Soil Attribute Prediction Using Terrain Analysis

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ABSTRACT

This study is based on the hypothesis that catenary soil development occurs in many landscapes in response to the way water moves through and over the landscape. Furthermore, terrain attributes can characterize these flow paths and, therefore, soil attributes. Significant correlations between quantified terrain attributes and measured soil attributes were found on a 5.4-ha toposequence in Colorado. Slope and wetness index were the terrain attributes most highly correlated with surface soil attributes measured at 231 locations on a 15.24-m grid. Individually, they accounted for about one-half of the variability in 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. The computed and measured ranges of terrain and soil attributes, respectively, can be used to enhance an existing soil map, even when the exact form of the relationship is unknown. As a first approximation, a linear relationship was assumed and the interpolated predictions of A horizon thickness and pH compared reasonably well with the observed. Such techniques may also be applied as a first step in unmapped areas to guide soil sampling and model development.

SOIL SURVEY has played a key role in the development of pedology (Simonson, 1991) and soil maps have become valuable tools for natural resource management. But, standard soil surveys were not designed to provide the high-resolution (about 1:6000 scale) models and maps of the soil continuum required in detailed environmental modeling applications and site-specific crop management (Petersen, 1991). Conventional soil maps neither delineate all of a field's inherent variability nor represent specific soil attribute variation. Ranges given for some attributes, particularly those describing hydraulic properties, often vary by an order of magnitude. Furthermore, the nearest sampled pedon used to derive mapping unit attributes could be kilometers from the point of interest. Creating detailed soil maps of about 1:6000 scale is expensive by conventional methods. Accurate and inexpensive quantitative alternatives are needed.

Until recently, most soil scientists have emphasized the vertical relationships of soil horizons and soil-forming processes rather than the horizontal relationships that characterize traditional soil survey (Buol et al., 1989). Soil spatial patterns have been captured and displayed as choropleth maps with discrete lines representing the boundaries between map units, which implies homogeneity within map units (Burrough, 1986; Gessler, 1990). Two problems follow from this approach: (i) the lines drawn on the soil survey maps may not accurately depict the boundaries between map units (see Long et al., 1991); and (ii) the inferred homogeneities do not exist for many physical and chemical attributes that affect environmental modeling and soil-specific management.

There have been many attempts to characterize the spatial variability of measured soil attributes (Beckett and Webster, 1971; Webster, 1985; Yates and Warrick, 1987; Loague and Gander, 1990). These attempts have concentrated on the characterization of patterns, rather than on the linking of pattern to process. Quantitative interpolation techniques (e.g., kriging) often ignore pedogenesis while methods based on landscape position have lacked a consistent quantitative framework. Soil properties, soil erosion class, and, to a lesser extent, productivity have been related to landscape position (e.g., Walker et al., 1968; Furley, 1976; Daniels et al., 1985; Stone et al., 1985; Kreznor et al., 1989; Carter and Ciolkosz, 1991). For example, organic matter content and A horizon thickness, B horizon thickness and degree of development, soil mottling, pH, depth to carbonates, and water storage have all been correlated to landscape position (Kreznor et al., 1989). Most of these studies use qualitative mapping units that delineate head slopes, linear slopes, and footslopes, rather than quantifiable topographic attributes to map soils.

The high cost of collecting soil attribute data at many locations across landscapes has created a need for methods of inferring air and water properties of soils using pedotransfer functions (Bouma, 1989) or economical surrogates derived from soil morphological properties (Rawls et al., 1982; McKeague et al., 1984; McKenzie and MacLeod, 1989; Williams et al., 1990; McKenzie et al., 1991). The most common surrogates used are soil texture, organic matter, soil structure, and bulk density. Methods that organize the land surface according to a formal geomorphological model of landform and interlandform relations (Speight, 1974; Ruhe, 1975; Weibel and DeLotto, 1988; Dikau, 1989; Lammers and Band, 1990; Gessler, 1990; Mackay et al., 1991) show potential for improving soil attribute prediction (Moore et al., 1993; McKenzie and Austin, 1993). Geomorphological position influences horizonation and soil attributes. The relationships between topographic attributes, such as elevation, slope, aspect, specific catchment area, and plan and profile curvature, and hydrological and erosional processes occurring in landscapes have been outlined by Speight (1974) and Moore et al. (1991). Lammers and Band (1990) developed techniques for producing a set of landform files, which they called a *feature model*, describing the morphometry, catchment position, and surface attributes of hillslopes and stream channels of a catchment. Dikau (1989) demonstrated how digital terrain analysis could be applied to quantitative relief from analysis to define basic relief units for geomorphological and pedological map-

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Abbreviations: DEM, digital elevation model; GIS, geographic information system; GPS, global positioning system; USLE, universal soil loss equation.

ping (see also Ruhe, 1975). The main topographic attributes used to define these relief units were slope, plan curvature, and profile curvature. This approach provides a systematic basis for derivation of complex relief units. It may be possible to use these relief units to stratify the measured soil attributes and separate the micro- and mesoscale (length scales of <10 and 10–1000 m, respectively) spatial variabilities.

