Using Terrain Attributes to Develop Management Zones for Potassium Fertility

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Introduction

Site-specific management of nutrients in soils requires that a field be broken into management zones, each with similar values for likely crop response and nutrient concentrations. The zoning strategy avoids the problems of over-application of inputs in areas where they are not needed and under-application of inputs where they are needed (Cahn et al., 1994; Ferguson et al., 2002). A high degree of spatial autocorrelation among adjacent samples indicates parcels of land to be grouped together into management units. The goal of many studies is to determine the minimum sampling density required to account for spatial autocorrelation of the properties of interest (Lauzon et al., 2005).

The procedure of delineating management zones and analyzing spatial autocorrelation of soil properties can be augmented by the use of ancillary data when correlations between expensive soil data and less-expensive data exist. Ancillary data may include published soil mapping units, remotely sensed reflectance data, soil profile electrical conductivity, and terrain attributes (Cox et al., 2003; Jung et al., 2006).

Since the widespread availability of digital elevation models (DEMs), terrain attributes have become more easily quantified. Terrain attributes such as slope and elevation have been widely used in soil survey and continue to be a fundamental consideration in the understanding of landscapes (Soil Survey Division Staff, 1993). Another useful terrain attribute for the study of soil variability is the topographic wetness index (TWI), which incorporates the hydrological upstream contributing area and slope (Quinn et al., 1995). The TWI has great potential as ancillary data in studies of soil properties that are influenced by the activity of water. This is because landscape shape and position have a strong influence on soil functions as they direct overland flow and soil moisture through convergent and divergent pathways (Schaetzl and Anderson, 2005a). This has been used successfully in models of soil properties in several studies, but have not been used in regards to nutrient distributions. The objectives of this study were to:

- examine the spatial distribution of K availability in the soil drainage toposequence
- relate the distribution of K to properties of the landscape such as soil type, soil landscape position, and terrain attributes
- determine whether a three dimensional model of soil property variance could be used to account for spatial autocorrelation, thereby increasing the statistical power of the analysis. We hypothesized that K is no exception to the power of water to transform soil landscapes, and that terrain attributes would relate well to K fertility.

Methods and Materials

To investigate the relationships between terrain attributes, soil wetness, soil K plant availability, and ECEC at three depths, we examined a drainage toposequence in the Muscatatuck Uplands Region of Jennings County in Southeastern Indiana. We chose the site based on drainage classes of the soils described in the Soil Survey and because of the prominence of the soils in the region. The site has never been artificially drained. Corn and soybeans have been grown on the site for at least the past 30 years. No-till methods of cultivation have been incorporated during the past 10 years of management. Uniform K treatments have been applied to the site for its known history.

Soil samples were taken with a hydraulic probe collecting 4 cm cores to a depth of 1.5 m in a grid pattern at 20 m intervals in four main transects running north to south across the soil series. Samples were collected at depths 0-10, 25-35, and 55-65 cm. Nested samples were taken at 5 m intervals in two key sub-transects, one running north to south in a zone of what was expected to be high soil variation, and one running east to west in a zone of expected low variation. A total of 128 borings were made and 384 samples were taken to the laboratory for analysis. Exchangeable K (M3K), Mg, Al, and Ca were measured using the Mehlich 3 extractant and ion-coupled-plasma spectrometry (Helmke and Sparks, 1996). Long-term plant-available K values were obtained after a 7 day extraction period using the tetraphenyl boron (TPB) method modified by Cox et al. (1996) and measured with flame emission spectrometry.

Effective cation exchange capacity (ECEC) was calculated by summation of the exchangeable cations Ca, Mg, K, and Al, excluding Na+ (Grove et al., 1982; Sumner and Miller, 1996). Elevation values for the site and surrounding landscape were taken from a published digital elevation model (DEM) of the State of Indiana with a 1.5 m resolution, horizontal accuracy better than 1.5 m, and vertical accuracy better than 1.8 m at a 95% confidence interval (State of Indiana, 2006). The elevation data were then resampled using bilinear convolution to a grid cell size of 8 m (ESRI, 2005). The 8 m resolution was chosen to provide sufficient topographical detail without overburdening statistical and terrain analysis resources. Analysis performed with elevation models resampled to other resolutions, slightly higher and lower, were attempted and gave results equivalent to those presented in this paper.

