DIVISION S-6—SOIL & WATER MANAGEMENT & CONSERVATION

Soil Water Retention as Related to Topographic Variables

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ABSTRACT

Digital elevation models were proposed and used as a data source to estimate soil properties. This study evaluated variability of texture and water retention of soils for a gently sloping 3.7-ha field located in the long-term precision farming research site at the Beltsville Agricultural Research Center, MD. The specific objectives of this research were (i) to characterize variability of water retention across the hillslope, and (ii) determine and describe any correlations of soil water retention with soil texture and surface topography. Soil was sampled along four 30-m transects and in 39 points within the study area. Textural fraction contents, bulk density, and water retention at 0, 2.5, 5.0, 10, 33, 100, 500, and 1500 kPa were measured in samples taken from 4- to 10-cm depth. A 30-m digital elevation model (DEM) was constructed from aerial photography data. Slopes, profile curvatures, and tangential curvatures were computed in grid nodes and interpolated to the sampling locations. Regressions with spatially correlated errors were used to relate water retention and texture to computed topographic variables. Sand, silt, and clay contents depended on slope and curvatures. Soil water retention at 10 and 33 kPa correlated with sand and silt contents. The regression model relating water retention to the topographic variables explained more than 60% of variation in soil water content at 10 and 33 kPa, and only 20% of variation at 100 kPa. Increases in slope values and decreases in tangential curvature values, i.e., less concavity or more convexity across the slope, led to the decreases in water retention at 10 and 33 kPa. Results of this work show a potential for topographic variables to be used in interpretation of field-scale variability of soil properties and, possibly, yield maps in precision agriculture.

Agricultural and environmental modeling and assessment have many uses for soil hydraulic properties. These properties are notorious for difficulties and high labor costs involved in measuring them. Therefore, there is a trend to estimate soil hydraulic properties from other readily available data (Bouma, 1989; Rawls et al., 1991). Until recently, estimation of soil hydraulic properties was done exclusively from other soil properties available from soil survey (Pachepsky et al., 1999). However, the level of detail given by soil surveys is not sufficient in some applications, in particular, applications related to site-specific agriculture (Schepers and Francis, 1998).

Soil properties are known to be related to landscape position (Ruhe, 1956). Geomorphic information has long been routinely used in soil mapping (Northcote, 1954). Geomorphometry was proposed as a data source to predict soil properties (Moore et al., 1993; McKenzie and Austin, 1993; McSweeney et al., 1994).

Two basic approaches to relate soil properties to landscape position have been suggested to date. The first is based on separating hillslopes into distinct sections, i.e., summit, upper and lower interfluve, shoulder, backslope, upper and lower linear, footslope, toeslope, etc. It has been shown that soil properties within a section vary much less than between sections, so that distinct values of soil properties can be assigned to each section (Ovalles and Collins, 1986). Section-specific regression equations can also be developed to correlate soil properties (Brubaker et al., 1994).

The second approach to relate soil properties to landscape positions is to use topographic variables, or terrain attributes, i.e., mathematical characteristics of the land surface shape, such as slope, profile, plan and tangential curvatures, and aspect (Evans, 1980; Mitásova and Hofierka, 1993; Shary, 1995). These variables can be computed directly at the nodes of a grid and used for statistical correlation with soil properties at these nodes (Walker et al., 1968; Kingbiel et al., 1987; Odeh et al., 1991; Moore et al., 1993). Topographic variables can be used to subdivide the terrain into areas having distinctly different shapes, and average values of soil properties can be defined for these areas (Kreznor et al., 1989; Pennock and de Jong, 1987; Lark, 1999). The topographic variables are also employed to generate secondary terrain attributes, like wetness index or sediment transport index, that in turn can be used in soil-landscape correlations (McSweeney et al., 1994; Thompson et al., 1998, McKenzie and Ryan, 1999).

The readily available information on relationships between soil hydraulic properties and topographic variables is surprisingly scarce, although published results demonstrate some strong correlations (Halvorson and Doll, 1991; Mapa and Pathmarajah, 1995). Much more is known about dependencies of soil hydraulic properties on soil texture, organic matter content, and bulk density (Pachepsky et al., 1999). Soil texture, organic matter, and bulk density are known to reflect landscape position (Van den Broek et al., 1981; Kreznor et al., 1989). Therefore, one can hypothesize that soil hydraulic properties should have some relationship to landscape position. However, different basic soil parameters may have different dependencies on landscape position, and this may weaken dependencies of soil hydraulic properties on topographic variables.

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Table 1. Selected properties of soils in soil association of the study site.

Soil attributes	Cedartown	Galestown	Matawan
Drainage	**SED**	**SED**	**MWD**
Slope, %	**0–5**	**0–5**	**0–5**
Corn yield, kg ha^{-1}	**430**	**370**	**740**
Thickness of horizons, cm			
A	**3–8**	**3–5**	**3–8**
E	**8–20**	**5–20**	**8–18**
Thickness of layers (cm) for the following properties:	**0–30**	**0–28**	**0–50**
Clay, %	**2–7**	**4–10**	**2–10**
Percent passing sieve number			
4	**95–100**	**95–100**	**100–100**
10	**85–100**	**75–100**	**100–100**
40	**40–90**	**45–70**	**50–75**
200	**5–25**	**4–25**	**15–30**
Organic matter, %	**0.5–2**	**0.5–2**	**0.5–2**
pH	**3.6–5.5**	**3.6–5.5**	**3.6–5.5**
Available water capacity, %	**5–10**	**6–8**	**6–9**

This study evaluated variability of texture and water retention of soils across a gently sloping field located in the long-term precision farming research site at the Beltsville Agricultural Research Center, MD. We hypothesized that differences in water retention might account for observed variability in yields. The specific objectives of this research were (i) to characterize variability of water retention across the hillslope and (ii) to determine and describe any correlations of soil water retention with soil texture and surface topography.

