Raster sampling of soil profiles

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ABSTRACT

Three soil profiles in Wisconsin, USA, were sampled using a 10 × 10 cm raster: a Mollisol (1 × 1 m), Alfisol (1 × 1 m), and Entisol (1 × 0.5 m). The soils were described in the field, and samples were taken from the center of each cell. Soil organic carbon concentration, texture, and color were measured and used to revise field-delineated horizons and their boundaries. Using soil texture, an Eb horizon was identified on the raster maps in the upper part of the field-delineated Bt horizon of the Mollisol. Soil color, soil texture, and Ti showed little lateral variation. The pH tended to vary the most laterally. The raster method characterizes soil profiles in two dimensions and can be used to quantify lateral variation and improve field delineation of soil horizons.

1. Introduction

Soils are heterogeneous, complicating soil description. Soil scientists characterize a soil profile by dividing the profile into horizons based on properties observed in the field. These properties generally include color, texture, and structure. After horizon delineation, one soil sample is taken from each horizon for laboratory analysis. As a result, only the vertical variation of a soil profile is measured.

However, lateral variation of soil profiles and their three-dimensional counterparts, pedons, can occur within short distances. Various studies have found considerable lateral variation of soil chemical and physical properties within a single pedon (e.g. Raupach, 1951; Patterson and Wall, 1982; Stolt et al., 1993). In some cases, more than one soil order may be found within 2 m (e.g. Phillips, 1993).

The field delineation of soil horizons can be problematic. Field observations are generally qualitative or semi-quantitative, and horizon differentiation requires decisions that are based on pedological experience (e.g. Schelling, 1970; Arkley, 1976; Hartemink and Minasny, 2014). Discontinuous or thin horizons may be overlooked (Boone et al., 1999).

In this study, we used the raster method as a soil profile research tool. A raster contains equally spaced data points (Goodchild, 1992) and is commonly used in digital soil mapping (McBratney and Minasny, 2003). Few studies have used rasters to study spatial variation of soil properties in a soil profile (Davis et al., 1995; Schwen et al., 2014; Adhikari et al., 2016; Zhang and Hartemink, 2017). A raster of 10 × 10 cm squares was used to study three soil profiles: an Alfisol (1 × 1 m), Mollisol (1 × 1 m), and Entisol (1 × 0.5 m). Specifically, this research aimed to use raster data to: (i) evaluate the field-delineation of horizons, (ii) examine the spatial distribution of soil properties in two dimensions, and (iii) quantify soil property variation horizontally within 1 m.

2. Materials and methods

2.1. The sites

Three soils in Wisconsin, USA were studied: an Alfisol, Mollisol, and Entisol. These soils were described in detail by Grauer-Gray and Hartemink (2016). The Alfisol was a fine-silty over clayey, mixed, superactive, mesic Typic Hapludalfs (NewGlarus silt loam series) formed in loess over a mixture of sand, clay, and glauconite derived from the underlying bedrock. The Alfisol was located in the Driftless Area (latitude 43°20′.71″ N, longitude 90°3′2.77″ W) at 320 m above sea level (m.a.s.l.). The soil occurred on a 6% slope in the shoulder position. The area has a mean annual temperature of 7.4 °C and a mean annual precipitation of 860 mm. Five horizons were delineated in the field with three occurring in the upper 100 cm (Table 1). The upper two (Ap, Bt) horizons formed in loess while the lower (2Bw, 2Bt, Cr) horizons formed in weathering products from the underlying bedrock.

