SESSION 7: SOILS AND OVERBURDEN

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CONSTRUCTING VEGETATION PRODUCTIVITY EQUATIONS BY EMPLOYING UNDISTURBED SOILS DATA: AN OLIVER COUNTY, NORTH DAKOTA CASE STUDY[1]

by:

Jon Bryan Burley[2], Kenneth J. Polakowski[3], and Gary Fowler[3]

Abstract. Surface mine reclamation specialists have been searching for predictive methods to assess the capability of disturbed soils to support vegetation growth. We conducted a study to develop a vegetation productivity equation for reclaiming surface mines in Oliver County, North Dakota, thereby allowing investigators to quantitatively determine the plant growth potential of a reclaimed soil. The study examined the predictive modeling potential for both agronomic crops and woody plants, including: wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), corn (*Zea mays* L.), grass and legume mixtures, Eastern red cedar (*Juniperus virginiana* L.), Black Hills spruce (*Picea glauca* var. *densata* Bailey), Colorado spruce (*Picea pungens* Engelm.), ponderosa pine (*Pinus ponderosa* var. *scopulorum* Engelm.), green ash (*Fraxinus pennsylvanica* Marsh.), Eastern cottonwood *Populus deltoides* Bart. ex Marsh.), Siberian elm (*Ulmus pumila* L.), Siberian peashrub (*Caragana arborescens* Lam.), American plum (*Prunus americana* Marsh.), and chokecherry (*Prunus virginiana* L.). An equation was developed which is highly significant ($p<0.0001$), explaining 81.08% of the variance (coefficient of multiple determination=0.8108), with all regressors significant ($p\leq0.048$, Type II Sums of Squares). The measurement of seven soil parameters are required to predict soil vegetation productivity: percent slope, available water holding capacity, percent rock fragments, topographic position, electrical conductivity, pH, and percent organic matter. While the equation was developed from data on undisturbed soils, the equation's predictions were positively correlated (0.71424, $p\leq0.0203$) with a small data set (n=10) from reclaimed soils.

Additional Key Words: landscape planning, soil science, prime farmland reclamation, agroecology

Introduction

Reclamation research has led to the formative development of empirical prediction models to forecast the suitability of reconstructed soils (neo-sols) to support plant growth. This approach can aid in creating post-disturbance landscapes usable for agriculture, forested lands, transportation right-of-ways, naturalized vegetation associations, and urban vegetation applications. These equations may render the current time consuming and expensive reclamation assessment methods such as reference evaluation procedures to become obsolete (Doll and Wollenhaupt 1985). This paper employs Oliver County, North Dakota as a case study to investigate some of these important landscape vegetation productivity research issues.

Investigators have pursued several different methodologies to generate vegetation productivity predictive models based upon soil characteristics (Burley 1995a). Dunker, *et al.* (1992) present a recent overview and findings associated with numerous predictive efforts. One methodology primarily developed in the United States is a technique we call the "heuristic sufficiency approach" which builds pseudo empirical models to predict plant growth. The problem with this approach is that the variables in the equation may be redundant and the equation may be over specific. The major problem with the sufficiency approach is it is non-statistical. Another approach is the "reclaimed soil approach" which has been pursued quite intensively by some investigators, especially in Illinois and Kentucky. This approach is certainly empirical and

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statistical; however, to build a model with strong external validity will require the detailed assessment of plant growth across hundreds of reclaimed soils, an expensive and time consuming approach. In the long term this model building approach based upon reclaimed soils is probably the most scientifically sound in methodology; however, the data base to build such models will require substantial research expenditures and currently, no research team has built such an extensive data set. At best most researchers have built reclaimed soil models from several soil types for several crop types. In contrast, data gathered from all crop types grown on all soil types will be necessary to build strong externally valid models. Nevertheless, one federal agency, the Natural Resources Conservation Service, has been spending approximately 1 million dollars per county to construct extensive data sets from primarily un-mined landscapes, recording soil characteristics including the growth of numerous vegetation types across all of the soils in a specific county. These data sets could form the basis for building predictive models, a "soil survey approach." A review of the literature and formative ideas associated with Soil Conservation Service soil survey data modeling approach can be found in Burley (1992). The methodological foundations for this approach were described by Burley and Thomsen (1987). Currently, several soil survey based productivity equations have been generated for particular counties in the United States of America. For Clay County, Minnesota, Burley *et al.* (1989) describes an equation useful in reconstructing landscapes for agronomic crops, Burley and Thomsen (1990) describe an vegetation equation for both crops and woody plants, and Burley (1990) presents a sugar beet (*Beta vulgaris* L.) equation. Burley and Bauer (1993) have described two equations for Polk County, Florida. Their first equation is applicable to woody plants and crops in upland landscape settings and the second equations is suitable for primarily lowland woody plants. The first two county equation was reported by Burley (1995b) where a vegetation model was developed for Clay County, Minnesota, and Cass County, North Dakota. In addition to generating equations, Burley (1994) presented the relationship of the equation approach to several state surface mining reclamation laws and regulations including the states of North Dakota, Wyoming, South Dakota, Minnesota, Michigan, and Indiana. Finally, Burley and Thomsen (1990) present an application of one equation to a mining site in Clay County, Minnesota. These studies form the essential literature associated with the soil survey predictive approach employed in this study.

Study Area and Methodology

Oliver County, a predominately agricultural landscape, resides in North Dakota's coal mining region. In a description of Oliver County's physiography, Weiser (1975:116) states, "Oliver County is on the western border of the area in North Dakota where soils formed in glacial deposits, and on the eastern border of the area where soils formed in residuum weathered from bedrock." Weiser (1975:1) notes that, "ninety-two percent of Oliver County is farmed. Most farms are a combination of livestock, feed-grain and cash-grain enterprises, but there are a few large ranches and cash-grain farms." Weiser (1975:1) also states, "The mining of lignite and the generating of electricity by coal-fired steam are of increasing importance to the economy."

Weiser (1975:113) presents a complete classification of each soil type examined in the study. Primarily the soils examined in this investigation are mollisols such as the Williams series (fine-loamy, mixed, Typic Agriborolls) and Mandan series (coarse-silty, mixed, Pachic Haploborolls). A few entisols are also included such as the Cohagen series (loamy, mixed, calcareous, frigid, shallow, Typic Ustorthents) and the Trembles series (coarse-loamy, mixed, calcareous, frigid, Typic Ustifluvents). Most of the soils are neutral or slightly alkaline. A few soils are saline in character. These soils comprise the physical substrates studied by Weiser. In the Oliver County study, 102 soil descriptions and associated crop production data were utilized.

The methodological approach was identical to the procedures described by Burley and Thomsen (1987) and reviewed recently by Burley (1996), where a soil depth weighting factor was applied to soil parameters (independent variables) and principal component analysis was applied to agronomic and woody plant productivity values (dependent variables) to search for covarying vegetation types. Both the dependent variables and independent variables selected for the study of Oliver County, North Dakota were derived from Weiser (1975). Multiple regression procedures were then applied to search for regressors which can predict plant growth for a linear combination of vegetation types. Table 1 lists the soil parameters employed in this study. The soil factors are similar to the factors selected in the development of previous studies, with the exception that bulk density soil profile values were not available for this study. Table 2 describes the vegetation variables selected in the study, including silage corn. The result of these

Table 1. Main effect independent variables and units of measurement from the U.S. Soil Conservation Service (Weiser 1975 and U.S. Department of Agriculture 1951).

Abbreviation	Factor	Unit of Measurement
FR	% Rock Fragments	Proportion by weight of particles > 7.62 cm
CL	% Clay	Proportion by weight
HC	Hydraulic Conductivity	Inches/hour (1 inch = 2.54 cm)
PH	Soil Reaction	pH
EC	Electrical Conductivity	Mmhos/cm
OM	% Organic Matter	Proportion by weight
AW	Available Water Holding Capacity	Inches/inch, cm/cm
TP	Topographic Position	Scale 0 to 5 Where: 0=Low (Standing Water) 2.5=Mid-slope, 5=High (Ridge Lines)
SL	% Slope	(Rise/Run)*100

Table 2. Dependent variables and units of measurement as recorded and published by the U.S. Soil Conservation Service (Weiser 1975).

Abbreviation	Vegetation	Measured Average Yield
Evergreen Trees		
JV	*Juniperus virginiana*	feet/20 years
PD	*Picea glauca densata*	feet/20 years
PP	*Picea pungens*	feet/20 years
PS	*Pinus ponderosa scopulorum*	feet/20 years
Deciduous Trees		
FP	*Fraxinus pennsylvanica*	feet/20 years
PD	*Populus deltoides*	feet/20 years
UP	*Ulmus pumila*	feet/20 years
Deciduous Shrubs		
CA	*Caragana arborescens*	feet/20 years
PA	*Prunus americana*	feet/20 years
PV	*Prunus virginiana*	feet/20 years
Agronomic Crops		
SW	Spring Wheat	bushels/acre
BA	Barley	bushels/acre
OA	Oat	bushels/acre
SI	Silage Corn	tons/acre
GL	Grass/Legume	tons/acre

1 meter = 3.281 feet; 1 foot = 0.3048 meter
1 hectoliter = 2.837 U.S. bushels;
1 U.S. bushel = 0.363 hectoliter
1 hectare = 2.471 acres; 1 acre = 0.405 hectare
1 kilogram = 2.2046 pounds avoirdupois;
1 pound = 0.4536 kilogram
1 kilogram = 1.10×10^{-3} ton, 1 ton = 907 kilograms

procedures is the generation of equations which employ soil parameters to predict a productivity index.

The productivity index is a unitless number, indicating relative productivity. By using Burley and Thomsen's (1987) method, reported vegetation productivity scores have typically ranged in scale from five to minus ten, where a score of five is a highly productive soil and a score of minus 10 is an unproductive soil.

An equation generated by this procedure was compared to a set of 10 reclaimed soils supplied by Dr. G. Halvorson from the Land Reclamation Research Center, North Dakota State University. The origin and description of this small data set is presented in Burley (1995). The equation developed in this Oliver County study was applied to the soil properties of the reclaimed soils and compared to actual yield values by computing the Pearson product-moment correlation. used to generate a predicted productivity score

Results

Table 3 illustrates the eigenvalues (latent roots) for the Oliver County dependent crop/woody plant variables. The eigenvalue associated with the first principal component axis contains 76.721 percent of the variance in the data set and is a primary candidate for further modeling analysis. The second and third principal component eigenvalues are greater than 1.0, suggesting that the second and third axes may also merit further modeling study. All other eigenvalues are smaller than one and thus are typically not considered for further analysis. The first three

Table 3 Principal Component Analysis eigenvalues of the covariance matrix for Oliver County, North Dakota, dependent variables.

	Eigenvalue	Proportion	Cumulative
PRIN1	11.5081	0.76206	0.76721
PRIN2	1.3379	0.089194	0.85640
PRIN3	1.0183	0.067886	0.92429
PRIN4	0.5352	0.035682	0.95997
PRIN5	0.2834	0.018896	0.97886
PRIN6	0.1205	0.008031	0.98689
PRIN7	0.0911	0.006070	0.99297
PRIN8	0.0498	0.003318	0.99628
PRIN9	0.0334	0.002226	0.99851
PRIN10	0.0151	0.001009	0.99952
PRIN11	0.0065	0.000432	0.99995
PRIN12	0.0004	0.000030	0.99998
PRIN13	0.0003	0.000018	1.00000
PRIN14	0.0000	0.000002	1.00000
PRIN15	0.0000	0.000000	1.00000

eigenvalues comprise over 92% of the variance in the crop/woody plant variables.

Table 4 presents the eigenvectors for the first five principal components. The coefficients for the first eigenvector are all positive and range from 0.275 to 0.162, suggesting that the dependent variables covary together and relatively equitably. This first set can be considered an all crop/woody plant response axis.

The coefficients for the second eigenvector can be arranged in three groups: positive coefficients, negative coefficients, and coefficients near zero. This second component axis suggests the dependent variables may be divided into a crop group negatively associated with the axis, a Ponderosa Pine/Siberian Peashrub group unassociated with the axis, and a general woody plant group positively associated with the axis.

The coefficients for the third eigenvector can be divided into two broad general groups. The first group is a set containing one coefficient greater than 0.4 and the second group contains coefficients less than 0.4. The woody plant Cottonwood contains a coefficient greater than 0.4 and all other variables contain values smaller than 0.4, with most of the values ranging near the value zero. This third set could be characterized as a Cottonwood response axis.

Table 4 Principal Component Analysis eigenvectors for Oliver County, North Dakota, dependent variables. See Table 2 for a definition of each variable. The letter "Z" attached to the end of each variable indicates that the variable has been standardized to a mean of zero and a standard deviation of 1.

	PRIN1	PRIN2	PRIN3	PRIN4	PRIN5
SWZ	0.26533	-.33929	0.15995	-.02214	-.04577
BAZ	0.26556	-.33747	0.15978	-.01862	-.05497
OAZ	0.26532	-.33957	0.15889	-.02314	-.04689
SIZ	0.26099	-.31749	0.12371	0.00652	-.03857
GLZ	0.27037	-.27483	0.17292	0.03092	0.01076
PSZ	0.25322	-.01422	-.45122	0.17704	0.20248
PPZ	0.24233	0.31424	0.29091	-.38440	0.30375
PDZ	0.24233	0.31424	0.29091	-.38440	0.30375
JVZ	0.26558	0.04200	-.28443	0.18449	0.45146
FPZ	0.27499	0.07863	-.17781	0.11668	0.19601
POZ	0.16159	0.35116	0.47523	0.75314	-.02890
UAZ	0.27345	0.23994	-.11174	-.08721	-.35124
PVZ	0.27330	0.24208	-.05510	0.03729	-.44571
PAZ	0.27058	0.18289	-.17143	-.20844	-.44339
CAZ	0.26639	0.02788	-.34974	0.05873	0.06213

Since the eigenvalues associated with the remaining principal components are less then 1.0, interpretation of the remaining sets of eigenvectors for further analysis is considered unnecessary. The first three axes merit further investigation.

Table 5 illustrates the selected model representing the best equation developed from the first principal component. This equation is the all crop/woody plant model. The equation is not over specific (terms in equation = 13, C(p) = 14.09); over specific equations contain more terms than the Mallows' C(p) value (see Burley 1988). The equation explains 81.08 percent of the variation in the crop/woody plant axis.

A stepwise, maximum R-squared procedure was initiated for the second eigenvector and then for the variable Cottonwood. Statistical analysis revealed best model equations with coefficient of multiple determination values of 0.2834 associated with the second eigenvector and 0.0725 for the Cottonwood equation. Each equation explained relatively low amounts of variance in the Oliver County data set. In addition, many of these equations were over specific. For example, a model for an equation derived from the second eigenvalue axis was over specific at the six

Table 5 Stepwise Maximum R^2 Improvement--Best equation selected.

R-square = 0.81083312 C(p) = 14.09255633

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	12	942.48974442	78.54081204	31.79	0.0001
Error	89	219.88228464	2.47058747		
Total	101	1162.37202906			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.50452660	0.24894486	10.14757008	4.11	0.0457
SLZ	-2.42593246	0.27062970	198.52112848	80.35	0.0001
AWZ	1.01860203	0.23236161	47.47670439	19.22	0.0001
FRZ	-1.98174961	0.36135098	74.30864258	30.08	0.0001
FRZFRZ	0.24521274	0.05872842	43.07147271	17.43	0.0001
TPZTPZ	-0.59309805	0.18066683	26.62541299	10.78	0.0015
ECZECZ	-0.92280839	0.18250496	63.16463267	25.57	0.0001
HCZHCZ	-0.20010668	0.09831059	10.23582352	4.14	0.0448
HCZAWZ	-0.63992792	0.16638745	36.54443455	14.79	0.0002
SLZTPZ	0.97386757	0.22872542	44.78898062	18.13	0.0001
ECZPHZ	0.97913197	0.28591670	28.97367992	11.73	0.0009
AWZCLZ	-0.71410862	0.21886327	26.30165100	10.65	0.0016
OMZECZ	1.87147762	0.31451985	87.47287530	35.41	0.0001

Bounds on condition number: 6.227012, 546.3928
The above model is the best 12-variable model found.

variable equation level (C(p)=3.735). Even with one variable entered into the Cottonwood model, the equation was over specific (C(p)=0.979). Therefore, all equations for the second and third principal component axes were rejected as insignificant with low powers of predictability and often containing a high degree of collinearity among the independent variables, due to low C-plot scores. Only the first axis provided an equation with an acceptable level of predictability, yet not over specific.

Finally, the Pearson product-moment correlation between the predicted score and the yield results from reclaimed soils was 0.71424 ($p \leq 0.0203$). Indicating that there is a positive statistical relationship between the soil survey approach and vegetation productivity on reclaimed soils.

Discussion

The procedures reported by Burley and Thomsen (1987) and applied to Clay County, Minnesota, appear to be applicable to Oliver County, North Dakota. A highly specific equation was constructed, with a definitive overall highly significant regression ($p<0.0001$), and an R-squared value similar to past reported equations.

The multivariate analysis revealed that the woody plants and agronomic crops covary. In other words, the soil conditions suitable for spring wheat are similar to the soil requirements for Colorado spruce and for the mixture of grass and legume. In addition, silage corn, an agronomic variable not employed in past productivity equation investigation, also followed this covariance pattern. Very little theoretical work or ecological modeling has been conducted to explain and predict this covariance phenomenon. In many respects, this covariance phenomenon is contrary to results typically presented in vegetation ecology ordinations such as in Curtis (1959). If the covariance phenomenon is corroborated by future investigations, this covariance may prove to be a powerful construct in reconstructing soil profiles across a wide variety of landscape conditions where high levels of vegetation growth are

required for prime farmland, urban landscapes, transportation right-of-way, and erosion control situations. This covariance phenomenon may merit further investigation by agro-ecologists.

In addition to the covariance phenomenon, some reclamation specialists unfamiliar with these modeling techniques become concerned about the mixing of harvest values from botanical species, such as oat, with harvest values from aggregated plant associations such as grass and legume. However, there are no strict investigatory rules limiting concurrent examination of hierarchical vegetation categories as dependent variables. Instead, the multivariate analysis examines variables and presents evidence concerning their covariance. Covarying categories can be represented in the same response axis; while categories that do not covary might be represented in different response axes (recall that these axes are orthogonal and thus independent). This study and past studies suggest that hierarchical vegetation categories between herbaceous plant associations, agronomic crop species, and woody plant species covary. The vegetation productivity concordance between hierarchical types is an investigatory topic that has been relatively unexplored and may merit further inquiry.

In contrast to the covariance phenomenon, the multivariate analysis presented in this study also suggested that at least two other models may merit development; however, further investigations revealed that these models were weak in predictive ability. Presently, the sugarbeet model reported by Burley (1990) is the only equation derived from a second latent root. All other equations were derived from the first latent root (largest eigenvalue), corroborating the covariance phenomenon.

When applying regression analysis using the first eigenvector, the results of statistical analysis (Table 5) revealed Equation 1 (Figure 1). Interpreting such an equation may be difficult. The equation contains a combination of linear main effect terms, squared terms and numerous interaction terms. The equation is relatively similar to other reported equations where steep slopes and a substantial portion of rock fragments reduce vegetation productivity; while increased available water holding capacity and abundant organic matter can increase vegetation productivity. Such findings are not new, but rather the results of the analysis allow the reclamation specialist to quantitatively assess these soil parameters.