Terrain attributes of slope, relative elevation, and topographic wetness index (TWI) were calculated for the land surface at the study site using the DEM grid cell resolution of 8 m. Slope and relative elevation were chosen because they represent landscape features that have been used to classify and categorize the soils historically (Nickell, 1976). TWI was chosen (and other terrain attributes such as curvature and aspect were rejected) after examining relationships to soil properties in preliminary investigations. Slope was rejected in the final models because of its lack of significance after accounting for stronger relationships between soil attributes and TWI and relative elevation. The topographic wetness index (TWI) is calculated from the upslope area contributing flow and slope angle:

$$TWI = \ln\left(\frac{\alpha}{\tan(\beta)}\right)$$

where α = the upslope area in m^2, per unit contour length, contributing flow to a pixel, and β = slope angle acting on a cell measured in radians (Lindsay, 2005; Quinn et al., 1995).

Statistical analyses were conducted using SAS statistical software (SAS Institute, 2003a). The Mixed procedure was used to fit a linear model with correlated residuals of soil variables to terrain attributes, to test for significance, and to predict values between the sampled points based on terrain attribute values at those points. Linear models were chosen to maximize explanatory power and emphasize relationships between terrain and soil. Spatial autocorrelation at the site is assumed to follow a three-dimensional (x, y, depth) anisotropic exponential model. The purpose of the spatial regression analysis is to determine whether terrain attributes can explain some of the variability of K concentrations in the field. If terrain attributes are able to explain variation of

K availability, then they can provide a useful, inexpensive input of relevant data to site-specific K management efforts.

Results

Initial investigations of K concentrations indicated spatial patterns within the field that appeared to correspond to landscape features. The landscape features were related to the flow of water across soil series based on elevation differences and surface properties.

Exchangeable Potassium

Exchangeable K (M3K) decreased with soil depth (Figure 1). The 0-10 cm depth had significantly higher concentrations than the other two depths ($p < 0.0001$). This is expected given the history of uniform surface K fertilization in the field and the tendency of plants to cycle soil nutrients toward soil surfaces. M3K was significantly higher in the moderately well-drained Cincinnati/Nabb soils than the poorly-drained Cobbsfork ($p < 0.0001$), and somewhat-poorly-drained Avonburg soils ($p < 0.0001$). Higher values of M3K on the edges of the field are partially explained by increases in effective cation exchange capacity (ECEC).