MATERIALS AND METHODS

Study Area and Data Collection

The 3.7-ha study area, located at the USDA Beltsville Agricultural Research Center, MD, (76°50′25″ W, 39°01′15″ N), is a long-term site for studying crop and soil management used in precision farming research in nonirrigated conditions. Soil cover of the site is defined as Cedartown-Galestown-Matawan soil association (NRCS, 1995). Cedartown and Galestown are siliceous, mesic Psammentic Hapludults, whereas Matawan is fine loamy, siliceous, semiactive, mesic Aquic Hapludult. Slope gradients range from 0 to 5%, and the predominant topsoil texture has been defined as a loamy sand for this soil association by the soil survey. Table 1 presents some characteristics of these soils from the soil survey report (NCRS, 1995).

Topographic survey of the site was made by the Air Survey Corp., VA. The airborne stereophotography was used. Total of 555 photogrammetric mass points were defined across the site with the average area per mass point about 140 m^2. Soil was sampled along four transects positioned in different landscape elements and at nodes of a 30- by 30-m grid as shown in Fig. 1. The sampling locations were 2 m apart within each transect. All samples were taken in duplicate from points 30 cm apart. There were 54 duplicated transect samples and 39 duplicated grid samples. Sampling depth was 4 to 10 cm. The same topographic variables were assigned to the duplicated samples.

Soil texture was measured with the hydrometer method. Soil water retention was measured at 0, 2.5, 5, 10, 33, 100, 500, 1500 kPa by means of a sand table and pressure plate. Bulk density and porosity were computed.

Topographic Variables

Elevation values were obtained from a digital elevation model constructed by interpolation of the photogrammetric mass points data to nodes of a 30- by 30-m grid. The 30-m spacing was selected as the spacing at which the USGS made available DEMs for the USA (7.5-Minute DEM 30- by 30-m data spacing at http://rockyweb.cr.usgs.gov/elevation/dpi_dem.html; verified July 9, 2001). This resolution was assumed to be sufficient to capture the spatial variability of gently sloping terrain in the study area. Because there is no unanimous opinion regarding the best method to interpolate topography (Wise, 1998), we built five different DEMs using inverse square distance interpolation, kriging, minimum curvature interpolation, radial basis function method, and triangulation with linear interpolation. Those were selected on the basis of common methods reported in the literature. All DEMs were built by the SURFER software version 7.00 (Golden Software, Inc., 1999).

Values of maximum slope, profile curvature and tangential curvature were used as topographic variables for the study area. Profile curvature is defined as curvature of the surface cross-section made in the direction of maximum slope. This is the uphill rate of change in slope. Negative (positive) values

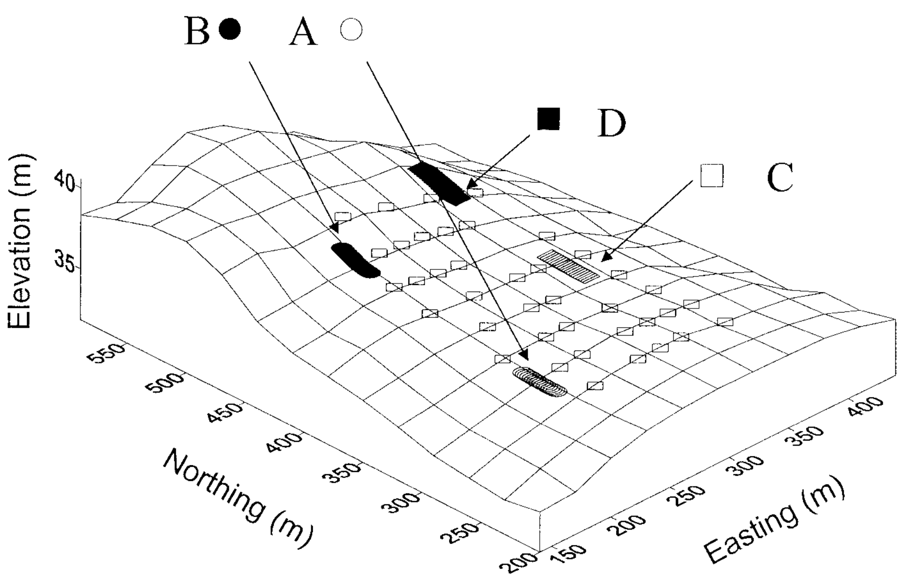

Fig. 1. Location of sampling sites and topography of the site; symbols ○, ●, □, and ■ show location of 30-m long Transects A, B, C, and D, respectively, grid sampling locations are shown with symbol .

of profile curvature indicate convex (concave) flow paths where a surface flow accelerates (slows down). Tangential curvature is defined as curvature of the vertical surface cross-section made perpendicular to the direction of maximum slope. Negative (positive) values of tangential curvature represent areas of divergent (convergent) flow (Mitásova and Hofierka, 1993). Maximum slope (s), the profile curvature (v), and the tangential curvature (h) can be expressed by derivatives of the dependence of the elevation $z = f(x,y)$ on horizontal coordinates x and y (Evans, 1980):

$$s = \sqrt{f_x^2 + f_y^2}$$
$$v = \frac{f_{xx}f_x^2 + 2f_{xy}f_xf_y + f_{yy}f_y^2}{s^2(1 + s^2)^{3/2}}$$
$$h = \frac{f_{xx}f_y^2 - 2f_{xy}f_xf_y + f_{yy}f_x^2}{s^2(1 + s^2)^{1/2}} \quad [1]$$