Hairston and Grigal (1991) found that topographically stratifying soil-related attributes (organic matter, total N, and soil water) helps reduce the apparent variation of these properties, even in subdued terrain. Odeh et al. (1991) stressed the importance of land unit delineation to design optimal sampling patterns that reduce extrapolation error and thus misclassification of soil. They found that slope, plan and profile curvature, upslope distance, and area accounted for much of the soil variation in their study area. The use of slope, aspect, and elevation in soil survey was described by Klingbiel et al. (1987). Walker et al. (1968) attempted to correlate a range of depth characteristics, such as thickness of the A horizon, to slope, aspect, curvature, elevation, and flow path length (distance to hillslope summit). McBratney et al. (1991) used topographic information for region partitioning to improve the representation of geostatistically mapped soil attributes.

Climate, parent material, topography, and biotic factors influence soil formation (Jenny, 1941, 1980), but climate often exerts control at coarser scales than of interest here. For this study we chose a site with relatively uniform parent material, so that a large proportion of the local soil variation (i.e., within hillslopes) can be attributed to changes in landform. The rationale is that, in many landscapes, catenary soil development occurs in response to the way water moves through and over the landscape as subsurface and overland flow, respectively. Recently, Martz and De Jong (1991) stated that, "the general pattern of association between soil loss and landform class supports the earlier suggestion that water is the dominant erosional agent in the basin. Low soil loss was associated with sites of low catchment area and high soil loss was associated with sites of high catchment area. The only exception to this trend is the midslope class which has low catchment area, but moderately high soil loss. However, sites in the midslope class normally have steeper slopes than other low catchment area sites. Surface depressions with the potential for water ponding sporadically interrupt this pattern and produce sites of soil deposition." Therefore, it may be hypothesized that the spatial distribution of topographic attributes that characterize water flow paths also captures the spatial variability of soil attributes at the mesoscale. We attempted to test this hypothesis by examining the correlation between soil and quantitative topographic attributes. We compared data from terrain analysis, conventional soil survey sources, and extensive soil sampling of a toposequence in Colorado.

METHODS

Relative elevation and A horizon thickness (both in meters) were measured at 231 sites on a regular 15.24-m grid by Peterson et al. (1991). In addition, extractable P (ppm), OM (%), pH, and sand, silt, and clay contents were measured for these sites at depth increments of 0 to 0.1, 0.1 to 0.2, and 0.2 to 0.3 m. These measurements were made by agronomists as part of an agroecosystems project between 1985 and 1989 (Peterson et al., 1988, 1991; Wood et al,. 1991a,b), before our study was conceived.

The following primary and secondary topographic attributes were calculated from the measured 15.24-m grid-based DEM:

Primary—slope (%), aspect (degrees clockwise from north), specific catchment area (m^2 m^{-1}), maximum flow path length (m), profile curvature (m^{-1}), and plan curvature (m^{-1});

Secondary—wetness index (Wetind), stream power index (Strpind), and sediment transport index (Sedind).

The DEM covers a 5.4-ha toposequence consisting of a single plot and encompasses most, but not all, of a single catchment. As a result the computed specific catchment areas only represent those areas within the DEM. This highlights the limitations of conventional agronomic approaches to data collection where plots are studied rather than whole catchments or drainage units. The curvature parameters were calculated at 171 of the 231 points—values were not computed along the boundary nodes of the DEM. The secondary indices are parameters related to surface and subsurface water and sediment transport processes. We have included these attributes in an attempt to relate pattern to process. Only the relationships between topographic attributes and soil attributes measured in the top 0.1 m of soil profile are explored here.