Partitioning the linear combinations from the regression equation into each regressor effect or combination of effects, such as in Figure 2 can be useful to understand the contribution each soil parameter makes toward the assessment of vegetation productivity. Figure 2 is a graph which illustrates a negative relationship between vegetation productivity and % slope. Figure 2 is obtained by plotting the

$$
\begin{aligned}
\text{Oliverplants} = \; & 0.505+[(SL-5.662)*0.971^{-1}*(-2.426)] \qquad \text{[Eq. 1]} \\
& +[(AW-0.162)*0.028^{-1}*(1.019)] \\
& +[(FR-1.661)*4.334^{-1}*(-1.982)] \\
& +[((FR-1.661)*4.334^{-1})^{2}*(0.245)] \\
& +[((TP-2.721)*0.971^{-1})^{2}*(-0.593)] \\
& +[((EC-3.128)*2.074^{-1})^{2}*(-0.923)] \\
& +[((HC-2.655)*3.569^{-1})^{2}*(-0.200)] \\
& +[((HC-2.655)*3.569^{-1})*((AW-0.162)*0.028^{-1})*(-0.640)] \\
& +[((SL-5.662)*0.971^{-1})*((TP-2.721)*0.971^{-1})*(0.974)] \\
& +[((EC-3.128)*2.074^{-1})*((PH-7.535)*0.322^{-1})*(0.979)] \\
& +[((AW-0.162)*0.028^{-1})*((CL-25.081)*13.899^{-1})*(-0.714)] \\
& +[((OM-0.707)*1.097^{-1})*((EC-3.128)*2.074^{-1})*(1.871)]
\end{aligned}
$$

Where:	Oliverplant	=	Oliver County vegetation productivity value
	SL	=	% Slope
	AW	=	Available Water Holding Capacity
	FR	=	% Rock Fragments
	TP	=	Topographic Position
	EC	=	Electrical Conductivity
	PH	=	pH
	OM	=	Organic Matter

Figure 1. Oliver County, North Dakota vegetation productivity equation.

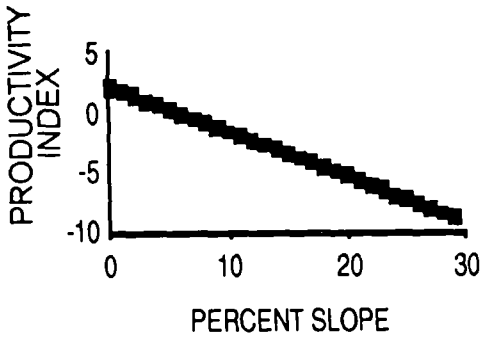

Figure 2. Main-effect relationship between percent slope and productivity index.

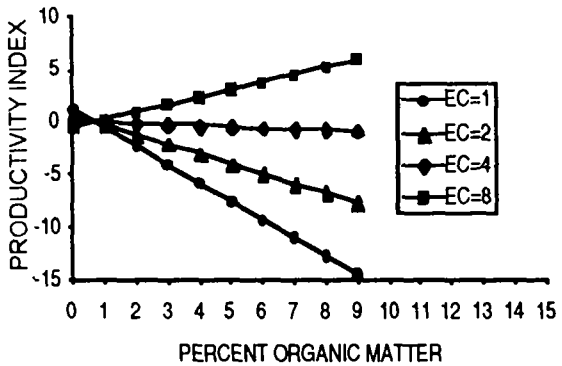

Figure 3. Productivity index determined by an electrical conductivity and percent organic matter interaction term (EC=Electrical Conductivity).

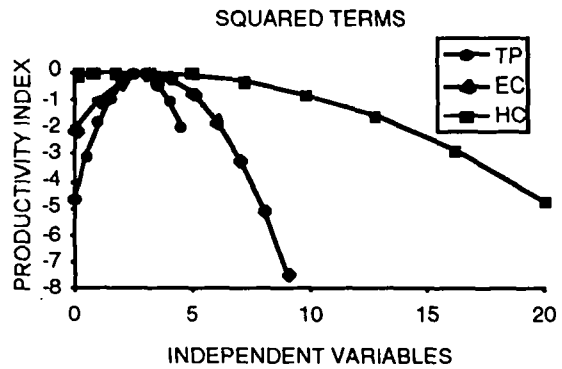

Figure 4. Parabolic relationship between squared terms and productivity index (TP=Topographic Position, EC=Electrical Conductivity, HC=Hydraulic Conductivity).

relationship between the dependent variable and a term in the regression equation containing percent slope, dropping all other regression terms, in this case Oliverplants = $[(SL-5.662)*0.971^{-1}*(-2.426)]$. In contrast to Figure 2, Figure 3 illustrates a partition of an interaction term where there is a linear relationship between percent organic matter and vegetation productivity across a variety of electrical conductivity settings. As electrical conductivity increases, the slope of the linear expression changes from a negative inverse setting to a positive proportional condition. The interaction term suggests that when electrical conductivity settings are low, low organic matter soil conditions will result in larger vegetation productivity levels; when electrical conductivity values are increased, increased organic matter will result in improved vegetation productivity levels. Notice in Figure 3 that no single electrical conductivity treatment across all percent organic matter levels will result in consistently obtaining the highest vegetation productivity level. The four lines illustrate the interaction relationship. These partition and graphing techniques allow the investigator to more fully understand and interpret the linear contributions within the equation. Burley (1988) demonstrates a comprehensive examination of a vegetation productivity equation by partitioning and graphing the results.

Not all regressors demonstrate an inverse or proportional relationship. For example according to the equation, moderate to low hydraulic conductivity rates, middle topographic positions, and moderately high electrical conductivity levels also maximize vegetation productivity, suggesting that there is an optimum parabolic (curvilinear) relationship for these regressors. Figure 4 illustrates the relationship for the squared terms from Equation 1 which contain a negative Beta coefficient.

The linear, interaction and parabolic forms of the independent variables are the basis of the vegetation productivity multiple regression equations presented for Clay County, Minnesota and now for Oliver County, North Dakota. The equation [Equation 1] provides a quantitative numerical approach to assess the vegetation productivity potential of various soil conditions.

As with some empirical equation modeling investigations, the interaction terms can be difficult to interpret. In general, some of the interaction terms can be considered correction factors, indicating a more complex relationship and allowing the independent

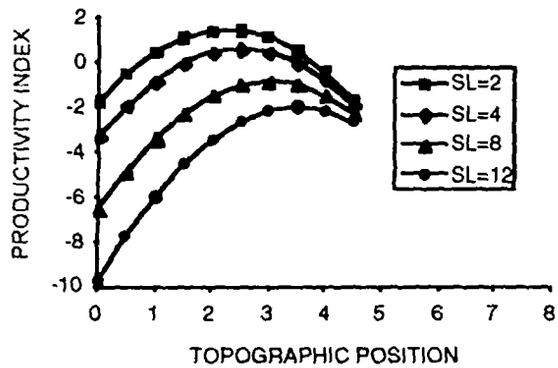

Figure 5. Productivity index determined by a combination of three terms: topographic position squared, topographic position and percent slope, and percent slope (SL=Percent Slope).

variables to more readily predict productivity. Figure 5 illustrates the depiction of a regressor that could be considered a correction of the term, allowing a better statistical fit. Note that slight slopes with middle topographic positions result in the largest vegetation productivity. Even though topographic position and percent slope are associated with interactions terms, the plot in Figure 5 demonstrates how a complex association of terms can result in a simple graphical expression of agricultural productivity where curves do not cross, suggesting a relatively intelligible interpretation of the equation.

In contrast to some counter intuitive segments of a large regression equation, some of these interaction terms found in the equation may intuitively make "common sense." For example, as organic matter increases, the water holding capacity and cation exchange capacity of some soils may increase, allowing electrical conductivity values to be greater without adversely affecting plant growth. Plants may be able to tolerate a greater level of salts/nutrients in the soil, provided water is present. In contrast, other interaction terms may be more difficult to explain, such as available water holding capacity times percent clay, where high levels for both variables are suggested as being disadvantageous for agronomic crops and woody plants. Although intuitively one might conclude that a wet clay soil may not be beneficial for crops and many woody plants, supporting investigatory evidence may not be as apparent. Consequently, some of the variables may be difficult to explain. Nevertheless, identification of these variables as significant regressors provides a pool of soil-plant relationships that may merit further study. There are still many multiple factor soil-plant investigations that have not been fully explored.

Some reclamation specialists may have reservations about the presentation of numerous interaction regressors identified in Equation 1 that may not seem intuitively meaningful. However, the methodological process originally presented by Burley and Thomsen (1987) is strictly an empirical procedure. The selection for study of any predictor for further analysis, whether a main-effect term (linear), a squared term (parabolic), a two-way interaction term, a five-way interaction term (examples in Dunker et al. 1992), a ten-way interaction term (originally hypothesized by Doll and Wollenhaupt 1985), an autoregressive term, or an exponential term, is in many respects a biased selection process, where the investigator makes an educated guess. The researcher must make a heuristic decision concerning which variables to test. Unless the investigator conducts a statistical analysis there is no reason to actually believe that a dependent variable and an independent variable are related in any mathematical manner. Thus, until a statistical examination is conducted, a main effect linear relationship is just as arbitrary as an obscure two-way interaction term. Through statistical analysis the terms are evaluated for internal validity. Acceptance or rejection of these terms may require an extensive number of investigations by numerous investigators over a substantial length of time. One reported investigation does not typically supply definitive answers, but may suggest directions for further research. Therefore, the large number of unusual interaction terms and regressors expressed in an equation should not be readily accepted or rejected.

While the internal validity of the regressors presented in Equation 1 are statistically supported, the equation presented in this paper and in others has an external validity shortcoming. The major external validity issue concerning the applicability of these models is that the equations are built from soil profiles and vegetation productivity values in a pre-mining condition. With the exception of this paper and the dissertation work prepared by Burley (1995a), no reclamation research specialist has reported the development of a soil survey model employing post-mining soil profiles and associated vegetation productivity scores.

Closing Remarks

Formative concepts concerning the development of vegetation productivity equations for assessing the plant growth potential of post-mining soil

profiles has led to the generation of inferential/empirical vegetation productivity equations. While much work remains ahead for reclamation research specialists to validate the models, develop theoretical constructs to explain the models, and expand the body of knowledge associated with soil-plant interactions, this paper illustrates that vegetation productivity models for North Dakota are possible. In reclamation planning and design, specialists can employ the equation to study and predict the vegetation productivity of various landscape configuration possibilities and to obtain an indicator of reclamation success.

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PRODUCTIVITY OF PRIME AND NONPRIME TOPSOIL RECLAIMED IN EQUIVALENT TOPOGRAPHIC POSITIONS

by

Gary A. Halvorson and M. V. Nathan

Abstract. Coal companies in North Dakota are required to separate primeland topsoil from non-primeland topsoil before mining. Following mining, the prime topsoil must be replaced in a prime location and the nonprime topsoil in a nonprime location. This separate handling of these materials is expensive and may be unnecessary. This research was conducted to (1) compare the productivity of prime and nonprime topsoil materials placed side by side in different topographic positions, and (2) to determine whether the separate handling of prime and nonprime topsoil is necessary. Plots were established at two different sites. The selected topsoil materials from Bowbells (prime soil), Williams and Zahl (nonprime soils), were transported to the reclaimed side of the pit and placed on separate plots adjacent to each other in the same topographic position. Plots were constructed on both prime and nonprime topographic positions and at the Coteau site two different topsoil depths were evaluated. In the first year of the study, dry matter yields and grain yields were lower on Zahl than on Bowbells or Williams topsoils. These differences could be accounted for by differences in initial soil moisture levels. The year 1993 was a wet year and the crop had sufficient available moisture in the profile throughout the season in the top 0 to 60 cm depth. At both sites there were no significant grain yield differences between prime and nonprime soils. No significant grain yield differences were observed between the topographic positions in the landscape. In 1994, at the Falkirk site no significant differences in yield could be determined between the three different soil series. At the Coteau site the wheat grown on the Zahl soil yielded slightly less than that growing on the Williams and Bowbells soils. As would be expected in a year when moisture was short, topographic position made a difference in yield. Depth of topsoil made no difference in yield for 1994.

Additional Key Words: mining, soil moisture, landscape

Introduction

Current federal and state regulations require separate handling of prime and nonprime topsoils. According to the present interpretation of prime farmland criteria, soils designated prime in the ustic moisture zone of North Dakota qualify because of landscape position. Most of these soils occur on nearly level or concave positions of the landscape and receive runoff from adjacent soils in a higher position which do not meet prime farmland criteria. Prime soils are therefore the product of microclimate and local surface and root zone hydrology rather than macroclimate or parent material.

In western North Dakota, availability of water is the most dominant factor controlling crop yields. Under conditions of limited rainfall, which is the general rule, the yield potential of primeland may not be significantly different from the yield potential of nonprime land. If the differences in the productivity

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capabilities of prime and nonprime soils are the results of moisture differences due to topographic location rather than to differences in the properties of soil materials, then the currently required separate removal and placement of topsoil materials is unwarranted. In addition, higher overall productivity of reclaimed land may be attained by replacing available soil materials uniformly on an area reshaped to the most effective topographic configuration.

In a greenhouse study, yields on reclaimed prime soils were initially higher than on reclaimed nonprime soils (Carter and Doll, 1983). After soil structure had been reestablished yields between the soils were not different.

Carter and Doll, (1987) reported that "*in situ*" soil properties such as bulk density, macropore space, and hydraulic conductivity are the soil parameters most severely disrupted during mining and reclamation. In continued studies, Carter (1991) found that average values of soil chemical properties, texture, and calculated percents of pore sizes were not significantly different between prime and nonprime soils located in a 25 acre site. Bulk densities at all measured depths were generally higher from prime soils than nonprime during all four years of the study.

Topography has been shown to influence crop yields on land reclaimed following mining in North Dakota (Doll et al., 1984). A method to quantify the relationship between the topographic redistribution of water and wheat yields was developed (Halvorson and Doll, 1991).

This study was undertaken to compare the productivity of prime and nonprime topsoil materials when placed side by side in different topographic positions.

Methods and Materials

One site was selected at the Coteau Properties Freedom Mine. Two plot areas were selected which would be reclaimed as rangeland with a topsoil depth of about eight inches. One of these was located on a hilltop to simulate a nonprime topographic position and the other was nearby on a toeslope position to simulate a prime topographic position. Two more plot areas were selected nearby which would be reclaimed as cropland with a topsoil depth of 15 inches. One site was on a hilltop and one was on a toeslope position to simulate nonprime and prime topographic positions, respectively. The other location was at the Falkirk Mine. Only two plot areas were selected at this location, one in a prime topographic position and the other in a nonprime topographic position which were reclaimed with a cropland soil depth of 15 inches.

Two nonprime soils used in this study were: the Zahl loam series (fine-loamy, mixed Entic Haploboroll) which is found on hilltops and shoulder positions and the Williams loam series (fine-loamy, mixed Typic Argiboroll) which is located on sideslopes and hilltops. The one prime soil used was the Bowbells loam series (fine-loamy mixed Pachic Haploboroll) which is located on footslopes and toeslopes.

Subsoil from each soil series was not segregated. Mixed subsoil was laid down at uniform depths on graded spoil material. Scrapers were used to transport the subsoil and topsoil to the plot areas. Topsoil from the Williams, Bowbells and Zahl soil series was placed on the plots at a depth of eight inches on rangeland plots and 15 inches on cropland and were replicated three times at each plot area. The plots were carefully leveled and smoothed with a bulldozer. The plots were disked and seeded to Stoa spring wheat (Triticum aestivum L.) on June 23, 1992. The plots at the Falkirk location were not completed until August, 1992 and therefore, were not planted for the first time until 1993. Soil samples from each plot were taken from each plot using recommended soil test procedures. Plots were fertilized with N and P for a 50 bushel per acre yield. Plots were seeded at the rate of one million live seeds per acre.

The plots were harvested by hand cutting three square meters from each plot, drying the bundles and then threshing the wheat in a small thresher. Yield data from three years, 1992-1994, is presented. Statistical

comparisons of the data were made within each years' data using analysis of variance and least significant difference (.05) comparisons. Least significant differences are for interaction means for all treatments at a site for a given year.

Results and Discussion

In 1992 wheat yields were very low because of the very late planting date at the Coteau site (Table 1). There were no significant differences between prime and nonprime topographic positions and no significant differences between cropland and rangeland soil depths. On the cropland soil depth wheat yields on the Zahl soil were significantly lower than on the Williams or Bowbells soils. This is mainly the result of a lower soil moisture content in the Zahl topsoil. Very little precipitation fell on these soils in the weeks prior to plot construction. The topsoil was removed from the surface five inches of the Zahl soil and the surface 15 inches and 25 inches from the Williams and Bowbells soils respectively, for plot construction. Since the surface was very dry and more moisture was available deeper in the profile, the topsoil material from the Zahl soil was the driest of the three soils. A plot of wheat grain yield versus initial soil moisture in the surface foot show the high correlation (r^2) = 0.71 between these two factors (Figure 1).

In 1993, growing season precipitation was 13.0 and 14.4 inches at the Coteau and Falkirk sites respectively, which was much above the average of 6.9 and 7.7 inches respectively. There were in fact, problems with minor flooding and water standing on the plots. In particular the prime topographic position at the Falkirk site had lower yields than the non-prime topographic position due to problems with too much water (Table 2). Wheat yields on the Bowbells and Williams soils on the prime topographic position were actually lower than on the Zahl soil. No yield differences between soils were noted on the nonprime topographic position. At the Coteau site in 1993 (Table 1) no statistically significant differences occurred between prime and nonprime topographic locations or between the three different soils tested. Wheat yields were significantly lower on the rangeland soil depth than on the cropland soil depth.

Table 1.Wheat grain yields (bu/ac) at the Coteau location, 1992-1994.

Topographic Landscape Position		
Soil Series	**Prime**	**Nonprime**
	Cropland - 1992	
Bowbells	9	10
Williams	8	9
Zahl	5	2
	Rangeland - 1992	
Bowbells	11	10
Williams	11	9
Zahl	9	8
LSD (0.5) = 3		
	Cropland - 1993	
Bowbells	52	52
Williams	46	50
Zahl	53	49
	Rangeland - 1993	
Bowbells	41	42
Williams	43	40
Zahl	44	39
LSD (0.5) = NS		
	Cropland - 1994	
Bowbells	30	31
Williams	29	26
Zahl	29	22
	Rangeland - 1994	
Bowbells	35	20
Williams	40	19
Zahl	29	18
LSD (0.5) = 6		

Table 2. Wheat grain yields (bu/ac) at the Falkirk location, 1993-1994.		
	Landscape Position	
Soil Series	Prime	Nonprime
	bu/ac	
	1993	
Bowbells	36	51
Williams	37	49
Zahl	45	51
LSD (.05) =8		
	1994	
Bowbells	34	26
Williams	39	32
Zahl	34	27
LSD (.05) = 11		

Wheat yields were somewhat lower in 1994 due to an extended period during the middle of the growing season with very little precipitation. At the Falkirk site no significant differences in yield between the three soils occurred (Table 2). Yields from the nonprime topographic position were significantly lower than yields from the prime topographic position. At the Coteau site in 1994 no differences in wheat yields occurred between cropland and rangeland soil depth (Table 1). The wheat yield on nonprime topographic positions was lower than on prime topographic positions. On the cropland soil depth in a nonprime topographic setting wheat yields were lower on the Zahl soil than on the Bowbells. On the rangeland soil depth in a prime topographic setting yields of the Williams soil were higher than the Zahl soil, but no significant differences between yields on the Zahl and the Bowbells soil occurred. Differences between the three soils did not occur on the other two plot areas at the Coteau mine.

Conclusions

Differences did occur in the treatments in the three years of the study. The Zahl soil yielded less in 1992 than the Bowbells soil, but this could be explained by the difference in initial soil moisture content. The Bowbells soil also yielded higher than the Zahl soil on the cropland soil depth in a nonprime topographic position in 1994. On the other hand in 1993 the Zahl soil yielded higher than Bowbells in a prime topographic position at the Falkirk location. Otherwise, the wheat yields from the three different soils were statistically equivalent. Overall, this is good evidence that the topsoil material itself from these three soils is of equal productivity.

