

Fig. 5. Partial correlation matrix showing the correlation between selected terrain and soil attributes at the Sterling, CO, site.

land flow—the low predicted values of the sediment transport index in this area tend to support this. The thinnest A horizons generally occur on the steepest and most convex areas (negative values of plan and profile curvature). Thick A horizons on steep slopes are associated with high values of wetness index and plan curvature (i.e., concave areas where water concentrates). Wetness index, which is a function of specific catchment area and slope, and plan curvature appear to characterize similar processes (i.e., overland and subsurface flow convergence).

Soils with organic matter content  $>1.6\%$  (Fig. 4e) occur mainly where the wetness index is  $>8$  (Fig. 3b) and where slopes are  $<2\%$  (Fig. 3a). Calcareous Bk horizons with pH 8 or more, underlie most of the area according to the soil survey (Amen et al., 1977). In parts of the field, material from Bk horizons is incorporated into A horizons by tillage. This occurs mostly where slopes are  $>2\%$  and A horizons are thin, or where calcareous sediment from eroded areas upslope is deposited on thick A horizons in toeslope positions. Finally, extractable P (Fig. 4c) is spatially related to the distributions of organic matter (Fig. 4e) and possibly to pH (Fig. 4g). Low P values are associated with low organic matter content, high pH, and slopes  $>2\%$ .

### Topographic and Soil Attribute Relationships

Because of space limitations, we will present a preliminary analysis of the relationships between topography and soil attributes using a subset of the results from a more comprehensive study. Figure 5 presents a scatter diagram of each pair of variables below the diagonal and the correlation coefficients of the same pairs of variables above the diagonal. From this matrix it can be seen that the terrain attributes most highly correlated with soil attributes are slope ( $|R| = 0.45\text{--}0.64$ ) and wetness index ( $|R| = 0.25\text{--}0.61$ ). In addition, the sediment transport capacity index, which is a measure of the erosion and transport potential of overland flow, is moderately correlated with A horizon thickness ( $R = -0.39$ ), pH ( $R = 0.45$ ), and sand ( $R = 0.42$ ) and silt ( $R = -0.33$ ) contents. The correlations between these three terrain attributes and soil attributes supports the hypothesis that the soil catena develops in response to the way water flows through and over the landscape.

The “best” combination of terrain variables for explaining the variation of measured soil attributes was explored using stepwise linear regression. Table 2 presents the intercepts, terrain attribute coefficients, and  $R^2$  for the “best” relationships describing the distribution of A horizon thickness, extractable P, organic matter,

pH, and sand and silt contents in the top 0.1 m of the soil profile. The numbers in parentheses indicate the order in which the variables were brought into the regressions. Only variables that improved the regressions at the 0.01 level were included. In many cases, profile and/or plan curvature were significant variables at the 0.05 level. These regression equations were then used to predict the spatial distribution of A horizon thickness, extractable P, organic matter, and pH. The predicted and measured values are compared in Fig. 4.

The regression equations presented in Table 2 explain from 41 to 64% of the variability of measured soil attributes. We consider this to be quite good. With higher resolution and larger scale digital elevation models (5-m grid as opposed to the 15.24 m used here) that can characterize microscale (length scales of <10 m) variations in the terrain, it may be possible to explain a higher proportion of the variance. Emerging technologies such as the GPS and other space- and aircraft-based methods may soon make this possible. However, because of the highly variable nature of soil attributes it is unrealistic to expect that the methods proposed here could explain more than about 70% of the variance. Even pedotransfer functions that relate soil textural properties to other soil attributes (e.g., hydraulic conductivity) do not explain more of the variability than this. Traditionally, soil scientists have not incorporated information about local processes (such as hydrology and soil erosion and deposition) in attempting to develop pedotransfer functions, and have not been able to predict the spatial variability of soil attributes within soil map units. The optimum scales for studying and characterizing landscape processes affecting the development of the soil catena are unknown and represent a major research need (Moore et al., 1991).