Multiple linear regression analyses relating soil to topographic attributes were performed using S-PLUS (Statistical Sciences, 1991). Stepwise regression was performed and only terrain attributes that significantly improved the regressions at the 0.01 level were brought into the regression at each step. In general, slope and wetness index were the two most significant variables, but for some soil attributes steam power index, aspect, and profile curvature were also significant. When the analysis was repeated at the 0.05 level, profile and/or plan curvature were also significant in many cases. The selection of the 0.01 level as the basis of the analysis was a somewhat arbitrary choice.

Study Location

The 5.4-ha study site is located in northeastern Colorado at Sterling in Logan County (40.37°N, 103.13°W). It is a long-term site for studying crop and soil management in dryland agroecosystems (Peterson et al., 1988, 1991) in which soil water is a major crop growth determinant. When the experiment began in fall 1985, the land had been cultivated for at least 70 yr, and had been most often in a winter wheat (*Triticum aestivum* L.)–fallow system with an occasional corn (*Zea mays* L.) crop prior to 1940. Pan evaporation averages 1000 mm per growing season and precipitation averages 400 mm yr^{-1} (Peterson et al., 1988).

The site contains a soil toposequence common to the geographic area (Wood et al., 1991a,b). The soils are well-drained, fine-loamy or fine-silty, mesic Aridic or Pachic Argiustolls of mixed mineralogy. They are formed in calcareous alluvial and eolian deposits and slopes range from 0 to 5% (Amen et al., 1977). The most recently published soil survey report for Logan County (Amen et al., 1977) divided the site into three soil mapping units, as shown in Fig. 1. Soil attribute values from the soil survey report and the USDA-SCS primary characterization data (Soil Conservation Service, 1991) alone were assigned to map unit delineations (Table 1). This is a common method of quickly creating inexpensive soil attribute maps but it stretches soil survey data far beyond their intended use. Furthermore, the resulting maps imply that soils are uniform within delineations.

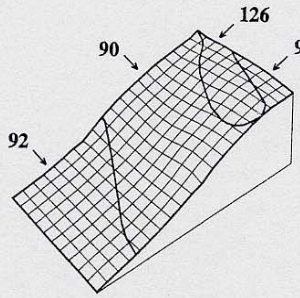

Fig. 1. Boundaries of the soil mapping units for the Sterling, CO, site. Mapping units shown are: 126, Weld; 92, Rango; and 90, Plantner.

Laboratory Analysis

Soil particle-size fractions were measured using the hydrometer method after dispersal with sodium hexametaphosphate (Day, 1965). Soil extractable P and organic matter were determined using the standard $NaHCO_3$ procedure and modified Walkley–Black method, respectively (Olsen and Sommers, 1982; Schnitzer, 1982). The pH was measured in water using a 1:1 soil/water ratio (McLean, 1982).

Calculating Topographic Attributes

Topographic attributes can be divided into primary and secondary (or compound) attributes. Primary attributes are directly calculated from a DEM and include variables such as elevation, slope, plan and profile curvature, flow path lengths, and specific catchment area. Compound attributes involve combinations of the primary attributes and can be used to characterize the spatial variability of specific processes occurring in the landscape (Moore et al., 1991, 1993). These compound attributes may be derived empirically, or by simplifying equations describing the underlying physics of the processes. Topographic indices provide a knowledge-based approach to soil-specific management and analysis and can be imbedded within the data analysis subsystems of a GIS. Because many GISs are based on a pixel or raster structure (i.e., grid cell), grid-based methods of terrain analysis can provide the primary geographic data for GIS applications.

A computationally efficient method of estimating primary terrain attributes from a grid-based DEM applies a second-order, central finite-difference scheme centered on the interior node of a moving three by three square grid network (Fig. 2).

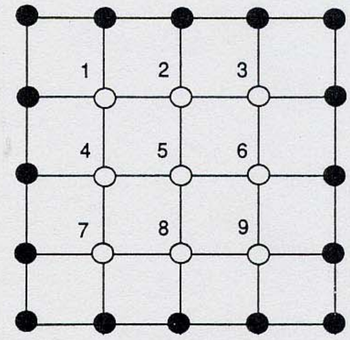

Fig. 2. Structure of a grid-based digital elevation model showing a moving three by three submatrix centered on node 5.

