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Modeling the complexity of different, recently deglaciated soil landscapes as a function of map scale

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Abstract

The scale at which a soil landscape (soilscape) is viewed has a significant impact on soil pattern and interpretations made from those patterns. Recently deglaciated soilscapes are particularly spatially complex. In order to understand how scale impacts pattern on complex soilscapes, we used a GIS to examine soil maps for 13 counties in the northern United States, all affected by Late Wisconsinan glaciation. We used an Arc™ macro language script to change the map scale and, when the change was to a smaller scale, group/dissolve soil map units based on similarities to a prescribed list of neighboring map unit characteristics. Similarity criteria included drainage class, taxonomic great group, parent material and slope. Soilscape complexity was measured at nine different scales and is based on various pattern metrics: number of punctate soil units km^{-2}, map unit polygons km^{-2}, map unit boundary length km^{-2}, and boundary length $\mathrm{polygon}^{-1}\ \mathrm{km}^{-2}$. Soilscape complexity as a function of scale was then examined by regressing pattern metric data against the size of the minimum map unit for each of the nine scales. Extrapolation of the regression lines to 1:10,000 (a scale larger than is typically mapped) illustrated how much additional information might accrue if these counties were to be mapped at that larger scale. In most cases, 2–10 times more map units would have been recognized and delineated at the two times larger map scale, but map unit boundary lengths would have increased by only about 1.5 times. Whether this additional information is of such a magnitude that it could justify remapping some of these complex landscapes at larger scales is an economic decision; our study provides much needed data on the magnitude of information gained by mapping soilscapes at larger scales.

Keywords: Map scale; Soil landscape analysis; GIS; Soil mapping

1. Introduction

Physical landscapes are spatially complex. Understanding the nature and genesis of spatial character and pattern is a difficult but not insurmountable task (Levin, 1992; Stoms, 1994; Turner et al., 1989).

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Changes in scale almost always change landscape pattern, necessitating that these variables be studied in concert (Meentemeyer, 1989; Levin, 1992; Qi and Wu, 1996). For these reasons, scale issues are central to landscape level questions in many fields (Penning-Rowsell and Townshend, 1978; Meentemeyer, 1989; Levin, 1992; Atkinson and Tate, 2000, Willis and Whittaker, 2002). Spatial patterns may change across scales such that a variable may be homogeneous at one scale and heterogeneous at another, and patterns found on a large scale map may even vanish at small scales (Turner et al., 1989; Lark and Beckett, 1995; Atkinson and Tate, 2000). Many features are known to be present on landscapes, e.g., small soil bodies, but not mappable because of scale limitations (Lyford, 1974; Johnson, 1990). In sum, there is not one correct scale at which to observe natural phenomena (Levin, 1992). Instead, a range of scales appropriate to the question and landscape in focus must be considered (Stoms, 1994; Meentemeyer and Box, 1987); each may contribute new and unique perspectives.

Soil landscapes (soilscapes) are some of the most complex and intricate of all physical landscapes (Campbell, 1979; Brubaker and Hallmark, 1991; Barrett and Schaetzl, 1993; Kabrick et al., 1997; Sinowski and Auerswald, 1999). This complexity arises because soils are an integration of many spatial systems, each of which is spatially complex (Phillips, 1993a,b, 2001). For example, in the functional factorial model of soil development (Jenny, 1941; Phillips, 1989), soil is viewed as being a function of several state factors: climate, organisms, relief, parent material, and time. These factors are neither wholly independent nor spatially homogeneous, creating complex soil patterns. Additionally, soil landscapes naturally regress and progress with time, further contributing to their spatial complexity (Johnson and Watson-Stegner, 1987; Phillips, 1993b,c). Small-scale disturbances such as tree uprooting (Stone, 1975; Schaetzl et al., 1990), as well as catastrophic disturbances by glaciers and widespread permafrost (Johnson, 1990; Clayton et al., 2001), also contribute to the spatial complexity of soilscapes. Because they are spatially complex at many different scales, knowing how much information is gained or lost as a function of scale is critical to the assessment of the soilscape (Lyford, 1974).

Soilscapes in recently glaciated regions are among the most complex of physical landscapes. Glacial activity commonly results in a variety of landforms, e.g., outwash plains, moraines, drumlin fields, lake plains, each of which has a complex surficial expression as well as variation in the subsurface (soil parent material). On many young glacial landforms, parent material commonly varies laterally and vertically; lithologic discontinuities are common (Schaetzl, 1998).

Soilscapes have been examined mainly within the field of soil landscape analysis, which traditionally has involved the quantitative characterization of the pattern and complexity of soil landscapes (Fridland, 1965, 1974; Hole, 1953, 1978; Hole and Campbell, 1985). Researchers in this field have used a variety of metrics to quantitatively describe and evaluate the soilscape such as those that measure the (1) numbers of soil taxa or species per unit area; (2) shape, size, wetness or development indices of soil polygons; (3) degree of pedologic contrast or nonuniformity per unit area and across boundaries; (4) number and location of punctate soil polygons (those wholly surrounded by a single soil type, like a donut hole) per unit area; and (5) orientation and interconnectedness of soil boundaries, among others (Hole, 1953, 1978, 1980; Pavlik and Hole, 1977; Haberman and Hole, 1980; Hole and Campbell, 1985).

Work in the arena of traditional soilscape analysis per se has lagged in recent years, with efforts being

Table 1
Relationship between map scales and minimum mapping unit size

Map scale	Minimum mapping unit size[a]	
	Acres	Hectares
1:10,000[a]	1.0	0.4
1:15,840	2.5	1.0
1:20,000	4.0	1.6
1:24,000	5.7	2.3
1:31,680	10.0	4.1
1:44,462[a]	19.8	8.0
1:62,500	39.0	15.8
1:63,360	40.0	16.2
1:100,000	100.0	40.5
1:125,000	156.0	63.0

[a] Interpolated from the equation, LOG($MMU_{(acres)}$)=(LOG (Scale)*2)-8, which was based on a regression ($r^2 = 0.99$) of NRCS minimum mapping units and scale. MMU sizes were originally established in acres, which is why we include those units here.

directed instead in the burgeoning area of pedometrics (e.g., Webster, 1994; McBratney et al., 2000; Carre and Girard, 2002; Hennings, 2002) and recently, on diversity of soil landscapes from the perspective of disturbed vs. undisturbed soil resources (Ibanez et al., 1995, 1998; Amundson et al., 2003). Under the rubric of pedometrics, advances in our understanding of scale issues and landscape complexity, and the various methods used to study these phenomena, have exploded (e.g., Ishida et al., 2003), partially prompting this study.

