Potassium Fertility and Terrain Attributes in a Fragiuudalf Drainage Catena

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Site-specific management of soil fertility has been based on soil sampling in grid patterns or within soil mapping units without taking full advantage of terrain—soil relationships. The goal of this study was to determine whether terrain attributes relate significantly to soil K availability. The topographic wetness index (TWI), a terrain attribute that comprises the upstream contributing area and the slope for a portion of land, relates to soil wetness. We estimated Mehlich-3 K (M3K), plant-available nonexchangeable K (PANK) with a modified tetraphenylboron extraction, effective cation exchange capacity (ECEC), and other soil variables from soil samples taken at three depths, and terrain attributes in a 3.6-ha farmed site in the Cincinnati catena, a major toposequence in the Muscatatuck Uplands region of Indiana. The PANK and M3K were significantly \( P < 0.0001 \) and \( P < 0.05 \), respectively) related to TWI and relative elevation in models with anisotropic spatial autocorrelation variance estimates in three dimensions (latitude, longitude, and soil depth). The PANK and M3K increased with decreasing TWI in the following drainage class order: poorly < somewhat poorly < moderately well drained. The M3K decreased with soil depth, while PANK increased. The PANK/M3K ratio was significantly higher in the poorly drained soils than in the moderately well-drained soils, implying greater mobility or weathering of K in wetter soils. The ECEC also related strongly to terrain attributes \( P < 0.0001 \) for relative elevation, TWI, and interaction effects). Possible mechanisms include lateral downslope leaching and K leaching. Terrain attributes can aid in soil K fertility evaluations on the Cincinnati catena because they relate well to soil K fertility measurements.

Abbreviations: DEM, digital elevation model; ECEC, effective cation exchange capacity; M3K, potassium extracted with Mehlich-3 extractant; PANK, plant-available nonexchangeable potassium; TPB, tetraphenylboron; TWI, topographic wetness index.

Site-specific management of nutrients in soils requires that a field be broken into management zones, each with similar values for probable crop response and nutrient concentrations. The zoning strategy avoids the problems of overapplication of inputs in areas where they are not needed and underapplication where they are needed (Ferguson et al., 2002; Cahn et al., 1994). Management zones are delineated according to the variability of the properties of interest using a grid of sampling points spaced close enough together to capture the soil spatial variability. 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 (Jung et al., 2006; Cox et al., 2003; Kravchenko et al., 2006).

Since the widespread availability of digital elevation models (DEMs), terrain attributes have become more easily quantified. Terrain attributes are quantifiable surface properties related to changes in elevation usually calculated from DEMs. 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). An increasing body of research documents the relationships between terrain attributes derived from DEMs and soil properties (McBratney et al., 2003; Scull et al., 2003).

One useful terrain attribute for the study of soil variability is the TWI, which incorporates the terrain attributes of hydrologic upstream contributing area and slope (Quinn et al., 1995). Also called the compound topographical index, it has been used successfully in models of soil properties in several studies (Chaplot et al., 2000; Gessler et al., 1995; McKenzie and Ryan, 1999; Moore et al., 1993; Quinn et al., 1995; Ziadat, 2005; Fraisse et al., 2001). Campling et al. (2002) used terrain attributes including TWI to model the probability of soil drainage classes. Merot et al. (1995) compared TWI to published soil drainage classes and found that TWI could predict the distribution of waterlogged soils. 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 pedogenic functions as they direct overland flow and soil moisture through convergent and divergent pathways (Schaetzl and Anderson, 2005).

Studies of long-term K availability could benefit from TWI and other terrain attributes as ancillary data because soil moisture is an important component in the weathering of soil K-bearing minerals, it is the driving force in leissavage of soil clays and nutrients, and it plays an important role in the structural status of phyllosilicate clays, making expansion of the mineral lattice possible for exploitation of interlayer K reserves in native minerals. Differences in soil moisture can be related to landscape shape and position, attributes that are quantifiable with terrain analysis.

Spatial distributions of exchangeable K have been examined in pasture land heavily influenced by animal traffic and manure distributions (Officer et al., 2006), in agricultural fields (Lauzon et al., 2005), and in forest soils (Okae-Anti and Ogoe, 2006), but such studies have not focused on the relationships between pedogenic development of soils and nutrient distributions, and they have not examined nonexchangeable K or its relationship to pedogenesis.