The Sterling study site is a relatively small area and has limited ranges of the computed terrain attributes, particularly aspect (mostly northerly). To extend the methods described above to larger and more heterogeneous landscapes would require the introduction of additional descriptors including geology, stratigraphy, climate (precipitation and temperature), vegetation, and the radiation regime. Human activities have altered most soil landscapes, and the record of that activity is in the current stratigraphic record in the form of recently deposited sediments. In future, soil sampling and analysis could be better accomplished using a horizonation approach. The radiation regime is characterized in part by slope-aspect interactions and is important in modifying

the soil water and evaporation distributions in landscapes, and hence soil attributes and agronomic potential. The spatial distribution of radiation can be characterized using a relatively simple radiation index (see Moore et al., 1991, 1993) and becomes important at higher latitudes. Hutchinson (1991) described efficient methods of spatially interpolating monthly climatic data on the basis of latitude, longitude, and elevation. These methods could be used to provide the necessary data for a more extensive analysis aimed at predicting soil physical and chemical properties. We believe that in more heterogeneous landscapes the plan and profile curvatures may be more significant than reported here.

Surface soil properties are most modified by land management. Therefore, features of lower horizons in the profile may show greater response to topographic attributes (e.g., degree of leaching, distribution of Na, etc.). Also, the topography of the contact between the consolidated and unconsolidated materials or the presence of sedimentary features in the regolith may be significant in some landscapes.

### Enhancing Soil Attribute Maps from Soil Surveys

The estimated range in slope for the Sterling field, based on soil slope classes reported in the county soil survey (0–5%), is essentially identical to the range (0.1–5.2%) of the slope estimates from the DEM of the field. The soil survey here has provided an accurate range of slope estimates for the field but the survey can be enhanced with DEM data that can represent the distribution of terrain and soil attributes within soil survey map delineations.

In the following discussion we attempt to illustrate how enhanced soil attribute maps could be derived from conventional soil survey sources using terrain attributes to spatially distribute soil attributes within a field or map unit. If we assume that the range of soil attribute values for a field is largely a function of terrain, the assignment of values to grid cells according to slope position, wetness index, or other terrain attributes could be more realistic than assigning mean values based on the soil survey alone. In other words, we can use the appropriate terrain attributes to scale the reported range of soil attribute values to obtain spatially distributed estimates of soil attributes or soil attribute maps.

To demonstrate, in a simple way, how our proposed approach can be expanded and applied, we assume that,

Table 2. Regression equations relating measured soil properties in the top 0.1 m to significant terrain attributes ( $P < 0.01$ ).

Terrain attribute	A horizon depth	Organic matter	Extractable P	pH	Sand	Silt
	m	%	mg kg <sup>-1</sup>		%	
Intercept of regression	0.096	0.285	-3.039	7.508	46.417	23.466
Attributes						
Slope	-0.053(1)†	-	-1.466(1)	0.190(1)	2.941(1)	-2.009(1)
Wetness index	0.031(2)	0.190(1)	2.311(2)	-	-1.320(2)	2.076(2)
Stream power index	-	-0.070(2)	-0.769(3)	-	-	-
Aspect‡	-	-0.002(3)	-	-0.003(2)	-	-
Profile curvature	-	-	-	-	27.592(3)	-27.241(3)
R <sup>2</sup>	0.503	0.482	0.483	0.409	0.517	0.636

† Numbers in parentheses indicate the order in which the variables were brought in to the regressions.

‡ Aspect measured in degrees clockwise from west.

as a first approximation, soil attributes are linearly related to terrain attributes. With this assumption, either of the following relationships can be used to predict the spatial distribution of soil properties:

$$\gamma_p = \gamma_{i,\min}$$

$$+ (\gamma_{i,\max} - \gamma_{i,\min}) \sum_{k=1}^n \left( \frac{T_k - T_{k,\min}}{T_{k,\max} - T_{k,\min}} \mu_k \right)_i \quad [8a]$$