Soilscape analysis is typically performed using modern, large-scale county soil maps as base data (Pavlik and Hole, 1977; Schaetzl, 1986). In the United States, these maps are produced by the Natural Resource Conservation Service (NRCS), or its predecessor, the Soil Conservation Service (SCS). They are available for many of the counties in the United States in both digital and hard copy formats. Prior to about 1970, most county soil maps existed only at small scales, usually between 1:63,360 and 1:250,000. Since then, most counties have been remapped at larger scales of 1:15,840–1:20,000, using an aerial photography base. Soil landscape analysis, typically performed on the latter type of maps, has never been performed across scales, however, largely because the

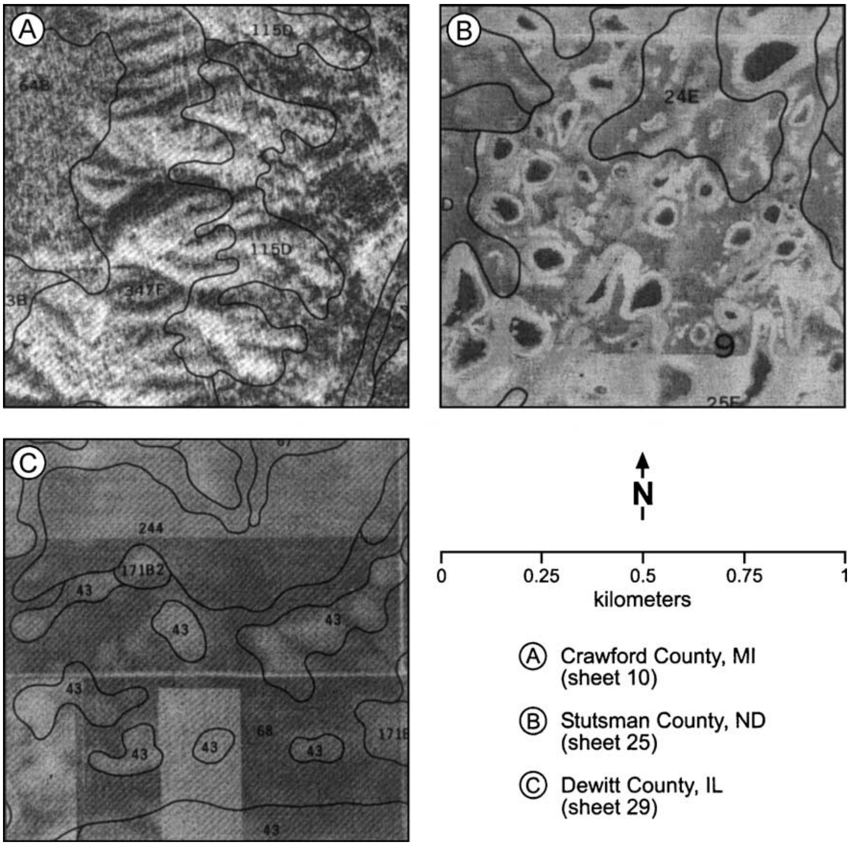
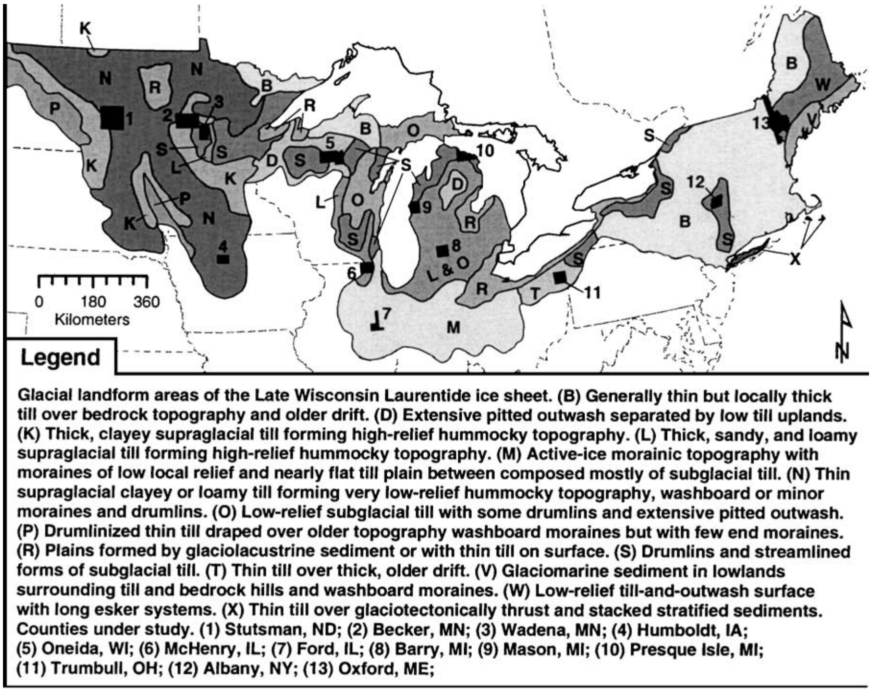


Fig. 1. Examples of soil maps from various NRCS county soil surveys, showing the landscape on an aerial photo base, the existing soil map unit boundaries, and inclusions of soil bodies too small to be delineated because of scale limitations. In short, the features are smaller than the NRCS-mandated minimum mapping unit. (A) The dissected edge of a sandy, plateau-like upland in central Michigan (Werlein, 1998). Soils in the steep, dry valleys on the image are highly variable in degree of development, largely because of aspect differences (Hunckler and Schaetzl, 1997). (B) The Prairie Pothole region of North Dakota (Clayton, 1967). Many of the small, glacial kettles are too small to delineate at the existing map scale (Abel et al., 1995). (C) Reticulate pattern on the Woodfordian Drift Plain of eastern Illinois. These features are probably remnants from a period of permafrost that occurred subsequent to the retreat of the ice sheet (Johnson, 1990).

scales at which soil maps exist are so few and widely disparate.

For any map, and soil maps are no exception, scale determines the size of the smallest legible delineated polygon, referred to as the minimum mapping unit (mmu). For modern county soil maps with a scale of 1:15,840, the minimum mapping unit is 1 ha (Table 1). Most landscapes, however, have complex soil bodies which are too small to be represented on soil maps, even those at large scales (Lyford, 1974; Fig. 1). These small soil bodies usually go unmapped, often categorized as similar or dissimilar map unit inclusions (Wilding et al., 1965; Brubaker and Hallmark, 1991). At larger map scales, however, they could, theoretically, be delineated, thereby providing more information about the landscape. At present, there is no logical way to determine the amount of additional information about such soil bodies that could be gained by mapping at larger scales (although, see Lark and Beckett, 1995 for a possible example). This study attempts to provide this type of data for recently glaciated landscapes. Specifically, we ask what could be learned about the soil landscape if soil maps could be generated for different, especially larger, scales. Can information about the physical landscape that may exist but which cannot be shown on the map because of scale limitations be gleaned from soil maps by examining the landscape at different scales, developing scale-dependent relationships and extrapolating?