Plants use soil solution K, exchangeable K, and nonexchangeable K. Exchangeable and soil solution K equilibrate quickly with each other and are of paramount importance for plants (Sparks et al., 1980). While many soils of temperate regions contain little K on the exchange phase, and even less in the soil solution, crop demand for K is high. Nonexchangeable K, or K that is more closely bound with soil mineralogy, is often relatively plentiful in soil systems. Transformations from the nonexchangeable forms of K to the exchangeable forms to replenish depleted exchange or solution phases are therefore necessary for plants in natural systems (Bertsch and Thomas, 1985). Nonexchangeable K has been estimated to supply 70 to 80% of the K used by crops for some cropped soils in Norway (Ogaard and Krogstad, 2005) and 80 to 90% of K used by crops in alluvial soils in Punjab (Mengel, 1985). In fact, nonexchangeable K from micaceous minerals and their weathering products is the most important long-term source of K in most soil systems (Bertsch and Thomas, 1985). In this study, we used a 7-d tetraphenylboron extraction to approximate PANK, setting up a long-term diffusion gradient analogous to long-term multiple-season cropping, or long-term natural-systems activity in which K is slowly extracted from native soil minerals and incorporated by plants (Cox et al., 1996; Carey and Metherell, 2003). We also used an extraction of exchangeable K to provide estimates of the K more immediately available to plants (Mehlich, 1984).

Plants probably obtain significant amounts of their K needs from the subsoil (Carey and Metherell, 2003; Rao et al., 2001; Woodruff and Parks, 1980). Rao et al. (2001) found that values of subsoil exchangeable K concentrations were between 60 and 90% of values of surface (0–15-cm depth) K. Carey and Metherell (2003) noted that lack of a full accounting for nutrient budgets in a New Zealand soil K study was explained by plant uptake of K below the sampling depth of 7.5 cm. In this study, we examined K availability at three key depths, corresponding to the expected depths of the Ap, E, and Bt horizons of the soils in the catena.

The objectives of this study were: (i) to examine the spatial distribution of K availability in the soil drainage toposequence; (ii) to relate the distribution of K to properties of the landscape such as soil type, soil landscape position, and terrain attributes; and (iii) to 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 that help to govern the flow of water in the soil landscape would relate well to K fertility.

MATERIALS AND METHODS

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 (Fig. 1). The site is located in UTM Zone 16 at 626725 E and 4321472 N. Soils at the site are Cobbsfork (formerly classified as Clermont, a fine-silty, mixed, active mesic Fragic Glossaqualf), Avonburg (a fine-silty, mixed, active mesic aeric Fragic Glossaqualf), Nabb (a fine-silty, mixed, active, mesic Aquic Fragiudalf), and Cincinnati (a fine-silty, mixed active, mesic Oxyaqual Fragiudalf) in the U.S. Soil Taxonomy (Soil Survey Staff, 1999). We chose the site based on drainage classes of the soil described in the Soil Survey Geographic (SSURGO) database of the National Cooperative Soil Survey (Soil Survey Staff, 2007) and because of the prominence of the soils in the region. The soil series in the catena represent approximately 59,000 ha in Jennings County, or 60% of the total area of the county, as well as large portions of the surrounding region covering southeastern Indiana and southwestern Ohio (Soil Survey Staff, 2007; Ransom et al., 1987; Gray, 2000; Nickell, 1976). The site has never been artificially drained. Corn [Zea mays (L.)] and soybean [Glycine max (L.) Merr.] have been grown on the site for at least the past 30 yr. No-till methods of cultivation have been incorporated during the past 10 yr of management. Uniform K treatments have been applied to the site for its known history; however, no K was applied in the year of sampling. Yields have been historically rather uniform, although detailed data do not exist. The parent material for the sampling depth for all soils sampled was found to be loess overlying a deeper paleosol developed in glacial till.

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 catena. Samples were collected at depths of 0 to 10, 25 to 35, and 55 to 65 cm. The depths roughly correspond to the expected locations of the A, E, and upper Bt horizons of the soils. Nested samples were taken at 5-m intervals in two key subtransects, 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 (Fig. 1). A total of 128 borings was made and 384 samples were taken to the laboratory for analysis. All soils were allowed to air dry in a greenhouse, and were then crushed and passed through a 2-mm sieve.