The Mollisol was a fine-loamy, mixed, superactive, mesic Pachic Argiudolls formed in loess over outwash (Troxel silt loam series) formed in loess over a mixture of sand, clay, and glauconite derived from the underlying bedrock. The Mollisol was located in Dane County (latitude 43°8′.32″ N, longitude 89°32′.10″ W) at 330 m a.s.l. The area has a mean annual temperature of 7.8 °C and a mean annual precipitation of 840 mm. The soil occurred at the footslope position, and contained a buried A horizon at 59 cm due to sedimentation of soil eroded from upper parts of the soilscape. Redoximorphic features occurred at 77 cm. Five horizons were...
Table 1
Profile characteristics of the Alfisol (fine-silty over clayey, mixed, superactive, mesic Typic Hapludalfs), the Mollisol (fine-loamy, mixed superactive mesic Pachic Argiudolls), and the Entisol (a mixed, mesic Typic Udipsammments) in Wisconsin, USA.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>Moist color</th>
<th>Structure</th>
<th>Sand  (g/kg)</th>
<th>Silt (g/kg)</th>
<th>Clay  (g/kg)</th>
<th>Texture class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfisol</td>
<td>Ap</td>
<td>0–20</td>
<td>Very dark grayish brown (10YR 3/2)</td>
<td>Granular, subangular blocky</td>
<td>124</td>
<td>653</td>
<td>224</td>
<td>Silt loam</td>
</tr>
<tr>
<td></td>
<td>Bt</td>
<td>20–68</td>
<td>Dark yellowish brown (10YR 4/4)</td>
<td>Subangular blocky</td>
<td>189</td>
<td>546</td>
<td>286</td>
<td>Silt loam</td>
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<tr>
<td></td>
<td>2Bw</td>
<td>68–125</td>
<td>Strong brown (7.5YR 4.5/7)</td>
<td>Subangular blocky</td>
<td>691</td>
<td>68</td>
<td>241</td>
<td>Sandy clay loam</td>
</tr>
<tr>
<td>Mollisol</td>
<td>Ap1</td>
<td>0–18</td>
<td>Very dark brown (10YR 2/2)</td>
<td>Granular</td>
<td>129</td>
<td>665</td>
<td>206</td>
<td>Silt</td>
</tr>
<tr>
<td></td>
<td>Ap2</td>
<td>18–39</td>
<td>Very dark brown (10YR 2/2)</td>
<td>Platy</td>
<td>114</td>
<td>665</td>
<td>221</td>
<td>Silt loam</td>
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<tr>
<td></td>
<td>A2</td>
<td>39–59</td>
<td>Very dark brown (10YR 2/2)</td>
<td>Subangular blocky</td>
<td>91</td>
<td>657</td>
<td>252</td>
<td>Silt loam</td>
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<tr>
<td></td>
<td>Ab</td>
<td>59–77</td>
<td>Black (10YR 2/1)</td>
<td>Subangular blocky</td>
<td>105</td>
<td>645</td>
<td>250</td>
<td>Silt loam</td>
</tr>
<tr>
<td></td>
<td>Bt</td>
<td>77+</td>
<td>Dark yellowish brown (10YR 3/4)</td>
<td>Angular blocky</td>
<td>101</td>
<td>625</td>
<td>274</td>
<td>Silty clay loam</td>
</tr>
<tr>
<td>Entisol</td>
<td>Ap</td>
<td>0–24</td>
<td>Very dark brown (10YR 2/2)</td>
<td>Granular</td>
<td>874</td>
<td>59</td>
<td>67</td>
<td>Loamy sand</td>
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<tr>
<td></td>
<td>Bw1</td>
<td>24–55</td>
<td>Dark yellowish brown (10YR 4/6)</td>
<td>Structureless</td>
<td>930</td>
<td>27</td>
<td>43</td>
<td>Sand</td>
</tr>
</tbody>
</table>

2.2. Soil sampling and analysis

The soil profile walls of the Alfisol and the Mollisol were divided into a 1 × 1 m raster of 10 × 10 cm squares to 1 m depth (Fig. 1). The soil profile wall of the Entisol was divided into a 1 × 0.5 m raster of 10 × 10 cm squares to 0.5 m depth. Soil samples were collected from the center of each raster square. Bulk density samples were taken from each depth interval, with a single (250 mL) sample taken in the Alfisol and multiple (100 mL) samples taken in the Mollisol (n = 2) and the Entisol (n = 3).

