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Assessment of soil spatial variability at multiple scales

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Abstract

Quantification of soil spatial variability across multiple scales is important in ecological modeling, environmental prediction, precision agriculture, and natural resources management. This study investigates the variability of soil map units and soil properties at multiple scales using two case studies, and demonstrates that soil spatial variability is a function of map scale, spatial location, and specific soil property. In the first case study, the variability of soil components within a map unit, termed map unit purity, was examined at three orders of soil surveys in the Backswamp Watershed in South Carolina. Soil maps of Order I (1:7920), Order II (1:24,000) and Order IV (1:250,000) were independently obtained and examined in a Geographic Information System (GIS). The results showed that the area-weighted mean purity P_m for the Order II soil map when compared to the Order I delineations was 51–99% for soil taxonomic units (soil series to order) and 65–85% for soil properties important for land management in the area (texture, structure, surface thickness, hydrologic group, and drainage class). Corresponding values of P_m for the Order IV map were 24–81% and 60–90% when compared to the Order II delineations. In the second case study, 324 soil samples were collected across the Minnesota River Basin using a nested hierarchical sampling design that allowed for variability assessment at multiple scales through a hierarchical analysis of variance. A-horizon thickness, depth to calcium carbonate, and surface soil pH values were summarized by soil regions, hillslope positions, clusters, and point scales. The majority of the variability (over 50% in most cases) for all three soil properties was at the local point scale, suggesting that careful examination of short-range soil property variability should not be overlooked. Possible causes of variability ranged from climate at the basin scale to localized effects of differential infiltration and runoff caused by the differences in landscape positions and soil characteristics. We recommend a hierarchical sampling approach similar to the one used in this study to inventory soil spatial variability at multiple scales so that an understanding could be developed not only for soil property variability across the landscape, but also for determining at what scale the variability is most likely to occur.

Keywords: Map unit purity; Soil survey; Nested sampling; Local variability; Soil landscape

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1. Introduction

Information about soil variability is important in ecological modeling, environmental prediction, precision agriculture, and natural resources management. Spatial variability of soil input data can strongly influence the reliability of the results of logical, empirical, and physical models of soil and landscape processes (Burrough, 1993; Foussereau et al., 1993; Wilding et al., 1994). With growing interests in landscape perspective and watershed modeling to address diverse environmental, ecological, agricultural, and natural resource issues, an adequate understanding of soil variability as a function of space and time becomes

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essential. However, in spite of voluminous literature published in the past three decades or so, knowledge about soil variability is still dispersed and requires further synthesis (e.g., Burrough, 1993; Heuvelink and Webster, 2001). In particular, there is a need to quantify soil variability across multiple scales, which will undoubtfully enhance the use of soils information in diverse applications.

Among many factors influencing soil variability is the issue of scale. Considerable work has been done investigating soil variability at a single scale, which provides useful information at that particular scale (e.g., Beckett and Webster, 1971; Webster, 1985; Agbu and Olson, 1990; Gaston et al., 1990; Schellentrager and Doolittle, 1991; Moore et al., 1993; Mahmoudjafari et al., 1997; Thompson et al., 1997; Boehm and Anderson, 1997). However, quantification of soil variability at multiple scales is often desirable for modeling and prediction, which provides a basis for developing an understanding regarding scales of influence on variability and a framework upon which scaling of data may be possible. Limited studies have been done so far to investigate soil spatial variability across multiple scales (Burrough, 1983a, b; Edmonds et al., 1985; Wösten et al., 1987; Pennock and de Jong, 1990; Sylla et al., 1996; Dobermann et al., 1997). Moore et al. (1993) suggested that the optimum scales for characterizing soil landscape processes affecting the development of catena (a sequence of related soils that differ primarily because of topography and drainage) are unknown and represent a major research need.