Here f_x, f_y, f_{xx}, f_{xy}, f_{yy} are partial derivatives of the function $f(x,y)$:

$$f_x = \frac{\partial f}{\partial x};\ f_y = \frac{\partial f}{\partial y};\ f_{xx} = \frac{\partial^2 f}{\partial x^2};\ f_{xy} = \frac{\partial^2 f}{\partial x \partial y};\ f_{yy} = \frac{\partial^2 f}{\partial y^2}; \quad [2]$$

The partial derivatives were estimated from a grid-based digital elevation model by the moving three-by-three grid network described by Moore et al. (1993). The second order polynomial

$$z = \frac{1}{2}rx^2 + \frac{1}{2}ty^2 + sx^2 + px + qy + u \quad [3]$$

was fitted to the nine points of three-by-three networks and values of p, q, r, s, u and t were computed as suggested by Shary (1995):

$$p = (-z_{i-1,j+1} + z_{i+1,j+1} - z_{i-1,j} + z_{i+1,j} - z_{i-1,j-1} + z_{i+1,j-1})/(6w);$$
$$q = (z_{i-1,j+1} + z_{i,j+1} + z_{i+1,j+1} - z_{i-1,j-1} - z_{i,j-1} - z_{i+1,j-1})/(6w);$$
$$r = (z_{i-1,j+1} + z_{i+1,j+1} + z_{i-1,j-1} + z_{i+1,j-1} - 2(z_{i,j+1} + z_{i,j-1}) + 3(z_{i-1,j} + z_{i+1,j}) - 6z_{i,j})/(5w^2);$$
$$t = (z_{i-1,j+1} + z_{i+1,j+1} + z_{i-1,j-1} + z_{i+1,j-1} - 2(z_{i-1,j} + z_{i+1,j}) + 3(z_{i,j+1} + z_{i,j-1}) - 6z_{i,j})/(5w^2);$$
$$s = (-z_{i-1,j+1} + z_{i+1,j+1} + z_{i-1,j-1} + z_{i+1,j-1})/(4w^2);$$
$$u = (2(z_{i,j+1} + z_{i-1,j} + z_{i+1,j} + z_{i,j-1}) - (z_{i-1,j+1} + z_{i+1,j+1} + z_{i-1,j-1} + z_{i+1,j-1}) + 5z_{i,j})/9. \quad [4]$$

Here the first and the second subscripts denote the grid lines parallel to the y and x axes, respectively, w is the grid spacing. These coefficients were used in Eq. [2] as approximations of the derivatives

$$f_x \approx p;\ f_y \approx q;\ f_{xx} \approx r;\ f_{xy} \approx s;\ f_{yy} \approx t. \quad [5]$$

Values of slopes and curvatures were computed at all but boundary nodes of the elevation grids by means of Eq. [1] to [5]. Values of slopes and curvatures at the points of water retention and texture measurements were computed from the nodal values of those variables by bilinear interpolation (Press et al., 1992). Slopes are unitless, curvatures have the dimension per meter in this study.

Statistical Analysis

A linear regression was used to express the dependencies of water retention on topographic variables and to estimate the proportion of variation in water retention that could be explained by topographic variables. The data had spatial structure, and for this reason we used the least square model with correlated errors (Thisted, 1988).

The linear regression model

$$\theta - \theta_0 = (T - T_0)\beta + \varepsilon \quad [6]$$

relates the vector $\boldsymbol{\theta}$ of observed water retention values to the matrix of values of topographic variables T. The vector $\boldsymbol{\theta}$ has m elements, θ_i, $i = 1,2,3, \ldots m$, m is the number of measurements. The matrix T has elements t_{ij} which are values of the jth topographic variable in the ith measurement point; $j = 1,2, \ldots N$, and N is the total number of topographic variables taken into regression. The vector $\boldsymbol{\beta}$ contains regression coefficients β_j, $j = 1,2, \ldots N$. Vector $\boldsymbol{\theta_0}$ and matrix T_0 contain average values of observed water retention and topographic variables, respectively. The vector ε contains the regression errors ε_i, $i = 1,2,3, \ldots M$.

In the ordinary least square model, errors ε_i are assumed to be independent and to belong to the same normal distribution $\mathbb{N}(0, \sigma^2)$ with the zero mean and the variance σ^2. Therefore, the vector ε belongs to the normal distribution of independent normally identically distributed values $\mathbb{N}(0, \sigma^2 I)$ where I is the identity $m \times m$ matrix with all diagonal elements equal to one. Because there is correlation between errors, all off-diagonal elements are equal to zero. This model has $N+1$ parameters, N values of β_j and value of σ^2 to be found from the data.