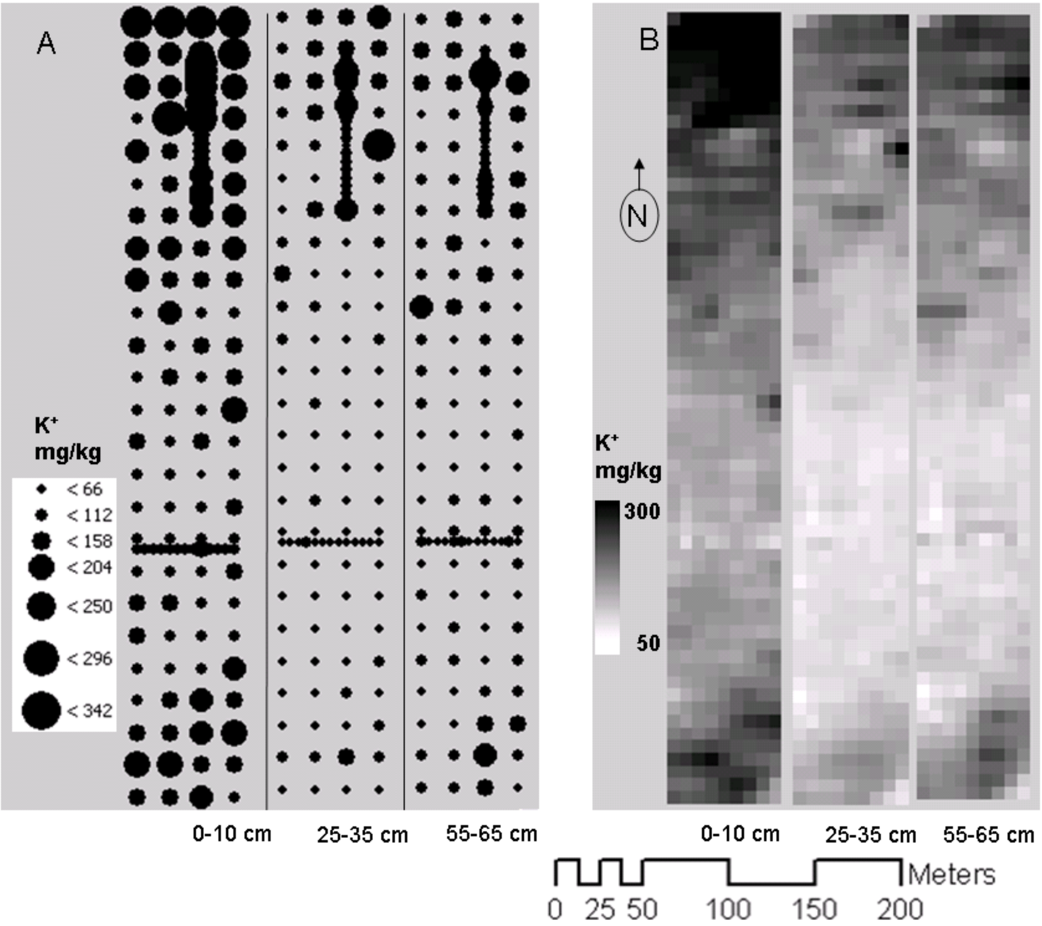

Figure 1. A) Measured values of exchangeable K concentrations (mg K kg^{-1}) at three depths; B) the stochastic prediction raster of K concentrations (mg K kg^{-1}) using terrain attributes as predictors.

M3K was significantly correlated to TWI. While elevation by itself is not a significant constituent effect, the interaction between relative elevation and the 0-10 cm depth of M3K is highly significant ($p < 0.0001$) with a coefficient of -16.7. While a number of explanations are possible, this may lend support to a hypothesis that saturated overland flow transports some amount of surface-applied K from soils at relatively higher elevations to soils at lower elevations. The relationship between M3K and the TWI at all depths ($p < 0.05$) lends support to the hypothesis relating K to soil wetness in soil series. Spatial differences in M3K at the site are striking considering the moderating influence of the historical uniform application of K.

Effective Cation Exchange Capacity

The ECEC increased with depth at the study site (Figure 2). The 55-65 cm depth has significantly higher ECEC values than the 25-35 cm depth ($p = 0.0002$), while the 25-35 cm depth has higher ECEC than the 0-10 cm depth ($p < 0.0001$). The two components that dominate ECEC in most soils are soil organic matter and clay. Soils in the Cincinnati series, which have been referred to as "buttermilk flats" because of their light color, have relatively low organic matter content (Steinhardt and Franzmeier, 1979). Ransom et al. (1987) reported organic carbon