The grid spacing of this network is λ. We can simplify the mathematics by using the following notation. Forward and backwards difference schemes were used to handle nodes on the edges of the DEM.

$$f_x = \frac{\partial z}{\partial x}, \quad f_y = \frac{\partial z}{\partial y}, \quad f_{xx} = \frac{\partial^2 z}{\partial x^2},$$
$$f_{yy} = \frac{\partial^2 z}{\partial y^2}, \quad f_{xy} = \frac{\partial^2 z}{\partial x \partial y} \qquad [1]$$

where z is the elevation, x and y are the orthogonal directions in the horizontal plane, and

$$p = f_x^2 + f_y^2, \qquad q = p + 1 \qquad [2]$$

If Z is the node elevation shown in Fig. 2, then the central finite-difference forms of the partial derivatives for the central node 5 can be written as:

$$f_x = \frac{Z_6 - Z_4}{2\lambda}, \quad f_y = \frac{Z_2 - Z_8}{2\lambda},$$
$$f_{xy} = \frac{-Z_1 + Z_3 + Z_7 - Z_9}{4\lambda^2},$$
$$f_{xx} = \frac{Z_4 + Z_6 - 2Z_5}{\lambda^2}, \quad f_{yy} = \frac{Z_2 + Z_8 - 2Z_5}{\lambda^2} \qquad [3]$$

Table 1. Soil attribute data estimated for map units in a cropped field near Sterling, CO.

Source†	Attributes				
M	Map unit number	126	90	92	126,90,92
M	Location	Summit	Side	Toe	Whole field
M	Mapped as:	Weld	Plantner	Rango	Weld, Plantner, Rango
S	Sampled as:	Weld	Satanta	Albinas	Weld, Satanta, Albinas
M	Drainage	wd	wd	wd	wd
M	Runoff	slow	medium	slow	slow-medium
M	Slope, mm^{-1} × 100	1–3	3–5	0–3	0–5
M	A horizon depth, m	0.18	0.18	0.66¶	0.18–0.66
S	Organic C × 1.72, 0–0.1 m, g kg^{-1}	0.165	0.155	0.220	0.155–0.220
S	Extr. P, 0–0.1 m, mg kg^{-1}‡	27	17	42	17–42
S	Sand, 0–0.1 m, %	45	54	42	42–54
M,S	pH (1:1), 0–0.3m	6.6–7.8	6.6–8.0	6.6–7.8	6.6–8.0
S	Bk horizon depth, m	0.51	0.38	0.65	0.38–0.65
M	Water supply, rank	intermediate	lowest	highest	—
M	Yield, t/ha^{-1}§	1.7–4.0	1.7–2.6	2.0–3.7	1.7–4.0

† M = map unit component data from soil survey report, Logan County, Colorado (Amen et al., 1977); S = soil samples from similar soils, Primary Characterization Data (Soil Conservation Service, 1991)
‡ $NaHCO_3$-extractable P.
§ Range in wheat yield potential is related to low or high management levels as defined by the USDA-SCS.
¶ Includes buried A horizon materials with mollic colors.

The maximum slope, β (in degrees), aspect, ψ (measured in degrees clockwise from north), and curvature (m^{-1}) of the midpoint in the moving grid can then be calculated using the following relationships:

$$\beta = \arctan(p^{1/2}),$$

$$\psi = 180 - \arctan\left(\frac{f_y}{f_x}\right) + 90\left(\frac{d_x}{|f_x|}\right), \quad \text{and}$$

$$\text{curvature} = \frac{f_{xx}\cos^2\phi + 2f_{xy}\cos\phi\sin\phi + f_{yy}\sin^2\phi}{q^{1/2}\cos\upsilon} \qquad [4]$$

where υ is the angle between the normal to the surface and the section plane and ϕ is the angle between the tangent of the given normal section and the x axes (Kepr, 1969; Moore, 1990; Mitasova and Jaroslave, 1993). The two directions of meaningful curvature for hydrological and geomorphological applications are in the direction of maximum slope (profile curvature) and transverse to this slope (plan curvature). Profile curvature is a measure of the rate of change of the potential gradient and is therefore important for water flow and sediment transport processes; plan curvature is a measure of the convergence or divergence and hence the concentration of water in a landscape. For profile curvature, φ,

$$\cos\upsilon = 1, \quad \cos\phi = \frac{f_x}{(pq)^{1/2}}, \quad \text{and} \quad \sin\phi = \frac{f_y}{(pq)^{1/2}}$$

$$\text{so that } \varphi = \frac{f_{xx}f_x^2 + 2f_{xy}f_xf_y + f_yf_y^2}{pq^{3/2}} \qquad [5]$$