In the least square model with correlated errors, errors ε_i belong to normal distribution $\mathbb{N}(0, \sigma^2 C)$, where C is the $m \times m$ correlation matrix, so that C_{ik} is the correlation coefficient between ith and kth error. The semivariogram of errors is used to compute the elements of the correlation matrix as

$$c_{ik} = 1 - y(d_{ik})/\sigma^2 \quad [7]$$

Here γ is the semivariogram, d_{ik} is the distance between the ith and kth sampling points, σ^2 is the sill of the semivariogram (Pinheiro and Bates, 2000). This regression model has more parameters than the ordinary least square model; the list of parameters includes the range, ρ, and the nugget effect, c_0, of the semivariogram along with N values of β_j and the value of sill σ^2. Estimates of values of β_j, σ^2, ρ, and c_0 are computed simultaneously during a nonlinear optimization with the minimum likelihood criterion.

We used Splus software (MathSoft, 1999) to fit the least square model with correlated errors to our dataset. Averages of duplicated measurements were used for this regression. The software required specifying the type of semivariogram equation and initial estimates for the range and nugget. To specify the type of semivariogram equation, we applied the ordinary least square model first, obtained values of errors, and computed their semivariogram with the SURFER software (data not shown). An isotropic semivariogram was used because of the similarity in orientation of transects. The visual inspection of graphs suggested that the Gaussian variogram model with the nugget in the form

$$y = \sigma^2\{c_0 + (1 - c_0)[1 - \exp(-(d/\rho)^2]\} \quad [8]$$

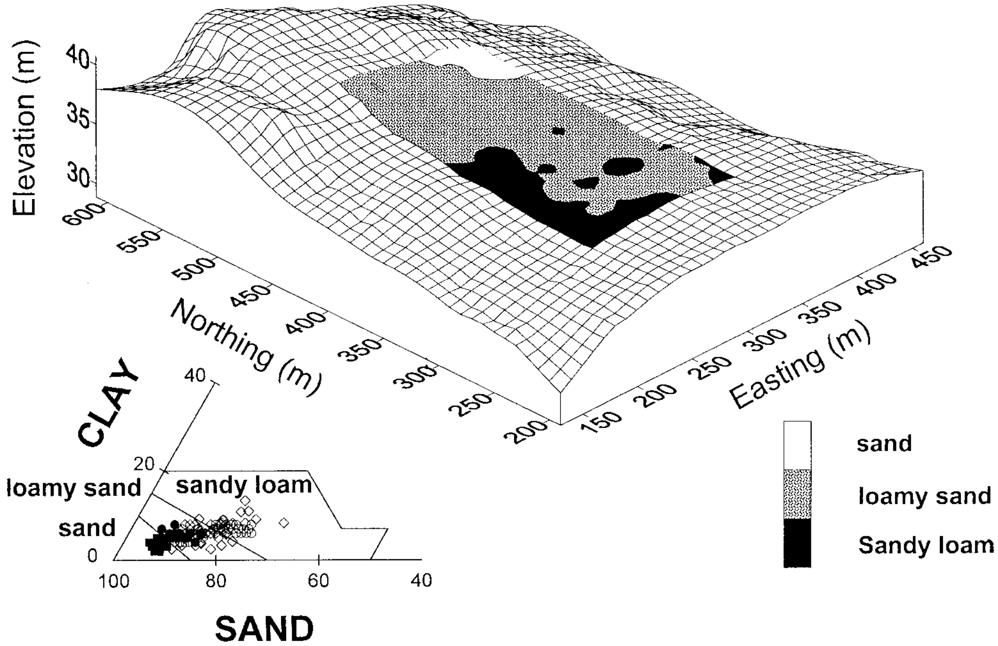

Fig. 2. Distribution of soil texture. Symbols in the textural triangle are the same as in Fig. 1.

is the most suitable for our data. Initial estimates of the range and the nugget effect were set at 10 m and at 0.2, respectively.

The *t*-test, *F*-test, and the Kolmogorov-Smirnov tests were used to test hypotheses about the equality of average values, equality of variances and the difference between distributions of regression residuals and normal distribution, respectively. All statistical comparisons were made at the 0.05 significance level.

RESULTS

The spatial distribution of soil texture is shown in Fig 2[1]. Sands, loamy sands, and sandy loams are represented in the study area. The range of textures is wider than suggested by the soil survey. A comparison of Fig. 1 and Fig. 2 shows that soils on steeper slopes represented by Transects B and D are richer in sand and poorer in silt than soils in Transects A and C.

Topographic variables computed after applying different interpolation methods are compared in Fig. 3. The values of slopes vary least among interpolation methods. The coefficients of determination (R^2) between slope values calculated by different methods are all greater than 0.99. Curvatures show more differences especially when they are small. In Fig. 3, values of R^2 range from 0.92 to 0.99 and from 0.84 to 0.95 for profile and tangential curvatures, respectively. The tangential curvatures obtained after applying the inverse distance interpolation method showed the largest differences from the tangential curvatures obtained after application of other interpolation methods. Slopes, profile curvatures, and tangential curvatures ranged from 0.001 to 0.039, from -1.05×10^{-3} m^{-1} to 0.62×10^{-3} m^{-1}, and from -0.95×10^{-3} m^{-1} to 0.50×10^{-3} m^{-1}, respectively, in the study area.

The distribution of soil texture is reflected in relationships of soil texture to the computed topographic variables shown in Fig. 4a for the minimum curvature interpolation method. Topographic variables complement each other in distinguishing zones of different texture

[1] The map is obtained by means of the SURFER software using the inverse distance interpolation from sampling points.