Thus, the purpose of this research is to determine the relationships between scale and pattern in complex soil landscapes (recently deglaciated regions). Specifically, we develop a series of soil maps of different scales, from existing county soil maps, in order to evaluate the effect of scale on landscape complexity. Various pattern metrics are used to describe the soil landscapes at different scales. The statistical relationships between the pattern metrics at various scales are compared for several glaciated landscapes to determine which is the most scale-sensitive, thereby quan-



Glacial landform areas of the Late Wisconsin Laurentide ice sheet. (B) Generally thin but locally thick till over bedrock topography and older drift. (D) Extensive pitted outwash separated by low till uplands. (K) Thick, clayey supraglacial till forming high-relief hummocky topography. (L) Thick, sandy, and loamy supraglacial till forming high-relief hummocky topography. (M) Active-ice morainic topography with moraines of low local relief and nearly flat till plain between composed mostly of subglacial till. (N) Thin supraglacial clayey or loamy till forming very low-relief hummocky topography, washboard or minor moraines and drumlins. (O) Low-relief subglacial till with some drumlins and extensive pitted outwash. (P) Drumlinized thin till draped over older topography washboard moraines but with few end moraines. (R) Plains formed by glaciolacustrine sediment or with thin till on surface. (S) Drumlins and streamlined forms of subglacial till. (T) Thin till over thick, older drift. (V) Glaciomarine sediment in lowlands surrounding till and bedrock hills and washboard moraines. (W) Low-relief till-and-outwash surface with long esker systems. (X) Thin till over glaciotectonically thrust and stacked stratified sediments.
Counties under study. (1) Stutsman, ND; (2) Becker, MN; (3) Wadena, MN; (4) Humboldt, IA;
(5) Oneida, WI; (6) McHenry, IL; (7) Ford, IL; (8) Barry, MI; (9) Mason, MI; (10) Presque Isle, MI;
(11) Trumbull, OH; (12) Albany, NY; (13) Oxford, ME;

Fig. 2. Locations of counties examined in this study, set within a map showing the limit of Woodfordian glaciation and the various types of landform assemblages within.

tifying the amount of information that can be gained by mapping their soils at larger scales.

2. Study area

The study area lies within the Late Wisconsinan Woodfordian glaciated region (Fig. 2). This glaciation, which spanned roughly 20–9.5 ka, was the most recent Pleistocene glacial advance in the continental United States (Clayton and Moran, 1982). The Woodfordian glacier left behind a diverse collection of landforms typical of recently glaciated landscapes (Mickelson et al., 1983). Glacial landforms within the selected counties include till plains, outwash plains, glaciolacustrine plains, end moraines, ground moraines, interlobate moraines and drumlin fields, all with varying degrees of bedrock and loessial influence. Finally, soil parent materials range in texture from clay to silt and sand.

Table 2
Dominant geomorphic features and soil characteristics of the 13 counties studied

County, state	Map scale	Dominant landforms	Dominant parent materials	Dominant great groups (% of county area)
Albany, NY	1:15,840	Till plains	Loamy glacial till	Dystrochrepts (24%)
		Drumlin fields	Loess	Hapludalfs (22%)
		Outwash plains	Silty and clayey lacustrine sediments	Udipsamments (11%)
Barry, MI	1:15,840	Till plains	Loamy glacial till	Hapludalfs (36%)
		End moraines	Sandy outwash	Glossudalfs (27%)
		Interlobate moraines	Sandy glacial till	Udipsamments (13%)
Becker, MN	1:20,000	End moraines	Loamy glacial till	Eutroboralfs (36%)
		Drumlin fields	Sandy outwash	Calciaquolls (10%)
		Outwash plains	Organic materials	Haploborolls (10%)
Ford, IL	1:15,840	Till plains	Loess	Endoaquolls (58%)
		Outwash plains	Silty and clayey outwash	Argiudolls (35%)
		Glaciolacustrine plains	Silty lacustrine sediments	Argiaquolls (4%)
Humboldt, IA	1:20,000	Ground moraines	Loamy glacial till	Endoaquolls (61%)
		Recessional moraines	Alluvium	Hapludolls (29%)
		Fluvial terraces		Calciaquolls (4%)
Mason, MI	1:15,840	Glaciolacustrine plains	Sandy outwash	Haplorthods (30%)
		Outwash plains	Silty lacustrine sediments	Haplaquods (13%)
		End moraines	Organic materials	Glossudalfs (11%)
McHenry, IL	1:20,000	End moraines	Loess	Hapludalfs (33%)
		Outwash plains	Loamy glacial till	Argiudolls (33%)
		Glaciolacustrine plains	Loamy outwash	Endoaquolls (19%)
Oneida, WI	1:20,000	Pitted outwash plains	Loamy glacial till	Haplorthods (53%)
		Till plains	Sandy outwash	Borosaprists (13%)
		End moraines	Organic materials	Borohemists (11%)
Oxford, ME	1:20,000	Bedrock controlled end moraines and drumlins	Compact glacial till	Haplorthods (81%)
			Loose glacial till	Haplaquepts (3%)
		Outwash plains	Sandy outwash	Dystrochrepts (3%)
Presque Isle, MI	1:15,840	Outwash plains	Sandy outwash	Eutroboralfs (20%)
		Till plains	Loamy glacial till	Haplorthods (19%)
		Glaciolacustrine plains	Organic materials	Borosaprists (13%)
Stutsman, ND	1:20,000	Ground moraines	Loamy glacial Till	Haploborolls (72%)
		Outwash plains	Sandy outwash	Calciaquolls (15%)
		End moraines	Alluvium	Endoaquolls (3%)
Trumbull, OH	1:15,840	Till plains	Loamy glacial till	Ochraqualfs (50%)
		Glaciolacustrine plains	Silty lacustrine sediments	Fragiaqualfs (17%)
		Outwash plains	Clayey glacial till	Hapludalfs(13%)
Wadena, MN	1:20,000	Drumlin fields	Loamy glacial till	Udipsamments (33%)
		Outwash plains	Sandy outwash	Borosaprists (17%)
		Till plains	Organic materials	Eutroboralfs (12%)

We selected 13 counties representative of the many types of soil and landform assemblages within the Woodfordian border (Fig. 2; Table 2). We limited our selection to those counties for which both digital and paper county soil surveys were available. Due to the improved quality of recent NRCS soil surveys, only surveys more recent than 1989 were utilized. With the exception of Wadena and Becker Counties (MN), each county lies within a unique NRCS Major Land Resource Area (MLRA). In short, our goal was to select recently mapped counties that represented a large range of Woodfordian soilscapes (Table 2).