Similarly, for plan curvature, ω,

$$\cos\upsilon = \left(\frac{p}{q}\right)^{1/2}, \qquad \cos\phi = \frac{f_y}{p^{1/2}}, \quad \text{and} \quad \sin\phi = \frac{f_x}{p^{1/2}}$$

$$\text{so that } \omega = \frac{f_{xx}f_x^2 - 2f_{xy}f_xf_y + f_yf_x^2}{p^{3/2}} \qquad [6]$$

The plan area in the horizontal plane characterized by each node or grid point is $A_h = \lambda^2$. Jenson and Domingue (1988) described a computationally efficient algorithm for estimating flow directions and hence catchment areas and drainage path lengths for each node in a regular grid DEM based on the concept of a depressionless DEM. They assumed that water flows from a given node (say node 5 in Fig. 2) to one of eight possible neighboring nodes (nodes 1–4, 6–9 in Fig. 2), based on the direction of steepest descent. Upslope flow paths computed using this algorithm tend to zigzag and therefore are somewhat unrealistic. Moore et al. (1993) described a modification of this algorithm that allows flow from one node (say node 5) to be distributed to multiple nearest neighbor elements in upland areas above defined channels on a slope-weighted basis. This new algorithm allows flow divergence to be represented in a grid-based method of analysis. The algorithm can be combined with the above finite-difference approach to estimate a wide variety of hydrologically significant topographic attributes.

Three hydrologically based compound indices that have potential use in predicting the spatial distribution of soil properties and in soil-specific crop management are the wetness index, w, the stream power index, Ω, and a sediment transport capacity index, τ (Moore et al., 1991). The wetness index has been used to characterize the spatial distribution of zones of surface saturation and soil water content in landscapes (Moore et al., 1988, 1993) and appears to be useful for mapping forest soils (Skidmore et al., 1991). The stream power index is directly proportional to stream power ($= \rho g q \tan\beta$, where ρg is the unit weight of water, q is the discharge per unit width, and β is the slope angle), which is the time rate of energy expenditure and so is a measure of the erosive power of overland flow. The sediment transport index characterizes erosion and deposition processes and, in particular, the effects of topography on soil loss (Moore et al., 1992; Moore and Wilson, 1992). This index is analogous to the length–slope factor in the USLE, but is applicable to three-dimensional landscapes. The wetness, stream power, and sediment transport indices, in their simplest forms, can be expressed, respectively, as:

$$w = \ln\left(\frac{A_s}{\tan\beta}\right), \qquad \Omega = A_s\tan\beta,$$

$$\tau = \left(\frac{A_s}{22.13}\right)^m\left(\frac{\sin\beta}{0.0896}\right)^n \qquad [7]$$

where A_s is the specific catchment area (m^2m^{-1}), β is the slope angle (degrees), and $m = 0.6$ and $n = 1.3$. The assumptions in all three equations are that A_s is directly proportional to q, and steady-state conditions prevail (Moore et al., 1991; Moore and Wilson, 1992).

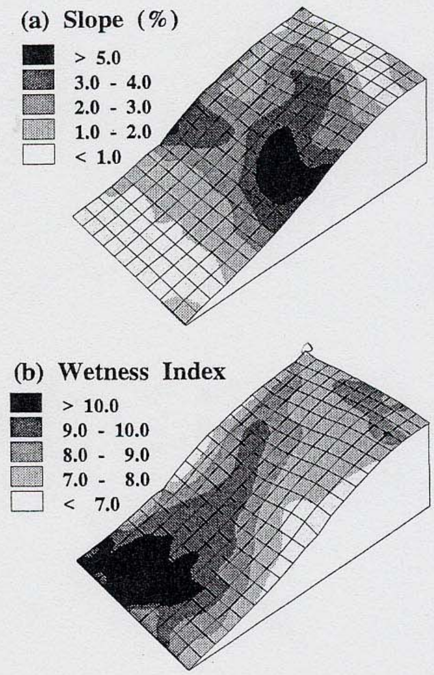

Fig. 3. (a) Slope and (b) wetness index computed from the 15.24-m grid-based digital elevation model of the Sterling, CO, site.

RESULTS AND DISCUSSION

Figure 3 presents shaded class intervals of slope and wetness index calculated by the grid-based terrain analysis methods and superimposed on an isometric projection of a 15.24-m grid DEM of the study site. Figures 4a, 4c, 4e, and 4g show the measured spatial distribution of A horizon thickness and the P, organic matter, and pH distributions, respectively, in the top 0.1 m layer of soil.

