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

by:

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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 ($p\leq 0.048$, 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, $p\leq 0.0203$) 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 Agrihorolls) 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 x 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 eqnation 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

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

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.

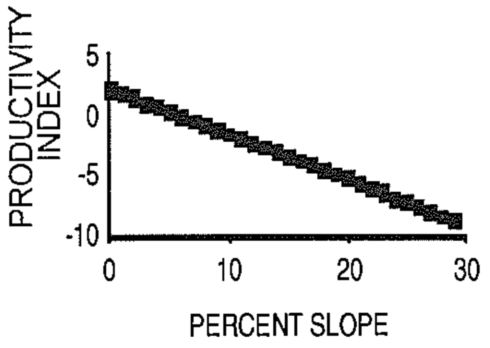

Figure 2. Main-effect relationship between percent slope and productivity index.

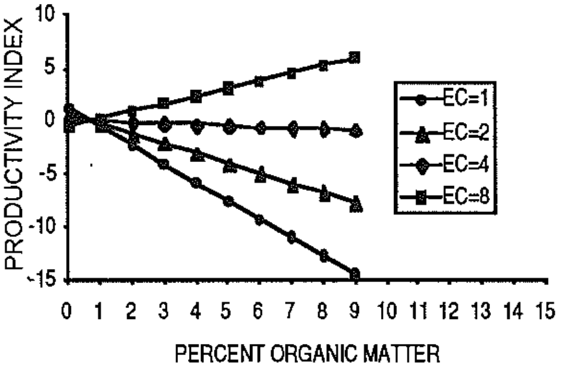

Figure 3. Productivity index determined by an electrical conductivity and percent organic matter interaction term (EC=Electrical Conductivity).

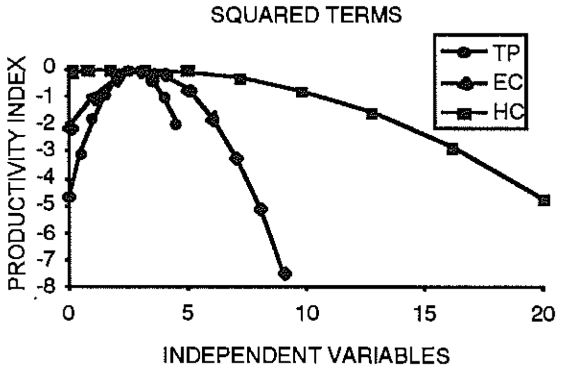

Figure 4. Parabolic relationship between squared terms and productivity index (TP=Topographic Position, EC=Electrical Conductivity, HC=Hydraulic Conductivity).

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

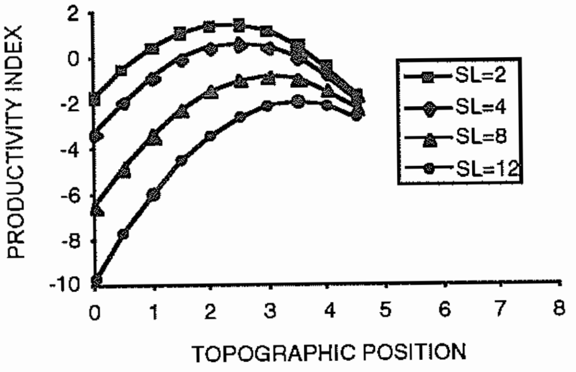

Figure 5. Productivity index determined by a combination of three terms: topographic position squared, topographic position and percent slope, and percent slope (SL=Percent Slope).

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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