Soil variability is influenced by different combinations of soil-forming factors acting through space and time. In a general framework, soil variability may be considered as a function of five space–time factors, i.e., spatial extent or area size, spatial resolution or map scale, spatial location and physiographic region, specific soil property or process, and time factor. Exact expression of such a function is very difficult, if not impossible, to establish, in part because of the diversity and complexity of the relationships. Nevertheless, broadly speaking, it might be expected that as spatial extent, spatial resolution, or time scale increase, the magnitude of soil variability would increase, reaching a possible maximum and then starting to stabilize or decrease as space or time dimensions continue to increase; however, the mode and magnitude of such changes depend on where the soil is located in the landscape (i.e., spatial location) and which soil type or specific soil property is of concern. For reviews on soil spatial variability, readers are referred to Burrough (1993) and Heuvelink and Webster (2001).

Soil surveys have traditionally overlooked spatial variability within map units for a variety of reasons including scale limitations and inadequate quantitative data. Soil mapping typically partitions the soil in the landscape into more or less discrete entities using map units. Soil surveyors map the soil with a conceptual model of soil variation in mind based often on air photo interpretation and collated information on the soil and its relations with landform, geology, vegetation, and land use (Dijkerman, 1974; Soil Survey Division Staff, 1993). Field observations are made at a selected number of locations chosen by soil surveyors using formal knowledge and intuitive judgment. On a soil map, the map unit boundaries are clear lines across which the observed differences are deemed significant and within which the soil is relatively homogeneous. Variation within soil map units is acknowledged, but described qualitatively in vague terms. Moreover, virtually every delineation of a map unit in all soil surveys includes other soil components or miscellaneous areas that are not identified in the name of a map unit. Many of these components are either too small to be delineated separately at a given soil survey scale or deliberately included in delineations of another map unit to avoid excessive detail in the map or the legend (Soil Survey Division Staff, 1993). These inclusions reduce the homogeneity or purity of map units and often affect interpretation or modeling. However, soil surveys traditionally have lacked appropriate sampling design to present quantitative estimates regarding spatial variability within and across map units. Quantification of map unit purity for different scales of soil maps is an area needing improvement in modern soil surveys (Arnold and Wilding, 1991).

There are five orders of soil surveys in USA, ranging from the Order I for the most detailed mapping (minimum delineation size ≤1 ha, 1:15,840 or larger cartographic scale, mapping units mostly consociations) to the Order V for very general mapping (minimum delineation size 252–4000 ha, 1:250,000 or smaller cartographic scale, mapping units largely associations) (Soil Survey Division Staff, 1993). Consociations are cartographic map units represented dominantly by a single soil taxon (usually soil series), and associations (or complexes) consist of two or more dissimilar components occurring in a regularly repeating pattern (Soil Survey Division Staff, 1993). The orders of soil surveys are intended to assist the identification of operational procedures for the conduct of a soil survey, and to indicate general levels of quality control that affect the kind and precision of subsequent interpretations and predictions. Juracek and Wolock (2002) compared the spatial and statistical differences between 1:24,000 and 1:250,000 digital soil maps and related attributes for Kansas and concluded that although the two databases were correlated, the potential exists for substantial site-specific variability between them. Comparing different orders of soil maps for the same area would be beneficial to enhance the understanding and quantification of soil map unit purities.

Upchurch and Edmonds (1991) suggested three issues regarding sampling for soil spatial variability assessment: (i) location of sample points, (ii) size of sample, and (iii) total number of samples to be collected. In order to address issues (i) and (iii), a sampling design must be chosen. Wilding (1985), Webster and Olive (1990), Wollenhaupt et al. (1997), de Gruijter (2002), and others provided summaries of different soil sampling designs. These methods vary in ease of use, scale of appropriate application, resources needed, and accuracy of data. There are two fundamentally different approaches to sampling according to de Gruijter (2002): the design-based approach, followed in classical survey sampling, and the model-based approach, followed in geostatistics. An extensive discussion comparing these two approaches is presented by Brus and de Gruijter (1997). In the following, common strategies used in design-based approach relevant to this study are highlighted.

Simple random sampling has the advantage of being unbiased (Webster and Olive, 1990), but may result in uneven coverage of an area, hence requiring a large sample size across a small area to ensure adequate coverage. Simple random sampling basically ignores any knowledge about the landscape to be sampled. Therefore, this method is typically not used for spatial variability assessment. Stratified random sampling employs information about the landscape to assist in the location of samples. This is done by dividing the sampling area into smaller areas (called strata) that are less variable than the entire landscape and then randomly locating sample points within each of the sub-units. This sampling design provides spatial variability information at multiple scales based on the number of strata present. Stratified random sampling may be further modified into multistage sampling (de Gruijter, 2002).