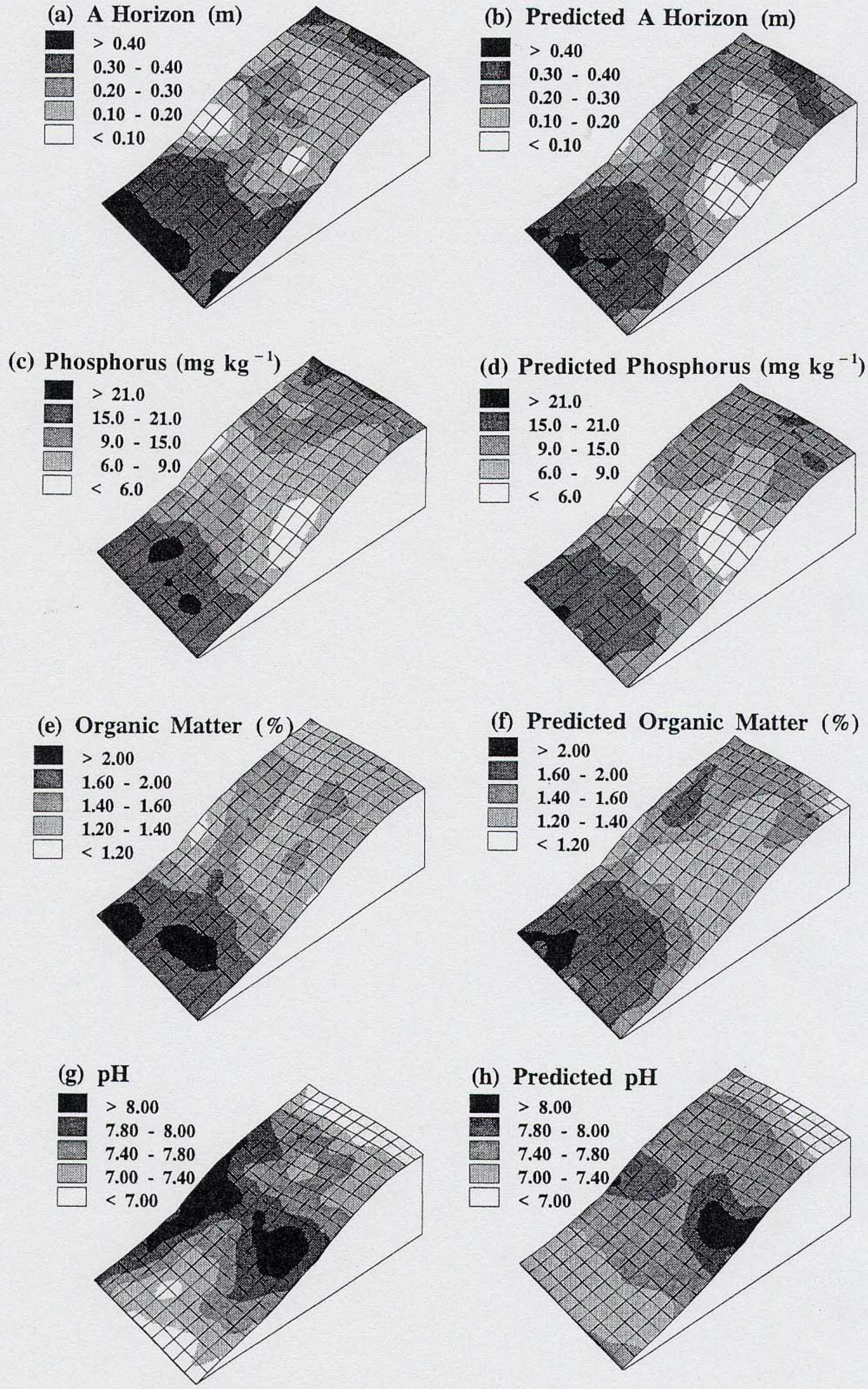

Fig. 4. Measured and predicted soil attributes at the Sterling, CO, site.

A horizons thicker than 0.25 m are mostly confined to summit and toeslope positions where slopes are <2% (Fig. 3a and 4a) and at or immediately downslope of areas with the greatest concavity (profile curvature). Where slopes steeper than 2% have thick A horizons, they are associated with areas that have a wetness index >8.0 (Fig. 3b). Here additional subsoil water has apparently allowed greater root activity than in adjacent areas that are just as steep but not so wet. To some extent the A horizon is a "fossil record" of root activity that reflects the redistribution of water by the terrain. Wetter areas could also have more vegetation cover and consequently less erosion. Thick A horizons in toeslope positions may result from the deposition of sediments carried in over-