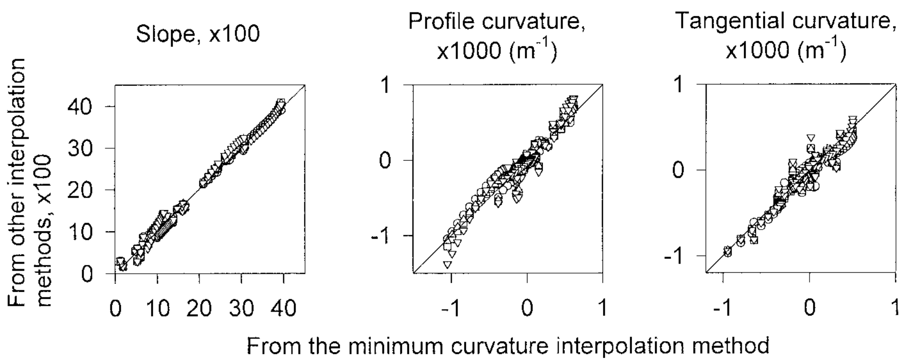

Fig. 3. Comparison of elevation interpolation methods used to compute topographic variables in sampling locations; ○—inverse distance interpolation, □—kriging, △—radial basis functions, ▽—triangulation with linear interpolation all compared with the minimum curvature method. Lines show one-to-one dependencies.

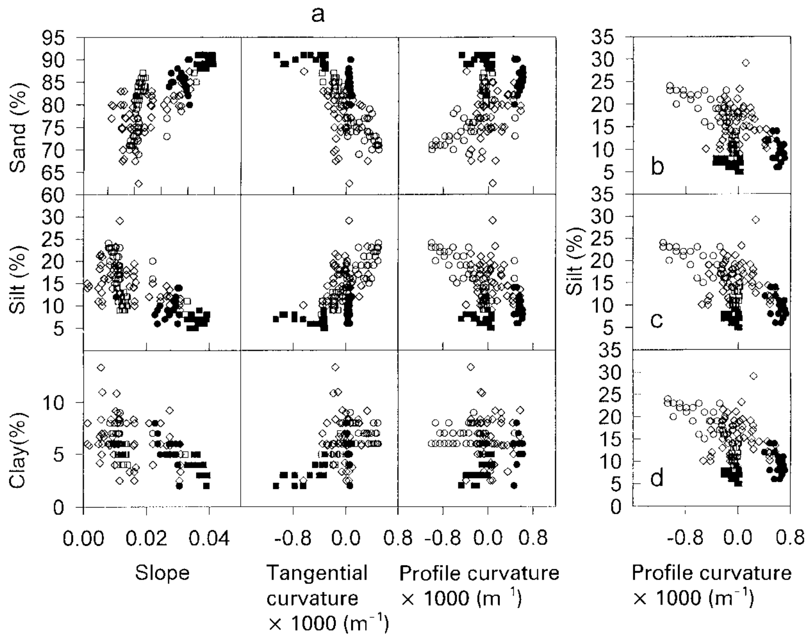

Fig. 4. Relationships between soil textural component contents and topographic variables; symbols ○, ●, □, and ■ show data from Transects A, B, C, and D, respectively, grid sampling is shown with symbol ◇. a, b, c, d—minimum curvature, inverse square distance interpolation, kriging, and radial basis functions interpolation methods, respectively.

within the landscape. For example, slope separates Transects B, D, and A reasonably well by sand and silt contents in soil. However, slope values are useless for distinguishing Transects A and C by soil texture. Profile curvature, on the other hand, does not discriminate Transects C and D, but discriminates Transects A and C well by their silt content, something that slope does not do. Tangential curvature discriminates Transects D and B by their clay content better than other topographic variables. All this indicates that slope and both curvatures may serve as predictors of distributions of soil texture in this landscape. Other interpolation methods used to relate texture to topographic variables led to similar results (i.e., Fig. 4b,c,d).

Data on soil water retention in transects are summarized in Table 2. Differences among transects for average values of water contents at the same capillary pressure were statistically significant in most cases (Table 2). Only average water contents at 0 kPa and average water contents at 1500 kPa did not differ between Transects C and D, and the Transect pairs A, B and C, D did not differ in their average water contents at 100 kPa. Water retention in Transects A and B was larger than in Transects C and D at low capillary pressure of 2.5 kPa. Transects A and C showed higher water retention than Transects B and D at capillary pressures greater than 2.5 kPa. The coefficients of variation were less than 5% for water contents at zero capillary pressure, within the 5 to 10% range for the water contents at capillary pressures from 2.5 to 33 kPa, and mostly within 15 to 20% range for capillary pressures 100 kPa and larger.

The relationship between soil water retention and soil texture is shown in Fig. 5. No significant correlation was found for water-satiated soil at 0 kPa. The relationship between water retention and sand or silt content emerges at 2.5 kPa, although Transect B is far off the

Table 2. Soil texture and soil water retention in transects†.

	Transects			
	A	B	C	D
	Soil textural components (%)			
Sand	73.5 ± 2.6	85.3 ± 2.5	83.5 ± 1.9	89.8 ± 1.2
Silt	19.6 ± 2.7	9.3 ± 2.3	11.3 ± 1.7	6.6 ± 1.1
Clay	6.9 ± 0.9	5.4 ± 1.4	5.1 ± 0.8	3.6 ± 0.9
Capillary pressure, kPa	Soil water content (m^2 m^{-3})			
0	0.481 ± 0.018	0.476 ± 0.014	0.498 ± 0.024	0.501 ± 0.020
2.5	0.288 ± 0.027	0.303 ± 0.038	0.254 ± 0.021	0.265 ± 0.016
10	0.193 ± 0.011	0.138 ± 0.011	0.155 ± 0.016	0.126 ± 0.009
33	0.154 ± 0.010	0.113 ± 0.009	0.123 ± 0.012	0.106 ± 0.008
100	0.076 ± 0.017	0.062 ± 0.019	0.075 ± 0.013	0.065 ± 0.005
500	0.049 ± 0.030	0.044 ± 0.006	0.041 ± 0.007	0.047 ± 0.008
1500	0.047 ± 0.008	0.039 ± 0.006	0.044 ± 0.007	0.042 ± 0.008

† Average value and standard deviation are separated with the '±' sign.