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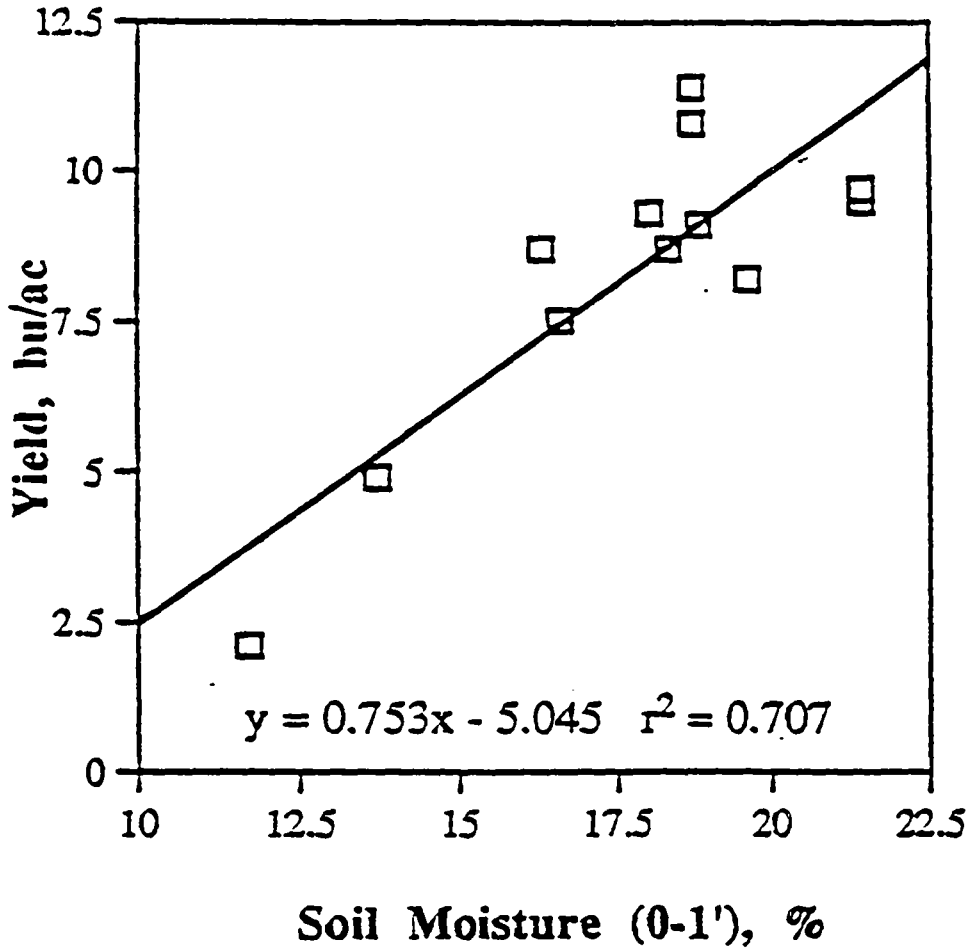

Figure. 1. The relationship between initial soil moisture at the 0-1 foot depth and grain yield in 1992 at the Coteau site.

A METHODOLOGY FOR EVALUATING THE COSTS OF SELECTIVE HANDLING OF OVERBURDEN MATERIALS[1]

by
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Abstract. Selective handling of overburden materials involves implementing mining techniques that will reduce the probability of creating acid mine drainage (AMD). These include separately handling toxic materials and placing them in locations in the backfill to limit their exposure to air and water, or blending alkaline- and acid-producing materials to create a neutral rock mass. This paper uses three selective handling situations and estimates the additional costs of selective handling above those which would normally be incurred during mining. Scenario 1 depicts a 2-m (6-ft) toxic shale layer (acid-producing) on top of the coal that must be specially handled and placed within non-toxic layers in the backfill. Scenario 2 has a 2-m toxic shale layer over the coal and also a 2-m layer of alkaline material, and these two layers are blended during backfilling. Scenario 3 details specially handling a 0.4-m (1.4-ft) toxic layer located 5 m (15 ft) up from the coal bed which requires blasting in two stages. Based on these scenarios and the overburden layers separately handled, additional costs for loading and hauling the material ranged from $663 per 46 by 43 m (150 x 142 ft) cut (or about $3,348 per ha or $1,353 per acre) for scenario 1 to $1,119 per 46 by 43 m cut (or about $5,652 per ha or $2,284 per acre) for scenario 2. These cost estimates do not include additional management costs, additional blasting costs, or training costs for equipment operators.

Additional Key Words: acid mine drainage, acid-producing materials, backfilling, land reclamation, mine hydrology, reclamation economics.

Introduction

Selective handling of overburden materials refers to several techniques that are designed to reduce the probability of encountering an acid mine drainage (AMD) problem during and after mining. These techniques are currently being used by surface mine operators to meet their Surface Mining Control and Reclamation Act (SMCRA) permit obligations and to minimize the costs of post-mining reclamation, especially with regard to AMD treatment. In 1979, the West Virginia Surface Mine Drainage Task Force (SMDTF, 1979) published "Suggested Guidelines for Method of Operation in Surface Mining of Areas with Potentially Acid-Producing Materials." This publication outlined techniques for handling surface water, ground water, and overburden during the mining process to help control the production of AMD. The task force recommended: 1) identification of acid- or alkaline-producing materials before mining, 2) mixing or blending acid and alkaline materials during backfilling when alkaline materials were in greater amounts than acid-producing materials, and 3) isolation of acid-producing material within the backfill to minimize contact with air and water when insufficient alkaline materials were available to neutralize potential acidity.

The selective handling process has two stages: analysis and implementation. The analysis stage involves identifying the quantity, type, and location of acid- and alkaline-producing materials in the overburden. The implementation stage involves developing and carrying out the selective handling plan. The plan may incorporate a number of techniques including special blasting or fragmentation techniques; blending, mixing, and isolation of overburden layers during backfilling; the use of liners or seals; alkaline addition; and total removal and disposal of acid-producing materials off site or in a refuse area.

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Analysis

It is necessary first to determine the composition of the overburden in order to select the best mining methods, the proper equipment, and the most efficient selective handling techniques. There are three primary techniques currently used to determine overburden characteristics: 1) acid-base accounting, 2) leaching and weathering procedures, and 3) modeling of hydrogeochemical systems based on data from Acid-Base Accounting (Perry 1985, Skousen et al. 1987). Each technique has advantages and disadvantages and the techniques may also be used alone or in combination. All techniques require sampling distinct rock units in the overburden and subjecting the rocks to whole rock analysis or leaching procedures. The results of the analysis should give the operator an estimate of the quantity, type, and distribution of acid-producing and acid-neutralizing materials in the overburden. Continued sampling and analysis of overburden should occur during the mining process.

Implementation

Once the composition and distribution of the overburden materials have been established, a plan for overburden removal and replacement can be developed. The hydrological characteristics of the site are important in determining this plan and may designate the areas on the site where placement of acid-producing materials should or should not occur. In general, it is best to keep toxic materials isolated from water to minimize leaching of acid into water courses. **Fragmentation** refers to the practice of blasting or ripping overburden into predetermined sizes. The operator's goal is to minimize the total surface area of acid-producing materials by leaving those strata largely intact, thereby reducing their acid-producing potential. In contrast, operators attempt to maximize the total surface area of alkaline strata by blasting or ripping them into the smallest possible fragments to enhance their neutralizing capability (Skousen and Larew 1994).

If analysis of the overburden indicates that there will be enough alkaline-producing material at the site to neutralize the acid-producing material, the mine operator may choose to **blend** these two materials. There are two ways to blend. The first is by pushing and mixing the alkaline and acid-producing materials together with equipment during overburden removal and placement. The other method, called **layering**, involves placing a layer of alkaline material on top of a layer of acid-producing material.

Isolation involves placing acid-producing material away from the highwall and above the pit floor in the backfill. Isolation is designed to minimize the contact of acid-producing material with oxygen and water. Isolation is accomplished by placing alkaline material above, below, and around the acid-producing material. In its most elaborate installation, a low permeability barrier or seal of compacted material is placed above or around the acidic material. Clay, shale, or synthetic **seals** or liners reduce air contact with acid-producing material and decrease water infiltration into the acid material.

Alkaline material in the form of limestone or other lime products can be imported when insufficient quantities of alkaline materials are found on-site to neutralize the acid-producing materials or to create a neutral rock mass. These products can be used in conjunction with the other selective handling techniques. They can be blended with or placed strategically around the acid-producing materials (Meek 1991, Skousen and Larew 1994). **Total removal** involves taking the acid-producing materials from the mining site to an area that is better suited for their disposal. Refuse sites are a common location for disposing of acid-producing materials. The area that receives the toxic materials will also need to be analyzed, sufficient alkaline material emplaced, and the entire area compacted and reclaimed.

Selective handling techniques are not mutually exclusive. These methods can be used to complement each other in some situations, while in others it may be more efficient to concentrate on a single technique with which the operator has the most confidence and familiarity.

Costs of Selective Handling

Estimating the costs of selective handling is a more complex task compared to evaluating the costs of AMD treatment systems as demonstrated in Phipps et al. (1991). With AMD treatment systems, costs can be broken down into investment costs, chemical reagent costs, annual labor and maintenance costs, and management costs (Skousen 1991, Skousen et al. 1993). These costs can be estimated separately and added together to get the total cost of the AMD treatment system. Management costs--the most difficult costs to quantify--are a small proportion of total costs with AMD treatment. With selective handling of overburden, management costs can be substantial, both in terms of developing the original toxic materials special handling plan to obtain the SMCRA permit and in day to day operations to identify, move, blend, or isolate acid-

forming materials. Selective handling practices are highly site specific. Costs will vary greatly depending on whether the acid-forming strata lie directly on top of the coal, or occur in multiple strata throughout the overburden. In the latter case, blasting may have to be conducted in multiple stages, with the overburden above each acid-forming stratum blasted separately.

Several studies have been concerned with the costs of selective handling. Kelley et al. (1982) developed a mining engineering plan to integrate selective placement of overburden into the mining cycle. They used a two bench, dragline operation as a case study and compared it to a typical shovel-truck contour mining method. Their goal was to find the most cost-effective method of selective placement for their particular mining situation. They found that truck haulback of toxic overburden was more cost effective in the mountainous Appalachian Coal Region of the eastern U.S than the use of draglines. They did not attempt to break out the incremental costs due to selective handling.

Meek (1991) evaluated the costs and effectiveness of a number of selective handling procedures employed at the Upshur Complex of Island Creek Coal Corporation in West Virginia. The techniques employed on the site include isolation and placing the toxic material above the pit floor; layering non-toxic overburden above the toxic material; covering acid-producing material with a plastic liner; and mixing phosphate and alkaline materials with toxic materials. The study found that all the selective handling techniques added significant costs to the mining operation, but that each technique reduced the total amount of acid produced on the site. Of the techniques used at the site, Meek found the two most cost-effective practices were the addition of phosphate to toxic material and the placement of a liner above toxic material. The study also compared these costs of selective handling with the costs of water treatment over specified time periods. At this site, mining costs (including special handling costs and alkaline amendments) were estimated to be $47,000 per ha ($19,000 per acre) compared with annual treatment costs of $8,400 per ha ($3,400 per acre). Therefore, if water treatment continued for more than six years, selective handling techniques resulted in lower overall reclamation costs.

Skousen and Larew (1994) studied the costs and effectiveness of transporting alkaline materials about 1.6 km (1 mile) and blending these materials with acid-producing overburden at a coal mine near Masontown, WV. The authors estimated the costs of transporting the alkaline material to be about $9,900 per ha ($4,000 per acre) and the costs of water treatment per year to be about $800 per acre. Like Meek's study, selective handling and importing alkaline materials was expensive during the mining phase of the operation, but this process eliminated the long-term treatment of AMD. If water treatment was necessary on the site for more than five years, selective handling was a more cost-effective reclamation approach.

The primary limitation of the latter two studies is their site specific focus, and the results cannot be effectively applied to other sites. The goal of this paper is to present a method for estimating the incremental costs of special handling toxic materials during the mining process for a contour surface mining operation in Appalachia. The method attempts to separate the costs of special handling into their individual components and then determine how each of the component costs vary with different mining situations and geologic characteristics.

The analysis is simplified in this paper by assuming that all SMCRA conditions have been met (i.e., any special core drilling to determine geologic layers, analysis by acid-base accounting, and other costs to obtain the necessary SMCRA and National Pollution Discharge Elimination System (NPDES) permits). The cost of gaining information needed to obtain the SMCRA permit includes any expenses necessary to develop a toxic materials special handling plan including identification and classification of overburden layers. While the three example scenarios are simplified from real world conditions, the method should be readily adaptable to other conditions.

Methods

Three scenarios are used to capture the different cost components that may be encountered when using selective handling on a contour surface mine using the haulback method. Each scenario is based on actual mine conditions found in West Virginia. All three scenarios are assumed to have a single, 1.5-m (5-ft) thick coal bed and an average ground surface slope of 25 percent. Based on this slope, the mine in each case is developed into the hillside to a distance of 39 m (129 ft) correlating to a highwall height of 20 m (64 ft), using the rule of thumb of 0.3 m (1 ft) of highwall for every 2.5 cm (1 inch) of coal (Sengupta 1993). Each stage or cut is 46 m wide (150 ft) along the contour and 39 m (129 ft) into the hillside. However, land area is calculated from 46 m in width and 43 m in length (142 ft) up the slope equaling 1,978 m^2 or 0.198 ha (21,300 sq ft or about 0.49 acres). Topsoil is stockpiled and spread later on the reclaimed area during typical contour mining, so no additional costs

are assumed for topsoil handling and placement with these scenarios except for increased hauling distance. For scenario 1, there is a 1.8-m (6-ft) acid-producing layer that lies directly on top of the 1.5-m coal bed. Scenario 2 adds a 1.5-m alkaline layer located in the middle of the overburden. Scenario 3 has only a 0.4-m (1.4-ft) acid-producing layer in the middle of the overburden.

All scenarios are compared to a typical contour mining operation using the haulback method that does not utilize special handling (Figure 1). As shown, pit (cut) 1 has been backfilled and reclaimed with the overburden from pit 3 and the topsoil from pit 4. The coal has been removed in cut 2 and backfilling may begin with overburden from cut 4 and topsoil from cut 5. It was assumed that machinery operators possess sufficient skills to identify, move, and place toxic materials adequately.

The additional equipment and labor costs of selective handling for one 46-m cut were calculated by determining the increased number of front-end loader cycles required to load overburden, toxic material, and topsoil. Each front-end loader cycle takes approximately one minute (based on field observation) and loads 10 cubic meters (13 cubic yards) of material. The total time per front-end loader cycle was 20 percent longer when handling toxic or alkaline material than when loading overburden because of the greater effort required to keep these materials separated from the rest of the overburden.

The number of truck cycles needed to haul the material was calculated based on truck and front-end loader capacities. Cycles were then converted to time, using data from Caterpillar, Inc. (1991). Truck turning and maneuvering was estimated to take 0.7 minutes at the loading site and 1.1 minutes at the dump site. Trucks hauled 30 cubic meters (39 cubic yards) of material, and loading time was assumed to be 3 minutes (three loader cycles). Travel time from the loading to the unloading site was based on an average speed of 13 km per hour (8 miles per hour). Finally, half a minute of slack time for each truck cycle was added to ensure the loader remained busy. The cycle time was estimated to be 7 minutes for the 183-m (600-ft) haul (2 pit widths back and forth or a total of 4 pit widths), 7.5 minutes for the 275-m (900-ft) haul (3 pits widths back and forth), 8 minutes for the 367-m (1200-foot) haul (4 pit widths), and 8.5 minutes for the 459-m (1500-ft) haul (5 pit widths). The costs developed in this paper should be added to the costs incurred for a typical mine operation per 46 by 43 m (150 by 142 ft) pit or per ha.

Results and Discussion

Scenario 1

While scenario 1 is the most simplistic of the three, it illustrates many of the management issues encountered with selective handling. Scenario 1 has a 1.8-m toxic (acid-producing) shale layer over the coal bed and a 4.4-m (14.5-ft) layer of oxidized material to encapsulate toxic material above the pavement and away from the highwall (Figure 2).

Figure 3 shows the mining process in six stages. The first cut has been fully reclaimed. The reclamation process proceeded as follows. After the coal was removed from cut 1, part of the oxidized material from cut 4 (no acid-producing potential) was placed on the pit floor or pavement of cut 1; then the toxic material from cut 3 was placed over the oxidized material, and then the remaining oxidized material from cut 4 was used to cover the toxic material. The overburden from cut 4 was then backfilled in cut 1, followed by a layer of topsoil from the newly opened cut 5. The coal from cut 2 is removed while overburden from cut 4 and topsoil from cut 5 are being placed in cut 1. The backfilling process in cut 2 then continues with part of the oxidized material from cut 5 being placed on the pavement of cut 2, followed by the toxic layer from cut 4, the remainder of oxidized material from cut 5, then backfilling with overburden from cut 5, and finishing with topsoil from cut 6 until cut 2 is fully reclaimed. Figure 4 shows a cross section of a fully backfilled cut with the dark area representing the toxic material placed within encapsulating layers of oxidized material.

With the mining system described above, the primary additional costs of selective handling are: 1) a longer haul of one additional cut length (46 m one-way or 92 m for round trip) for the overburden and topsoil; 2) additional costs incurred from having to shift the front-end loader from loading oxidized material in cut 4 to loading toxic material in cut 3 and then back to loading the remaining oxidized material in cut 4; and 3) delays involved when handling toxic material or when switching from one material to another. The equipment used in the operation is shown in Table 1. Total haul length for hauling the toxic material is 183 m (600 ft) or 2 pit widths back and forth, the length of the haul for overburden is 275 m (900 ft, or 3 pit widths) because it has to be moved the length of one additional cut, and the haul for topsoil is 366 m (1200 ft, or 4 pit widths). If selective handling were not being used, there would be one less cut, reducing the haul length for the overburden and topsoil by 92 m (300 ft).

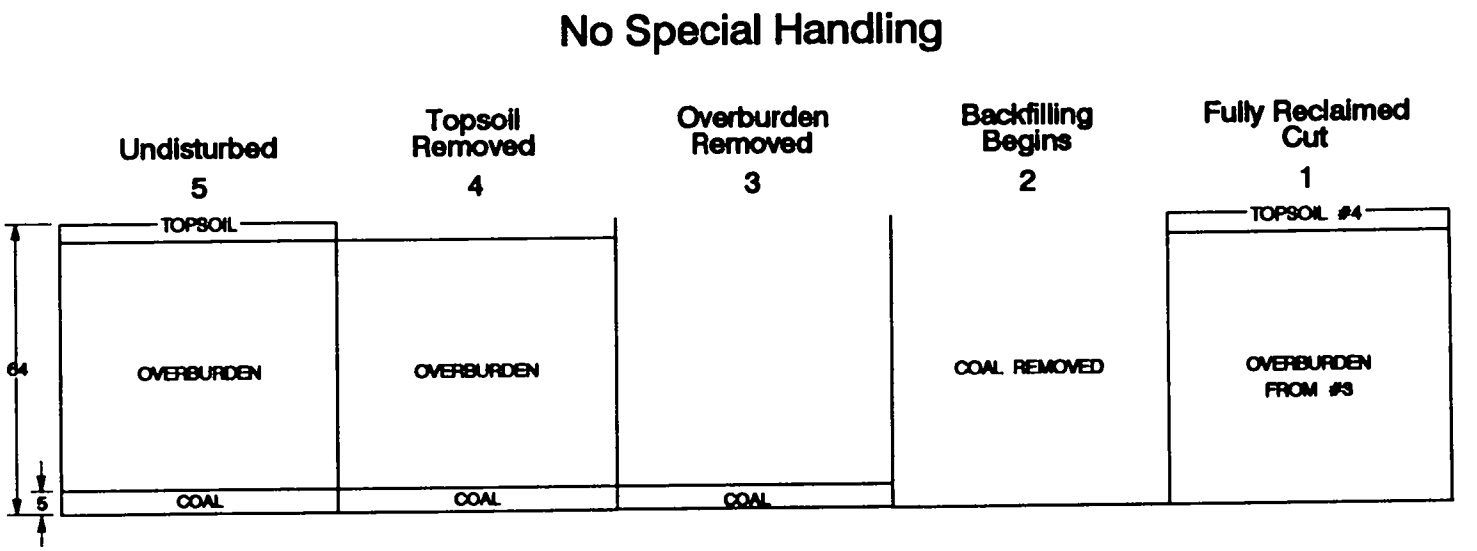

Figure 1. A simplified view of the mining process for a typical contour surface mining operation in West Virginia. Normally three pits are open at any one time to remove topsoil, overburden and coal. Cut 1 is fully reclaimed and shows the material and pit number used for backfilling.