or

$$\gamma_p = \gamma_{i,\min}$$

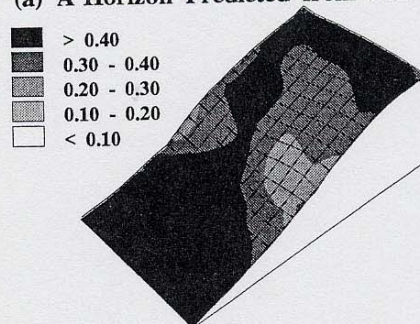
$$+ (\gamma_{i,\max} - \gamma_{i,\min}) \sum_{k=1}^n \left( \left[ 1 - \frac{T_k - T_{k,\min}}{T_{k,\max} - T_{k,\min}} \right] \mu_k \right)_i \quad [8b]$$

where  $\gamma_p$  is the predicted soil attribute at the point of interest,  $\lambda_{i,\max}$  and  $\lambda_{i,\min}$  are the maximum and minimum values of the soil attribute in the field or mapping unit  $i$  (from soil survey),  $\mu_k$  is a weighting coefficient for terrain attribute  $k$  ( $\sum \mu = 1$ ),  $T_k$  is the value of the  $k$ th terrain attribute at the point of interest,  $T_{k,\max}$  and  $T_{k,\min}$  are the maximum and minimum values of the terrain attribute in the field or mapping unit  $i$ , and  $n$  is the number of terrain attributes used in the analysis. Equation [8a] is used for positively correlated variables and Eq. [8b] for negatively correlated variables. The values of the weighting coefficients could be assigned in a number of ways, but might, for instance, be set proportional to the fraction of the total variance explained by each variable.

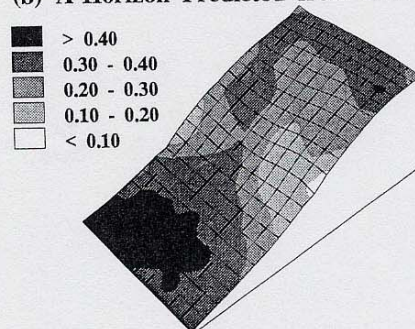
As an example, we used this approach to predict the spatial distribution of A horizon thickness and pH. For A horizon thickness we assumed  $\gamma_{\min} = 0.18$ ,  $\gamma_{\max} = 0.66$  (Table 1) with slope (negatively correlated) and wetness index (positively correlated) being the topographic attributes. We arbitrarily assigned weighting coefficients ( $\lambda$ ) of equal value (0.5) to these topographic attributes. For pH we assumed  $\gamma_{\min} = 6.6$ ,  $\gamma_{\max} = 8.0$  (Table 1), with slope (positively correlated) as the topographic variable. The results are presented in Fig. 6a and 6c, respectively. The range of values in each mapping unit was available for pH but only one value for each mapping unit was available for A horizon thickness (Table 1). Hence the  $\gamma_{\min}$  and  $\gamma_{\max}$  values used for pH in the above predictions are probably close to the actual range of values in the field. The  $\gamma_{\min}$  and  $\gamma_{\max}$  values used initially for the prediction of A horizon thickness were probably too large (we designated dark-colored buried subsoil horizons as A horizon in Table 1). We recomputed the predicted A horizon thicknesses using  $\gamma_{\min} = 0.05$  and  $\gamma_{\max} = 0.55$  and the results are presented in Fig. 6b.

The mean difference between the measured and predicted A horizon thicknesses shown in Fig. 6a and 6b are 0.40 and 0.31 m, respectively. These compare with the mean difference of 0.29 between the measured and predicted values using the regression equation (Fig. 4b). Similarly, the mean differences for prediction of pH using

(a) A Horizon Predicted from Soil Survey (m)



(b) A Horizon Predicted from Soil Survey (m)



(c) pH Predicted from Soil Survey

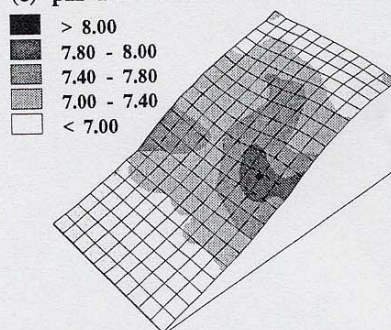


Fig. 6. Predicted A horizon thickness using (a) a minimum and maximum A horizon thickness of 0.18 and 0.66, respectively, and (b) a minimum and maximum A horizon thickness of 0.05 and 0.55, respectively, and (c) pH using a minimum and maximum A horizon thickness of 6.6 and 8.0, using terrain attributes to spatially distribute the range of reported soil attributes available from conventional soil survey and primary characterization databases (Eq. [8a] and [8b]).