3. Materials and methods

3.1. Data

Our methodology consisted of three basic steps: acquiring and preparing the data for processing, data processing, and statistical analysis (Fig. 3). To construct the database for GIS operations, both hard (paper) copy and digital format soil surveys were acquired for each of the 13 counties (Table 2). Information on hard copies was utilized to aid in the determination of the parent material and dominant landforms for each soil series. Digital soil information was also downloaded from the NRCS SSURGO ftp site as ArcInfo™ coverages and tables and reprojected from decimal degrees to UTM using ArcToolbox™ GIS software. Attribute tables were then extracted from the downloaded data sets. Attribute data, which would later provide the basis for the scale change process, were stored in either the Map Unit Interpretation Records (MUIR) format, which provides tab delimited attribute data tables, or the recently devised National Soil Information System (NASIS) format, which provides data tables in Microsoft Access software format. Pertinent attributes (map unit symbol, soil series, drainage class, great group classification, and slope) were selected from the original database and used to create a criteria table for the scale change process (Fig. 3). Mean slope values were derived from each mapping unit. Because many of the soils have lithologic discontinuities, the parent material was determined for both the upper and lower solum, for each soil series. For map unit complexes, which have two or more soil series represented by one

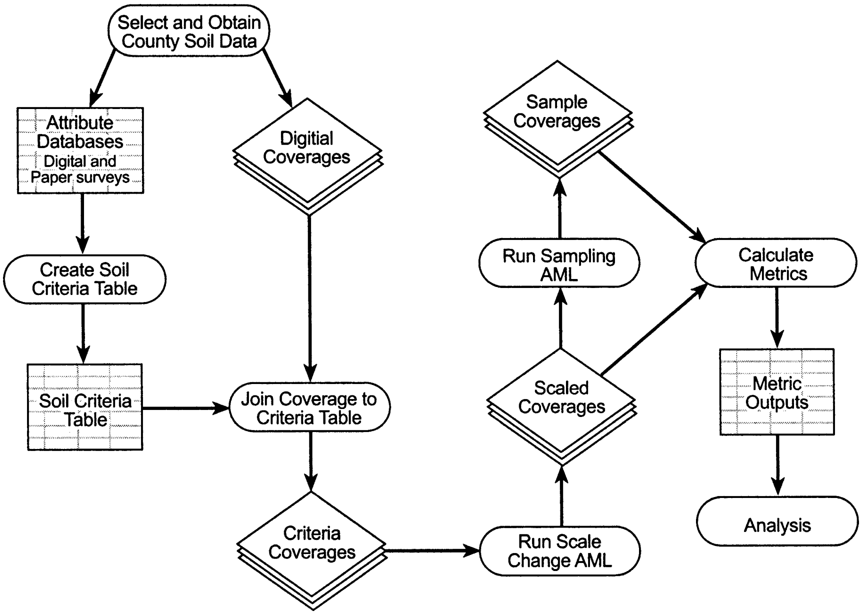


Fig. 3. Flow chart showing the data preparation and processing procedures used in the study.

map unit symbol, the dominant soil series was determined and the attributes were applied from that soil series. Once the final attributes were established, the resulting table was joined with the spatial data based on map unit symbol. In cases where polygons represented data with no discernable parent material, such as water or open pits, the polygons were given a "no data" designation. All soil coverages were processed at a scale of 1:20,000. Those counties originally obtained at a larger scale (1:15,840) were rescaled to 1:20,000 using the cartographic model Arc™ Macro Language (AML) (see below).

3.2. Cartographic modeling

An Arc™ Macro Language (AML) script was developed to change the scale of each soil map. To accomplish this, the size of the minimum mapping unit (mmu) was first established for each standard NRCS scale (Table 1). To determine the mmu for two nonstandard scales, however, a regression line was constructed using the established NRCS minimum mapping unit data. This regression line allowed for the determination of the mmu for any intermediate scale (Table 1).

The scale change operation was central to this research; it was accomplished by eliminating all map unit polygons smaller than the minimum mapping unit for each set map scale. Polygons smaller than the minimum mapping unit were dissolved into one of their surrounding polygons. The dissolve process merged adjacent polygons based on set standards (map unit symbol, series, drainage class, great group classification, upper parent material upper, lower parent material lower, and mean slope) obtained from the soil criteria table (Fig. 4). The first step in the scale change operation was to examine the series of the polygon to be dissolved and compare it to surrounding polygons. Some polygons have only one neighbor; these type of wholly surrounded polygons are referred to as punctate (Hole, 1978). In such cases, the punctate unit was dissolved into its only neighbor. If the polygon to be dissolved had more than one neighbor, but only one adjoining polygon was found to be of the same series, the polygon smaller than the mmu was dissolved into that neighbor. If more than one of the surrounding polygons were of the same series, the AML moved on to the next criterion: drainage class. If the polygon to be dissolved matched only one neighbor's drainage class, it was dissolved into that neighboring polygon. If no matches for drainage were found, the degree of difference in drainage class was determined for all neighbor polygons, and the neighbor with the least degree of difference was used to dissolve the polygon. Again, if one neighboring polygon was not the clear answer or if multiple neighboring polygons were of the same drainage class, the AML moved on to the next criterion. The third step in the dissolve process was to determine which neighboring polygon had the most matches out of a combination of four remaining variables: mean map unit slope, upper and lower solum parent material, and great group classification. The neighboring polygon that displayed the most matches out of the four was then selected as the polygon into which the dissolution took place. If there was a tie or no matches after this step, the longest shared boundary was used as the dissolution criterion. After the polygons were dissolved, the results were manually viewed (as map coverages) to determine if the AML procedure functioned appropriately. This quality control operation helped verify that the AML was using the correct logic when making dissolve decisions.

It is important to note that the newly created, smaller scale soil maps do not represent "reality" because if the landscape had been mapped at the smaller scale, different lines than ours—different map unit boundaries—would surely have been drawn by the mapper. In most instances, two adjoining map units that were below the mmu would have been combined by the mapper, were they to map the area at a smaller scale, but boundaries of the resultant map units would have been shifted in the process. For those map units that were larger than the mmu, some degree of line generalization would have occurred, and long, narrow "tongues" that extended out from otherwise large map units might have been eliminated. Thus, our newly formed, smaller scale maps represent one possible reality, but perhaps not the most likely one. Still, this was the best we could, given the limitations of the model.