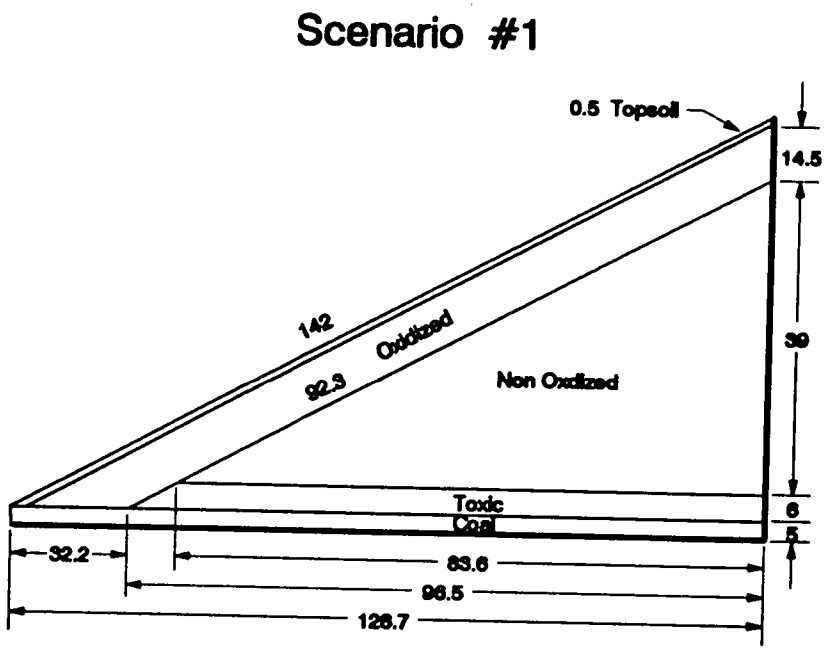

Figure 2. Undisturbed geologic cross-section for scenario 1 (all numbers in feet) with a 6-ft toxic layer overlying the coal bed.

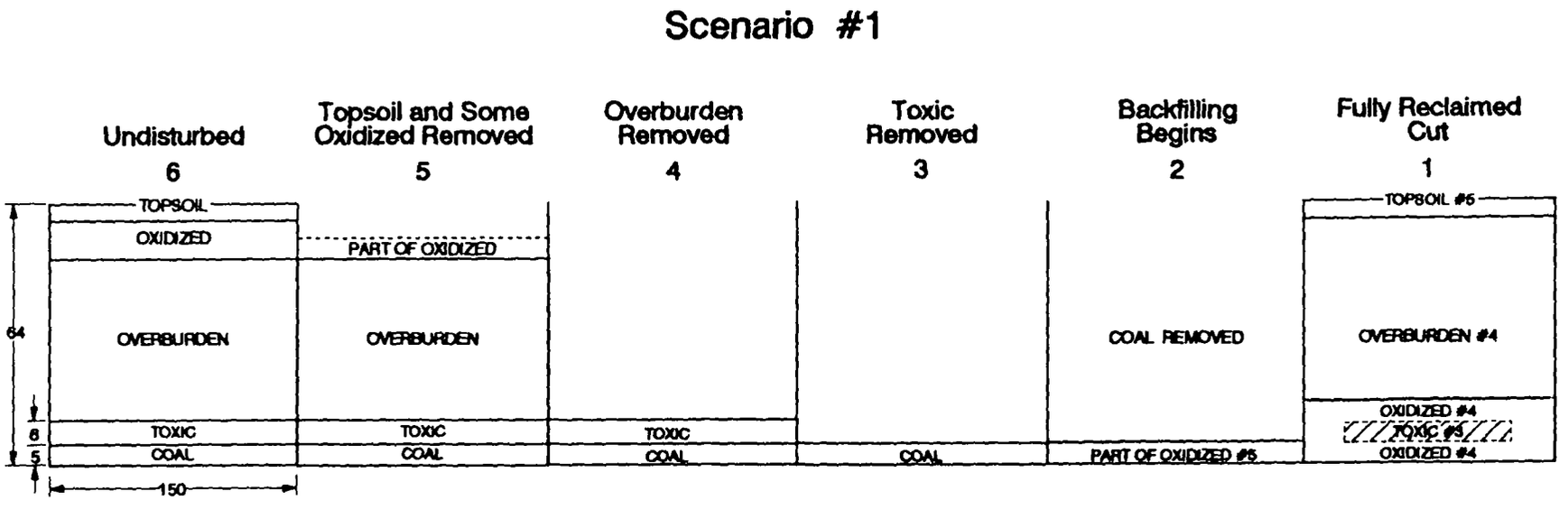

Figure 3. Simplified view of the mining process of a contour operation (scenario 1) where a 6-ft toxic layer above the coal bed is being selectively handled. Cut 1 is fully reclaimed and shows the material and pit number used for backfilling. In this case, four pits are open.

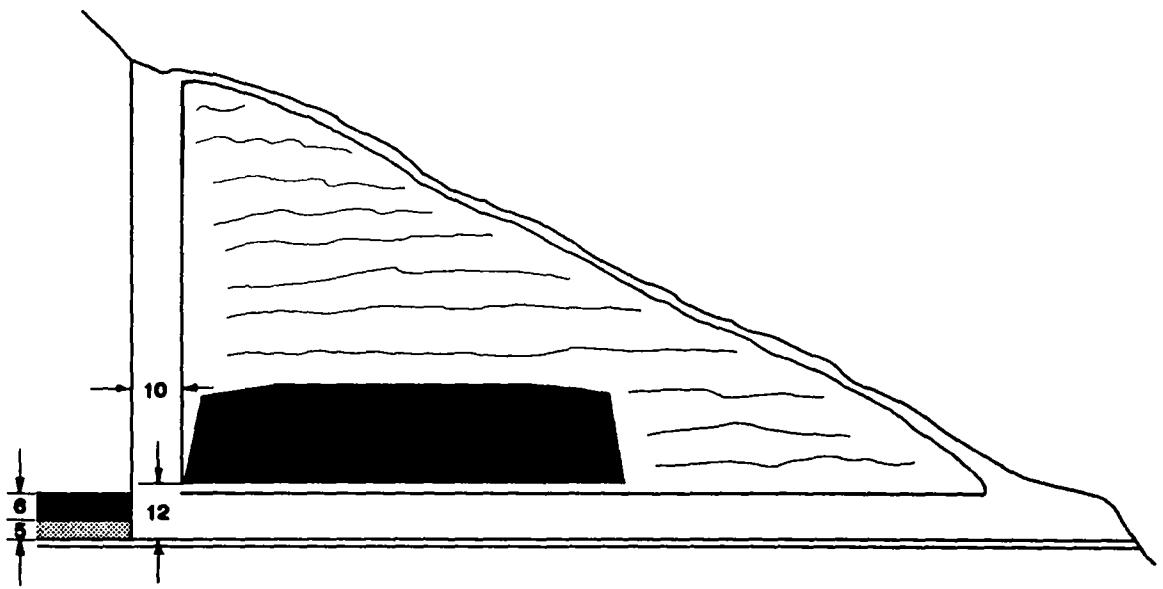

Figure 4. Cross sectional view of a fully backfilled cut for scenario 1 (numbers are in feet). The black material is the 6-ft toxic material special handled and placed on a layer of oxidized, non-toxic material.

Table 1. Types and purpose of equipment used in contour surface mining.

Type	Number	Capacity	Purpose
Cat D8[1]	1		backfilling
Cat D9	1		ripping and pushing
Cat 992	1	13 cu yds	front-end loader
Cat 773	3	50 tons	rock trucks

[1]Use of a specific brand name does not constitute endorsement of a product or its performance by the U.S. Bureau of Mines, the National Mine Land Reclamation Center, West Virginia University, or any of its affiliates.

Selective handling increased front-end loader time by an estimated 56 minutes and truck time by an estimated 278 minutes for each 46-m (150-ft) reclaimed cut. Using Caterpillar, Inc. (1991) costs (plus $39 per hour for the equipment operators), operation costs for the equipment were estimated to be $184 per hour for the loader and $104 per hour for the rock truck (under extreme terrain conditions). The total estimated increase in costs due to selective handling for both a front-end loader and rock trucks was $663 per 46 by 43 m (150-ft) cut ($3,348 per ha or $1,353 per acre). The results are shown in Tables 2 and 3.

Table 2. Estimated additional costs for a front-end loader in scenario 1 having a 1.8-m (6-ft) toxic layer above the coal bed.

	Cubic Yards	Loading Cycles	Total Time (min)	Increase For Selective Handling (min)	Cost of Increase ($184/hr)
Overburden (1 min)	21,655	1,667	1,667	0	0
Toxic (1.2 min)	3,607	278	334	56	$172
Topsoil (1 min)	394	30	30	0	0
Total	**25,656**	**1,975**	**1,975**	**56**	**$172**

Table 3. Estimated additional costs for rock trucks in scenario 1 having a 1.8-m (6-ft) toxic layer above the coal bed.

	Cubic Yards	Truck Cycles	Total Time (min)	Increase For Selective Handling (min)	Cost of Increase ($104/hr)
Overbrdn (7.5 min)	21,655	555	4,163	278	$482
Toxic (7.0 min)	3,607	92	644	0	$0
Topsoil (8.0 min)	394	10	80	5	$9
Total	**25,134**	**657**	**4,887**	**283**	**$491**

Scenario 2

Scenario 2 adds a 1.5-m (5-ft) layer of alkaline material in the middle of the overburden (Figure 5). In this scenario, selective handling involves blending the alkaline material with the toxic material as it is placed on oxidized material above the pavement. This procedure requires opening one more cut than scenario 1. The mining process is shown in seven stages in Figure 6. The first cut has been fully reclaimed. The reclamation process proceeded as follows. After the coal was removed in cut 1, part of the oxidized material from cut 5 is placed on the pavement. Then the toxic material from cut 3 and the alkaline material from cut 4 are placed on top of the oxidized layer, followed by the remaining oxidized material from cut 5. Backfilling continues with the lower overburden layer from cut 4 (OB2) and the upper overburden layer from cut 5 (OB1). Backfilling of cut 1 is finished with the topsoil from cut 6.

Additional costs for selective handling in scenario 2 (Figure 6) based on no selective handling (shown in Figure 1) occur because oxidized material, OB1, and topsoil must be hauled two additional cuts and alkaline material and OB2 must be hauled an additional cut. As in scenario 1, front-end loader time is increased by 20 percent when handling the toxic or alkaline materials. Total and incremental costs for the front-end loader and rock trucks are given in Tables 4 and 5.

Front-end loader time was estimated to increase by 101 minutes. Rock truck time would increase by 467 minutes per 46-m cut. Valuing the time as before for both a front-end loader and rock trucks, this would add $1,119 to the cost of mining for each 46 by 43 m cut, or $5,652 per ha ($2,284 per acre). The additional costs of scenario 2 are due to the two additional open cuts and the increased front-end loader time from having to selectively handle both toxic and alkaline materials.

Table 4. Estimated additional costs for a front-end loader in scenario 2 having toxic and alkaline layers that are selectively handled.

	Cubic Yards	Loading Cycles	Total Time (min)	Increase For Selective Handling (min)	Cost of Increase ($184/hr)
Oxidized (1 min)	9,750	750	750	0	0
Toxic (1.2 min)	3,607	278	333	56	$172
Alkaline (1.2 min)	2,930	225	270	45	138
OB1 (1 min)	4,118	317	317	0	0
OB2 (1 min)	4,857	374	374	0	0
Topsoil (1 min)	394	30	30	0	0
Total	**25,656**	**1,974**	**2,074**	**101**	**$310**

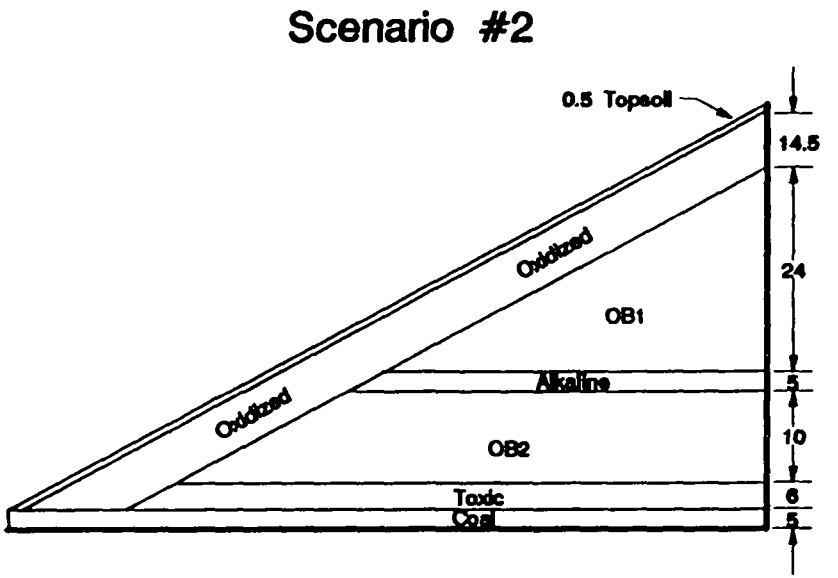

Figure 5. Undisturbed geologic cross-section for scenario 2 (all numbers in feet). This example has a 6-ft layer of toxic material overlying the coal bed and a 5-ft layer of alkaline material higher in the overburden. OB1 and OB2 are abbreviations for overburden sections 1 and 2.

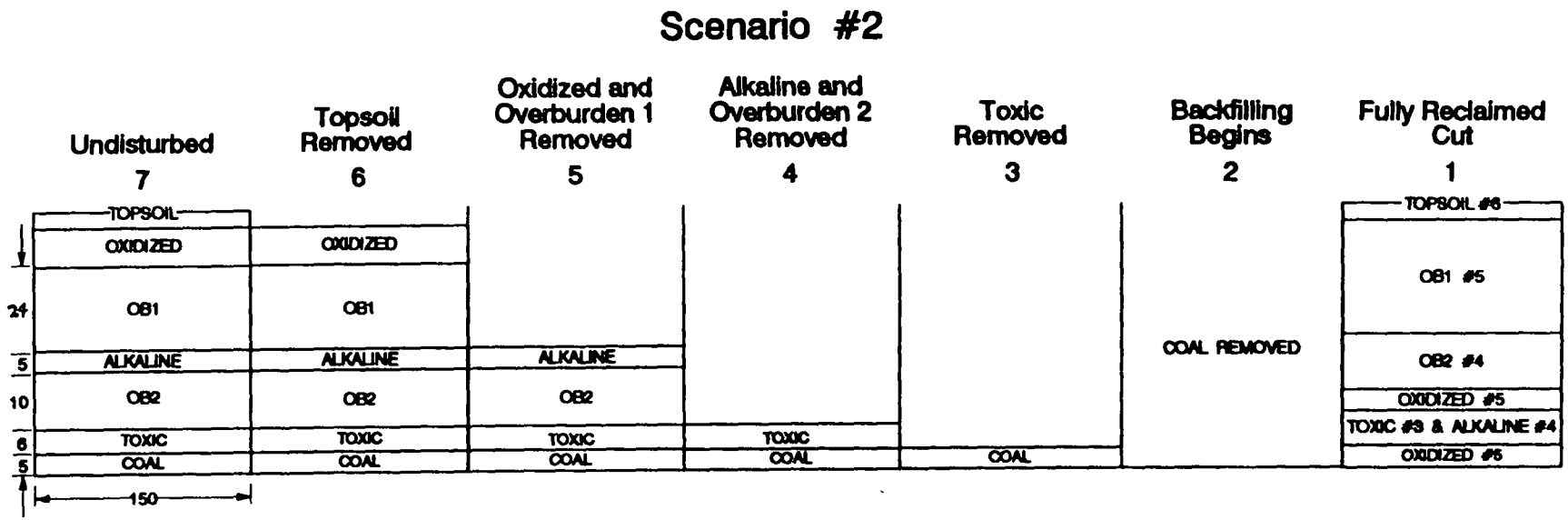

Figure 6. Simplified view of the mining process of a contour operation (scenario 2) where toxic and alkaline layers are being selectively handled and blended during backfilling. Cut 1 is fully reclaimed shows the material and pit number used for backfilling. Under scenario 2, five pits are open.

Table 5. Estimated additional costs for rock trucks in scenario 2 having toxic and alkaline layers that are selectively handled.

	Cubic Yards	Truck Cycles	Total Time (min)	Increase For Selective Handling (min)	Cost of Increase ($104/hr)
Oxidized (8.0 min)	9,750	250	2000	250	$433
Toxic (7.0 min)	3,607	92	644	0	$0
Alkaline (7.5 min)	2,930	75	563	38	66
OB1 (8.0 min)	4,118	106	848	106	184
OB2 (7.5 min)	4,857	125	937	63	109
Topsoil (8.5 min)	394	10	85	10	$17
Total	**25,656**	**658**	**4721**	**467**	**$809**

Scenario 3

The final scenario has only one stratum that requires special handling: a 0.4-m (1.4-ft) toxic layer located 4.6 m (15 ft) up from the coal bed (Figure 7). The complication in this scenario arises from the need to blast in two stages to allow special handling of the toxic layer and to avoid fracturing it into small pieces. Like scenario 1, this case also increases rock truck haul times because of the need for one additional cut, and also involves 20 percent more front-end loader time when handling toxic material.

Figure 8 shows the mining process in six stages. Cut 1 was reclaimed in the following manner. First, part of the oxidized material from cut 4 was placed on the pavement, followed by placing the toxic material from cut 3 and the remaining oxidized material from cut 4 on top. Backfilling of cut 1 continues with the lower overburden layer (OB2) from cut 3, and then the upper overburden layer (OB1) from cut 4. Finally, backfilling is concluded with the topsoil layer from cut 5.

The total and incremental costs of the front-end loader and rock trucks are given in Tables 6 and 7. The methodology is identical to that used in the earlier scenarios. Total front-end loader time per 46-m cut increased by only 6 minutes (due to the small volume of toxic material) and rock truck time increased by 221 minutes. Total cost increased by $401 per 46 by 43 m cut, or $2,025 per ha ($818 per acre).

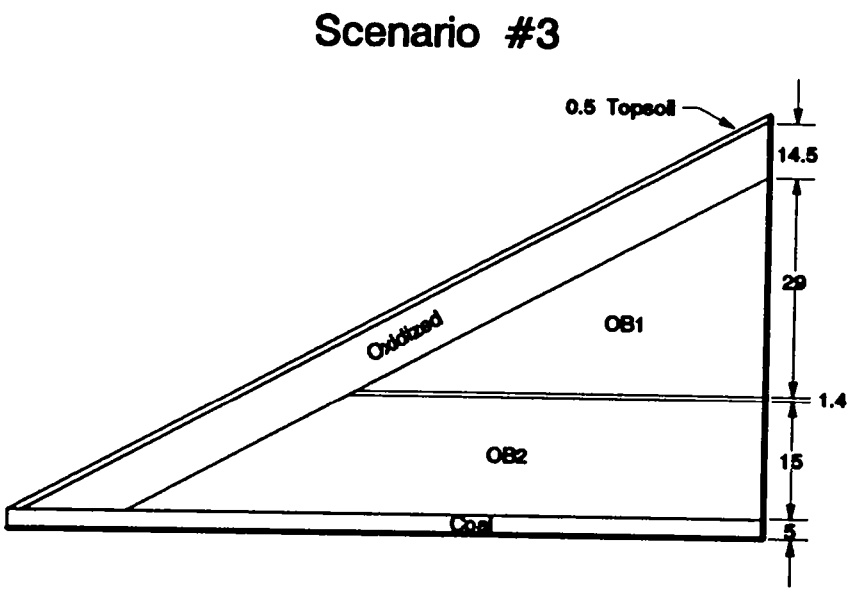

Figure 7. Undisturbed geologic cross-section for scenario 3 (all numbers in feet). This overburden is separated by a small toxic layer in the middle of the overburden. OB1 and OB2 are abbreviations for overburden sections 1 and 2.