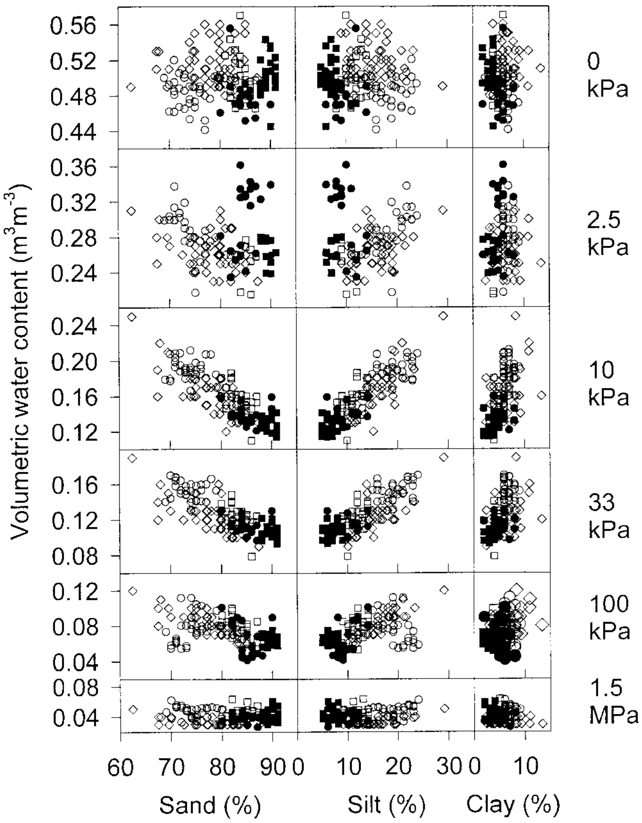

Fig. 5. Relationships between soil water retention and contents of textural components; symbols ○, ●, □, and ■ show data from Transects A, B, C, and D, respectively, grid sampling is shown with symbol ◇.

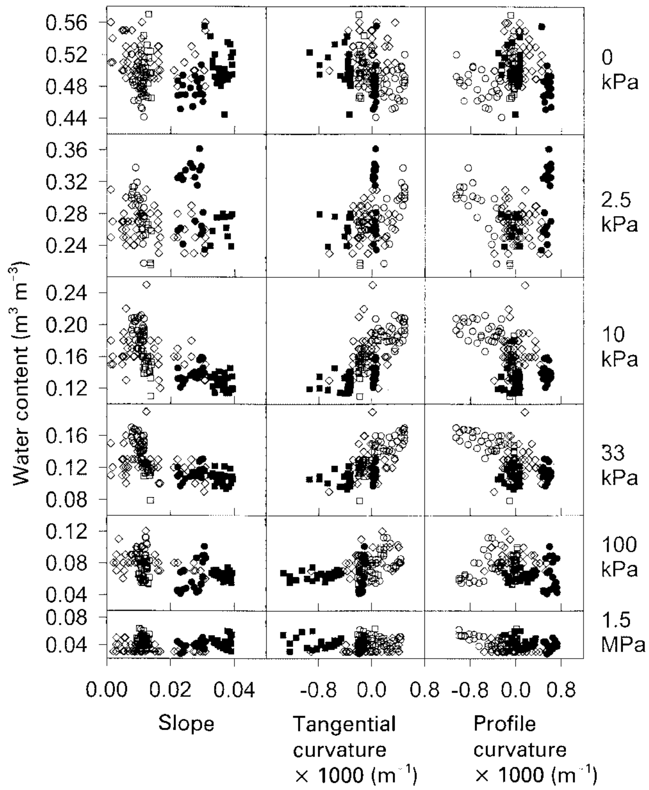

Fig. 6. Relationships between soil water retention and topographic variables; symbols ○, ●, □, and ■ show data from Transects A, B, C, and D, respectively, grid sampling is shown with symbol ◇.

trend line. A relatively strong relationship ($R^2 = 0.703$) between water content and sand content, as well as between water content and silt content, was observed at capillary pressures of 10 and 33 kPa. The relationship degraded as capillary pressure increased further, and R^2 of relationships between water content and sand content was 0.231 at 100 kPa, and 0.004 at 1.5 MPa. The coefficient of determination of the relationship between water content and clay content was approximately 2.3 times less than that of relationships between water content and sand or silt contents.

Since water retention at some capillary pressures exhibits a strong dependence on texture (Fig. 5), and texture reflects topographic variables (Fig. 4), a relationship between water retention at some capillary pressures and topographic variables should be expected. Dependencies of water contents at several capillary pressures on slope and curvatures are shown in Fig. 6. Satiated water content did not exhibit any dependence on topographic variables. As capillary pressure rises, some dependencies emerge. Water contents at 10 and 33 kPa show relationships with slope and curvatures. The coefficients of determination, R^2, are equal to 0.451, 0.423, and 0.266 for regressions of water contents at 10 kPa on slope, tangential curvature, and profile curvature respectively. The regressions of water contents at 33 kPa on slope, tangential curvature, and profile curvature have R^2 of 0.345, 0.432, and 0.310, respectively. Although the coefficients of determination are not high for each of the topographic variables, they are statistically significant.