Transect sampling is an optimized cluster sampling that typically involves sampling along a hillslope from summit to toeslope. This sampling design allows the investigation of environmental gradients that commonly occur along a landscape continuum. Provided that transects are representative of a larger physiographic region, data collected can be related back to the region using modeling. The disadvantage of this sampling design is that it lacks interpretations in the third dimension and also imposes restrictions on the population that can be sampled, which can be less desirable for some statistical inferences. Systematic sampling design overcomes this shortcoming by laying out a grid at a known spacing (in the form of square, triangle, or hexagonal) and sampling where two lines intersect, thus providing an even coverage of an area. Scales associated with systematic sampling are usually limited to small areas because of the large number of samples required for an accurate assessment of variability. However, systematic sampling can result in a large bias if there is a periodicity within the population, which could be a result of anthropogenic influences such as fertilizer applications, liming, and tillage (Petersen and Calvin, 1986). If periodicity can be recognized, developing an adaptation of the systematic sampling design is common.

Nested (or multi-stage hierarchical) sampling with replication at each level utilizes the advantages of the above several sampling methods. It involves dividing the area of interest into classes and then subdividing these classes until the smallest units are reached. The result is a hierarchical system that allows for the population to be studied at several scales (Edmonds et al., 1985; Wollenhaupt et al., 1997). The particular merit of this sampling method is that a wide range of spatial scales can be covered in a single analysis. This is particularly valuable where variation occurs in spatial scales that differ by several orders of magnitude simultaneously (i.e., where the variation is nested) (Webster and Olive, 1990). Using the hierarchical analysis of variance, the amount of total variance contributed by each level in the nested sampling could be determined. In the nested sampling, the way in which classes are divided into subclasses would be based on objectives and supporting data available. Once divided into classes, sampling can be random, systematic, or along transects. Wollenhaupt et al. (1997) suggested that nested sampling may result in an uneven coverage of an area. This uneven coverage may be tolerable, if one desires to make statements about a large region, separating local from regional variations. Youden and Mehlich (1937) were the first to apply nested sampling to soil spatial variation. The method was later utilized to study soil spatial variability in relation to sampling distance (Webster and Butler, 1976; Nortcliff, 1978), map unit interpretation (Edmonds et al., 1985), soil survey (Olive and Webster, 1986), and mapping procedures for land evaluation (Riezebos, 1989).

The objectives of this study were two-fold: (1) to investigate soil variability as a function of spatial resolution or map scale, spatial location and physiographic region, and specific soil property, and (2) to quantify the variability of soil type and selected soil properties at multiple scales using two approaches. Two case studies are present here that demonstrate the dependence of soil variability as a function of scale on the location in the landscape and the soil property in question. In the first case study, soil component and property variabilities at three map scales were studied for a coastal plain watershed in South Carolina. In the second case study, soil property variability at four scales in the Minnesota River Basin was quantified using a nested hierarchical sampling design and statistical analysis.

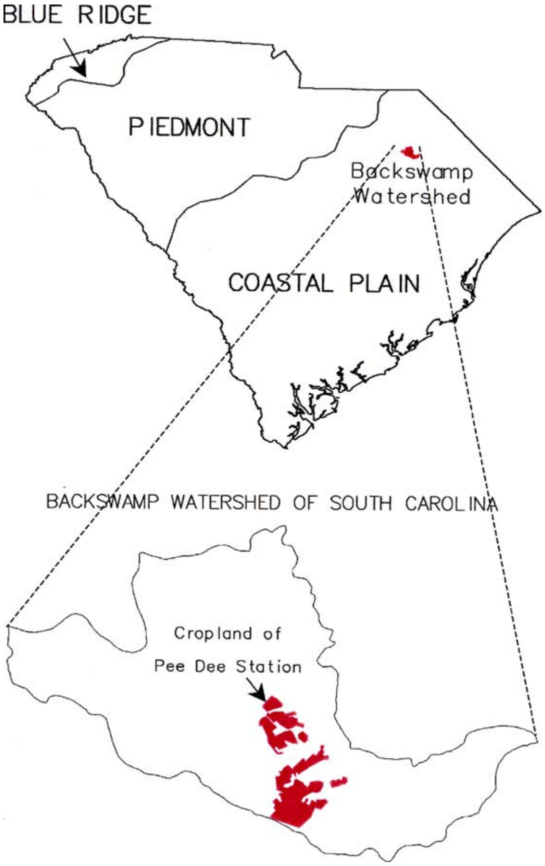


Fig. 1. The Backswamp Watershed in the Coastal Plains of South Carolina and the croplands at the Pee Dee Research and Extension Center located in the southern part of the watershed.