Exchangeable K (M3K), Mg, Al, and Ca were measured using the Mehlich-3 extractant and ion coupled plasma spectrometry (Helmeke and Sparks, 1996). Long-term plant-available K values were obtained after a 7-d extraction period using the tetraphenylboron (TPB) method modified by Cox et al. (1996) and measured with flame emission spectrometry. Plant-available nonexchangeable K was calculated for each soil sample at each depth and was defined as
The ECEC was calculated by summation of the exchangeable cations Ca, Mg, K, and Al, excluding Na+ (Grove et al., 1982; Sumner and Miller, 1996). Sodium concentrations in these soils are insignificant compared to the dominant bases and Al (Nickell, 1976; Ransom et al., 1987).

Elevation values for the site and surrounding landscape were taken from a published 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 (Indiana Geographic Information Council, 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 topographic 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 here.

Terrain attributes of slope, relative elevation, and 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). The 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. Relative elevation values were centered at zero for the average elevation; lower elevations were given negative values representing meters below the mean value, and higher elevations were given positive values. Slope was calculated as the average change in elevation from the cell of interest to the surrounding eight grid cells divided by the distance between the centers of the adjacent grid cells. The TWI is calculated as

\[ \text{TWI} = \ln \left( \frac{\alpha}{\tan \beta} \right) \]

where \( \alpha \) is the upslope area (m²) per unit contour length contributing flow to a pixel, and \( \beta \) is the slope angle acting on a cell (radians) (Lindsay, 2005; Quinn et al., 1995).

Statistical analyses were conducted using SAS statistical software (SAS Institute, 2003b). 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 was assumed.
RESULTS

Initial investigations of K concentrations indicated spatial patterns within the field that appeared to correspond with land-scape features. The landscape features were related to the flow of water across the catena based on elevation differences and surface morphometry. The probable directions of overland flow from the center of the study site are to the north–northwest and to the south–southwest, downward in elevation toward the better-drained soils on the bevel (Fig. 2). Flow probably converges in concave areas as it approaches the drainagegeways of the site, as can be inferred from the values of the wetness index. Some channelization is evident in areas around the study site. Figure 2 illustrates the interfluve or nose-slope characteristics of the topography. The interfluve extends to the west perpendicular to the direction of the study site, with both the north and south ends of the site lying at sideslope positions. These ends are characterized by increases in slope and resulting decreases in TWI values. Descriptive statistics for the soils at the site indicate the mean values and the ranges of values for terrain attributes and soil properties (Table 1).

Exchangeable Potassium

Exchangeable K decreased with soil depth (Table 2). The 0- to 10-cm depth had significantly higher concentrations of M3K than the other two depths \( (P < 0.0001) \). This is expected, given the history of uniform surface K fertilization in the field and the process of phytocycling, the tendency of plants to cycle soil nutrients toward soil surfaces (Jobbagy and Jackson, 2001). Mehlich-3 K 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 \( (P < 0.0001) \) (Table 2, Fig. 3). Higher values of M3K on the edges of the field are partially explained by increases in ECEC.

Mehlich-3 K was significantly correlated with TWI (Table 3). While elevation by itself is not a significant constituent effect, the interaction between relative elevation and the 0- to 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 the catena. Spatial differences in M3K at the site are striking considering the moderating influence of the historical uniform application of K (Fig. 3).

Tetraphenylboron-Extractable Potassium and Plant-Available Nonexchangeable Potassium

The TPB K and PANK are quite similar because PANK is calculated from TPB K minus a relatively small amount of M3K. Values for TPB K are between 75 and 98% nonexchangeable K, and only 2 to 25% exchangeable K. The discussion of PANK, therefore, applies also to TPB K.