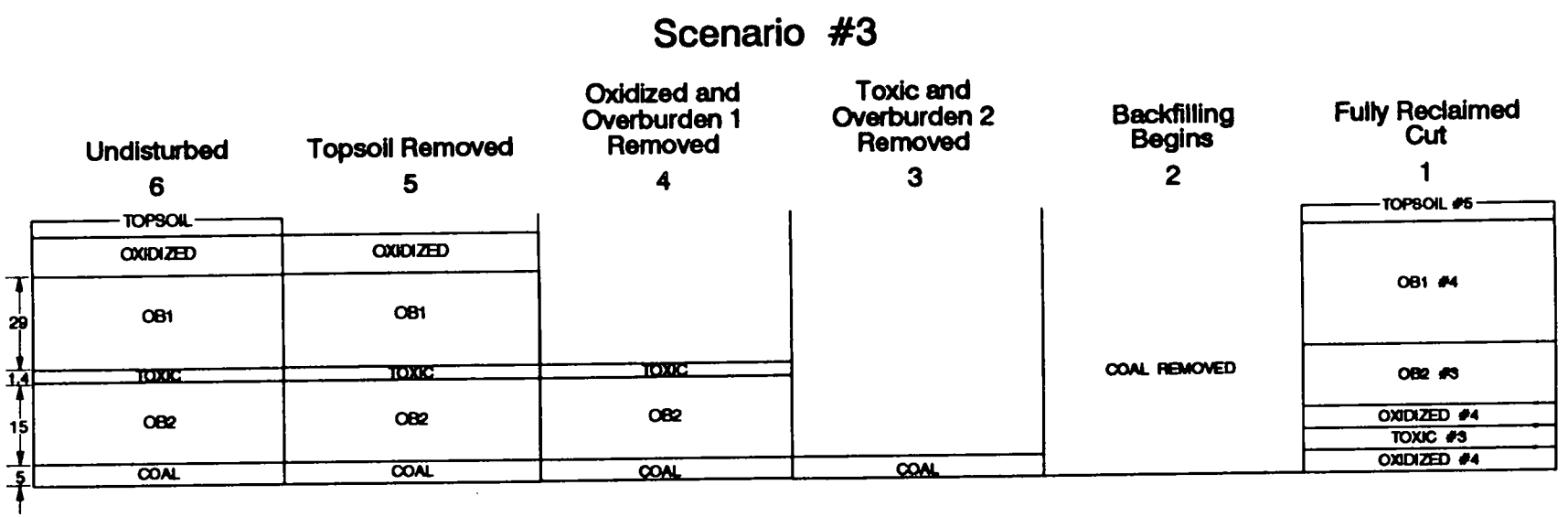

Figure 8. Simplified view of the mining process for scenario 3. This example shows a toxic layer being selectively handled and the remainder of the overburden being removed in two phases. Cut 1 is fully reclaimed and shows the material and pit number used for backfilling.

Table 6. Estimated additional costs for front-end loader in scenario 3 having a 0.4-m (1.4-ft) toxic layer.

	Cubic Yards	Loading Cycles	Total Time (min)	Increase For Selective Handling (min)	Cost of Increase ($184/hr)
Oxidized (1 min)	10,787	830	830	0	0
Toxic (1.2 min)	415	32	38	6	$18
OB1 (1 min)	6,013	463	463	0	0
OB2 (1 min)	8,047	619	619	0	0
Topsoil (1 min)	394	30	30	0	0
Total	**25,656**	**1,974**	**1,980**	**6**	**$18**

Table 7. Estimated additional costs for rock trucks in scenario 3 having a 0.4-m (1.4-ft) toxic layer.

	Cubic Yards	Truck Cycles	Total Time (min)	Increase For Selective Handling (min)	Cost of Increase ($104/hr)
Oxidized (7.5 min)	10,787	277	2,078	139	$241
Toxic (7.0 min)	415	11	77	0	$0
OB1 (7.5 min)	6,013	154	1,155	77	133
OB2 (7.0 min)	8,047	206	1,442	0	0
Topsoil (8 min)	394	10	80	5	$9
Total	**25,656**	**658**	**4,832**	**221**	**$383**

Conclusion

This paper presented three selective handling situations and estimated the additional costs associated with extra front-end loader time and rock truck time in these situations. Based on a toxic layer just above the coal and the necessity for placing that material on a layer of oxidized material, selective handling required the opening of an additional 46-m (150-ft) wide pit (compared to a non-selective handling plan) and cost an additional $663 per pit or about $3,348 per ha ($1,353 per acre) to reclaim. Other scenarios with more complex overburden handling schemes increased the costs of selective handling to $1,119 per pit or $5,652 per ha ($2,284 per acre) to reclaim. In actual mining situations, the costs of selective handling would increase if the toxic material were distributed more widely or unevenly throughout the overburden and may thereby make the cost of mining coal on the site too costly. The cost estimates do not include additional management costs, additional blasting costs, or training costs for equipment operators. In a given situation, each of these factors could add to the costs of selective handling.

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SELENITE-SELENATE SPECIATION IN MINE SOILS AND SALT SOLUTIONS: A COMPARISON OF ATOMIC ABSORPTION SPECTROSCOPY AND ION CHROMATOGRAPHY

by

Shankar Sharmasarkar, George F. Vance, and Florence Cassel-Sharmasarkar

Abstract. Coal mining activities may enhance bioavailability of selenium (Se) species in soils, which can subsequently cause toxicity and contamination problems. Information on comparative applications of spectroscopy and chromatography for selenite (SeO_3^{-2}) - selenate (SeO_4^{-2}) speciation in coal mine soils is limited. Aqueous extracts (triplicates) of five soil samples, collected from reclaimed coal mine sites in the Powder River Basin, Wyoming, and a set of SeO_3^{-2}-SeO_4^{-2} salt solutions (0.5, 1, 5, 10 and 25 mg/L, in triplicates) were speciated using atomic absorption spectroscopy with hydride generation (AAS-HG) and ion chromatography (IC). The objective of this study was to compare these two methods for Se speciation. The results indicated that AAS-HG was capable of analyzing very low Se concentration which could not be detected by IC. Presence of excessively high concentrations of SO_4^{-2} affected chromatographic Se speciation, either by shifting or overlapping Se peaks. For such cases, AAS-HG was more useful than IC. However, IC was capable of speciating aqueous SeO_3^{-2} - SeO_4^{-2} directly without any sample pretreatment, whereas AAS-HG measured SeO_3^{-2} + SeO_4^{-2}, and SeO_3^{-2} in separate runs and SeO_4^{-2} was calculated from the difference, i.e., spectroscopic speciation was an indirect method. For both Se species, AAS-HG and IC data were comparable within the limit of standard deviation, indicating the reliability of both methods for Se speciation. Thus, chromatographic and spectroscopic techniques could be applied to speciate solution Se; however, each had its own analytical limitations. For some of the speciation data there were some discrepancies, which could be due to mutual interconversions between SeO_3^{-2} and SeO_4^{-2} in the solutions, or integrational error during analysis, or some impurity in the original salts used to prepare the Se solutions. An overestimation of Se concentrations by spectroscopy was observed, which was probably due to the fact that AAS-HG estimated selenite as a component rather than a species. In aqueous soil extracts, SeO_4^{-2} was estimated to be the predominant Se species. The simultaneous use of both the spectroscopic and chromatographic techniques was instrumental in understanding details of Se speciation.

Additional Key Words: Selenium, Coal Mine Soil, Analytical, Contamination.

Introduction

The environmental importance of selenium (Se) has been attributed to its potential to cause either toxicity or deficiency to humans, animals and some plants within a very narrow concentration range (Lakin 1972). Levels as low as 0.01 mg/L are known to cause deformation and death to wildfowl (Ohlendorf 1989). The U.S. Environmental Protection Agency designated 0.01 mg/L Se as the primary drinking water standard (USEPA 1986). Selenium solubility and availability depends on the relative concentrations of

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various species present in soil solutions (Masscheleyen and others 1990), which subsequently can govern biotoxicity or deficiency. Four major Se species, selenide (Se^{-2}), elemental Se (Se^{0}), selenite (SeO_3^{-2}) and selenate (SeO_4^{-2}), can be present in soils and other geological materials (McNeal and Balistrieri 1989).

Selenium has been reported to occur naturally in association with coal mine materials of Wyoming (Sharmasarkar and Vance 1995a). In the western United States, several seleniferous coal mine environments are found where prolonged atmospheric exposure and subsequent areal oxidation of the mined materials may result in oxidized Se species, such as SeO_3^{-2} and SeO_4^{-2} in the soil solutions. Such conditions may often lead to enhanced solubility and bioavailability of these species for plant uptake and aquifer contamination. Thus, it is necessary to understand the suitable methodologies for precise determination of SeO_3^{-2} - SeO_4^{-2} in solutions. Both atomic absorption spectroscopy with hydride generation (AAS-HG) and ion chromato-graphy (IC) have been recognized as useful tools for Se analysis in soil extracts (Blaylock and James 1993); however, the efficiency of each technique may vary depending on the nature of the system under analysis. Information on comparative applications of AAS-HG and IC for SeO_3^{-2} - SeO_4^{-2} analysis in coal mine soils is not available. Therefore, a comparative study of the spectroscopic and chromatographic methods of Se assay is fundamental in the evaluation of Se solubility behavior in coal mine soils. The objective of the current study was to compare spectroscopic and chromatographic methods of SeO_3^{-2} and SeO_4^{-2} assay in aqueous soil extracts and Se salt solutions. The Se salts were used to compare the two methods in relatively homogeneous solutions, in addition to the heterogeneous mine soil extracts. The results of this study will be useful in understanding Se speciation techniques and similar approach can be applied for other contaminant assay.

Materials and Methods

Mine Soil Sampling

Five mine soils (S1, S2, S3, S4, and S5) were used for this study. The samples were collected from reclaimed coal mine sites in the Powder River Basin, Wyoming. The climate of these mine environments is temperate and semi-arid, with an average daily temperature of 5-90 °F, and an annual precipitation range of 11-18 inches. The geology of the area is comprised of Fort Union and Wasatch formations of early tertiary age, and consists of continental type sediments deposited in fluvial, lacustrine and swampy environments. The lenticular strata consist of alternating sand, silt and claystone, with occasional coal beds (Naftz and Rice 1989). Mine soil samples were air-dried, finely ground (<2 mm), and stored at room temperature in polyethylene bags until analysis.

Soil Extraction

Water extracts of the mine soils were prepared by shaking samples with distilled deionized water (solid to solution ratio = 1:2) on a reciprocating shaker (Eberbach Corporation) at 180 cpm for 24 h followed by heating (90 °C) in a waterbath for 30 min. After cooling to room temperature (24±1 °C) the suspensions were centrifuged (International Equipment Company, Model K) at 2500*xg* for 15 min followed by filtration through 0.45μ glass fiber filters. We used water extracts because aqueous Se is a potential concern to the Wyoming Department of Environmental Quality - Water Quality Division (WDEQ-WQD 1993) that has defined 0.01, 0.05 and 0.05 mg/L Se levels in groundwater as marginal levels for Class I (domestic), II (agricultural), and III (livestock) standards, respectively. Details on Se extraction procedures have been discussed by Spackman and others (1994). One sample (Id. S5) that had very low concentrations of SeO_3^{-2} - SeO_4^{-2} (<0.01 mg/L), was spiked with 15 mg/L SeO_3^{-2} - SeO_4^{-2} solution, and used as a check for this study.

Preparation of Selenite-Selenate Salt Solutions

Measured quantities of sodium salts of selenite (Na_2SeO_3) and selenate (Na_2SeO_4) were dissolved in distilled deionized water to prepare 0.5, 1, 5, 10 and 25 mg/L SeO_3^{-2}-SeO_4^{-2} solutions. The salts were purchased from Aldrich Chemical Company, Inc., Milwaukee, WI. Between analysis, the soil extracts and salt solutions were stored in polythene bottles at 4 °C.

Table 1. Analytical Parameters for SeO_3^{-2} and SeO_4^{-2} Analysis by Atomic Absorption Spectrophotometry and Ion Chromatography.

Parameters	Atomic absorption spectrophotometry	Ion Chromatography
Detection mode	Continuous absorbance	Suppressed electrical conductivity
Instrumental settings	Hollow cathode lamp (Ne gas, 15 mA current), Quartz cell, 196 nm wavelength, 0.7 nm slit width	Ion exchange separator column (AS9), Guard column (AG9), 50 µL loop
Flame	Air-acetylene (oxidizing); Flow rate: acetylene (20), air (50); Pressure: air (500 kPa), acetylene (85 kPa)	--------
Reagents	Reducing agent: 0.8 M $NaBH_4$ - 0.25 M NaOH; Sample matrix: 6 M HCl	Mobile phases: 5.4 mM Na_2CO_3 - 5.1 mM $NaHCO_3$, water, Flow rate: 2 mL/min; Regenerant solution: 0.013 M H_2SO_4, Flow rate: 5 mL/min
Carrier gas	N_2 (350 kPa)	N_2 (700 kPa), He (120 kPa)
Integration time	10 s	10 min
Boundary limits	Se detection: 0.001 mg/L, Se quantification: 0.1 mg/L	Se detection: 0.01 mg/L, Se quantification: 40 mg/L

Selenite-Selenate Speciation by AAS-HG and IC

Concentrations of SeO_3^{-2} and SeO_4^{-2} in the aqueous soil extracts and salt solutions (triplicates) were compared by both spectroscopic and chromatographic methods. Solutions having SeO_3^{-2} - SeO_4^{-2} concentrations greater than the limits of quantification were diluted before analyses. In the spectroscopic method, total SeO_3^{-2} + SeO_4^{-2} in solution was analyzed after a HCl digestion using a continuous flow hydride generator (Varian, Model VGA-76) attached to a Perkin-Elmer (Model 2280) atomic absorption spectrophotometer (AAS-HG) (Spackman and others 1994). Solution SeO_3^{-2} concentration was analyzed before HCl pretreatment. Dissolved SeO_4^{-2} was calculated from the difference between these two data. Details of Se speciation using AAS-HG have been described by Cutter (1985) and Fio and Fujii (1990). Simultaneous speciation of SeO_3^{-2} - SeO_4^{-2} was carried out using an ion chromatographic (IC) method with electrical conductivity detection (Dionex 2000i ion chromatography with AI-450 software, version 2.12). The details regarding Se analysis by these methods were described in Blaylock and James (1993). The operational conditions for SeO_3^{-2}-SeO_4^{-2} analysis by both AAS-HG and IC are described in Table 1. In the AAS-HG method, SeO_3^{-2} is reduced to H_2Se by $NaBH_4$-NaOH. The nascent hydride formed due to reduction is then replaced by an inert carrier gas (N_2) and passed through a heated quartz cell. The instrument records an absorbance reading at a Se resonance line corresponding to the wavelength of 196 nm.

In the IC method, different anionic species are retained inside an anion exchange column as the ions pass through. During the passage of the eluent (Na_2CO_3-$NaHCO_3$), ions are released, and the corresponding conductivities are recorded by the instrument relative to the retention times of different species. The conductivity response appears in the form of chromatograms, and concentrations of the ions in a sample solution are calculated from recorded peak areas of standard solutions. For both instrumental analyses, reference SeO_3^{-2}-SeO_4^{-2} solutions were used as standards. However, because of differences in

quantification limits between AAS-HG and IC, two sets of standards were used. Thus, for spectroscopy we used 0 (control), 0.005, 0.01, 0.02, 0.04, 0.08 and 0.10 mg/L SeO_3^{-2} - SeO_4^{-2} solutions; whereas for chromatography concentration levels were 0 (control), 0.05, 0.10, 0.25, 0.50, 1.0, 5.0, 10, 20 and 40 mg/L SeO_3^{-2} - SeO_4^{-2}. These standard solutions were used in triplicate. It should also be noted that in addition to the use of reference solutions, and triplicate measurements as quality controls, the standards and sample solutions were run through identical experimental and instrumental conditions.

Results and Discussion

The regressional relationship for the response of both analytical methods to Se concentrations in standard solutions is shown in Figs. 1a and 1b. For AAS-HG, the response was absorbance, while for IC, peak area was used for Se quantification. The response of both instruments was significantly linear (r 0.99) within the limit of Se quantification. Similar conditions were also described by Blaylock and James (1993). It should be noted that for IC, the slope of the SeO_3^{-2} line was greater than that for SeO_4^{-2}. Ion chromatograms showing conductivity versus time plots for SeO_3^{-2}, SO_4^{-2} and SeO_4^{-2} are described in Fig. 2. Distinct peak separation was observed for different ions when there was no mutual peak interference (Fig. 2a). In such cases AAS-HG is useful for Se speciation.

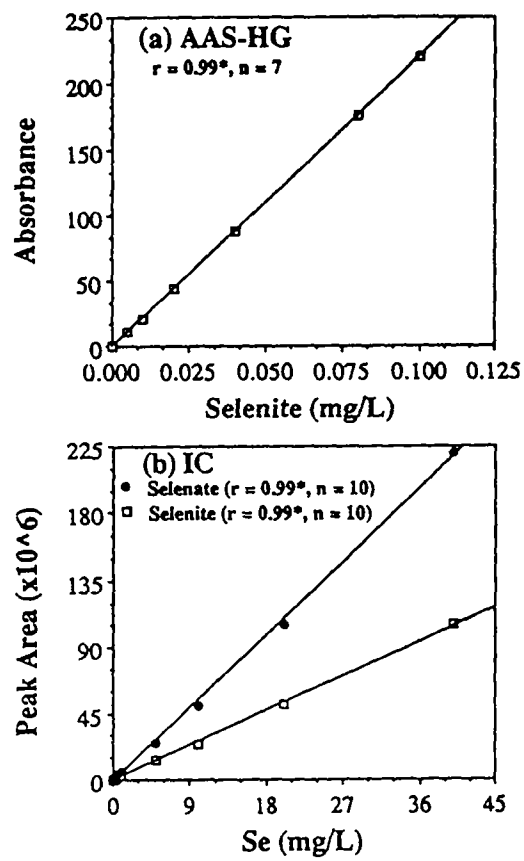

Figure 1. Se quantification by: (a) AAS-HG, (b) IC. (*r = correlation coefficient, n = number of samples, * = significant at P<0.01).

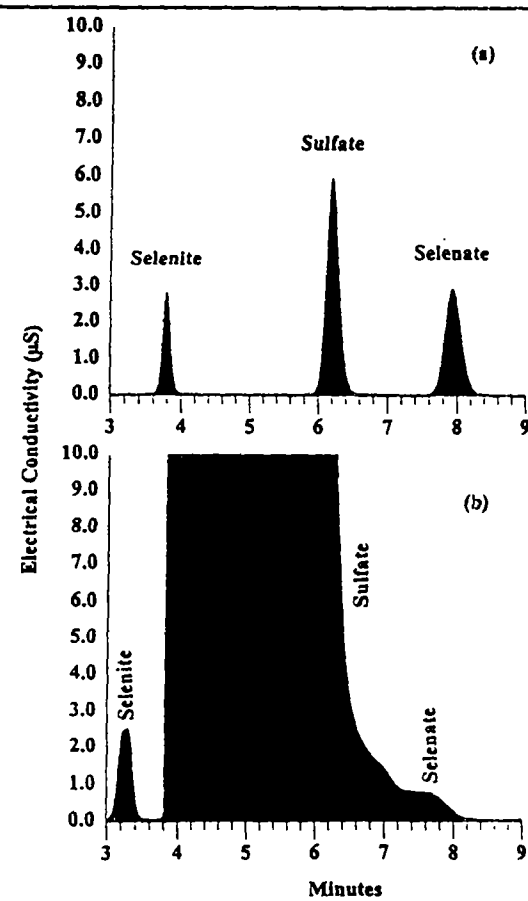

Figure 2. Ion chromatograms: (a) distinct peaks (20 mg/L of each ion), (b) shifting and overlapping of peaks (sample ID. S5+15 mg/L).

Table 2. Spectroscopic and Chromatographic Speciation of SeO_3^{-2} and SeO_4^{-2} in Mine Spoil Extracts and Salt Solutions.*

Samples	SO_4^{-2} (mg/L)	SeO_3^{-2} AAS-HG	SeO_3^{-2} IC	SeO_4^{-2} AAS-HG	SeO_4^{-2} IC
		(mg/L)			
S1	90	0.27 ± 0.02	0.25 ± 0.06	0.90 ± 0.06	0.81 ± 0.05
S2	315	0.18 ± 0.01	0.18 ± 0.08	0.13 ± 0.05	0.13 ± 0.06
S3	85	0.06 ± 0.01	0.04 ± 0.01	0.10 ± 0.01	0.13 ± 0.07
S4	203	0.06 ± 0.01	0.06 ± 0.04	3.42 ± 0.36	3.24 ± 0.60
S5	4270	0.002 ± 0.000	BDL	0.002 ± 0.000	BDL
S5+15 mg/L	4270	14.91 ± 0.23	14.24 ± 0.86	14.88 ± 0.23	ND (PO)
0.5 mg/L	0.5	0.58 ± 0.01	0.50 ± 0.07	0.42 ± 0.03	0.51 ± 0.06
1 mg/L	1	1.09 ± 0.03	1.00 ± 0.08	0.94 ± 0.17	1.00 ± 0.07
5 mg/L	5	5.30 ± 0.04	4.66 ± 0.18	5.33 ± 0.67	4.88 ± 0.38
10 mg/L	10	11.65 ± 0.10	9.35 ± 0.17	9.31 ± 1.35	9.43 ± 0.08
25 mg/L	25	26.66 ± 0.69	24.40 ± 0.53	23.99 ± 2.30	24.28 ± 0.35

* Values are mean of three replications ± SD (standard deviation). AAS-HG = Atomic Absorption Spectrophotometry with Hydride Generation, IC = Ion Chromatography. BDL = Below Detection Limit, ND = Not Detected, PO = Peak Overlap.