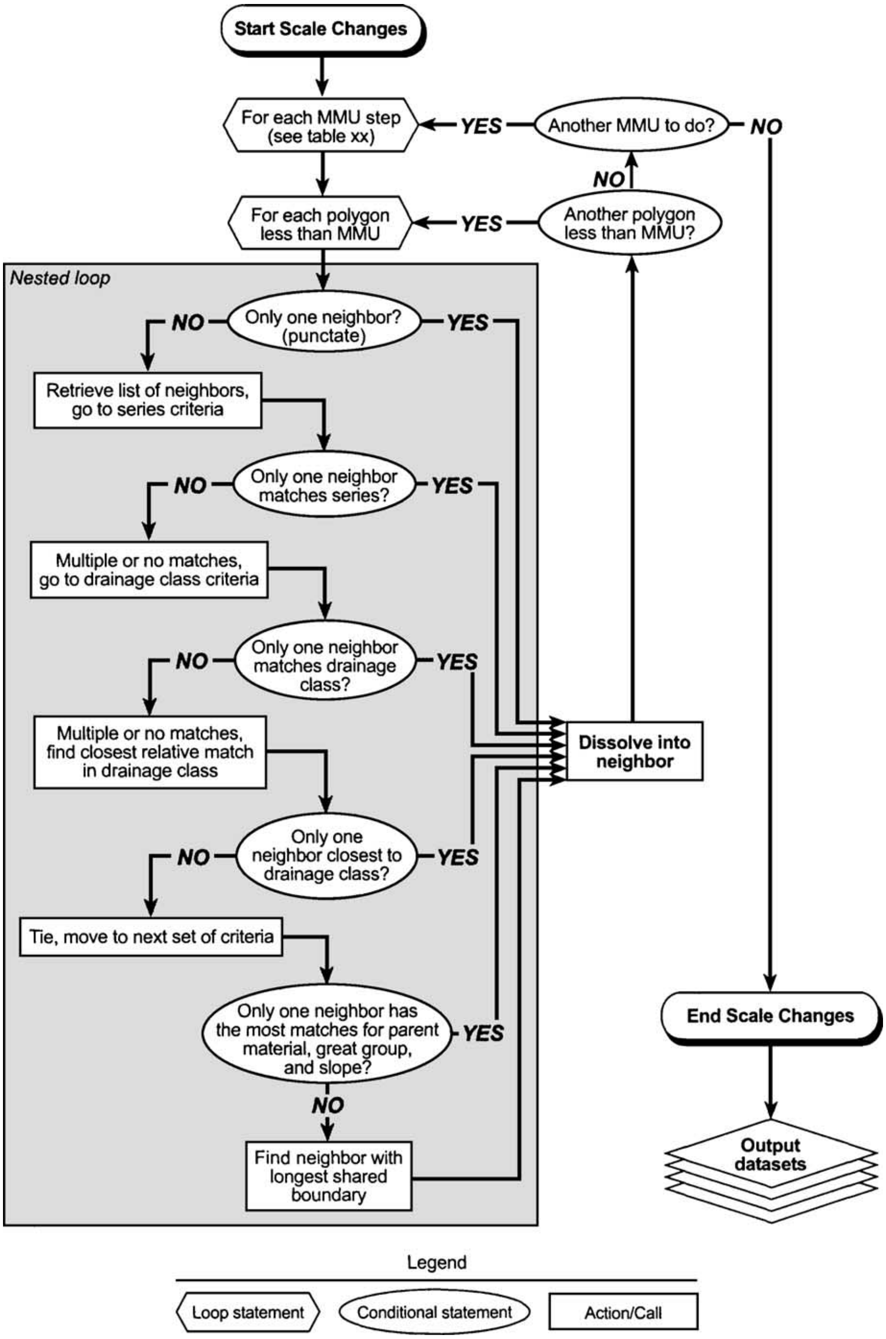


Fig. 4. Flow chart of the Arc Macro Language (AML) procedure used to create soil maps of various scales, from one large scale map.

A second AML script was also developed to calculate each of four pattern metrics for the entire county data sets (13 in all) as well as county samples: number of punctate soil units km^{-2} (NPunc) (Eq. (1)), map unit polygons km^{-2} (MUP) (Eq. (2)), map unit boundary length km^{-2} (MBL) (Eq. (3)), and boundary length polygon^{-1} km^{-2} (BLP) (Eq. (4)). The equations for each of these metrics are listed below.

$$\mathrm{NPunc} = n_{\mathrm{pp}}/\mathrm{km}^2 \tag{1}$$

where n_{pp} is the number of punctuate polygons and km^2 is the total area of the coverage.

$$\mathrm{MUP} = n_{\mathrm{p}}/\mathrm{km}^2 \tag{2}$$

where n_{p} is the number of polygons in the coverage.

$$\mathrm{MBL} = \left(\sum \mathrm{al} - B\right)/\mathrm{km}^2 \tag{3}$$

where n is the number of polygons in the coverage, al is the length of the arcs for all n, and B is the boundary length of either the county or the sample (see below).

$$\mathrm{BLP} = \frac{\left(\sum \mathrm{al} - B\right)/n_{\mathrm{p}}}{\mathrm{km}^2} \tag{4}$$

The first metric, NPunc, was chosen because it captures the essence of small, isolated map units that, at smaller map scales, might not be able to be delineated (Fig. 1). The second and third metrics, MUP and MBL, respectively, provide information on the complexity of the soilscape, not necessarily based on the actual number of soil series, which would be pedodiversity, but on the complexity of the polygons themselves, and their number/density. Finally, the last metric (BLP) was chosen to represent the degree to which the outline of a standard, soil map unit polygon is complex and crenulated vs. nearly circular; it is a characteristic which varies in opposition to the first three metrics, i.e., positive vs. negative slopes with changes in scale.

Finally, we wanted to ascertain some measure of the spatial variation within the county-based data sets for each of the four metrics. Therefore, we developed a third AML script to take 50 random, quadrat samples from the county, at each scale. The circular quadrats were set at 50 times the mmu of the soil map with the smallest scale. For the 1:125,000 (our smallest scale map) map, the mmu is 63 ha (Table 1), necessitating that the sampling quadrats were 3150 ha in area (3167 m in radius). Each of the 50 sample quadrats was randomly generated within the bounding coordinates of the coverage. Due to the irregular shape of some counties, some quadrats fell outside of county boundaries but were still located within the coverage boundaries. To alleviate this problem, we developed an inset buffer within the county boundary, to ensure that all sample quadrats fell wholly within the county. Data from the 50 randomly located quadrats were then generated for each county and compared to whole-county data.

3.3. Statistical analysis

Parametric statistical tests were used to analyze both the county data and data from the 50 quadrats. All data were transformed using logarithmic transformations, $Z=\log_{10}(X)$ for county data and $Z=\log_{10}(X+0.00001)$ for sample data. Regression analyses were performed using the REG procedure in the SAS™ statistical package (SAS, 1999). The purpose of the regression equations was to facilitate prediction of landscape properties, based on the four pattern metrics, at larger scales. Logarithmic regressions were used to linearize the data. Using the GLM procedure in SAS™, Levene test was used to check for homogeneity of variances within metrics, whereas the m test was used to test for homogeneity of variances across metrics (Crow et al., 1960).

Pattern metric data can quantitatively describe the complexity of a soil landscape, and if examined at different scales, thresholds and critical scales can be discovered where specific patterns manifest, providing insight into significant processes operating hierarchically. The metric data from the entire county and the county samples were tabulated (Table 3) and then examined using regression equations [$\log Y = A + B(\log X)$] derived from the former data set. Figs. 6 and 7 illustrate the variation in the four pattern metrics as the scale of soil maps is changed.