The soil samples (~200 g) were air-dried. Dry and moist color measurements were taken using Munsell soil color charts. Samples were finely ground to approximately 2 mm. Elemental metal content was measured using portable X-ray fluorescence (pXRF) with a Delta Professional pXRF Analyzer (Olympus Scientific Solutions Americas, Inc.) that was calibrated with a 316 stainless steel reference coin. Soil organic carbon (SOC) was measured with a Flash EA 1112 Series NC Soil Analyzer (Thermo Electron Corporation). Soil reaction (pH) was measured in 1:1 soil to water with an Oakton pH/CON 510 Series meter (Vernon Hills, IL, USA). Texture was determined using the hydrometer method (Bouyoucos, 1962).

2.3. Data analysis

Bulk densities were averaged to calculate the bulk density of the Mollisol and Entisol depth intervals. Statistics of properties by depth and by horizon were calculated using the doBy package (Højsgaard et al., 2014) within the R statistical package (R Core Team, 2016). Coefficients of variation (CVs) by depth were calculated by dividing the standard deviation (SD) by the mean. As CVs are only valid for ratio variables (Webster, 2001), pH was back-transformed to H+ concentrations and CVs were calculated for the H+ concentrations. CVs were taken from within this blur, and the RGB values were recorded. The RGB color was converted to HSV color in the R statistical package (R Core Team, 2016). HSV color spaces are transformations of RGB color spaces, which describe color using three color coordinates: Hue (H), Saturation (S), and Value (V) (Smith, 1978).

Fig. 1. Soil profiles rastered for field measurements and soil sampling (10 × 10 cm). The Mollisol and the Alfisol were sampled to 100 cm depth, and the Entisol was sampled to 50 cm depth.
were used to measure the horizontal variation of all properties except hue. For hue, a non-ratio variable, standard deviations (SDs) were used. Variation was designated as low (CVs < 10%), medium (CVs 10–20%), or high (CVs ≥ 20%).

Raster maps of soil properties (particle size fractions, HSV soil color, SOC concentration, pH, Al, Fe, Si, Ti, and Zr concentration, and Ti/Zr ratio) were created using the ggplot2 package (Wickham, 2016) within the R statistical package (R Core Team, 2016). The field-delineated horizon boundaries, rounded to the nearest 5 cm depth, were super-imposed on the maps. The raster maps (except for saturation) were created using Peter Kovesi’s perceptually uniform color gradients (Kovesi, 2015) in the palette package (Wright, 2016) within the R statistical package (R Core Team, 2016).

In order to compare the raster data to the field-delineated horizons, raster samples were assigned to soil horizons based on the location of the field-delineated boundaries. As raster samples were taken from the center of the depth intervals, the intervals containing horizon boundaries were considered to occur along a horizon boundary only if the boundary occurred > 2 cm from the depth interval boundary.

SOC stocks were calculated to 100 cm depth for the Alfisol and Mollisol and to 50 cm depth for the Entisol. Horizon sampling was simulated along each transect by setting SOC concentration and bulk density values equal to the values from the middle depth interval of each horizon or, for horizons with an even number of depth intervals, by averaging the values of their two middle depth intervals.

3. Results

3.1. Color

Hue decreased with depth in the Alfisol and Entisol (Fig. 2). In the Mollisol, the hue angle was highest in the Ab horizon and lowest in the Bt horizon. Saturation and value followed the reverse pattern of hue, with one exception; in the Alfisol, value was highest in the Bt horizon. Overall, hue, saturation, and value corresponded well with soil horizons delineated in the field. Only low to medium horizontal variation occurred.

3.2. Texture

Clay content was highest in the middle depth intervals of the Alfisol Bt horizon (30–60 cm depth) and in the lower depth interval of the Mollisol Btb horizon (90–100 cm depth) (Fig. 3). In the Entisol, clay content was low but slightly higher clay content occurred at 10–30 cm depth. Sand content followed the reverse pattern of clay content in the Mollisol and the Entisol. Silt content was fairly uniform vertically in the Mollisol and the Entisol, though slight decreases with depth did occur. In the Alfisol, the sand and silt content changed sharply at the Bt/2Bw horizon boundary.