Regression equations obtained by the generalized least square method for topographic variables derived using the minimum curvature method were

$$\theta_{10} = 0.1769 - 1.002s - 11.36v + 22.99h$$
$$\theta_{33} = 0.1353 - 0.662s - 10.58v + 18.41h$$
$$\theta_{100} = 0.0895 - 0.716s + 5.11v - 2.712h \qquad [9]$$

Results of the regression analysis are shown in Table 3. The distributions of residuals did not significantly differ from normal distributions, and residuals did not show any spatial dependence. Slope, profile, and tangential curvatures used as predictors could explain about 67% of the variation in water retention at capillary pressures of 10 and 33 kPa. Topographic variables were not good predictors for the water retention at 100 kPa, being able to explain only about 20% of variation. Regression coefficients for the profile curvature were not significantly different from zero for 10 and 33 kPa capillary pressures. For the 100 kPa capillary pressure, regression coefficients for curvatures had low statistical significance. Ranges and nugget effects of the semivariograms of errors were similar for all three matric potential level. Signs of the coefficients in the regression equation indicated a decrease in water retention with an increase in slope or with the increase in convexity of the land surface shape across the slope. Sites with larger tangen-

Table 3. Results of the generalized least square regression analysis for water retention as a dependent variable and topographic variables as independent variables.

Soil matric potential	Parameters of semivariograms: Range (m)	Parameters of semivariograms: Nugget effect	Probability P†: Slope	Probability P†: Profile curvature	Probability P†: Tangential curvature	Accuracy of the regression: R^2	Accuracy of the regression: Residual mean square error
−10 kPa	13.3	0.211	0.001	0.211	0.044	0.671	0.0144
−33 kPa	13.4	0.212	0.012	0.163	0.043	0.605	0.0119
−100 kPa	11.8	0.190	0.002	0.428	0.754	0.220	0.0127

† Probability for coefficients in regression to be equal to zero.

tial curvature, i.e., with larger convergence of flows, had larger water retention. The interpolation method had only small effect on the accuracy of regressions and variance explained by regression (data not shown).

DISCUSSION

Dependencies of the water retention on topographic variables were well pronounced for capillary pressures between 10 and 100 kPa in the landscape under study. These dependencies, probably, exist because (i) the water retention exhibits a strong dependence on soil textural components, mainly on sand and silt content, and because (ii) soil texture is substantially coarser where the relief enhances transport of the fine material. Our results concur with results of many other studies which found soil texture be a leading predictor of water retention in sandy soils as compared with other soil properties (i.e., Haverkamp and Parlange, 1988; Schaap and Bouten, 1996). Bulk density was also a useful predictor of water retention in many regional studies (i.e., Hill and Summer, 1967; Paydar and Cresswell, 1996; Williams et al., 1992). However, in this study, bulk density did not correlate with water retention at capillary pressures above 50 kPa (data not shown). In contrast to soil texture, the satiated water content and bulk density did not depend on landscape position in this study. One possible reason for that is the generally coarse texture of soils in the site (Fig. 2). Dependencies of the bulk density on landscape position have been found in studies of soil with finer texture (Simmons et al., 1989; Mapa and Pathmarajah, 1995; Thomson et al., 1998).

The dependence of water retention on clay content was weaker than on other textural components. This seemingly contradicts other studies in which clay content was a leading predictor of water retention (Rawls et al., 1991). However, the range of soil clay contents was much narrower of this study (Fig. 3, 4). The effects of organic matter on water retention might also obscure the effect of clay content on water retention.

A search for the dependencies of water retention on topographic variables is justified only if (i) water retention is significantly different in different parts of the landscape, and (ii) the accuracy of relationships between water retention and topographic variables is comparable with the accuracy of average water retention estimates within a DEM grid cell. Both of these conditions are met in this study. Table 2 shows significant differences in water retention among transects at different landscape positions in the capillary range of soil matric potential. Soil variability within the 30 m DEM cells was represented by the variability within the 30-m transects in this study. Residual mean square errors of the regressions for 10 and 33 kPa (Table 3) were not significantly different from standard deviations of measured water contents across transects in most cases.

The accuracy of the water retention estimation from topographic variables can be limited both by the accuracy of the elevation estimates and by errors in interpolation and differentiation used to obtain the topographic variables from elevations. An increase in the density of elevation data could provide better estimates of curvatures. We did not observe any substantial effect of the interpolation method on the accuracy of the relationships between water retention and topographic variables, probably, because land surface is gently sloping at the site. However, this result cannot be generalized. Arguments for the use of various interpolation methods for elevation data have been made by many authors (see for examples Hutchinson 1989; De Floriani and Puppo, 1995; Wise, 1998). Uncertainty in the interpolation method selection obviously remains unresolved. Yet one more factor affecting the accuracy of the topographic variables is the type of approximations used to compute the same topographic variable. For example, computations of the curvatures and slopes differ in works of Shary (1991), Moore et al. (1993), and Florinsky and Kuryakova (1996). Wise (1998) has demonstrated that the different algorithms used to calculate gradient and aspect in different GIS packages can produce quite different results from the same DEM. A few secondary topographic variables derived from the slopes and curvatures, i.e., catchment area, wetness index, streampower index, flow path length, were listed as potentially useful variables in soil landscape relationships. In summary, there exist various approaches to topographic variable computations, and some experimentation may be necessary to select a procedure that will give the best predictors of soil water retention.