The regression equations, derived from the whole county data, were then extrapolated from 1:20,000 to 1:10,000 scale (Fig. 5). A delta (Δ) value could then be calculated by inserting the X axis value for the mmu at 1:10,000 (0.41 ha) into the regression equation, solving for Y, and determining the difference between it and the calculated Y value at $X=$1:20,000 (1.6 ha). The largest scale, 1:20,000, was selected because it is one of the most commonly used scales on county soil maps. We arbitrarily chose a scale of 1:10,000 for the larger scale maps because it seemed

Table 3
Pattern metric data (at 1:20,000), regression data and data for each of the 13 counties under study

	Whole county data						Sample data			
	Mean county value	*A*	*B*	R^2	Absolute	Ratioed[a]	*A*	*B*	R^2	Absolute
Punctate map units km^{-2}										
Albany, NY	0.3	−0.170	−1.393	0.99	2.1	8.1	−0.030	−2.829	0.57	11.4
Barry, MI	0.4	0.026	−1.576	0.99	3.9	9.7	0.219	−3.116	0.64	26.3
Becker, MN	0.7	0.215	−1.387	0.98	5.0	8.3	0.741	−3.124	0.67	88.8
Ford, IL	1.8	0.687	−1.345	0.96	14.3	8.8	1.411	−2.835	0.65	321.1
Humboldt, IA	2.2	0.737	−1.308	0.98	15.3	7.8	1.554	−2.916	0.67	480.2
Mason, MI	0.3	0.208	−2.122	0.71	10.5	40.1	−0.056	−3.124	0.68	14.0
McHenry, IL	0.4	−0.098	−1.262	0.99	2.1	6.0	0.253	−2.967	0.61	24.9
Oneida,WI	0.7	0.192	−1.255	0.97	4.1	7.0	0.901	−2.738	0.62	90.8
Oxford, ME	0.2	−0.448	−0.876	0.99	0.6	3.6	−0.076	−2.569	0.50	8.1
Presque Isle, MI	0.4	−0.251	−1.216	0.98	1.3	4.4	0.300	−3.016	0.66	29.1
Stutsman, ND	0.4	0.012	−1.277	0.98	2.8	7.3	0.393	−2.752	0.58	28.4
Trumbull, OH	0.4	−0.109	−1.124	0.99	1.7	5.3	0.358	−2.742	0.55	26.0
Wadena, MN	0.6	0.105	−1.024	0.98	2.5	5.0	0.840	−2.549	0.62	66.7
Polygons km^{-2}										
Albany, NY	11.0	1.234	−0.720	0.99	21.5	3.0	1.179	−0.558	0.90	14.2
Barry, MI	10.8	1.225	−0.734	0.99	21.5	3.0	1.218	−0.588	0.90	15.9
Becker, MN	9.6	1.155	−0.738	0.99	18.0	2.9	1.180	−0.574	0.91	13.6
Ford, IL	8.1	1.098	−0.867	0.99	19.0	3.4	1.073	−0.703	0.77	13.3
Humboldt, IA	9.9	1.226	−0.954	0.99	29.4	4.0	1.185	−0.713	0.88	17.7
Mason, MI	6.8	1.009	−0.631	0.99	11.1	2.6	1.054	−0.499	0.94	9.5
McHenry, IL	10.9	1.219	−0.733	0.99	20.9	2.9	1.209	−0.564	0.94	15.3
Oneida,WI	6.3	0.974	−0.645	0.99	10.4	2.6	0.982	−0.471	0.90	7.5
Oxford, ME	7.2	1.049	−0.596	0.98	11.8	2.6	1.074	−0.496	0.90	10.1
Presque Isle, MI	9.0	1.073	−0.640	0.98	12.0	2.3	1.111	−0.504	0.91	9.3
Stutsman, ND	8.4	1.128	−0.724	0.99	17.3	3.1	1.106	−0.551	0.93	12.1
Trumbull, OH	5.9	0.942	−0.607	0.99	9.2	2.6	0.913	−0.428	0.82	6.1
Wadena, MN	6.5	0.980	−0.630	0.99	10.3	2.6	1.031	−0.492	0.92	8.7
Polygon boundary length (m) km^{-2}										
Albany, NY	10089	4.073	−0.249	0.99	4680.7	1.5	4.035	−0.232	0.73	4180.4
Barry, MI	9731	4.050	−0.241	0.99	4175.0	1.4	4.047	−0.237	0.82	4136.6
Becker, MN	10032	4.056	−0.234	0.99	3974.6	1.4	4.066	−0.244	0.73	4269.9
Ford, IL	9231	4.057	−0.343	0.99	6252.2	1.7	4.048	−0.382	0.51	6841.3
Humboldt, IA	10413	4.113	−0.382	0.99	7811.1	1.8	4.094	−0.355	0.71	6843.6
Mason, MI	7491	3.935	−0.203	0.99	2833.5	1.4	3.955	−0.199	0.81	3094.5
McHenry, IL	10836	4.094	−0.232	0.99	4444.9	1.4	4.079	−0.225	0.76	4548.4
Oneida,WI	8071	3.964	−0.199	0.99	2903.9	1.4	3.954	−0.193	0.65	3036.2
Oxford, ME	7996	3.973	−0.199	0.96	3216.6	1.4	3.972	−0.205	0.75	3291.1
Presque Isle, MI	9430	4.020	−0.213	0.98	3226.4	1.3	4.028	−0.207	0.76	3053.3
Stutsman, ND	8652	4.007	−0.241	0.99	3940.7	1.5	3.987	−0.238	0.79	4018.6
Trumbull, OH	7768	3.950	−0.190	0.98	2781.0	1.4	3.908	−0.171	0.63	2420.9
Wadena, MN	9553	4.036	−0.214	0.98	3799.5	1.4	4.0380	−0.207	0.82	3698.1
Polygon boundary length (m) polygon^{-1} km^{-2}										
Albany, NY	0.7	−0.248	0.471	0.99	−0.4	0.5	1.360	0.326	0.94	−10.2
Barry, MI	0.7	−0.303	0.493	0.99	−0.4	0.5	1.332	0.351	0.92	−9.8
Becker, MN	0.3	−0.642	0.505	0.99	−0.2	0.5	1.389	0.331	0.90	−9.5
Ford, IL	1.1	−0.058	0.525	0.99	−0.6	0.5	1.479	0.321	0.77	−9.2
Humboldt, IA	1.1	−0.111	0.572	0.99	−0.6	0.4	1.413	0.357	0.91	−10.4
Mason, MI	0.9	−0.147	0.428	0.99	−0.5	0.5	1.405	0.300	0.91	−10.5

Table 3 (*continued*)

	Whole county data						Sample data			
	Mean county value	*A*	*B*	R^2	Absolute	Ratioed[a]	*A*	*B*	R^2	Absolute
Polygon boundary length (m) polygon^{-1} *km*$^{-2}$										
McHenry, IL	0.7	− 0.279	0.501	0.99	− 0.4	0.5	1.373	0.339	0.96	− 10.5
Oneida,WI	0.4	− 0.480	0.446	0.99	− 0.2	0.5	1.476	0.278	0.89	− 10.8
Oxford, ME	0.3	− 0.582	0.397	0.99	− 0.2	0.5	1.401	0.292	0.92	− 10.9
Presque Isle, MI	0.7	− 0.246	0.428	0.98	− 0.3	0.6	1.420	0.297	0.93	− 8.4
Stutsman, ND	0.2	− 0.872	0.483	0.99	− 0.1	0.5	1.385	0.313	0.93	− 10.6
Trumbull, OH	0.9	− 0.164	0.417	0.99	− 0.4	0.5	1.499	0.256	0.84	− 12.6
Wadena, MN	1.2	− 0.040	0.416	0.99	− 0.5	0.5	1.511	0.285	0.89	− 12.7

[a] Ratioed data provide another indicator of how much additional data the soil map could provide, if it were compiled at 1:10,000 vs. 1:20,000. The absolute value in the previous column represents the absolute magnitude of “gain” as determined by the regression equations (see Fig. 6). The ratioed is defined as Ratioed = metric value at 1:10,000/metric value at 1:20,000. A ratioed value of 2 implies that that metric would be twice as large at the larger map scale of 1:10,000.

like a reasonable next step, were one to remap these counties at a larger scale. Delta values indicate the information increase that can be gained by mapping soils at 1:10,000 vs. 1:20,000. Ratioed delta values (Table 3) provide similar information but express the information increase in a relative, rather than absolute, manner. Thus, relative delta data indicates how much more information would be gained by changing scale. We acknowledge that the slope of the regression line likely does change if it were to be extended much further, rendering our predictive equations less useful for applications in extremely large scale maps, e.g., 1:500. The discussion that follows examines the metrics and their implications for soil mapping and landscape ecology.