Soil texture only corresponded with the Alfisol Bw horizon. The greatest horizontal variation of soil texture occurred in the Alfisol Bw horizon, and mainly resulted from multiple horizontal changes of clay and silt content, though at 90–100 cm depth, the high variation of silt content resulted from one extreme value. In the Entisol, the high variation at 10–30 cm depth resulted from a few sharp horizontal changes in clay content, whereas the high variation at 40–50 cm depth resulted from multiple horizontal changes in both clay and silt content. High variation of sand content occurred in the Alfisol Ap and Bt horizons and in the Mollisol Bt horizon due to multiple horizontal changes, but occurred in the Mollisol at 20–30 cm depth due to an extreme value.

3.3. Soil organic carbon and pH

SOC decreased with depth in the Entisol, in the Alfisol to 40 cm depth, and in the Mollisol below 60 cm depth (Fig. 4). In the Mollisol, SOC was fairly constant in the upper three horizons (Ap1, Ap2, A2), but increased sharply with depth at the A2/Ab horizon boundary. Overall, SOC strongly corresponded with the Mollisol Ab and Btb horizons and weakly corresponded with the Entisol soil horizons and the Alfisol Ap horizon. High variation of SOC in the Mollisol topsoil/subsoil boundary interval resulted from a few, sharp horizontal changes, as the boundary varied with depth. High variation in the Entisol, and in the Mollisol and Alfisol subsoil horizons resulted from multiple horizontal changes. Soil pH did not correspond with soil horizons. In general, the horizontal variation of pH was high.

3.4. Aluminum, iron, silicon

Aluminum increased with depth in the Alfisol (Fig. 5). Levels were fairly uniform in the Entisol and in the Mollisol at 0–40 cm. Below 40 cm, the Mollisol contained multiple data points in which Al concentrations were below the detection limit of the pXRF. The Fe levels in the Alfisol and the Mollisol were lower in the topsoil than in the subsoil, but the reverse occurred in the Entisol. In the Alfisol, Si generally increased with depth in the topsoil and decreased with depth in the subsoil and at the topsoil/subsoil boundary. The distribution of Si was uniform in the Entisol and in the Mollisol at 0–40 cm depth, but below 40 cm depth, the distribution of Si in the Mollisol was irregular, with sharp horizontal changes in concentration occurring in multiple depth intervals.

In general, Fe corresponded with the soil horizons, but Al and Si did not. High variation of Al and Si occurred in the Mollisol and the Entisol, and high variation of Fe occurred in the Alfisol. The variation of Al in the Mollisol and Entisol resulted from multiple horizontal changes, but the variation of Si in the Mollisol primarily occurred due to a few sharp horizontal changes and the variation of Si in the Entisol resulted from an extreme value. The variation of Fe in the Alfisol resulted from multiple horizontal changes.

3.5. Titanium, zirconium, Ti/Zr

Titanium, zirconium, and Ti/Zr changed sharply at the Alfisol Bt/2Bw horizon boundary (Fig. 6). Zr increased with depth at the Mollisol topsoil/subsoil boundary. Little change occurred with depth in the Entisol for Ti, Zr, and Ti/Zr or in the Mollisol for Ti and Ti/Zr. The Ti, Zr, and Ti/Zr ratios closely corresponded with the Alfisol 2Bw horizon, and Zr corresponded with the Mollisol Btb horizon. High variation of Zr in the Entisol and in the Alfisol 2Bw horizon resulted from multiple horizontal changes. Only low to medium variation of Ti occurred.

3.6. Soil horizons and raster data

Raster maps were used to verify or revise the field delineation of soil horizons, using

1. Properties that were used to differentiate soil horizons in the field (color, texture)
2. Properties that are used in Soil Taxonomy horizon designations
3. Properties used to distinguish between parent materials in the literature (sand, silt, Ti, Zr, Ti/Zr) (e.g. Sudom and St. Arnaud, 1971; Karathanasis and Macneal, 1994; Schaeztl, 1998).