Plant-available nonexchangeable K was greater at the 55- to 65-cm depth than at 25 to 35 and 0 to 10 cm (Table 2, \( \alpha = 0.05, P < 0.0001; \) Fig. 4). The PANK values from the
Table 1. Descriptive statistics for K fertility and landscape properties at the study site in North Vernon, IN. Coordinates for latitude and longitude are given for UTM Zone 16.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Mean</th>
<th>SD</th>
<th>CV</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
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<td>Landscape features, n = 686</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>Lat., m northing</td>
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<td>143</td>
<td>–</td>
<td>4321234</td>
<td>4321722</td>
</tr>
<tr>
<td>Long., m easting</td>
<td>626724</td>
<td>21</td>
<td>-</td>
<td>626602</td>
<td>626756</td>
</tr>
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<td>Elevation, m</td>
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<td>1.18</td>
<td>0.49</td>
<td>233.8</td>
<td>239.4</td>
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<td>Slope, %</td>
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<td>1.03</td>
<td>0.77</td>
<td>0.11</td>
<td>5.81</td>
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<td>TWH</td>
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<td>1.08</td>
<td>12.1</td>
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<td>Soil features, n = 128</td>
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<td></td>
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<tr>
<td>pH</td>
<td>5.84</td>
<td>0.54</td>
<td>25.7</td>
<td>4.29</td>
<td>7.61</td>
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<td>TPB K†, mg kg⁻¹</td>
<td>1298</td>
<td>267</td>
<td>36.9</td>
<td>746</td>
<td>2197</td>
</tr>
<tr>
<td>M3K§, mg kg⁻¹</td>
<td>144</td>
<td>61.5</td>
<td>53.7</td>
<td>56.5</td>
<td>341</td>
</tr>
<tr>
<td>PANK¶, mg kg⁻¹</td>
<td>1157</td>
<td>240</td>
<td>9.3</td>
<td>645</td>
<td>2050</td>
</tr>
<tr>
<td>PANK/M3K</td>
<td>9.22</td>
<td>3.41</td>
<td>20.6</td>
<td>2.73</td>
<td>18.1</td>
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<tr>
<td>ECEC#, cmol kg⁻¹</td>
<td>10.5</td>
<td>2.62</td>
<td>42.8</td>
<td>5.75</td>
<td>24.7</td>
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<td>M3K/ECEC††</td>
<td>0.035</td>
<td>0.013</td>
<td>20.7</td>
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<td>0.075</td>
</tr>
<tr>
<td>0–10-cm depth</td>
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<td></td>
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<tr>
<td>pH</td>
<td>5.6</td>
<td>0.76</td>
<td>36.9</td>
<td>4.37</td>
<td>7.05</td>
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<td>478</td>
<td>25</td>
<td>767</td>
<td>3094</td>
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<td>M3K, mg kg⁻¹</td>
<td>77.5</td>
<td>40</td>
<td>36</td>
<td>32.9</td>
<td>265.3</td>
</tr>
<tr>
<td>PANK, mg kg⁻¹</td>
<td>1416</td>
<td>439</td>
<td>13.6</td>
<td>580.6</td>
<td>2811</td>
</tr>
<tr>
<td>PANK/M3K</td>
<td>20.4</td>
<td>5.93</td>
<td>32</td>
<td>3.1</td>
<td>33.5</td>
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<tr>
<td>ECEC‡, cmol kg⁻¹</td>
<td>12.6</td>
<td>3.67</td>
<td>51.6</td>
<td>6.4</td>
<td>27.7</td>
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<td>M3K/ECEC</td>
<td>0.016</td>
<td>0.0057</td>
<td>31</td>
<td>0.007</td>
<td>0.041</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>4.77</td>
<td>0.6</td>
<td>29.1</td>
<td>4.02</td>
<td>7.08</td>
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<td>TPB K, mg kg⁻¹</td>
<td>1717</td>
<td>441</td>
<td>29.2</td>
<td>916</td>
<td>3323</td>
</tr>
<tr>
<td>M3K, mg kg⁻¹</td>
<td>86.7</td>
<td>34.4</td>
<td>36</td>
<td>32.9</td>
<td>265.3</td>
</tr>
<tr>
<td>PANK, mg kg⁻¹</td>
<td>1637</td>
<td>410</td>
<td>12.6</td>
<td>867</td>
<td>3168</td>
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<td>PANK/M3K</td>
<td>12.9</td>
<td>4.47</td>
<td>29.7</td>
<td>3.1</td>
<td>26.1</td>
</tr>
<tr>
<td>ECEC, cmol kg⁻¹</td>
<td>14.5</td>
<td>4.54</td>
<td>39.7</td>
<td>6.31</td>
<td>37.5</td>
</tr>
<tr>
<td>M3K/ECEC</td>
<td>0.015</td>
<td>0.0039</td>
<td>25.1</td>
<td>0.008</td>
<td>0.03</td>
</tr>
</tbody>
</table>