According to the retention time of each species, the SeO_3^{-2} peak appeared first (3.77 ± 0.40 min) followed by SO_4^{-2} (6.02 ± 0.40 min) and SeO_4^{-2} (7.72 ± 0.40 min). However, extremely high concentration of SO_4^{-2} (in this case 4270 mg/L) caused a noticable shift in the SeO_3^{-2} peak toward a lower retention time (3.28 min) and masked the SeO_4^{-2} peak, subsequently resulting in a lack of SeO_3^{-2} - SeO_4^{-2} quantification (Fig. 2b). Shifting or overlapping of different peaks is often found to be a limiting factor for Se speciation by IC.

Spectroscopic and chromatographic speciation of SeO_3^{-2} and SeO_4^{-2} in mine soil extracts and salt solutions is shown in Table 2. For both species, the AAS-HG and IC data were comparable within the limit of standard deviations, which indicated the reliability of both methods for Se speciation. For some of the salt solutions, the detected concentrations of SeO_3^{-2} and SeO_4^{-2} did not exactly correspond to the experimental concentrations used, though the sum of SeO_3^{-2} and SeO_4^{-2} detected matched more closely with the experimental concentrations of SeO_3^{-2} + SeO_4^{-2} used. The slight discrepancy could be due to mutual interconversions between SeO_3^{-2} and SeO_4^{-2} in solutions, or integrational error during analysis, or some impurity in the original salts used to prepare the solutions. Similar observations were also made by Blaylock and James (1993). For most samples including both the soils and salts, a comparison of AAS-HG and IC data also indicated there was either slight overestimation of concentrations by spectroscopy or minor underestimation by chromatography. This was probably due to the fact that AAS-HG estimated selenite as a component rather than a species, i.e., some other selenite ions (for example, biselenite) in addition to SeO_3^{-2} might have been recorded by the instrument, whereas, IC recognized only SeO_3^{-2} and SeO_4^{-2} as species, not as components. It should be noted that for the sample S5, the IC method was not useful in speciating Se at very low level (<0.01 mg/L), whereas AAS-HG was able to detect as low as 0.002 mg/L Se. Another limitation of the IC method was peak overlapping (sample: S5+15 mg/L), where SeO_4^{-2} peak was masked by a large SO_4^{-2} peak. These are important findings with respect to the environmental quality standards.

In this sample the SeO_3^{-2} peak shifted because of the high SO_4^{-2}

concentration, which, however, was corrected by adjusting the retention time for SeO_3^{-2} during the data reprocessing in the AI-450 software. Thus, AAS-HG was capable of speciating all the samples, whereas IC could speciate Se only in samples with no SO_4^{-2} interference. Again it should be noted that IC can speciate Se in the same run unlike AAS-HG which requires separate runs and some sample pre-treatments. Finally, a close review of the data suggested that SeO_4^{-2} was mainly the predominant species in the aqueous soil extracts, which conformed with the observations from a Se speciation study previously conducted by Sharmasarkar and Vance (1995b). The knowledge acquired from this study should help in obtaining a broader view regarding spectroscopic and chromatographic analysis of Se as both components and species; we recommend simultaneous use of both methods.

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COMPACTION EFFECTS ON MINELAND SOIL QUALITY[1]

Padam P. Sharma, and Fredric S. Carter[2]

Abstract. Management of water is vital to sustenance of biomass production and environmental quality of reconstructed minelands in semi-arid North Dakota. Since water resides and moves through soil pores, quantification of soil pore characteristics is a key to evaluate soil quality for reclamation success. We measured field saturated hydraulic conductivity (K) by double-ring ponded infiltration method on 26 premine and postmine profiles. The same profiles, each installed with a neutron probe access tube and a set of five tensiometers, were used to monitor post-infiltration redistribution of water by measuring volumetric water contents and matric potentials with time. An empirical equation was fitted to the soil water retention data to derive proportional distribution of various sizes of pores, maximum water capacity, median pore size, and a depth weighted pore index (Ω) to compare efficiency of each profile to transmit and retain water. The undisturbed premine soils showed high Ω's and high proportion of effective pores (ε) with radii > 5 μm. The reclaimed mineland profiles show low Ω and general deficiency of pores effective in transporting water to deeper depths. The pooled data from the premine and postmine soil profiles included in this study show that K increased linearly with Ω and ε^2. We recommend that the K - ε relationship be further evaluated by measuring infiltration and pore size distribution from various locations under different management conditions. If feasible, the easily measurable, profile scale, K - ε relationship provides a quantitative tool to evaluate soil quality of premine and reclaimed soils.

Additional Key Words: Land Reclamation, Soil Structure, Soil Hydrology

Introduction

About 800 - 1000 hectares of prairie landscapes in western North Dakota are annually disturbed for surface mining of lignite coal. Following the Surface Mine Control and Reclamation Act (U. S. Congress, 1977) guidelines, federal and state regulations on surface mining mandate that the disturbed lands be reconstructed to a level of productivity and environmental quality equal to or better than before mining. To achieve this goal, previously stripped non-sodic subsoil (original lower B and upper C) and topsoil (original A and upper B) materials are respread over reshaped spoil. The depth of respreading depends upon the physical and chemical properties of the spoil. Scrappers are generally used to respread the materials at about 15-cm increments until the desired depths of subsoil and topsoils are achieved (Halvorson et al., 1986). Vegetation is re-established and, following the SMCRA guidelines, the quality of reclaimed soils are assessed on the basis of respread soil depth and biomass yield.

In the undisturbed Mollisols of western North Dakota, the natural prairie vegetation and associated granular soil structure supports rapid movement of water through well-developed inter-aggregate voids and biologically created macropores. When these soils are mined, the existing network of soil pores is destroyed.

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During land reclamation after surface mining, the frequent and heavy vehicular traffic used in spreading and leveling operations cause compaction resulting an abundance of fine sized inter-aggregate pores. As a result, reclaimed soils lack the effective pore volume and continuity needed for adequate distribution of water and roots (Chong et al., 1986). Potter et al. (1988) compared pore volumes of constructed mine soils of 4 and 11 years after reclamation with undisturbed soils. They observed that mesopore volume (pore radii > 15 μm) of reclaimed soils and associated hydraulic conductivities, especially of the subsoil layer, were significantly lower than the undisturbed soils.

Soil quality relates to the ability of soil to function as medium for plant growth, as partitioner and regulator of water, energy, and solute fluxes in the landscape and biosphere, and as filter and buffer for inorganic and organic pollutants (Larson and Pierce, 1994). A good quality soil sustains onsite productivity, efficiently utilizes available water and nutrients, and minimizes offsite damages to water and air quality. By replacing suitable soil material to specified depths, the current reclamation mitigation package seeks to reconstruct the rootzone and achieve reference area biomass productivity. However, it ignores the role of the root zone pore space to harvest precipitation water for maximum plant growth. While the current technology tries surficial control of overland flow and effluents to minimize onsite and offsite damages, it fails to stress the role of the reconstructed root zone pore structure to achieve hydrologic balance in the watershed.

Larson and Pierce (1994) favor the use of a dynamic systems approach to assess soil quality by evaluating a management system in terms of its actual performance in the watershed rather than an output comparison with other systems. A systematic observation of changes in soil quality parameters and their behavioral indications in energy, water, sediment, and solute fluxes in the watershed should be the proper approach to monitor the success of reclamation. Since water is the key integrator of these fluxes and water resides and moves through soil pores, we propose that characterization of pore structural aspects of root zone soil quality is fundamental to the restoration and sustenance of agricultural productivity and environmental quality of restored ecosystems

To understand the effect of root zone soil characteristics on distribution of water on reclaimed lands vis-à-vis that of premine lands and pre-law abandoned minelands, we measured infiltration, water retention and seasonal variability of soil water contents on surface coal minelands of North Dakota from 1989 to 1993. The data on seasonal distribution of soil water (Sharma et al., 1993) and infiltration experiments (Sharma et al., 1994) were presented elsewhere. In this paper, we report on water retention characteristics and infer the profile scale pore structural attributes of soil quality.

Materials and Methods

Constant head, ponded infiltration was measured by double ring method (Bouwer, 1986) on premine lands, abandoned minelands, and reclaimed mineland profiles at Indian Head (T144N R89W sec. 24 and 25) and Velva (T152N R81W Sec. 27,28, 33 and 34) mines in west-central North Dakota. Prior to water application, a neutron probe access tube was installed at the center of the inner ring using a hydraulically driven core sampler of equivalent diameter to the access tube. Additionally, side walls of the access tube hole was carefully repacked by pouring loose soil material around the tube and tamping with a small metal rod. Marriotte bottles were used to supply constant head of water in the rings and infiltration measured for 2 to 3 hours. The infiltration volume vs. time data were fitted with infiltration equations to evaluate the parameters of sorptivity and field saturated hydraulic conductivity (Sharma et al., 1994).

After about 15-22 days of the first infiltration run, tensiometers were installed inside the inner ring on 26 of a total of 40 profiles used for infiltration. The tensiometers were fitted with high flow (air-entry pressure = 100 kPa) porous ceramic cups and

installed at depths of 15, 30, 46, 61, and 76 cm. Before installation, each tensiometer tubing was plastered with wet bentonite, and installation, the space around the tensiometer tubing was back filled soil and repacked to prevent preferential flow.

The tensiometers were filled with de-aired, distilled water and closed with rubber septa. The hydraulic potential was measured with a transducer readout system by inserting a hypodermic needle through the septum (Marthaler et al., 1983). A second infiltration run was conducted until the deepest tensiometer indicated a steady state reading. Water supply was then stopped, and the profile covered with mulch and heavy plastic to prevent evaporation. After about 30 days of redistribution, the mulch and the plastic were removed to allow free evaporation.

During the redistribution process, measurements of neutron probe and tensiometers were recorded at short time intervals in the beginning then daily, and weekly, at later times. The measurements were discontinued when the top two tensiometers stopped functioning due to air-entry into the ceramic cups. At the end of the experiment of about 45 to 60 days, disturbed samples taken at the approximate depth of the tensiometer locations were used to determine 1500 kPa water contents in the laboratory using a pressure membrane apparatus (Klute, 1986).

The relationship between the volumetric water contents and the corresponding matric suctions at each tensiometer depth is represented by the following two parameter closed form equation (van Genuchten, 1980):

$$\Theta = (\theta - \theta_r)/(\theta_s - \theta_r) = [(1 + (\alpha h)^n]^{(1/n-1)} \quad (1)$$

In the above equation, Θ is relative saturation; θ is water content, m^3/m^3; θ_r is residual water content, m^3/m^3, θ_s is near saturation water content, m^3/m^3; and h is matric suction in kPa. For this analysis, we used θ_r equal to the laboratory measured 1500 kPa water content and θ_s equal to 85% of the total porosity (calculated from bulk density of the samples) to approximate incomplete satiation under field conditions. The θ_s and θ_r only represent the upper and lower limits of the fitted curve, and hence, do not have a physical meaning. The curve shape parameters, α and n are derived by nonlinear curve fitting of Eq. [1] to the measured data. For freely draining undisturbed and abandoned mineland profiles, Eq. [1] fitted the data fairly well with nonlinear regression coefficients > 0.95. For tensiometers at deeper depths of reclaimed soils and at highly sodic-clay profiles, the fitting of data was erratic with nonlinear $R^2 > 0.70$.

From Eq. [1], the rate of water desorption ($d\theta/dh$), defined as the water capacity (ϕ, 1/ kPa) is calculated as (Horton and Chung, 1991):

$$\phi = (n-1)\,(\theta - \theta_r)\,[1 - \Theta^{\{n/(n-1)\}}]\,/h \quad (2)$$

The matric suction (h) at which the ϕ is maximum (ϕ_{max}) is converted to corresponding median pore size (η, μm) by dividing 150 with h. The constant of 150 comes from the capillary equation between matric suction (kPa) and capillary radius (μm) at 20° C (Gupta et al., 1989). The median pore size is assumed to represents the size of pore at which most of the water at the point of measurement will be released due to forces of gravity, root extraction, or upward flux due to evaporative demand of the surface (Hillel, 1980). From N tensiometer measurements at the various depths, a depth weighted pore index (Ω) of the profile is calculated by cumulating the product of η and ϕ_{max} for each depth of measurement:

$$\Omega = 100/z \sum_{T=1}^{N} \eta\, \phi_{max} \quad (3)$$

Here, T is the count of tensiometers and z is the depth of the deepest tensiometer, cm. The factor of 100/z is used to extrapolate the Ω value to a meter of root zone depth. The Ω index is used to assess the relative depth integrated capacity of the various profiles to desorb water. Hence it is a measure of profile scale soil pore structure.

From the soil water retention data measured at each tensiometer depth, we derive

pore size distribution using the following pore classification scheme (Table 1).

Table 1: Classification of pore sizes

Pressure head (kPa)	Pore radii (μm)	Pore class
< 3	> 50	Macropores
3 - 30	5 - 50	Mesopores
30 - 1500	0.1 - 5	Micropores
> 1500	< 0.1	Residual pores

Note: The proportion of macropores and meso-pores (volume of pores with radii > 5 μm) are collectively called effective pores. Traditionally, the volume of water held in the effective pores is defined as drainable water, and that in the micropores is called available water.

Results and Discussion

To demonstrate the effect of compaction on water retention and water capacity curves, we purposefully chose six typical premine and postmine profiles from the data set. Table 2 lists the location, major characteristics, hydraulic conductivity (K), and depth averaged median pore size (η) and weighted pore index (Ω) of the six profiles. The undisturbed (Z215I, V116) and the compacted (Z511, Z004) premine soils mainly consist of the Flaxton - Williams association (Typic haploborolls) with wind and water deposited sediments overlying glacial tills. The root zone texture ranges from sandy loam to clay loam with undisturbed profiles having a well developed aggregated structure due to dominance of natural prairie vegetation. The topsoil and subsoil layers of the reclaimed profile at Indian Head (Z503), consisting of sandy loam to loam materials, are underlain by loam to silty clay, sodic minespoil materials. The profile at Velva (V102) shows a typical pre-SMCRA characteristics with haphazard respreading of overburden materials.

Table 2: Site characteristics and pore structural indices of six representative premine and reclaimed soil profiles.

Mineland Type	Location	Dominant Characteristics	$\eta^{\dagger}$ (μm)	$\Omega^{\ddagger}$ (μm/kPa)	$K^{\S}$ (cm/h)
Premine undisturbed	Z 215I	sandy loam, natural prairie	30 (12.7)	5.42	26.33
	V116	clay loam, natural prairie	46 (8.0)	7.91	11.82
Premine compacted	Z511	vehicle traffic, hay	26 (6.9)	0.85	1.54
	Z004	vehicle traffic, grazing	24 (11.8)	0.73	0.50
Postmine reclaimed	Z503	post-SMCRA, hay	21 (14.4)	0.93	1.64
	V102	pre-SMCRA, grazing	14 (3.3)	0.08	1.82

† Median pore size, ‡ Weighted pore index, § Satiated hydraulic conductivity. The numbers in parenthesis are standard deviations.

Representative Water Retention Curves

Figure 1 shows the soil water retention characteristics with depth of the two undisturbed prairie soils from the Indian Head (Z215I) and Velva mine (V116). The sigmoid-shaped curves show the fitted water content versus pressure head relationships (Eq. [1]), and the bell shaped curves represent the derived specific water capacity versus pore size relationships (Eq. [2]) with depth. The curve shapes are more pronounced on the well aggregated clay loam profile (V116) than the sandy loam profile (Z215I). Table 2 shows that the depth weighted pore index (Ω) and hydraulic conductivity of these two profiles are significantly higher than those of premine compacted and reclaimed soils.

Examples of water retention and specific water capacity curves of compacted premine soils in the vicinity of minelands are shown in Fig. 2. These profiles were subjected to heavy vehicular traffic during mining in the 1970's. After mining was completed in the early 1980's, profile Z511 was managed with alfalfa hay while the profile Z004 was used for intensive grazing. Compared to the undisturbed profiles (Fig. 1), the retention and specific water capacity curves of the compacted profiles (Fig. 2) are flatter. Compaction has decreased the total pore volume at the cost of inter-aggregate effective pores and increased the volume of intra-aggregate residual pores. Compared to the undisturbed profiles shown in Fig. 1, the weighted pore indices (Ω) of these two compacted profiles were < 1.0.

Figure 3 shows the soil water retention characteristics and specific water capacity curves of the reclaimed profiles listed in Table 2. The Z503 profile at the Indian Head mine was reclaimed under the SMCRA guidelines in the early 1980's and restored with grass-legume hay crop. The bulged shape of the 15-cm water capacity curve indicates that the topsoil of Z503 has an improved pore structure than subsoils at deeper depths. Compared to those of the undisturbed profiles which show pronounced curve shapes throughout the depth (Fig. 1), the deeper depths of this reclaimed profile has flatter shapes indicating poor structure development. The Z503 profile has a Ω index of 0.93 which is comparable with the compacted premine profiles (Table 2).

The profile at Velva (V102) was not reclaimed as per the SMCRA guidelines, and since the vegetation reestablishment, the land is used for grazing. This overgrazed, reclaimed profile at Velva (V102) shows a severe lack of porosity with depth. Despite overnight saturation, the deeper tensiometers in this profile did not show any response during infiltration and during subsequent redistribution process. The Ω index of 0.082 calculated from the three remaining tensiometers weighted for 1.0 m of root zone depth (Eq.[3]) indicates a massive structure.

Pore Size Distribution

The depth averaged pore size distribution of the 26 different profiles for which soil water retention characteristics were measured in the field are shown by bar diagram in Fig. 4. The number at the bottom of each bar represents the average total pore volume of which the proportion of macropores, mesopores, micropores, and residual pores are shown in shades. The number at the top of each bar denotes the weighted pore index (Ω) of each profile.

In general, the six undisturbed premine profiles and the two non-sodic profiles (Z213, Z214) in the abandoned minelands show higher pore volumes. In these profiles, macropores and mesopores (effective pores) constitute about 50% of total pore space. The comparatively higher Ω index of these profiles signify a pore structure with potential to efficiently transport and store precipitation and runon water.

Compared to the well structured soils, the total pore volumes and Ω indices of the four premine compacted soils and the six reclaimed soils are smaller in magnitude. The decrease in total pore volume due to compaction is mainly due to a decrease in the proportion of macropores and mesopores. Only about 25% of the total pore volume is occupied by effective pores. Of

the four premine compacted soils shown in Fig. 4, Z511 is the farthest from the mine area with a Ω index of 2.45. The Ω indices of other premine compacted and reclaimed profiles are < 1.0. The abandoned minelands, on the other hand, show high total pore volume and a wide range of Ω values. Though not compacted, the ability of abandoned mineland profiles to transport and retain water, as signified by the Ω index, is limited by the location of sodic clay materials in the root zone. The three sodic spoil profiles (Z211, Z703, V205) have the lowest Ω and hydraulic conductivities.

Hydraulic Conductivity vs. Pore Indices

The structural signature of a soil profile is typified by its pore characteristics defined by the number and size of pores, their continuity, tortuosity and stability. The entry and rate of movement of water and its retention in soil are dependent upon the depth integrated pore characteristics of the profile. While effective porosity is a measure of the volume of large size pores, the hydraulic conductivity is a measure of the continuity and tortuosity of these pores. A relationship between the two parameters is an indicator of relative pore structure of various premine and postmine soils with respect to their ability to transport water.

We regressed the hydraulic conductivity (K) calculated from ponded infiltration experiments (Sharma et al., 1994) against the volume of effective pores (ε) and the weighted pore index (Ω) derived from water retention experiments. The K-ε relationship was derived by nonlinear curve fitting of the form $y=ax^b$, of which, the exponent 'b' was 2.02. For clarity of interpretation, we refitted the data with $K=a\varepsilon^2$. The K-Ω relationship was derived by linear regression.