2. Case study I: soil variability as a function of three orders of soil surveys

2.1. Materials and methods

2.1.1. Study area

The 7485 ha Backswamp Watershed in northeastern South Carolina (Fig. 1) belongs mostly to the Southern Coastal Plain Major Land Resource Area (USDA-SCS, 1981). The Pee Dee Research and Education Center (hereafter referred to as the Pee Dee Center) of Clemson University is in the south-central part of the watershed. The Pee Dee River runs to the east of the watershed, and the Black Creek to the west. The Back Swamp cuts across the central part of the watershed and connects to the Pee Dee River. Most of the study area is nearly level to gently sloping, but some areas along streams and drainage ways are sloping to moderately steep. The soils on flood plains are nearly level and subject to frequent flooding.

Soils in the watershed were formed mostly in loamy and clayey fluvial sediments that originated in the Piedmont and Blue Ridge Mountains (Fig. 1). They are mostly deep and consist mainly of siliceous sand in the surface and kaolinitic clay in the subsurface. Predominant soils in the area are highly-weathered Ultisols, including 43% Paleudults, 19% Kandiudults, 14% Paleaquults, and 7% Hapludults. Representative soils in the uplands include the soil series of Norfolk (Typic Kandiudults), Noboco (Oxyaquic Paleudults), Goldsboro (Aquic Paleudults), Faceville

(Typic Kandiudults), Orangeburg (Typic Kandiudults), and Emporia (Typic Hapludults). Oval depressions known as Carolina bays occur throughout the Southern Coastal Plain. The poorly drained Rains (Typic Paleaquults) and Coxville (Typic Paleaquults) series typically occur in the bays, but also occur as irregular delineations. The Bonneau (Arenic Paleudults) and Blanton (Grossarenic Paleudults) sands are found on narrow rims around the bays as well as on flat upland landscapes. There are also very poorly drained soils such as Johnston (Cumulic Humaquepts) and Pamlico (Terric Haplosaprists) series that occur on the stream floodplains.

The majority of the watershed is in woodland. Pasture is of limited extent. About 30% of the land use in the area is for cultivated crops. The principal crops are tobacco, wheat, soybeans, cotton, corn, peanuts, and small grains. Soil drainage, hydrologic group, surface thickness, texture, and structure are among the most important properties for land-use interpretations in the watershed. The variability of these soil properties was thus examined in this study along with the soil taxonomic component delineations. These soil properties were determined based on the soil series descriptions in the survey area and the interpretations of typical pedon of each soil series.

2.1.2. Methodology

Independent soil maps were developed through standard soil surveys at two scales—1:7920 (Order I) and 1:24,000 (Order II). The Order II soil survey was conducted by the personnel of the USDA-Natural Resources Conservation Services (NRCS) for the entire watershed following the established procedures (Soil Survey Division Staff, 1993). Aerial photographs of 1:24,000 were used as the base maps for delineating soil boundaries. It is perceived in soil surveys that soils in a given area occur in a pattern that is related to geology, landform, relief, and natural vegetation of the area. Thus, limited field investigations of pedons, supplemented by an understanding of soil-landscape relationships, are considered sufficient to verify predictions of the kinds of soil in a study area and to determine soil boundaries (Soil Survey Division Staff, 1993). Field verifications were made at the Order II level of survey by traversing the watershed (normally at right angle to the slope gradients) and crossing as many predicted soil boundaries as possible. In each selected location, the soil was characterized and classified through augering to two meters. The number of sites investigated was determined according to the position in the landscape. In some areas only one or two sites per delineation were sufficient; while in others up to 10 sites per delineation were made. A total of 58 map units (consisting of 56 consociations and 2 complexes) were used at this level of survey. After field verifications, soil boundaries were finalized on the aerial photographs, then transferred to orthophotograph, and finally to a mylar for scanning into a Geographic Information System (GIS).