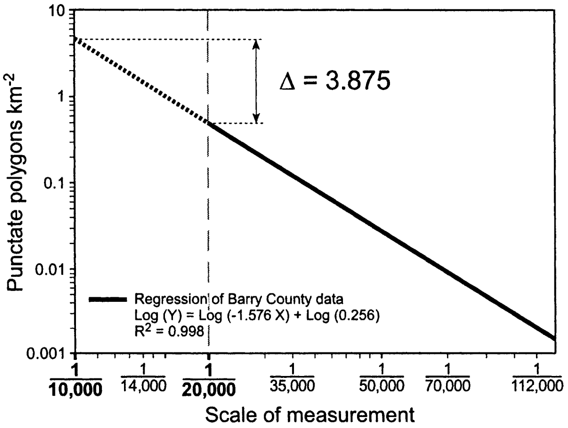


Fig. 5. An illustration of how the delta (*Δ*) values were calculated from the pattern metric regression equations.

4. Results and discussion

Punctate map units (NPunc) were used as a metric because, in our estimation, they would be common in recently deglaciated landscapes where they are represented as isolated depressions and hilltops. We assumed that punctate map units would become fewer as river systems became better defined and more controlling of the landscape form, i.e., as deranged drainage systems became more dendritic and integrated. We also assumed that punctate map units would be much more common at larger scales, since many are observable by the mapper but cannot be delineated due to mmu restrictions (Fig. 1). Data in Table 3 confirm that most counties have between 0.3 and 2 punctate units km^{-2}. The kame-and-kettle topography of Humboldt County, IA is particularly evident; punctate map units were more common here than in any other county; it almost has a “Swiss cheese” like appearance (Table 3). Conversely, in southern Maine, an integrated drainage system has developed on the underlying bedrock surface. The drift that overlies this bedrock surface is not thick enough to have obscured its influence, resulting in only 0.2 punctate units km^{-2}. In all cases, glaciated counties would have more punctate map units, i.e., absolute values are positive, if mapped at 1:10,000 rather than at 1:20,000 (Table 3). Generally, the number of increased punctate units was calculated to be >1 per km^2 for all counties except Oxford, ME, and as high as 10 or more for the highly kettled and hummocky landscapes of northern Iowa, eastern Illinois and western lower Michigan (Table 3). Ratioed *Δ* data suggest that 3.6 to more than 40 times as many punctate units could be mapped per km^2 at 1:10,000 in these glaciated counties (Table 3).

The absolute Δ values are much higher when calculated from the sample data than from the whole county data (Table 3). This difference is attributable, in large part, to the zero values for the various metrics in the smaller scale samples, which modifies the slope and results in an overestimation in the change in information, or delta. Mason County lacks this difference, although it contains a zero at the smallest scale, probably because it has a low number of punctate map units. This soil landscape composition may not contain the necessary heterogeneity to produce punctate soil patterns.

The data on punctate map units clearly indicate that map scale has a great effect on the amount of information that can be elucidated form maps as a function of scale. Isolated, punctate units do exist on the landscape, but simply cannot be mapped at the scales provided. A major contribution of this project is to not only provide evidence for this, but also to provide some indication of the magnitude of additional information about these types of map units that could be identified at larger map scales.

The second and third metrics are polygons km^{-2} (MUP) and polygon boundary length km^{-2} (MBL), respectively. We chose these metrics because they represented, to some degree, the time investment that the soil mapper must put into each unit area of the soilscape. Drawing large numbers of map unit boundaries on landscapes with complex terrain, in which the number of polygons and hence the total length of polygon boundaries is great, requires a significantly larger time investment than on simpler landscapes that have fewer map units. The data in Table 3 indicate that most of these landscapes have between 6 and 11 polygons km^{-2}, with polygon boundaries (map unit

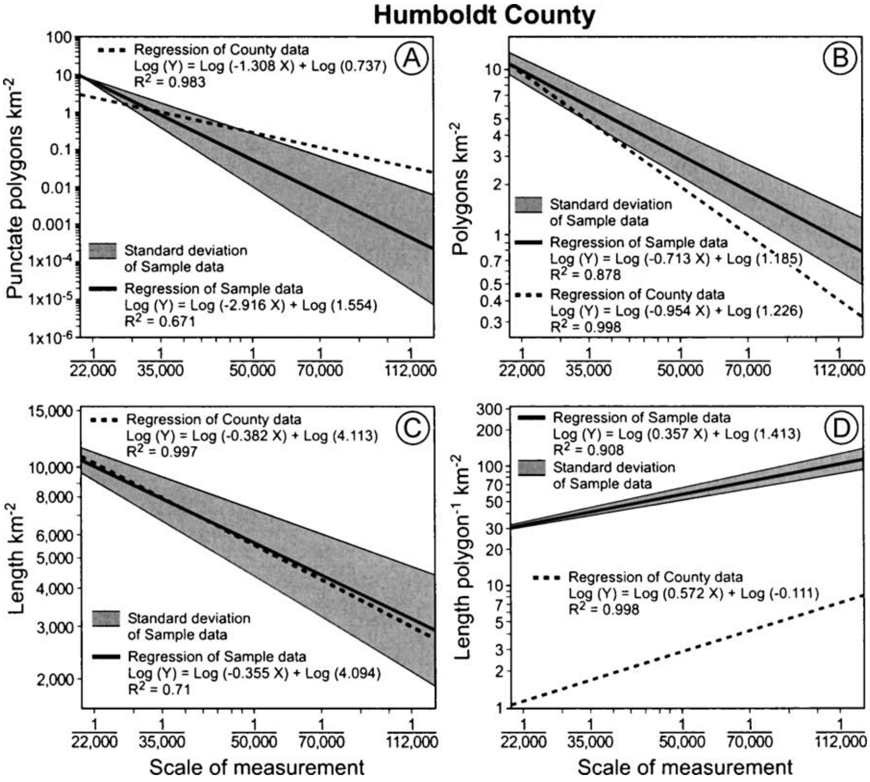


Fig. 6. Regression plots of the four types of pattern metric data available for Humboldt County, IA. The regression lines and the standard deviation error window around that line were calculated using the whole county data. The regression line that was calculated based on county sample data (dotted) is also shown.

edge lengths) ranging between about 8 and 11 km per km^2. As discussed earlier, the number of punctate map units km^{-2} increases at a map scale of 1:10,000 (Fig. 6), and given the strong correlation between these metrics and the number of punctuate polygons the results are as expected. At this scale, most counties would have 2–4 times as many map units per km^2 (Table 3).