Figure 5 shows that even for data from various heterogeneous premine and postmine soil profiles, K increased with ε^2 and the Ω index. Also shown in Fig. 5 inset, the best estimates for K (cm/h) for the data set included in this study are as follows:

$$K = 1.276 \times 10^{-4}\, \varepsilon^2 \qquad (r^2 = 0.86) \qquad [4]$$

$$K = 1.243 + 1.302\ \Omega \qquad (r^2 = 0.81) \qquad [5]$$

The intercept in Eq. [5] is not significantly different from 0. Of the 26 field measurements included in this regression, there were three outlier data from infiltration into coarse textured undisturbed and nonsodic abandoned mineland profiles. These profiles contained big desiccation cracks and numerous colonies of ants; in comparison to their effective porosities, these profiles had excessive infiltration rates.

Figure 5 demonstrates how a generalized profile scale K- ε or K- Ω type relationship is useful in comparing the pore structural qualities of premine and postmine profiles. For simplicity of measurement, we recommend that the K-ε relationship methodology be further evaluated with measurements on additional premine and postmine soils from different locations and under various management systems. As K can be easily measured from the steady state infiltration rate, ε can be calculated from the measurement of volumetric water content at 30 kPa (near field capacity) from undisturbed samples in the laboratory. On the other hand, development of the K-Ω relationship requires expert knowledge; it is time consuming, and the data is highly dependent upon precision and robustness of tensiometric instrumentation used under field environments.

Conclusions

The data, in general, show that the undisturbed soils have high effective porosities and associated hydraulic conductivities. The pore structural attributes of abandoned minelands show the widest range of variability depending upon the location of sodic spoil material in the profile. The post-SMCRA reclaimed profiles with subsoil and topsoil replacements show improved pore structure than when the sodic spoil materials are respread alone. However, the structural quality of these reclaimed profiles was only comparable to compacted premine soils and at a level significantly lower than that of the undisturbed premine profiles.

The data in this study and previous studies on soil structure of reclaimed soils in North Dakota and elsewhere indicate that soil structure regeneration due to natural processes of wetting-drying and freezing-thawing is extremely slow to nonexistent. With the current land reclamation technology and grass-legume hay crop as postmine land use for a decade or more seems to have improved the pore structure to a depth of about 0.3 m. The studies also point out that the deeper depths of reclaimed subsoil show a severe lack of pore space and pore continuity. The repercussion of this lack of adequate pore space in the subsoil results in a restricted root zone with lack of available water during drought and oxygen during floods. For sustained productivity of reclaimed soils, it is recommended that respreading technology, post-reclamation land management, and reclamation evaluation guidelines need to focus on increasing the effective porosity of the entire root zone.

Acknowledgments: This study was funded by the U. S. Congress appropriated grants from the USDI/Bureau of Mines through the National Mined Land Reclamation Center, Western Regional Program. The matching support and facilities were provided by the State of North Dakota. The authors appreciate the North American Coal Co. and Consolidated Coal for assistance and unlimited access to the study sites.

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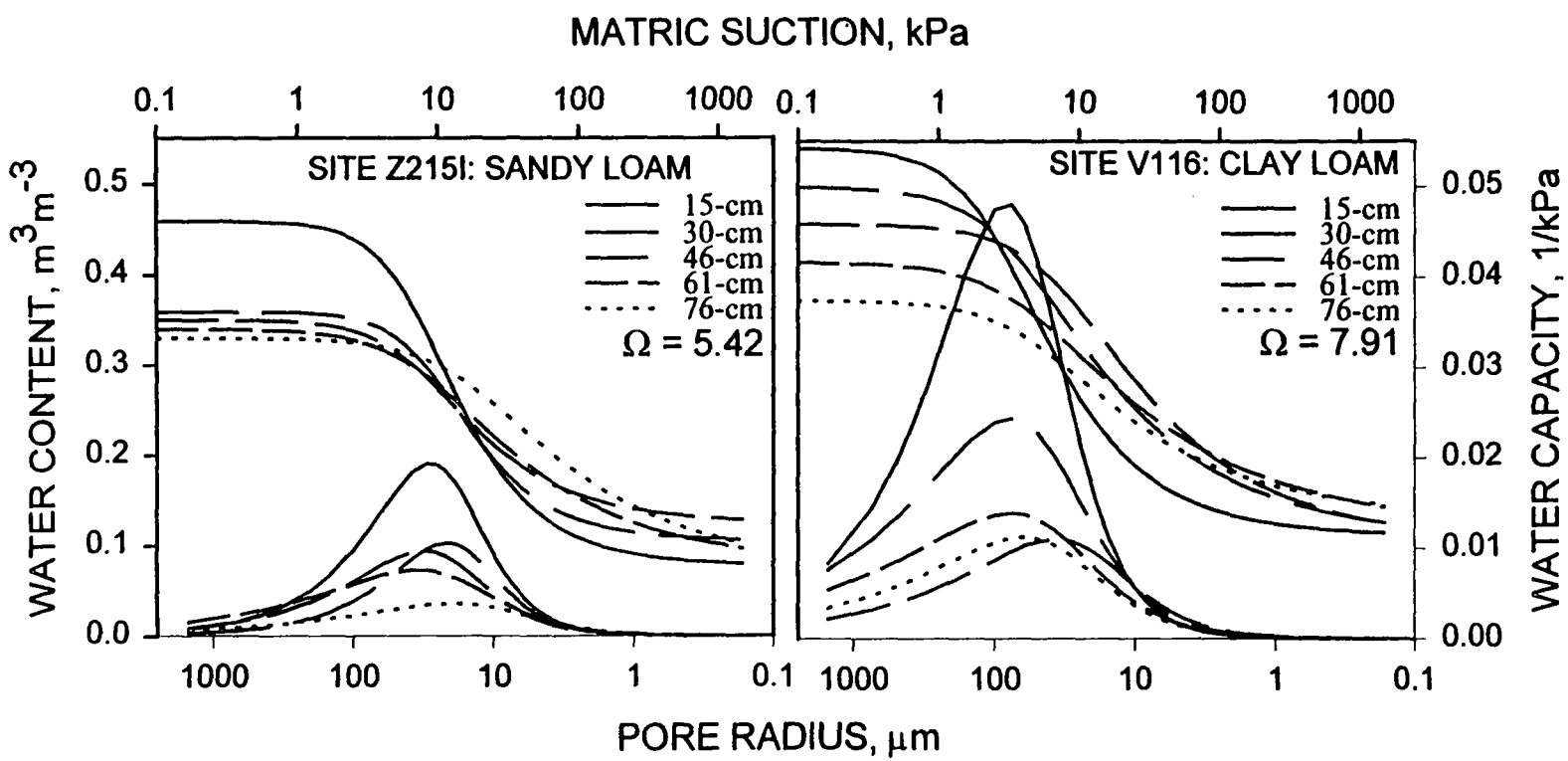

Fig.1: Fitted soil water retention and water capacity curves for two premine undisturbed profiles.

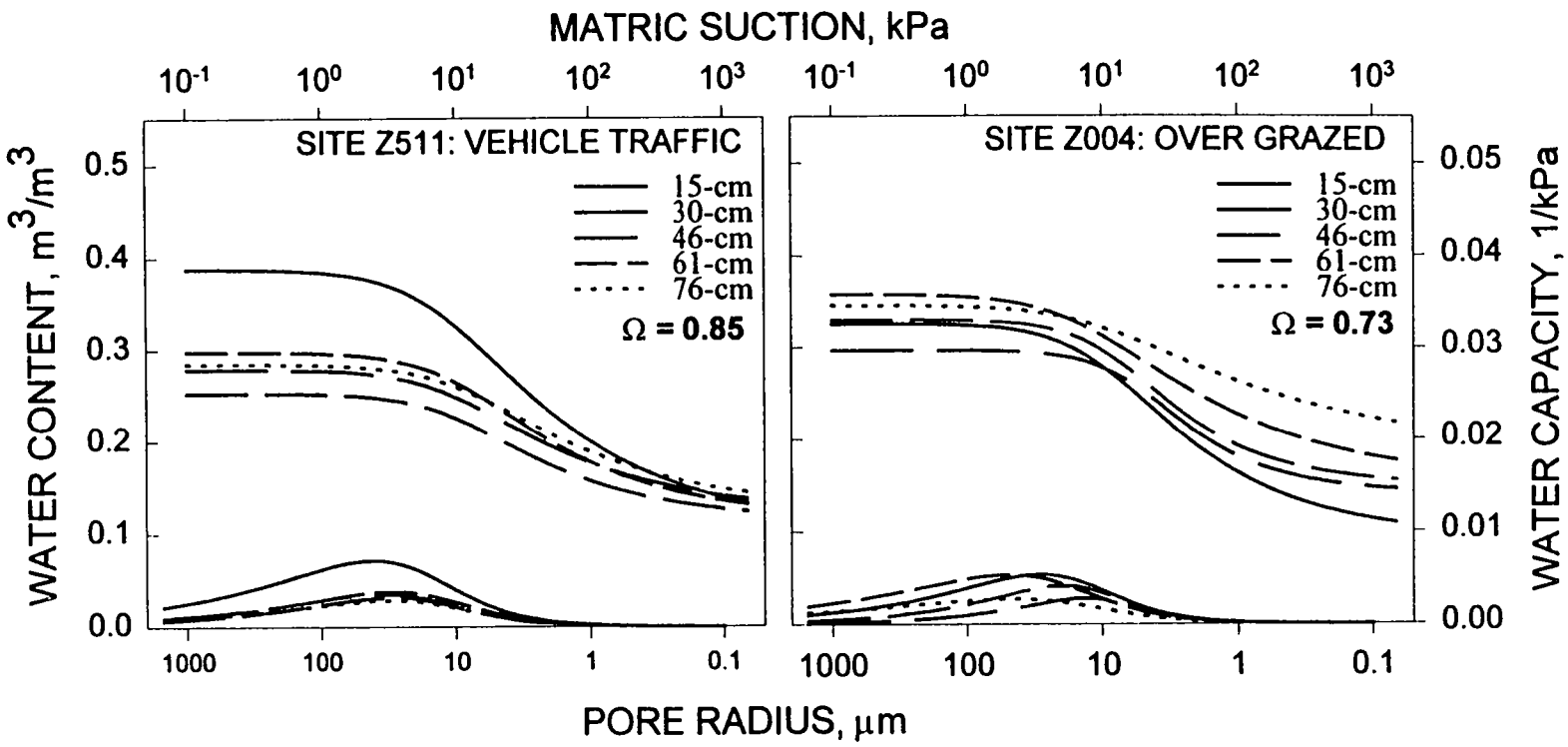

Fig. 2: Fitted soil water retention and water capacity curves for two premine compacted profiles.

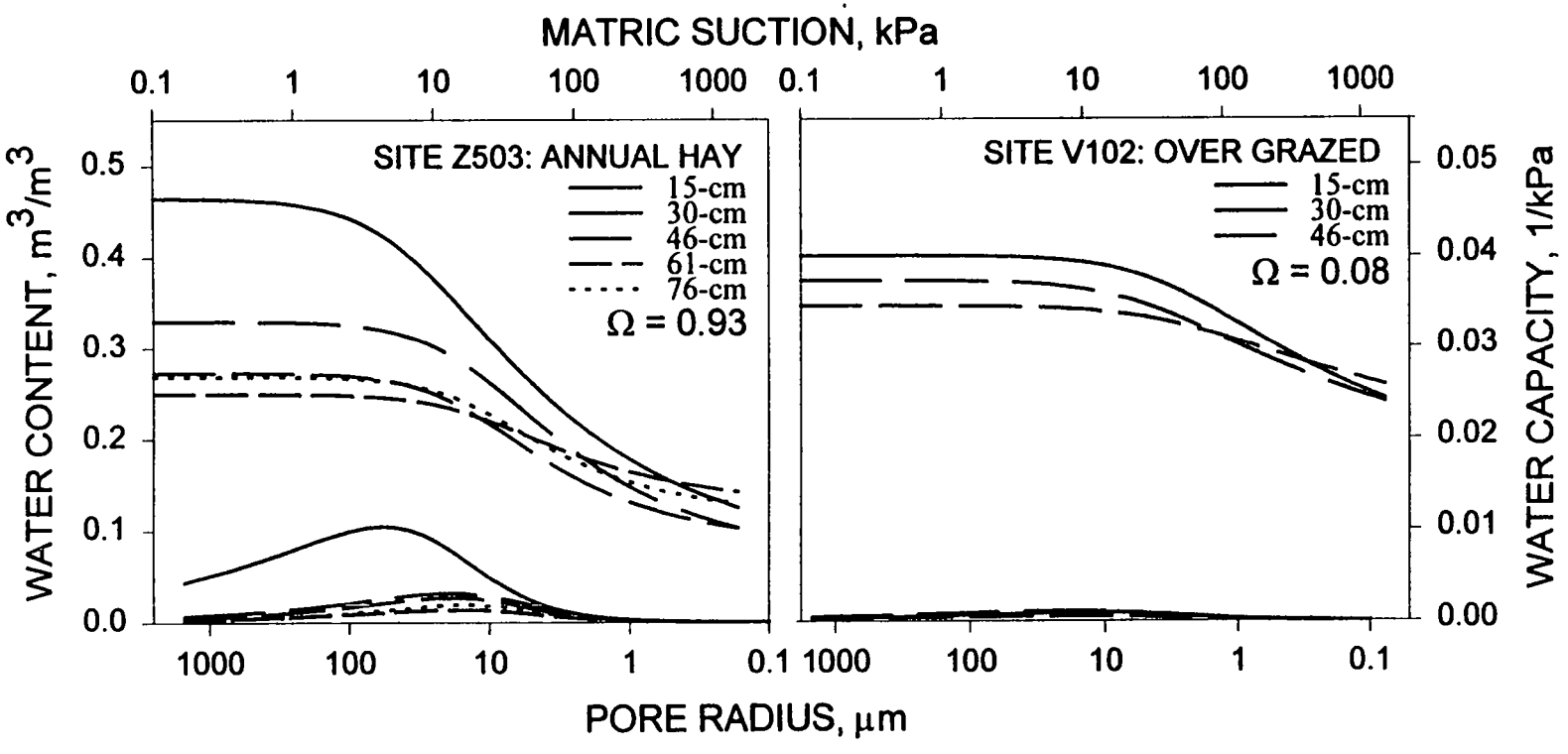

Fig. 3: Fitted soil water retention and specific water capacity curves for two reclaimed profiles.

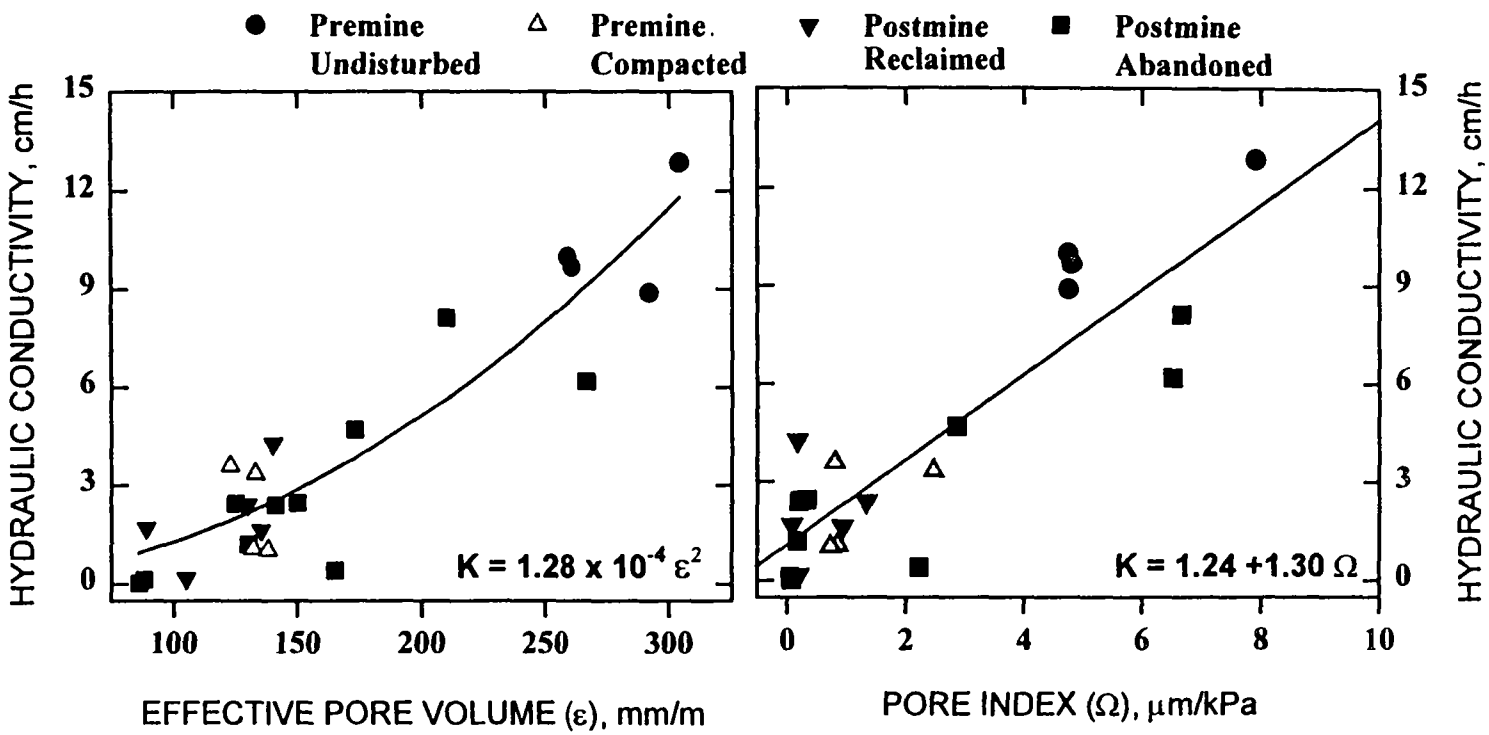

Fig. 5: Field saturated hydraulic conductivity(K) as a function of average volume of effective pores (ε) and weighted pore index (Ω) of premine and postmine soil profiles.

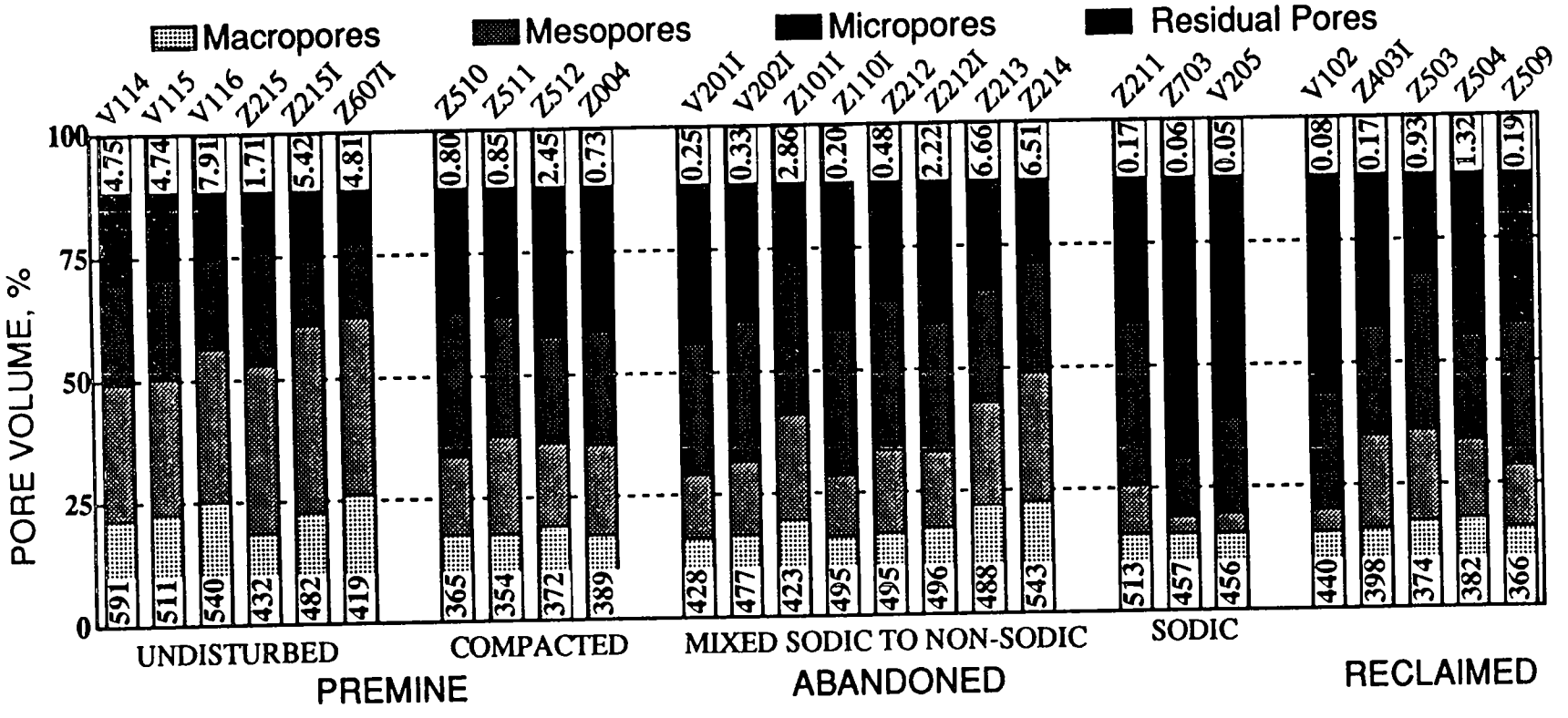

Fig. 4: Depth averaged pore size distribution of 26 pre- and post-mine soil profiles. The numbers at the bottom of each bar represent average total pore volume (mm/m), and those at the top represent the weighted pore index (Ω) of each profile.