The soils in the 341 ha cropped areas of the Pee Dee Center were further surveyed at the Order I level on a 30.4 m × 30.4 m grid. Aerial photographs of the area at the scale of 1:7920 were used as the base maps. A base line was first established from which a grid was located. Each node of the grid was numbered. Nodes that intersected with roads were used as benchmarks. The soil at each node was examined and classified by augering the soil to 2 m. If two adjacent points showed different soils, the soil halfway between the two points was further investigated. After each soil was identified, some soils were further grouped by their surface thickness, surface texture, or other important morphological features. There were a total of 28 consociations used in this level of survey for the area investigated. Boundary lines separating each soil were finalized on the aerial photographs and then transferred to orthophotograph for digitizing into a GIS.

The State Soil Geographic Database (STATSGO) soil map at the scale of 1:250,000 (Order IV) for the watershed was obtained from the USDA-NRCS National Cartography and GIS Center in Fort Worth, TX on a CD-ROM (USDA-NRCS, 1994). This CD-ROM contains state-level general soil maps and attribute data associated with each map unit interpretation. The STATSGO maps were compiled by the NRCS through generalizing more detailed soil survey maps, often county level soil maps that are at the scale of Soil Survey Geographic Database (SSURGO) (USDA-NRCS, 1995). Where SSURGO-level maps were not available, data on geology, topography, vegetation, climate, and Landsat images of the area were assembled (Reybold and TeSelle, 1989). The latter was the case for the watershed under study, as no detailed soil survey had been done in the past. A total of six soil associations were depicted on the

STATSGO map for the entire watershed, and only two associations for the croplands of the Pee Dee Center.

The three soil maps were analyzed in a GIS. Coincidence reports containing areal percentages of soil components on one map versus the other were generated. Component units examined in this study included soil series, similar soils (i.e., much alike to the named soil of a map unit in most properties that do not affect major interpretations), and several higher taxonomic units (including soil great group, suborder, and order). Selected soil properties were used to re-aggregate the map units, resulting in a number of secondary interpretive maps including surface thickness, surface texture, texture in control section, surface and subsurface pedality (only the shape of peds considered in this study), soil hydrologic group, and natural drainage.

To evaluate the overall purity of a thematic map, area-weighted mean purity P_m (%) was calculated by:

$$P_\mathrm{m} = \frac{1}{100}\int_{i=1}^{n}(P_i A_i), \tag{1}$$

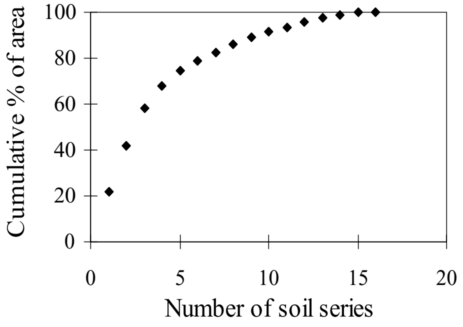
where P_i (%) is the purity of unit i on a thematic map of a higher order as compared to a lower order map, A_i (%) is the percent area of unit i on the map, and n is the total number of map units (excluding water bodies). For the Order II map, P_i was determined according to the Order I delineations; whereas for the STATSGO map, P_i was calculated based on the Order II delineations. Another index of the overall purity of a thematic map is the arithmetic average of all map units' purity $P_\mathrm{a} = \int_{i=1}^{n}(P_i)/n$. The index P_m should be a more appropriate representation of the overall purity of a thematic map than P_a, because the soils in the study area had significantly different areal coverages. For example, the top ten soil series of the largest extent in the watershed accounted for nearly 80% of the total watershed area (Fig. 2). Therefore, the purity of these soil map units should place more weight in determining the overall map purity.