Raster data confirmed the field delineation of the Alfisol soil horizons. The Ap/Bt horizon boundary closely corresponded with changes in soil color and a decrease in SOC concentration, and the Bt/2Bw horizon boundary closely corresponded with changes in soil color and soil texture. The peak in clay content in the Alfisol Bt horizon confirmed its delineation as a clay accumulation horizon. Sharp changes in sand, silt, Ti, Zr, and Ti/Zr around the Bt/2Bw horizon boundary confirmed the change in parent material between the Bt horizon and the 2Bw horizon.
Soil color raster data confirmed the location of two field-delineated horizon boundaries (A2/Ab, Ab/Btb) in the Mollisol. The other field-delineated boundaries (Ap1/Ap2, Ap2/A2) were delineated using soil structure, which was not assessed in the raster samples. Sharp changes in SOC content at the Ab horizon boundaries confirmed the delineation of this horizon as a buried A horizon (high SOC content), and the lower boundary of the Ab horizon as the location of the topsoil/subsoil horizon boundary. However, the Mollisol soil texture raster data did not correspond with the field delineated clay accumulation (Btb) horizon. Sand content, not clay content increased between the Ab horizon (60–70 cm depth) and the upper Btb horizon (80–90 cm depth) along the majority of the vertical transects. This lack of increase in clay content, accompanied by an increase in sand content, suggests the presence of an Eb horizon, at 80–90 cm depth. Soil texture raster data showed a considerable increase in clay content between 80 and 90 cm and 90–100 cm depth, suggesting the presence of a Btb horizon at 90–100 cm depth. Therefore, based on the raster data, we determined that the field-delineated Btb horizon (77+ cm depth) consisted of two horizons: an Eb horizon at 77–90 cm depth and a Btb horizon at 90+ cm depth. Soil color and SOC raster data confirmed the field horizon delineation of the Entisol soil horizons.

3.7. Soil organic carbon stock and sampling method

In this section, we compare the SOC stocks calculated from three sampling methods: raster sampling, fixed depth sampling, and horizon sampling. SOC stocks from raster sampling were 78 Mg C/ha for the Alfisol, 242 Mg C/ha for the Mollisol, and 88 Mg C/ha for the Entisol. SOC stocks from fixed depth sampling were 68–90 Mg C/ha for the Alfisol, 222–258 Mg C/ha for the Mollisol, and 70–116 Mg C/ha for the Entisol. SOC stocks from horizon sampling were 65–94 Mg C/ha for the Alfisol, 244–299 Mg/ha for the Mollisol, and 78–131 Mg/ha for the Entisol. Choice of transect affected the SOC stock results for both single transect methods (fixed depth, horizon), but greater variation occurred when sampling by horizons. In the Mollisol, horizon sampling consistently overestimated raster stock, but in the Alfisol and the Entisol, no pattern occurred.

4. Discussion

4.1. Lateral soil variation

In this section, the lateral variation of soil properties will be discussed and compared to the variation of the same properties in other soil profile/pedon studies (Table 2). For the measurement of lateral variation, we have chosen to use the coefficient of variation (CV). The
CV is commonly used to measure lateral variation of soil properties in the literature (e.g., Waynick and Sharp, 1919; Drees, 1970; Beckett and Webster, 1971). CVs are useful for comparing the variation of multiple soil properties and for comparing the variation of a soil property across a wide range of sample means. However, we did use standard deviation (SD) to measure the lateral variation of hue because CVs are not valid measurements of variation for non-ratio variables (see Webster, 2001).

The lateral variation of soil color was low (SDs $\leq 1^\circ$, CVs $< 10\%$) in the soil horizons of all three soils studied. Similarly, Adhikari et al. (2016) found only low lateral variation of soil color (HSV color coordinates) in an Entisol pedon. Soil color is a compound property, integrating SOC, Fe oxides, and other soil properties, so its variation cannot be attributed to a single property.

