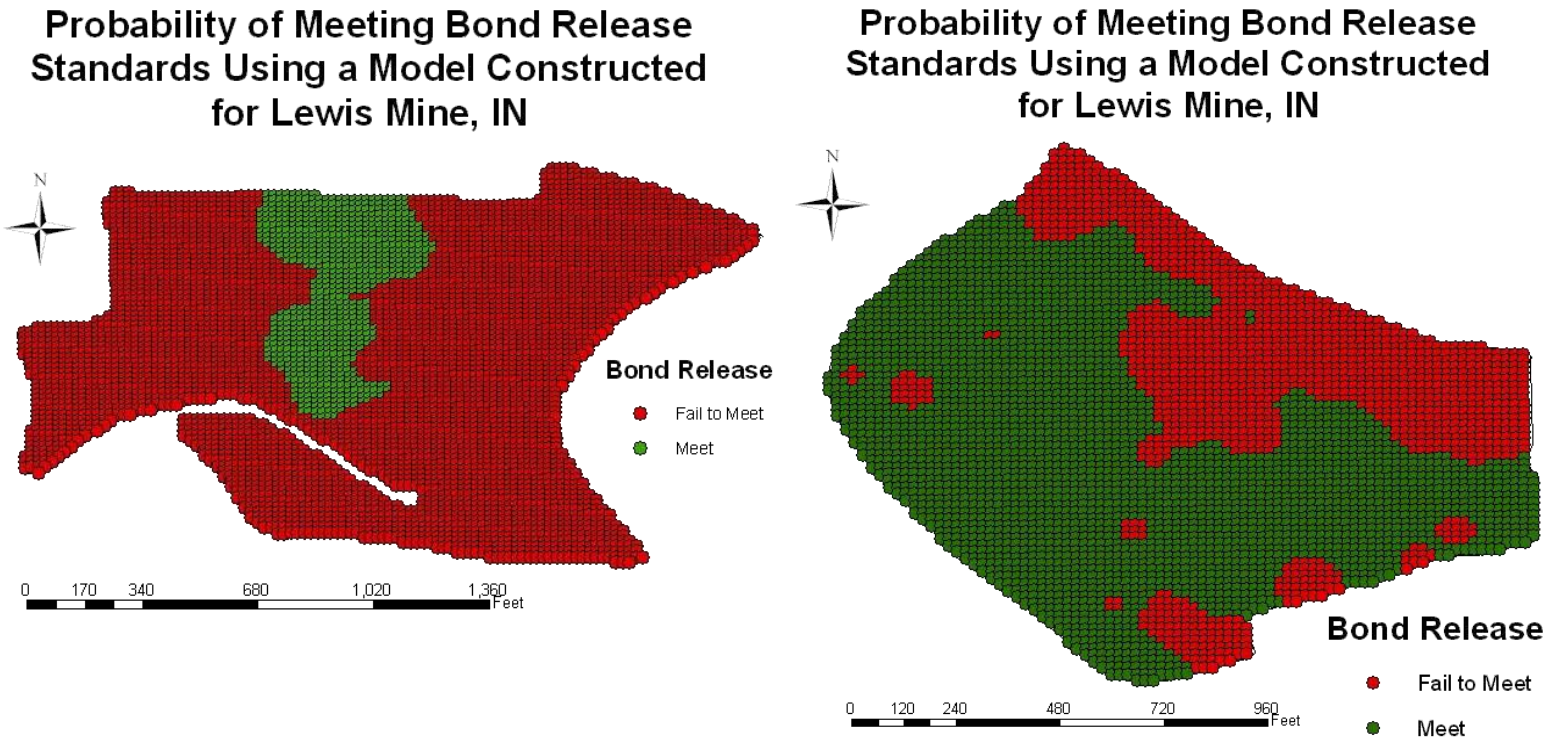

Fig. 20. The predicted probability for parts of the Cedar West and Cedar fields meeting bond release standards using a model developed for the Lewis Mine, IN. This model uses the bond release standards set for Lewis Mine, IN, not for the Cedar Creek Mine site.

Figure 20 shows the predicted probability for parts of the Cedar West and Cedar fields meeting bond release standards using a model developed for the Lewis Mine, IN. The constructed model includes the same variables as mentioned at the beginning of this report and was built using Lewis Mine crop yield targets, not the Cedar Creek Mine yield targets. The predicted probabilities in Fig. 20 are reflective of how a model built using Indiana bond release standards compares to Illinois standards. Interestingly enough, the predicted probabilities of meeting bond release standards in Fig. 20 correspond very well to corn yield variability in Fig 19. For example, the highest yielding portion of the Cedar West field is predicted as meeting bond release standards along with field areas around the old haul road for the Cedar field. While these areas are predicted as meeting bond release standards using the Indiana-based model, harvested yield on the Cedar Mine site routinely does not meet target yield in any field location using the Illinois-based system. Thus, while our model validation is successful in describing yield variability at the Cedar Creek Mine site, differences in regulation lead to different conclusions.

Conclusion

We are very encouraged by our model predictions in discriminating portions of fields that meet or fail to meet bond release standards across years. Models built using compaction and water related variables appear to be not only generalizable among fields within a mine site, but between mine sites.

In summary, successful soil-based models have been developed that adequately predict bond release. Compaction and water related variables are important in describing yield variation across years. We believe our soil-based modeling approach has clear benefits over the current yield-based system, thus we propose modeling soil variability as a diagnostic tool to identify problematic field areas and to complement yield-based requirements.

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