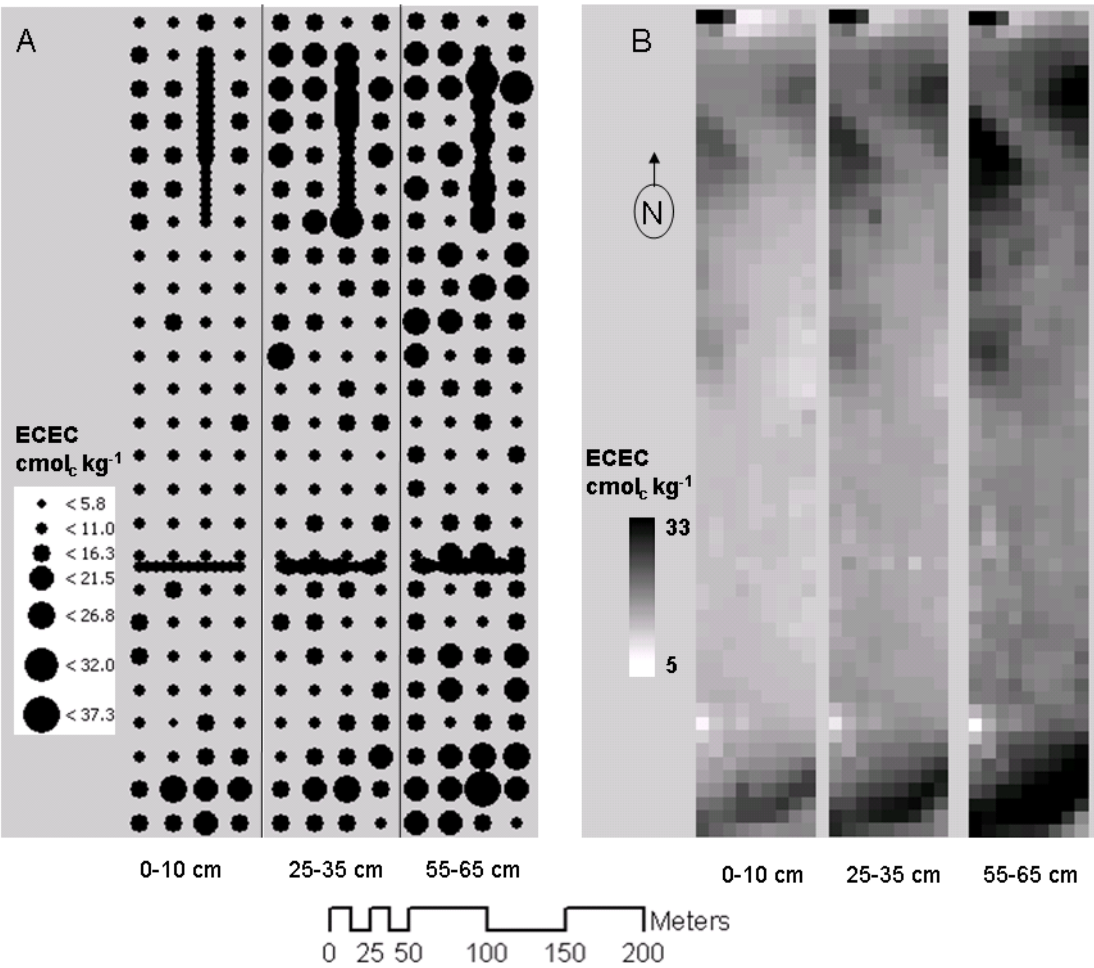

Figure 2. A) Measured values of ECEC (cmol kg^{-1}) at three depths of the study site; B) the stochastic prediction raster of ECEC (cmol kg^{-1}) using terrain attributes as predictors.

contents around 8 to 9 g kg^{-1} for the surface horizons. Low organic matter content means that soil clay should be of more importance to ECEC than organic matter in these soils. It is not surprising then that ECEC increases with soil depth at the study site.

ECEC is significantly higher in the moderately-well-drained Cincinnati/Nabb mapping unit than in the other soils ($p < 0.0001$) (Table 1). Also, the somewhat-poorly-drained Avonburg mapping unit has higher ECEC values than the poorly-drained Cobbsfork ($p = 0.0007$). ECEC values are fairly low throughout soil series. If K is more mobile in soils with lower ECEC values and less mobile in soils with higher ECEC values, some movement from the soils higher in the landscape with lower ECEC values to soils lower in the landscape with higher ECEC values should be expected. Relative elevation, the squared value of relative elevation, TWI, and interaction terms between these attributes are all significant effects in the prediction of ECEC in soil series ($p < 0.001$).

The strength of these relationships likely reflects the influence of water movement as a mechanism for soil development. With a unit increase in the relative elevation of the study site, ECEC at the site is expected to decrease by a factor of 11 cmolc kg^{-1}. A unit increase in the wetness index is expected to coincide with a decrease of 2.6 cmolc kg^{-1} in the ECEC. Strong relationships between ECEC and terrain attributes provide some supporting evidence for a hypothesis that lateral flow may be moving soil clay and organic matter from areas of relatively high elevation to lower elevations.

Discussion

Relationships between landscape features and soil properties have provided the means by which soils have been historically understood, mapped, predicted, and used (Soil Survey Division Staff, 1993). These relationships have largely been communicated in qualitative terms due to the difficulties of quantifying landscape features, even if the soil properties themselves were observed quantities. With the ability to easily manipulate data and to quantify landscape features with computer technology, the ability to quantify soil-landscape relationships is rapidly growing.

Significant relationships between terrain attributes and soil fertility data can provide a quantitative understanding of the availability of K in the Cobbsfork/Avonburg/Nabb/Cincinnati soil series, a major toposequence in southeastern Indiana. Exchangeable and nonexchangeable K concentrations were found to be higher in moderately-well-drained soils lower in the landscape than in poorly-drained soils in the higher, flatter areas of the site. PANK was strongly and negatively related to TWI and elevation ($p < 0.001$), and M3K was negatively related to TWI ($p < 0.05$). The TWI indicates areas more prone to wetness and to longer expansion of 2:1 clay minerals from which nonexchangeable K could be vulnerable to leaching and plant removal. Lower ECEC in the poorly-drained soils could provide a mechanism whereby M3K from higher in the landscape could be more mobile compared to K in the lower landscape positions. These data suggest that including low cost topographic features from DEM's for developing management zones may be useful for site specific management.

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