The mean lateral variation of particle size fractions in the soil horizons of all three soils tended to be low to medium (CVs $< 20\%$). Other studies have also found that soil horizons (Patterson and Wall, 1982; Stolt et al., 1993) and pedons (Smeck and Wilding, 1980) tend to contain low to medium lateral variation of particle size fractions. However, this study and the aforementioned studies did find high lateral variation of at least one particle size fraction, in at least one soil horizon or pedon studied.

In this study, high lateral variation of all three particle size fractions occurred. Lateral variation in the Entisol seemed to be related to mean particle size content with low variation (CVs $\leq 3\%$) occurring at high mean values (sand) and medium to high variation (CVs 15–25%) occurring at low mean values (silt, clay). Similar results were found for the Entisol studied by Adhikari et al. (2016). The highest lateral variation for silt (CVs 40–140%) and clay (CVs 20–35%) occurred in the Alfisol 2Bw horizon, possibly due to the heterogeneous parent material. The highest lateral variation of sand content occurred in the Alfisol and Mollisol soil horizons formed in loess. Comparing morphologically matched pedons, Mausbach et al. (1980) found the highest variation of sand content in pedons formed in loess. Sand and silt are generally considered to be immobile in the soil (e.g., Karathanasis and Macneal, 1994; Schaetzl, 1998), suggesting that lateral variation of the sand and silt particle size fractions in soil horizons is inherited from the parent material. Lateral variation of clay content in soil horizons may also have been partially inherited from parent materials, however, clay movement in the soil may have reduced or increased the magnitude of the variation.

The mean lateral variation of topsoil SOC was high in the Entisol (CVs 25%), but was low to medium in the Mollisol and the Alfisol (CVs $< 15\%$). Similar values occurred in the literature, with high mean lateral variation of SOC occurring in the topsoil of the Entisol studied by Adhikari et al. (2016), whereas low to medium variation of topsoil SOC or SOM generally occurred in Alfisol and Inceptisol topsoils (Reed and Rigney, 1947; Raupach, 1951; Ball and Williams, 1968; Patterson and Wall, 1982). This suggests that the variability of topsoil
SOC or SOM may be influenced by soil texture, as both Entisol topsoils were coarse-textured (> 80% sand) (Adhikari et al., 2016). Studies of lateral variation on scales larger than pedon scale have also found that coarse-textured soils tend to have greater variation of SOC or total C than finer-textured soils (Waynick and Sharp, 1919; Plante et al., 2006). Waynick and Sharp (1919) found higher lateral variation of total topsoil C in a sand (CV 22%) than in a silty clay loam (CV 9%) in a study of field-scale (0.5 ha) variation in California, USA. In a textural gradient in Saskatchewan, Canada, Plante et al. (2006) found high lateral variation of topsoil SOC (CV 26%) in the field with the highest sand content (79% sand), whereas little within-field variation occurred (CVs ≤ 12%) in the finer textured fields (≤ 45% sand). Therefore, soil texture, or at least sand content, appears to strongly influence the distribution of SOM and SOC in topsoil.

In subsoils, the mean lateral variation of SOC was medium to high (CVs > 10%), but much of this variation appears to result from low mean SOC content (< 10 g C/kg). Wilding et al. (2000) also found medium to high short-range (< 2 m) lateral variation occurring at low mean SOC contents in 13 pedons from Ohio and Texas.

The mean lateral variation of pH in the individual soil horizons was medium to high (CVs ≥ 18%), both in this study and in the literature (Reed and Rigney, 1947; Raupach, 1951; Adhikari et al., 2016). Only high lateral variation occurred in the Entisol in this study and in the Entisol studied by Adhikari et al. (2016), but low to medium variation occurred in the Mollisol and the Alfisol in this study and in the Alfisols studied by Reed and Rigney (1947) and Raupach (1951).