† Topographic wetness index = ln(Soil features, Elevation) − ln(1,000) − ln(Slope, %)
‡ K extracted with a Mehlich-3 solution.
§ Plant-available nonexchangeable K, calculated as TPB-extractable K minus Mehlich-3-extractable K.
¶ Effective cation exchange capacity calculated by summation of the cations Ca, Mg, K, and Al. The contribution from Na was assumed to be negligible.
M3K/ECEC b ab a 379
ECEC c b a 379
PANK/M3K c b a 379
TPB K b ab a 379
M3K a†† b b 379
Cincinnati/Nabb (moderately well drained) soils are significantly higher than PANK values from the Cobbsfork (poorly drained) soils (α = 0.05, P < 0.0001).

The increase in PANK with depth follows an expected pattern of soil leaching of clay and nutrients. Cox (1997) reported strong correlations between soil clay content and PANK concentrations for several midwestern soils. Field observations and laboratory investigations confirmed the increase of clay with depth in the soils at the study site (Winzeler, 2008). The process of leaching is a well-documented phenomenon for soils generally, and for the Cincinnati catena specifically (Ransom et al., 1987). Because the 55- to 65-cm depth is the expected depth for the presence of a clay increase associated with the Bt horizon, it is not surprising that it should have significantly higher PANK measurements. In addition, plant root uptake is generally strongest in surface horizons and should account for a decrease in surface PANK. The PANK represents a reservoir of K that is slowly capable of replenishing exchangeable K through a process of diffusion (McLean and Watson, 1985). This diffusion process can be regulated by the plant-induced K extraction at the soil–root interface (Barber, 1985). Because plants invest root density heavily in surface soils, the diffusion process should be strongest here, promoting greater diffusion of K from the nonexchangeable phase.

There are two probable mechanisms that explain the higher PANK and TBP K values in the Cincinnati/Nabb soils and the lower values in the Cobbsfork soils. They include the influence of soil moisture and the possibility of lateral movement across the catena due to fragipan influences on hydrology. Cincinnati/Nabb soils are classified as moderately well drained in Jennings County and are expected to be saturated for only a short time.
Evidence for a possible relationship between soil moisture and nonexchangeable K can be seen in a strong negative correlation between values of PANK and TWI for the site \( (P < 0.0001) \) (Table 3). The TWI, which quantifies a landscape’s propensity toward wetness and is based strictly on the shape of the surface of the soil, has been a reliable predictor of soil wetness in several studies (Campling et al., 2002; Merot et al., 1995). As TWI values increase, the probable wetness of a portion of land under a positive moisture balance increases. The model given in Table 3 indicates that expected PANK values at the study site decrease by a factor of 202 mg kg\(^{-1}\) with every unit increase in TWI. The TWI also appears as a significant interaction effect with several other model terms \( (P < 0.05, \text{ Table } 3) \).

Another possible mechanism for the differences between PANK values at the different soil drainage-class mapping units may be lateral flow. Water movement from poorly drained soils at the higher, level areas of the till plain to areas of depression could influence the transport of materials such as clays and nutrients. Higher concentrations of nutrients would be expected at lower elevations, and in areas of convergent flow if lateral movement of soil nutrients were occurring. Subsurface lateral flow of perched soil moisture in soils with fragipans has been reported in several studies (Needelman et al., 2004; Miller et al., 1971; Gburek et al., 2006; Needelman et al., 2004). We have seen higher K concentrations at the north and south

Table 3. Model parameters† relating soil K fertility to landscape features.