AVAILABILITY OF P AND K IN RESTORED PRIME FARMLAND[1]

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Additional Key Words: P fixation; soil mixing; Reclamation.

Abstract. Modifications in soil nutrient availability of mine soils were studied in greenhouse and field experiments to investigate the effect of topsoil and subsoil mixing on available P and to study the response of corn to P and K fertilization. Topsoil and subsoil from an unmined Sadler silt loam (fine-silty, mixed, mesic, Glossic Fragiudalfs) were mixed in different proportions, treated with P and subjected to wetting and drying cycles in a greenhouse. Available P decreased due to wetting and drying, and more so, soil mixing, particularly with a more acidic subsoil. Two-year field studies with corn were conducted at two sites, at site 1 the soil was constructed predominantly from a Belknap silt loam (coarse-silty, mixed, acid, thermic Typic Fluvaquents) using end-dump trucks and at site 2, from a predominantly Sadler silt loam using scraper pans. Phosphorus and K were applied in a randomized complete block factorial design with four replications. In the first year, corn response to K was observed in earleaf tissue but not grain yield, at site 1. No response was observed in the second year. This was attributed to unfavorable moisture distribution. Site 2 data showed no response to P or K in both years. Compaction and moisture stress were thought as possible causes. A progressive build-up in soil test P and K was observed at both sites. About 18 kg P ha^{-1} were required for a 1 mg kg^{-1} increment in Bray I extractable P on a disturbed compared to 12 kg P ha^{-1} on an undisturbed Belknap soil. For K, 15 kg K ha^{-1} were required for a disturbed soil compared to 8.7 for an undisturbed Belknap soil. These results suggest that higher P and K fixation due to soil mixing may contribute to higher fertilizer requirements on disturbed soils compared to undisturbed ones.

Introduction

Current regulations require that prime farmland disturbed by surface mining be restored to a productivity level equal to or greater than its premined state. Frequently, efforts in meeting this condition are limited by poor soil physical conditions, low fertility, and moisture limitations, which characterize surface mined soils.

Previous studies have indicated that soil compaction (Indorante et al., 1981; Grandt, 1988), and its associated effect on root development, contribute to the observed weather sensitivity of row crops. Acidity (Dancer and Jansen,

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1987), low organic matter (OM) levels (Powell et al., 1986), microbial population, diversity, and activity (Stroo and Jencks, 1982; Visser et al., 1983) have been associated with deficiencies of essential nutrients, such as N and P, and consequently low productivity of surface mined soils.

The natural decrease in OM content with increasing soil depth and the relative difficulty of completely segregating the A horizon from underlying subsoil strata during soil removal, stock-piling, replacement, and leveling operations, results in a significant reduction in OM of the replaced topsoil (Powell et al., 1986). Beckwith (1965) and Sanchez and Uehara (1980) observed that some subsoil materials possess a higher P fixation capacity than topsoil. Field observations (Snarski et al., 1981; Barnhisel, 1988) indicate that topsoil and subsoil blending degrades topsoil physical and chemical properties. Better crop response was observed with topsoil and subsoil materials placed separately as opposed to mixing them (Jansen et al., 1985).

Although progress has been made towards establishing lime and fertilizer recommendations for forage on post mine soils (Barnhisel, 1976), similar work remains for row crops. According to Dancer and Jansen (1987), higher Bray I extractable P levels were required to attain the same level of corn production on disturbed soil sites than on undisturbed ones. In some instances, poor crop response to added P has been reported, yet low extractable P levels were observed at the end of the growing season (Dancer, 1984). Surface mining activities seem to modify soil characteristics significantly, leading to a higher P fixation and correspondingly, a higher fertilizer requirement.

The objectives of the present study were: (1) to investigate the effect of topsoil and subsoil mixing on phosphorus availability, (2) to determine the nutritional status and yield of corn following P and K treatment on restored prime farmland, and (3) to monitor changes and transformations of soil P and K following the treatments.

Materials and Methods

Greenhouse study

To study the effect of topsoil and subsoil mixing on P availability, topsoil (TS, pH_w 6.9) and subsoil (SS1, pH_w 7.1) samples of a Sadler silt loam (fine-silty, mixed, mesic, Glossic Fragiudalfs) were collected from a non mined site in Ohio County, Kentucky. Mixtures of topsoil and subsoil were prepared to make up 0, 25, 50, 75, and 100% subsoil (%SS). Three 1-kg portions of each mixture were weighed out, and mixed thoroughly with 50, 100, and 150 mg P as finely ground triple super phosphate [$Ca(H_2PO_4)_2.H_2O$]. In plastic pots, the samples were watered to field capacity (0.3 kg kg^{-1}) with deionized water and allowed to dry to wilting point (0.1 kg kg^{-1}) under greenhouse conditions. At the end of each two wetting and drying cycles, 100 g soil sub samples were collected from each mixture. The experiment was repeated using the same topsoil but with a subsoil (SS2, pH_w 4.5), predominantly a Sadler, collected from a stock-pile of a surface mine. Soil analyses for exchangeable bases based on the neutral 1M NH_4OAc (Thomas, 1982), available P by the Bray I (Bray and Kurtz, 1945) and Mehlich III (Mehlich, 1984) and P fractionation (Chang and Jackson, 1957) were performed on the sub samples collected.

Field Experiments

Field studies were conducted at two post mined sites in Hopkins and Muhlenberg Counties, western Kentucky. Soil at site 1 was reconstructed predominantly from a Belknap silt-loam (coarse-silty, mixed, mesic, Glossic Fragiudalfs) using end-dump trucks during the fall of 1987. This field was in fertilized alfalfa (Medicago sativa L.) in 1988 and 1989. Soil test data for spring 1990 indicated low P and K levels (Table 1). Phosphorus (0, 32, and 64 kg P ha^{-1}) and K (0, 75, and 150 kg K ha^{-1}) were broadcast (as in 1988), applied as factorial in a randomized complete block design with four replications. The field was planted to corn (Zea Mays L.) in June 1990 and 1991. Nitrogen (160 kg N ha^{-1}) was applied at planting and top-dressed at 80 kg N ha^{-1}.

Soil at site 2 was replaced from a Sadler silt loam using scraper pans during the spring 1988. This field was in unfertilized soybeans (Glycine max L.) in 1989. Soil test data for spring 1990 indicated very low P and low K levels (Table 1). Phosphorus (0, 37, 74, and 111 kg P ha^{-1}) and K (0, 139, and 278 kg K ha^{-1}) were applied as factorial in a randomized complete block design with four replications. The field was planted to corn in June 1990 and 1991. Nitrogen was applied at the same rates as at site 1.

Table 1. Some characteristics of the soils used in this study#.

Soil	pH_w	OM	CEC	Ca	Mg	K	Na	BP
			Greenhouse experiment					
		%	cmol(+) kg^{-1}					mg kg^{-1}
TS	6.9	3.07	15.2	7.96	0.92	0.37	0.06	9.3
SS1	7.1	1.37	10.9	7.50	1.28	0.44	0.05	5.2
SS2	4.5	0.89	10.0	2.00	1.90	0.47	0.08	3.2

Site	Text	pH_w	CEC	Ca	Mg	K	Na	BS	OM	BP	NK
			Field experiments								
			cmol(+) kg^{-1}					%		mg kg^{-1}	
1	sil	7.0	12.9	6.5	1.2	0.2	0.1	61.8	1.6	4.9	79.9
2	sil	6.9	11.2	5.6	1.8	0.2	0.1	69.3	1.6	0.8	97.3

#pH_w, OM, CEC, Ca, Mg, K, Na, and BS refer to 1:1 soil to water pH, organic matter content, cation exchange capacity, NH_4OAc extractable Ca, Mg, K, and Na, and base saturation, respectively. BP and NK are Bray I and NH_4OAc extr. P and K, respectively. Text is soil texture based on the pipette method.

Soils were analyzed for available P according to the Bray I and Mehlich III both at planting before fertilizer application and at harvest. Phosphorus fractionation was performed according to the Chang and Jackson Procedure (1957). Ear-leaf tissue sampled at silking were analyzed for five nutrients. Nitrogen and P were determined by the micro-Kjeldahl procedure as presented by Jones and Case (1990). Potassium,

Ca, and Mg were determined by the nitric-perchloric wet-ashing procedure (Jones and Case, 1990).

Results and Discussion

Greenhouse study

Topsoil and SS1 had similar 1:1 soil to water pH (pH_w) values (Table 1), with TS having higher exchangeable Ca and Bray I extractable P, but lower K and Mg than SS1. Topsoil had higher OM and CEC than SS1 while subsoil 2 (SS2) had a lower pH_w, OM, exchangeable Ca, CEC, and Bray I extractable P, but higher Mg, K, and Na than TS and SS1.

The effect of subsoil mixing on topsoil available P is presented in Fig. 1. There was a significant decrease in Bray I extractable P with increasing proportion of subsoil added to topsoil. The effect was greater in soil mixtures where a more acidic subsoil medium, SS2, was introduced. Figure 1 shows that adding 25% of SS2 to TS caused almost a 50% decrease in Bray I extractable P. Similar results were obtained with Mehlich III extractable P.

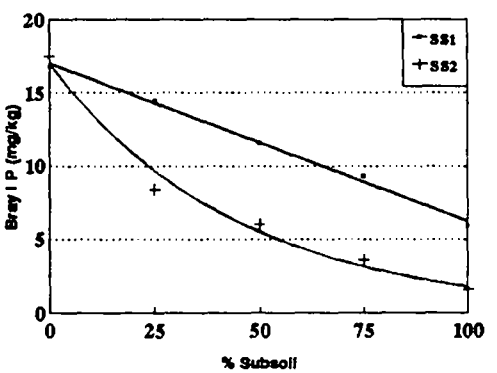

Fig. 1 Bray I P as affected by subsoil addition.

The decrease in available P (calculated as applied P minus extractable P) at a given time during the experiment was used as an estimate of the amount of P sorbed (Velayuthan, 1980). Table 2 shows that P sorption increased significantly as the proportion of subsoil in the mixture increased, particularly with SS2. These results relate closely with those of Beckwith (1965) that some subsoil materials exhibit a higher P fixation capacity.

Table 2. Sorbed P as affected by topsoil and subsoil mixing##.

%SS	Sorbed P SS1)		Sorbed P (SS2)	
	Bray	Mehl.	Bray I	Mehl.
	----------mg kg^{-1} ---------			
0	83.2	78.2	81.9	77.0
25	85.5	81.0	91.0	87.8
50	88.5	85.1	93.8	87.5
75	90.7	86.1	96.1	112.0
100	94.1	89.1	98.1	97.8
$LSD_{.05}$	2.0	3.0	2.0	2.3

Averaged across three P rates and eight cycles.

Field experiments

Soil characteristics at the beginning of field experiments are presented in Table 1. It is worth noting that soil at site 2 had much lower available P, compared to that at site 1, since unlike site 1, no previous P fertilization had taken place.

Corn response to P and K

Results for 1990 are summarized in Table 3. Phosphorus fertilization increased ear-leaf P and Ca significantly, but decreased K (possibly dilution). On the other hand, K application increased ear-leaf K, but decreased Ca and Mg contents. Many studies have reported

Table 3. Ear-leaf composition, yield, and soil test P and K as affected by P and K application, Site 1, 1990.

P rate	Ear-leaf N	Ear-leaf P	Ear-leaf K	Ear-leaf Ca	Ear-leaf Mg	Grain Yield	Bray I P
kg ha^{-1}	g kg^{-1}					Mg ha^{-1}	mg kg^{-1}
0	31.2	2.63	17.5	4.46	2.16	8.15	5.3
32	30.7	2.82	15.8	5.12	2.46	7.89	7.9
64	30.1	2.92	15.0	5.02	2.50	7.68	12.5
$LSD_{.05}$	1.2	0.14	1.2	0.51	0.41	1.37	2.9
K rate	N	P	K	Ca	Mg	Yield	NH_4OAc K
0	31.0	2.84	12.9	5.58	3.27	6.91	71.1
75	30.4	2.82	17.4	4.76	2.06	8.17	79.0
150	30.5	2.72	18.1	4.27	1.77	8.65	87.1
$LSD_{.05}$	1.2	0.14	1.2	0.51	0.41	1.37	9.7

that increased K uptake following K fertilization often decreases Ca and Mg uptake (Stout and Baker, 1981; Dibb and Thompson, 1985) and have attributed this to competition between K, and Ca and Mg during root uptake.

Results for grain yield indicated a significant response to K, but none for P. In general, yields were higher than the Phase III target value of 6.7 Mg ha^{-1} on this soil (Fehr et al., 1977). Optimum earleaf K content of about 18 g kg^{-1} corresponding to near maximum relative yield (ratio of any yield value to the maximum yield observed) was obtained at a soil test (NH_4OAc-K) value of about 86 mg kg^{-1} (Fig. 2). This is higher than the value of 71 mg kg^{-1} observed by Thom (1985) for a similar soil prior to disturbance.

Results for site 2 showed a significant response to K in ear-leaf tissue, but none for P (refer to Semalulu, 1992 for more detailed data). The lack of response to P, in spite of the very low initial soil test P level, was attributed to moisture stress. In addition, severe

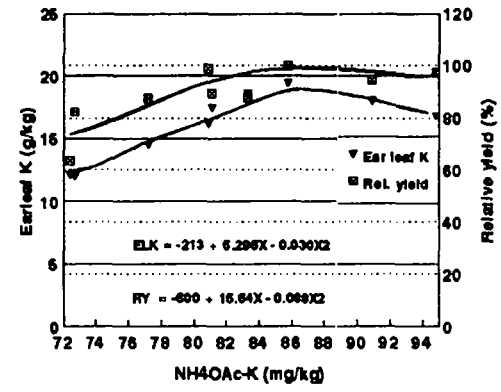

Fig. 2. Corn response to K, site 1.

compaction of soil at this site was observed during soil sampling (about 10 cm depth) the signs of which were evident during the growing season (prominent rip marks where the ripper had passed prior to seeding and water stagnation in some areas of the field during early spring). However, bulk density values were not determined.

Table 4. Changes in P fractions during the study

P rate	3/90			10/90			10/91		
	Al-P	Fe-P	Ca-P	Al-P	Fe-P	Ca-P	Al-P	Fe-P	Ca-P
kg ha^{-1}	mg kg^{-1}								
				Site 1					
0	21	79	19	14	181	33	21	157	31
32	24	57	18	21	184	37	31	178	40
64	29	59	24	32	193	41	43	203	45
$LSD_{.05}$	7	26	8	8	12	6	7	43	11
				Site 2					
0	9	82	20	5	90	27	8	81	25
37	8	90	17	7	101	25	18	111	31
74	10	83	16	12	105	25	42	129	39
111	9	90	21	15	114	33	43	152	52
$LSD_{.05}$	0.5	6	7	3	6	10	12	18	13

In 1991, climatic limitations severely affected crop performance at both sites (rainfall data presented in Semalulu, 1992). Heavy spring rains affected seed germination, in addition to possibly contributing to N loss. Also, the crop experienced water shortage at the later periods of growth, particularly during grain filling. Our results indicate a response to K at site 1 in the ear-leaf tissue, but not to P. Grain yields were lower than those in 1990, and not related to treatments. Similar trends were observed at site 2. Yields were lower than those for site 1. Compacted soil at site 2, coupled with unfavorable rainfall distribution as outlined above, might have further affected crop performance at site 2.

Phosphorus changes and transformations

There was a progressive increase in Bray I and Mehlich III extractable P due to P application, both at the end of a growing season and between years, proportional to the P rates applied. Table 4 shows that this was largely reflected in the aluminum phosphate fraction.

Figure 3 presents the relationship between the change in Bray I extractable P as a function of the total amount of P applied. Significant ($P<.01$) linear relationships were observed. For site 1,

$$Y = 0.498 + 0.057P;\ R^2 = 0.963 \quad (1)$$

and for site 2,

$$Y = -0.468 + 0.061P;\ R^2 = 0.824 \quad (2)$$

where Y is the change in Bray I extractable P (mg kg^{-1}), and P is the total amount of P (kg ha^{-1}) applied. From equation 1 and 2, the amount of P required to raise Bray I extractable P by 1 mg kg^{-1} was 17 kg ha^{-1} for site 1, and 16 kg ha^{-1} for site 2.

Previous work by Thom (1985) on an undisturbed Belknap silt loam soil in Webster County, western Kentucky, gave a value of 12 kg ha^{-1}. In studies on the P behavior of an undisturbed Sadler silt loam soil in Caldwell County, western Kentucky, Gallo (1989) reported high P immobilization by this soil. Results

from this study suggest an even higher P-fixation capacity after disturbance.

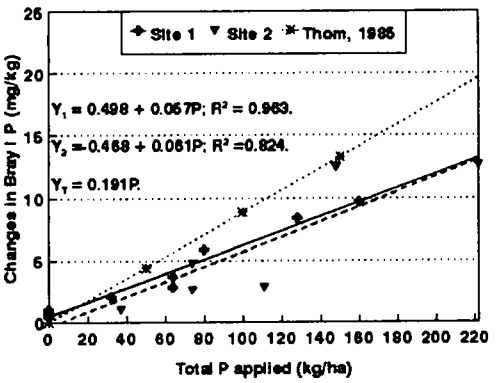

Fig. 3. Changes in Bray I P vs total P applied

Potassium changes and transformations

A progressive increase in NH_4OAc and Mehlich III extractable K was observed due to K fertilization. The change in NH_4OAc-K for site 1 was significantly related to total K applied ($P<.01$)

$$Y = 26.6 + 0.066K; \; R^2 = 0.738 \qquad (3)$$

where Y is the change in NH_4OAc extractable K, (mg kg^{-1}), and K is the total amount of K (kg ha^{-1}) applied.
From equation 3, 15 kg K ha^{-1} were required for to achieve a 1 mg kg^{-1} increment in NH_4OAc extractable K, which is higher than the value of 8.7 obtained by Thom (1985) for a similar soil prior to disturbance. However, a similar relationship for site 2 soil was not significant.

Conclusions

Soil compaction and moisture availability and distribution are major factors affecting corn growth on reclaimed soils. The optimum ear-leaf K concentration (18 g kg^{-1}) was obtained at higher NH_4OAc-K levels for a disturbed Belknap soil than for an undisturbed one (86 versus 71 mg kg^{-1}). Fertilization increased soil test P and K, and for P, this was most reflected in the aluminum phosphate fraction. Higher P and K rates were required to raise the soil test P and K levels of a disturbed Belknap soil by 1 mg kg^{-1} than for an undisturbed one (17 versus 12 kg P ha^{-1} and 15 versus 8.7 kg K ha^{-1}). Mixing of topsoil with subsoil during coal surface mining activities significantly reduces available P. The associated increase in P fixation of the resulting reconstructed soils probably accounts for the higher P fertilizer requirements as observed in the results of this study.

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