The highest mean lateral variation of Al occurred in the Mollisol B horizon (CV 90%). The mean lateral variation of Al was low in the Alfisol soil horizons, but medium to high in the Mollisol topsoil and in the Entisol soil horizons (CVs < 25%).

The lateral variation of Fe tended to be low to medium in all three soils, in the Entisol studied by Adhikari et al. (2016), and in the 20–50 μm and 5–20 μm fractions of the three Alfisol pedons studied by Drees (1970). The mean lateral variation of the individual soils, both in this study and in the literature (Drees, 1970; Adhikari et al., 2016), generally remained similar across soil horizons. However, lateral variation of Fe changed sharply at a soil horizon boundary, both in the Alfisol in this study and in an Alfisol studied by Drees (1970). The locations of these changes corresponded with the location of lithologic discontinuities, and on average, lower variation occurred in the upper soil horizons formed in loess than in the lower horizons formed in residuum or outwash (Drees, 1970). This implies that some lateral variation of Fe may be inherited from parent material.

The lateral variation of Si was low to medium in the Alfisol (CVs ≤ 11%), and the mean variation was similar across soil horizons. Lateral variation was low to high in the Mollisol and the Entisol, and mean variation increased with soil horizon depth.

The mean lateral variation of Ti was medium (CVs 14–16%) in the Entisol, in the Entisol pedon studied by Adhikari et al. (2016) and in the Alfisol 2Bw horizon. However, mean lateral variation of Ti was low (CVs ≤ 8%) in the Mollisol, in the 20–50 μm and 5–20 μm fractions of the three Alfisol pedons studied by Drees (1970), and in the Alfisol and Bt horizons. Overall, lower variation occurred in fine-textured soils/soil horizons (< 35% sand) and particle size fractions than in the coarser-textured soils/soil horizons (> 60% sand). In a study of twelve Ultisol pedons, Stolt et al. (1993) found that, in general, higher variation of Ti occurred in the sand (50–2000 μm) fraction than in the silt (2–50 μm) fraction. This suggests that Ti tends to be more variably distributed in the sand particle size fraction than in finer particle size fractions.

The lateral variation of Zr was medium to high in the Entisol in this study and in the Entisol studied by Adhikari et al. (2016), which both formed in outwash, as well as in the Alfisol 2Bw horizon, which formed in residuum. Only low variation occurred in the Mollisol and in the Alfisol and Bt horizons, all formed in loess. In the Alfisol pedons studied by Drees (1970), the mean lateral variation in the 20–50 μm and 5–20 μm fractions was low for the soil horizons formed in loess or till, but medium for soil horizons formed in outwash. Furthermore, Zr is generally considered to be immobile in the soil (e.g. Sudom and St. Arnaud, 1971; Schaetzl, 1998). This suggests that lateral variation of Zr is inherited from the parent material. Of the soil properties studied, pH tended to vary the most laterally while Ti tended to vary the least. Generally, Al and Si exhibited greater lateral variation than Fe, Ti, and Zr. The highest variation of Al and Si occurred in the Mollisol Bt

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**Fig. 4.** SOC concentration and pH of the raster squares sampled in the soil profile walls of a Mollisol, Alfisol, and Entisol. Horizontal lines indicate field-delineated horizon boundaries.
horizon (CVs > 80%), but does not appear to have resulted from the irregular accumulation of aluminosilicate clay or sand content, as little lateral variation of clay and only moderate variation of sand occurred. The lateral variation of sand, silt, and Zr, and to a lesser extent Fe, appears to be inherited from parent material. Lower lateral variation of silt, clay, and Zr occurred in loess than in outwash or residuum, but the reverse occurred for sand content. Previous studies have also found that variation of soil properties appears to be inherited, at least in part, from parent material (e.g. Mausbach et al., 1980; Wilding and Drees, 1983).