The fourth metric, boundary length per polygon km^{-2} (BLP) is different from the above metrics in that it measures the complexity of the outlines of the map units (Hole, 1953). In essence, this metric captures the irregularity of map unit outlines. We developed this metric because we assumed that there is a necessary amount of map unit boundary generalization, simply due to cartographic restrictions (McMaster, 1987; Muller, 1990). Metric four decomposes metric three by distinguishing between maps with a few large convoluted polygons vs. those with many smaller, less convoluted polygons. These two types of maps could, theoretically, attain the same value on metric three. Comparing these metrics for any two landscapes will significantly improve the discriminability of these two locations or shape characteristics.

The delta values for the fourth metric are negative, which shows that, at smaller map scales the complexity of soil polygon shapes decreases or simply that generalization occurs. The negative absolute delta values occur because as the length of the polygon boundaries increases, the number of polygons decreases, resulting in a positive slope to the regression line (Figs. 6 and 7). Ratioed delta data (Table 3) indicate that the relative degree of change is less for this metric than for the other three. This is to be expected, as the absolute magnitude of this metric is greater than any of the others. With increasing scale, soil patterns become much more complex and lose much of their spatial predictability (Gessler et al., 1995). This metric, boundary length per polygon km^{-2}, then provides information gain or loss across changes in scale due to map generalization and serves as a negative correlated test to the first three metrics.

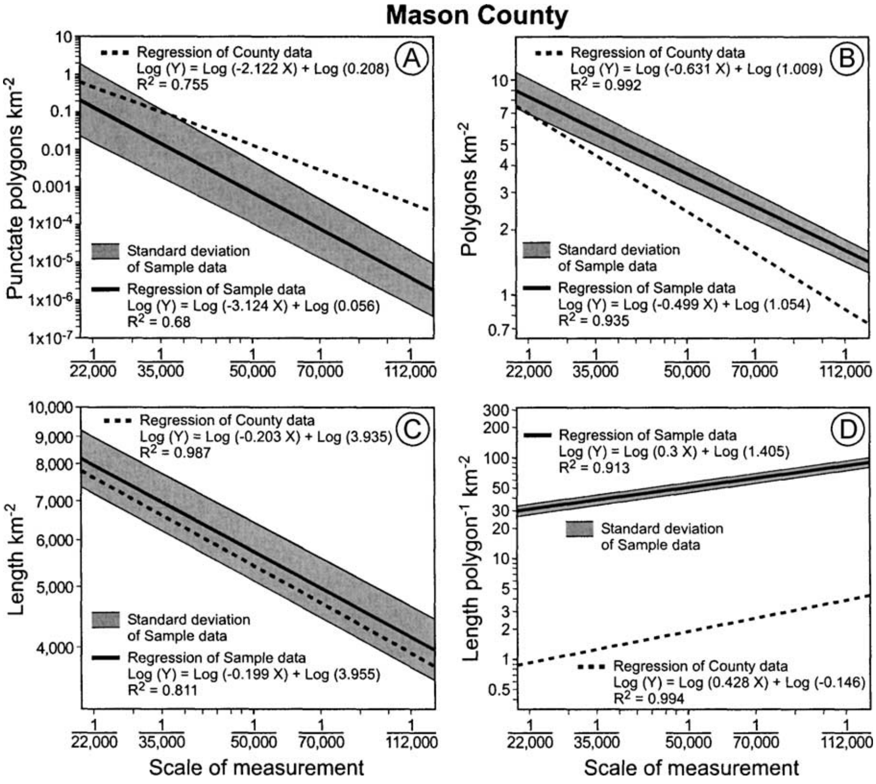


Fig. 7. Similar data as in Fig. 6, but for Mason County, MI.

Results of the Levene test show that variances for the number of punctate soil units km^{-2} metric are heterogeneous. The heterogeneity of the variances of this metric contributes to the difference in the slopes of the county and sample data. The same was true for polygons km^{-2} with the following exceptions: Ford, Oneida, and Oxford counties had homogeneous variances. While these counties do not contain the same landforms nor do they contain the same types of parent materials, it is important to remember that although the study sites have a glacial physiohistorical significance, the boundaries of our data sets are sociopolitical and as such, county shape alone may influence these results. Levene test results for length km^{-2} were different from the first two metrics. Variances tended to be homogeneous with the exception of Albany, Becker, and Humboldt counties, which were significantly different. Length per polygon km^{-2} also contains significant differences in the variances between scales, excluding Albany, Barry, and Mason counties. There are many factors which contribute to the variability in the data. Some potential contributing factors include, again, the varying shapes of the counties, the experience of the surveyors who map each county, and the budget constraints while conducting the soil survey. The four metrics selected for this study take into account several different phenomena occurring on the landscape. However, they cannot explain all variation occurring at the landscape level. Results of the *m* test state that variances between each metric are significantly different. This ensures that the metrics are not measuring the same physiographic characteristics.

5. Conclusions

Our study has examined how the scale of existing, paper soil maps affects the amount of information that can be portrayed on them. Mapping soilscapes at larger scales enables more information to be added to the map for two reasons: (1) the mapper is less constrained by, or concerned with, minimum mapping unit size, i.e., cartographic restrictions on the paper maps are eased; and (2) it can be assumed that more time would be available for the production of larger scale maps. To our knowledge, no previous work has been done to determine the additional information that results from an increase in map scale, for soil map applications.

Our work centered on these legacy limitations which exist for primarily paper maps. As soil maps become increasingly available in digital formats, some of these restrictions will be eased or eliminated. For example, minimum mapping unit sizes will be determine based not on cartographic restrictions, i.e., can the map symbol be placed entirely within the map unit, on the paper map, but on field-based time-of-mapping considerations. Thus, our work may be used to point out an advantage that digital soil maps may provide over traditional paper maps.

In our methodology, the amount of information gained by enlarging the scale of soil maps on complex, glaciated terrains generally ranges from 2–4 times that of existing maps [for total numbers of map units per km^2, to 3–10 times (for numbers of punctate map units per km^2)]. In short, by doubling the map scale more than twice the information can be portrayed on soil maps. We are not suggesting that this information is either necessary nor cost-effective, as that was not our objective. However, for decision makers, some knowledge of the amount of additional information is necessary before decisions are made to map soilscapes at larger scales.

Mapping soils at larger scales has costs and benefits. Bie and Beckett (1971) went as far as to quantify the effort required, in terms of surveyor days per unit area of a soil survey. They found that effort is directly related to the density of soil boundaries per unit area. Indeed, few question the assumption that more effort and time will result in soil maps that portray more information and are potentially more accurate. Complementing that conclusion, our study has shown that mapping at larger scales will also add to the information resource of soil maps, and we have been able to quantify the amount of additional soils information that can potentially be gained by mapping at larger scales. Thus, our study holds the potential to direct limited resources of time and money to map at a larger scale those soil landscapes that would show the greatest increase of information.

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