<table>
<thead>
<tr>
<th>Fertility property</th>
<th>Constituent landscape effects</th>
<th>Interaction effects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Int dep1 dep2 elev elev(^2) TWI x y y(^2)</td>
<td>dep1(^2) elev dep1(^2)TWI elev(^2)TWI elev(^2) TWI dep2(^2) elev dep2(^2)TWI df</td>
</tr>
<tr>
<td>M3K, mg kg(^{-1})</td>
<td>119.5 56.8*** -9.97** 13.3 NS -6.80* NS 0 0.001***</td>
<td>-16.7*** NS NS NS NS NS NS NS NS NS NS NS NS NS 374</td>
</tr>
<tr>
<td>TPK K, mg kg(^{-1})</td>
<td>3680 -1471*** -259*** -539 -482** -213*** NS NS NS</td>
<td>-162** 114.3** 59 48** -84 NS 373</td>
</tr>
<tr>
<td>PANK(^{#}), mg kg(^{-1})</td>
<td>3503 -1657*** -253*** -423 -230** -202*** NS NS NS</td>
<td>-150*** 129** 47 42** -79 NS 373</td>
</tr>
<tr>
<td>PANK/M3K</td>
<td>12.9 -3.8*** 7.5*** 2.1*** NS NS NS NS</td>
<td>-1.1** NS NS NS NS NS NS NS NS NS NS NS NS NS NS NS NS NS 378</td>
</tr>
<tr>
<td>ECEC(^{#}), cmol kg(^{-1})</td>
<td>-37.8 -15.3*** -10.2** -11.1*** -7.1*** -2.55*** NS NS</td>
<td>-0.6 1.3** 1.1*** 0.7*** -0.5 0.9** 372</td>
</tr>
<tr>
<td>M3K/ECEC(^{#})††</td>
<td>1.1 2.0*** 0.03 0.3* NS NS NS NS</td>
<td>-0.2* NS NS NS NS NS NS NS NS NS NS NS NS NS NS NS NS NS 376</td>
</tr>
</tbody>
</table>

* Significant at the \( P < 0.05 \) level. NS = not significant.

** Significant at the \( P < 0.01 \) level.

*** Significant at the \( P < 0.001 \) level.

† Int, regression intercept at 55–65 cm; dep1, 0–10-cm sample depth effect; dep2, 25–35-cm sample depth effect; elev, relative elevation with mean centered at 0 m effect; elev\(^2\), relative elevation squared effect; TWI = topographic wetness index effect; TWI = ln(a/tan b), where \( a \) is upstream contributing area (m\(^2\)) and \( b \) is slope (radians); \( x \), relative longitude effect; \( y \), relative latitude effect; dep1\(^2\) elev, interaction effect between relative elevation and the 0- to 10-cm depth; dep1\(^2\)TWI, interaction effect between the TWI and the 0- to 10-cm depth; elev\(^2\)TWI, interaction effect between the squared centered relative elevation and the TWI; dep2\(^2\)elev, interaction effect between relative elevation and the 25–35-cm depth; elev\(^2\) TWI, interaction effect between the TWI and the 25–35-cm depth.

‡ K extracted with a Mehlich-3 solution.

§ K extracted with a sodium tetraphenylboron solution.

¶ Plant-available nonexchangeable K, calculated as TPK-extractable K minus Mehlich-3-extractable K.

# Effective cation exchange capacity calculated by summation of the cations Ca, Mg, K, and Al. The contribution from Na was assumed to be negligible.

†† Exchangeable K (cmol kg\(^{-1}\)) divided by ECEC.
ends of the study site, areas of relatively lower elevation, but there is no strong evidence that areas of convergent flow are richer in K than nearby, less-channelized areas. Nevertheless, the strong lateral flow of perched water tables across soils with fragipans or fragic properties could be a mechanism for transport at the site.

**Plant-Available Nonexchangeable Potassium/Exchangeable Potassium Ratio**

The ratio of PANK to M3K was examined as a possible indicator of K leaching. Areas showing evidence of leaching should have higher PANK/M3K ratios because M3K is more easily leached than nonexchangeable K. We questioned whether one or more soil depths are more susceptible to K leaching than the others, or whether some areas of the field were more susceptible to K leaching than others. The ratio of PANK to M3K was significantly highest in the 25- to 35-cm depth, the expected depth of the E horizon (P < 0.0001). This zone of eluviation is the area traditionally associated with the movement of soil clay, organic matter, and oxides to deeper horizons. It is not surprising to see higher PANK/M3K ratios in the 25- to 35-cm depth. The next highest ratio was found in the 55- to 65-cm depth, followed by the 0- to 10-cm depth (all differences were significant: P < 0.0001). Because the surface horizons are relatively rich in M3K due to surface application in a no-till system, it follows expectation that the ratio would be lowest there (Fig. 5).

The poorly drained Cobbsfork soils had significantly higher PANK/M3K ratios than the other two mapping units (P < 0.0001), while Avonburg had higher PANK/M3K ratios than the moderately well-drained Cincinnati/Nabb soils. This might lend strength to a hypothesis relating K movement or leaching to soil wetness. Higher PANK/M3K ratios may be found in wetter landscapes as M3K is leached from the soil. The long-term expansion of 2:1 clay minerals may promote this mechanism by leaving interlayer K vulnerable to diffusion, plant uptake, and leaching.