The semivariograms of errors had ranges between 10 and 14 m, which were well within the lengths of transects. That, and a relatively small nugget effect (Table 3), underscored the need for the use of the least square model with correlated errors instead of the ordinary least square model. It was assumed that the variance of errors is the same for observations in all parts of the landscape. We did not have enough data to investigate the heteroscedasticity, i.e., nonequal variances in different parts of the landscape, which also can be handled in least square models with correlated errors (Pinheiro and Bates, 2000).

Substantial differences in soil texture were encountered along the slopes in this study, although slopes were gentle (slope gradients < 5%). The topography-correlated differences in soil texture can be attributed both to the differences in parent material and to erosion processes (Sobecki and Karathanasis, 1992; Tomer and Anderson, 1995). A differentiation in texture with splash and wash was recently observed in controlled experiments. Sutherland et al. (1996) observed in laboratory experiments a preferential removal of fine material with splash and wash that with time was likely to produce a coarser, nutrient depleted interrill soil matrix. Martinez-Mena et al. (1999) found that the texture of the sediment collected for two years from cropped and bare plots was finer than the texture of the matrix soil. The former was on the border between clay loam and silty clay loam, whereas the latter was close to the border between silty clay loam and silt loam. Even gentle slopes have a potential for a substantial texture differentiation.

The strongest relationship between soil water retention and topographic variables was observed at capillary pressures of 10 and 33 kPa, i.e., in the range where the soil reaches its field capacity. As the water content at the wilting point did not vary substantially, the available water capacity depended on landscape position. The strong effect of the landscape position and topographic variables on crop yields and on the impact of the weather pattern on yields in different parts of fields was documented in several studies (i.e., Halvorson and Doll, 1991; Simmons et al., 1989; Timlin et al., 1998). This effect is probably related to the spatial pattern of the available water capacity distribution, since the available water capacity is one of most important soil variables that affect yields of rainfed crops. Results of this work show a potential for the topographic variables to be used as interpretive attributes for yield maps in precision agriculture.

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Soil Property Changes during Conversion from Perennial Vegetation to Annual Cropping

Brian J. Wienhold* and Donald L. Tanaka

ABSTRACT

Management practices for conversion of land supporting perennial vegetation to crop production are needed. Effect of haying (hayed or not hayed), cropping (annual crop with no-tillage, minimum tillage, or conventional tillage, and no-tilled perennial crop), and N fertilization (0 or 67 kg ha^{-1}) on soil properties were measured in 1995 and 1997 at a Conservation Reserve Program (CRP) site in North Dakota having an Amor loam (Fine-loamy, mixed, superactive, frigid, Typic Haplustoll) soil in a spring wheat (*Triticum aestivum* L.), winter wheat, pea (*Pisum sativum* L.) rotation. Soil physical properties were not affected negatively by the management practices used. Haying and tillage practices influenced soil chemical properties. Organic C and total N content declined (1.2 Mg ha^{-1} for C and 0.1 Mg ha^{-1} for N) from 1995 to 1997. In hayed plots, organic C and total N increased as tillage intensity decreased while in non-hayed plots no pattern was observed. Haying and tillage influenced soil biological properties. Potentially mineralizable N at 0 to 0.05 m increased as tillage intensity decreased in 1997. In the 0.05- to 0.15-m depth, potentially mineralizable N increased from 1995 (118 kg ha^{-1}) to 1997 (146 kg ha^{-1}). By 1997, soil properties in hayed plots responded to cropping practices similarly to those in established cropping systems in this region. In non-hayed plots, management induced patterns had not developed by 1997. Haying, conservation tillage, and annual cropping are viable approaches for converting land to annual crop production.

The United States Food Security Act of 1985 established the Conservation Reserve Program (CRP) as a management program for conserving soil and water resources by placing highly erodible land into perennial vegetation for 10 yr. Similar programs have been used historically in the USA to control erosion (e.g., soil bank program) and influence grain supplies. Programs encouraging producers to plant perennial vegetation on cropland to reduce grain surpluses are also used in Europe (Olaf Christen, 2000, personal communication).

Establishment of perennial vegetation on previously cropped lands reduces the potential for wind and water erosion and sequesters C in soil organic matter and vegetation. As CRP contracts expire, one option available to landowners is to return these lands to crop production. Over half of the land enrolled in CRP was located in the Great Plains. Management practices that maintain gains made in soil and water conservation and C sequestration during CRP years are needed by landowners returning these lands to crop production (Lindstrom et al., 1994).

Conversion of CRP land to crop production will require practices that manage the extensive vegetation residue that accumulated during the contract years prepare a seedbed that will allow crop establishment and production, and provide sufficient fertility to meet crop needs. Residue management can be accomplished through fire, tillage, or haying. Fire results in losses of C and N and may leave the soil susceptible to wind and water erosion. Cultivation has been shown to increase greatly the susceptibility of many soils to wind and water erosion (Low, 1972). Haying removes much of the aboveground biomass while leaving plant crowns and other residue as protection against wind and water erosion. Initially, as residues decompose, N mineralization or immobilization may occur, depending on the proportion of legumes present in the stand. Since N is the nutrient most commonly limiting crop production and added in greatest amounts by producers in the northern Great Plains, the effect of residue management on N availability is a major concern.

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