2.2. *Results and discussion*

2.2.1. *Soil component variability within map units*

The total areal extent of major soil components was generally close to each other between the Order I and II maps (Fig. 3). However, there was a lack of soil boundary matching between the two maps and the spatial distributions of the soils on the two maps did not necessarily coincide. This is attributed to the nature of different survey methodologies used and the two base maps of different scales in each of the two surveys. Nevertheless, for each consociation delineation on the Order II map, 23–68% of the area coincided with the same soil series consociation on the Order I map (Table 1). The remainder consisted of 6–13 other series (Fig. 4a). When similar series were included, the purity of the delineations at the Order II level increased to 36–85%, with a mean P_a of 62% and P_m of 68% (Table 1). Taxonomic purity of the Order II map was almost 100% at soil order level, but ranged from 0 to 73% at great group level. Earlier studies have shown that compositional purities for soil map units represented by taxonomic units were commonly <50% (e.g., Wilding et al., 1965; McCormack and Wilding, 1969; Bascomb and Jarvis, 1976; Mokma, 1987; Nordt et al., 1991). Map units rarely comprise more than 40–50% of the soils named in map units (e.g., Mokma, 1987; Nordt et al., 1991; Wilding et al., 1994). This is not as serious as it may first appear,

(a) The Pee Dee Center in the Backswamp Watershed



(b) The entire Backswamp Watershed

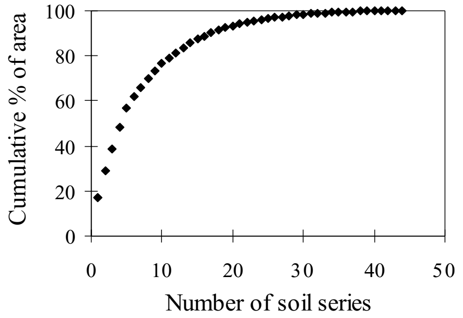


Fig. 2. Cumulative areal distribution of the soil series: (a) at the Pee Dee Center and (b) in the entire Backswamp Watershed.

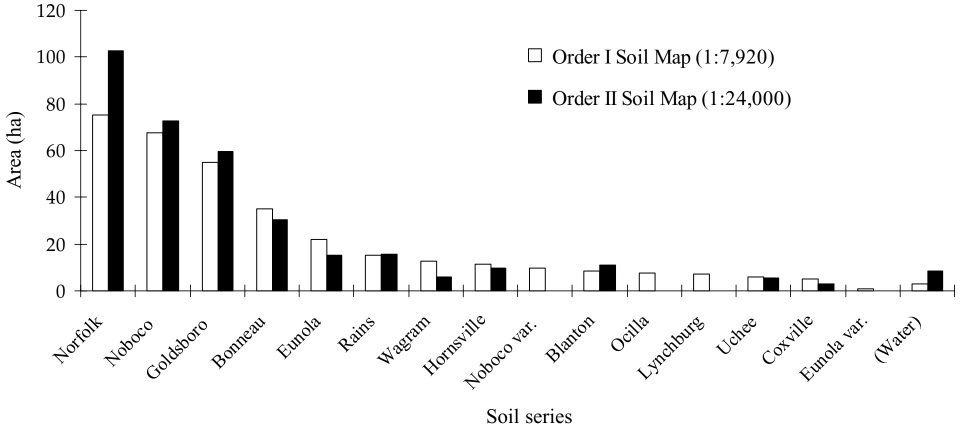


Fig. 3. Comparison of total area of each soil series identified on the Orders I and II maps for the croplands at the Pee Dee Center.

because the interpretive purity for most of these units is generally higher (see Tables 1 and 2 and the following section for further discussion). Note that the area-weighted mean purity P_m was 3–25% higher than the corresponding simple average purity P_a for the Order II map (Table 1).

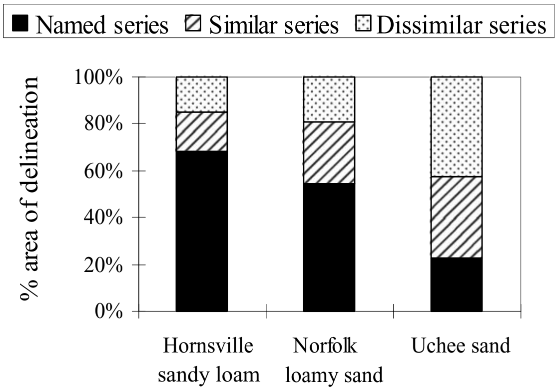
There were four soil series identified on the Order I map (i.e., Lynchburg, Ocilla, Noboco variant, and Eunola variant) that were not delineated on the Order II map. These were soils of minor extent in the watershed and each covered <5% of the area (Fig. 3). Thus, they were intentionally included in other soils (mostly the Goldsboro and Norfolk series) in the Order II survey.