**Effective Cation Exchange Capacity**

The ECEC increased with depth at the study site (Table 2, Fig. 6). The 55- to 65-cm depth had significantly higher ECEC values than the 25- to 35-cm depth (P = 0.0002), while the 25- to 35-cm depth had higher ECEC than the 0- to 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 catena, 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 C contents around 8 to 9 g kg\(^{-1}\) for the surface horizons of the Cincinnati catena. 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.

The ECEC is significantly higher in the moderately well-drained Cincinnati/Nabb mapping unit than in the other soils (P < 0.0001, Table 2). Also, the somewhat poorly drained Avonburg mapping unit has higher ECEC values than the poorly drained Cobbsfork mapping unit (P = 0.0007).

The ECEC values are fairly low throughout the catena (Table 2). Estimates for the poorly drained Cobbsfork mapping unit range from 8.3 cmol\(_c\) kg\(^{-1}\) in the 0- to 10-cm depth to 12.3 cmol\(_c\) kg\(^{-1}\) in the 55- to 65-cm depth. The highest estimates in the Cincinnati/Nabb mapping unit range from 12.6 to 16.6 cmol\(_c\) kg\(^{-1}\). As ECEC increases, the mobility of cation soil nutrients is thought to decrease because an increase in exchange capacity represents a larger number of exchange sites to which the cations can adhere. The increase in ECEC at the more well-drained edges of the field, therefore, could help to explain the higher values for M3K at these areas. If K is more...
Relationships between ECEC and terrain attributes are strong (Table 3). Relative elevation, the squared value of relative elevation, TWI, and the interaction terms between these attributes are significant effects in the prediction of ECEC in the catena ($P < 0.001$). The strength of these relationships probably 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$^{-1}$ (Table 3). 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.

Exchangeable Potassium/Effective Cation Exchange Capacity Ratios

The values of the ratio between M3K and ECEC indicate the extent to which the $K^+$ ion contributes to the ECEC calculated by summation of the bases and $Al^3+$. Higher M3K/ECEC ratios indicate higher prominence of $K$ in relation to the other cations that commonly dominate exchange sites. Strong relationships between terrain attributes and soil fertility data can provide a quantitative understanding of the availability of $K$ in the Cobbsfork–Avonburg–Nabb/Cincinnati catena, 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. The 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. Ratios between PANK and M3K were, in order from highest to lowest: poorly drained soils $>$ somewhat poorly drained soils $>$ well-drained soils. Lower ECEC in the poorly drained soils could provide a mechanism whereby M3K from higher in the landscape could be more mobile than $K$ in the lower landscape positions.

As expected, higher M3K/ECEC ratios occur in the surface depth (0–10 cm) than the other two depths ($P < 0.0001$, Table 2). This is probably due to the influence of uniform $K$ fertilizer applications to the surface of the soils as well as the preferential cycling of major plant nutrients toward the surface of the soils (Jobbagy and Jackson, 2001). Differences in the ratio between the two lower depths (25–35 and 55–65 cm) are not significant.

The only significant difference in M3K/ECEC ratios between soils is the higher values for the moderately well drained Cincinnati/Nabb mapping unit compared with those found in the poorly drained Cobbsfork mapping unit ($P < 0.0001$). The M3K/ECEC ratios did not relate well to terrain attributes (Table 3), possibly due to the influence of uniform $K$ fertility treatments applied to the surface soils. The only significant relationship ($P < 0.05$) was a positive one between relative elevation and the ratio, with a coefficient of 0.3.

**DISCUSSION**

Relationships between landscape features and soil properties have provided the means by which soils have historically been 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 catena, 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. The 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. Ratios between PANK and M3K were, in order from highest to lowest: poorly drained soils $>$ somewhat poorly drained soils $>$ well-drained soils. Lower ECEC in the poorly drained soils could provide a mechanism whereby M3K from higher in the landscape could be more mobile than $K$ in the lower landscape positions.
The traditional approach in pedology has been the analysis of single or multiple pedons with an eye toward the downward transport of materials through the soil column. Studies of fragipan-influenced soils emphasize the need to consider lateral transport as a viable mechanism for movement of soil materials across a catena.

REFERENCES
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