4.2. Raster sampling

Raster sampling extends fixed depth sampling into two dimensions. In this study, we found that SOC stocks varied by transect and by sampling method in all three soils. In the Mollisol, the consistent overestimation of raster SOC stock by horizon sampling probably resulted from the overestimation of SOC stock in a single horizon: the Ab horizon. The overestimation of the SOC stock of the Ab horizon appears likely for the following reasons: (1) the assumption that the 60–70 cm depth interval represents the entire 17 cm thick horizon, not just the upper 10 cm and (2) evidence from SOC raster data that the lower Ab horizon border varied with depth, indicating that the Ab horizon may be < 17 cm thick along some vertical transects.

Fixed depth sampling was less variable than horizon sampling in all three soils in this study. On a regional scale, Grüneberg et al. (2010) also found that fixed depth sampling results in lower variation for SOC stock than horizon sampling. Studying the storage of SOC in pedons, Vandenberghe et al. (2007) found that fixed depth sampling was consistently less variable than horizon sampling for the upper 60 cm of six soil types, but that horizon sampling was less variable than fixed depth sampling for the upper 30 cm of four of the soil types studied. Overall, fixed depth sampling appears to reduce SOC stock variation, but both the existence and the extent of this reduction may be influenced by sampling depth and soil type.

Raster sampling can be used to reduce the subjectivity of horizon delineation in the field. In this study, we found that raster data can be used to verify or revise field horizon delineations. Using raster data, we detected the presence of an E horizon in the Mollisol and confirmed the location of the Mollisol Ab horizon. We verified the field delineations of the Alfisol and Entisol soil horizons. In general, field horizon delineation occurs along a single vertical transect and uses qualitative and semi-quantitative soil property measurements (Fajardo et al., 2016). Raster horizon delineation examines multiple vertical transects and uses quantitative soil property measurements.

Using a raster, multiple soil samples are generally taken from field-delineated horizons in two dimensions (horizontally and vertically).
The raster resolution and the soil horizon location and thickness may result in a horizon being sampled at only one depth interval (i.e. the Mollisol Ab horizon) or not sampled at all. Thin horizons may also be overlooked when sampling by horizons (Boone et al., 1999).

The raster method has the following limitations:

1. Sampling is laborious and with a high-resolution raster (i.e. 5 cm) it is practically difficult. At such resolution, raster resolution limits the volume of soil that can be sampled without mixing, restricting the number and type of laboratory analyses that can be performed.
2. Raster samples may be obtained from horizon boundaries rather than horizons. Soil horizon boundaries often vary horizontally, so the single-transect field horizon delineation may differ from raster horizon delineation partially because of this horizontal variation.
3. A thin horizon may not be sampled.

Sampling method appears to affect the variation detected, but the nature of this effect is not consistent. Boone et al. (1999) stated that “… horizon-based sampling in some cases effectively reduces both depth-wise and horizontal variability”, but this and other studies have found that the reverse situation can occur for SOC stock (Grüneberg et al., 2010; VandenBygaart et al., 2007).

5. Conclusions

This study evaluated the use of the raster (multiple transects) method as a soil profile research tool. The raster method characterizes soil profiles in two dimensions and can be used to quantify lateral variation and improve soil horizon delineation by verifying or revising the field delineation of soil horizons.

Using the clay content raster data, we detected an E horizon in the Mollisol, which had not been identified in the field. Using raster data for color (HSV coordinates), particle size fractions, and in the case of the Alfisol Bt/2Bw horizon, Ti, Zr, and Ti/Zr, we confirmed the Alfisol and Entisol field horizon delineations and the delineation of the Mollisol Ab horizon.

Comparing the results of this study with other studies of lateral variation in pedons, we found that within distances of < 2 m:

- Soil color, texture, and Ti concentration were fairly uniform laterally.
- Topsoil SOC was fairly uniform laterally in the Alfisol, Inceptisol, and Mollisol soil orders.
- Of the soil properties studied, pH tended to vary the most laterally.

This study demonstrates that it is necessary to sample multiple
## References


Drees, L.R., 1970. Elemental Variability within a Sampling Unit. The Ohio State University, MS Thesis.