Eq. [8] (Fig. 6c) and the regression equation (Fig. 4h) are 0.45 and 0.31, respectively. These results show that Eq. [8] can effectively spatially distribute observed soil mapping unit properties to produce results that are comparable to direct linear regression analysis (see above). The major advantages of this method are that the data requirements are much lower and the data can be obtained from the existing soil survey and pedon characteristics databases. The method is, however, highly dependent on obtaining realistic estimates of the range of values, or some measure of the variability, of soil attributes over a field or within mapping units. This is difficult with conventional soil surveys. Young et al. (1991) addressed this problem and have recently pro-

posed specific field sampling methods for developing confidence intervals for soil attributes within mapping units.

Another potential method for spatially distributing soil attributes is to use terrain attributes to segment the landscape into essentially stationary process zones where attribute prediction may be done in a more statistically robust fashion. Dikau (1989) demonstrated one possible segmentation based on plan and profile curvature.

## SUMMARY AND CONCLUSIONS

Terrain modifies the distribution of hydrologic and erosional processes (i.e., soil water content, runoff and sedimentation) and soil temperature in fields. Terrain thereby affects the distributions of mineral weathering, leaching, erosion, sedimentation, decomposition, horizonation, and, ultimately, soil attributes. Soil survey maps and databases are readily available sources of estimated soil attribute data. However, the map resolution is generally inadequate for soil-specific management and detailed environmental modeling. Data from these sources can be enhanced using terrain attributes (computed from high-resolution DEMs) to spatially distribute estimated soil attribute data. These methods offer a promising, cost-effective means of creating the high-resolution maps needed for soil-specific crop management. They also allow existing basic data sets (e.g., soil survey primary characterization data) to continue to be used as new techniques and technologies develop. Using GIS to organize and build on these data sets will improve our knowledge of environmental processes and promote economical and sustainable land management.

Results indicate that significant correlations between quantified terrain attributes and measured soil attributes exist. Slope and wetness index were the terrain attributes most highly correlated with soil attributes measured at 231 locations in a 5.4-ha toposequence in Colorado. Individually, they accounted for about one-half of the variability of several soil attributes including A horizon thickness, organic matter content, pH, extractable P, and silt and sand contents. This represents an incorporation of finer scale process-based information relating to soil formation patterns in the landscape. A method is presented to illustrate how relationships between terrain and soil attributes may be used to enhance an existing soil map, even when the exact form of the relationship is unknown. Other methods such as cokriging (which requires an estimate of the variogram) or partial splines may prove a viable alternative, although they generally require a large number of data points. However, if different soil attributes have different variograms, the ideal sampling sites for the different attributes might not coincide with one another. Terrain-based techniques may also be applied as a first step to guide sampling and model development in unmapped areas.

In applying Eq. [8] some a priori knowledge of catenary sequences is needed (e.g., organic matter content increases downslope, base status is lower in wet areas, etc.). The underlying pedological or catenary models are usually developed during a soil survey but they are often reported only as verbal models, if at all. If the procedure is to be implemented, then survey practice must change so that these verbal models are presented explicitly and consistently. If this could be achieved, then more of the

surveyor's knowledge could be transferred than has hitherto been possible. We have attempted to outline one form that this quantitative framework might take.

Soil scientists and agronomists need to begin looking at whole catchments or drainage units, rather than individual plots. The results presented here show that, in particular, the hydrology of the catchment area outside of the plot has a significant impact on the soil attributes and, therefore, crop production potential of the plot.

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