The Order II map was used to examine the reliability of the existing STATSGO map for the watershed. Because associations were used in the STATSGO map unit designations, while consociations were used in the Order II mapping, the purity of the STATSGO map units was determined by encompassing all named soils in their unit designations. Thus, unlike the comparison between the Order I and II maps that both used soil consociations as mapping units, the comparison

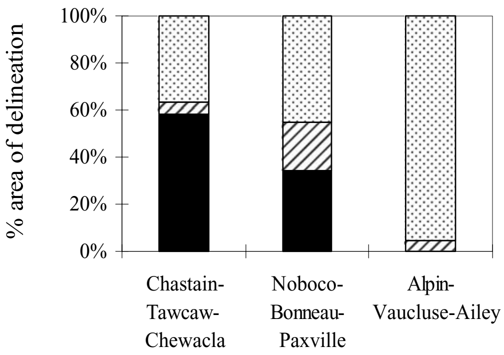
Table 1
Descriptive statistics of the composition and property purities (%) of the Order II soil map as compared to the Order I delineations for the croplands at the Pee Dee Center in the Backswamp Watershed

Theme	Overall purity, P_m (%)	Individual map unit purity, P_i (%)				
		Mean (P_a)	S.D.	Minimum	Maximum	n[a]
Composition purity (%)						
Soil series (named in consociations)	51.1	48.2	13.9	22.6	68.1	12
Similar series	68.1	62.0	14.3	35.8	84.8	12
Great group	64.8	40.1	31.9	0.0	73.4	6
Suborder	92.1	73.1	30.3	51.7	94.6	2
Order	99.8	99.8	0.0	99.8	99.8	1
Property purity (%)						
Surface texture	64.9	61.4	23.1	34.8	76.7	3
Surface thickness	84.8	68.5	19.0	51.6	89.1	3
Surface ped shape	79.4	74.7	15.2	63.9	85.5	2
Control section texture	82.8	71.9	10.0	64.3	85.8	4
Control section ped shape	70.2	72.8	22.2	48.5	100.0	5
Hydrologic group	73.1	55.9	19.4	32.3	78.8	5
Natural drainage	79.4	67.3	21.1	43.4	83.8	3

[a] n is the number of corresponding map units.



(a) Soil consociations of the Order II map



(b) Soil associations of the STATSGO-scale map

Fig. 4. Component variability of: (a) three soil consociations (representing the best, average, and the worse scenarios) of the Order II map in the croplands at the Pee Dee Center as compared to the Order I delineations and (b) three soil associations (representing the best, average, and the worse scenarios) of the STATSGO map as compared to the Order II delineations in the Backswamp Watershed.

between the Order II (representing SSURGO-level soil map) and STATSGO maps was only an approximation. The six associations used on the STATSGO map for the watershed reflected 0–59% in area size of named soil series (Table 2 and Fig. 4b). When the concept of similar soils was applied, the purity of the STATSGO map units increased to a mean P_a of 36% and P_m of 45% (Table 2). Some named series of the STATSGO map units did not exist in the watershed. This was because the names of soil associations used on the STATSGO map were constructed based on an area larger than the watershed under study and/or because an older set of series names was used when constructing the STATSGO.

2.2.2. Soil property variability within map units

Use of a specific soil property of interest may be preferred in conveying spatial variability. The area-weighted mean purity P_m of the Order II map ranged from 65% for surface texture to 85% for surface thickness (Table 1); whereas that of the STATSGO map, when compared with the Order II delineations, ranged from 60% for surface texture to nearly 90% for soil hydrologic group (Table 2). The interpretive purity of derived soil property maps varies considerably among soil properties and among different map units within the same soil map, but is generally higher than that of the original soil map. This is because of the possible similarity across map units for a given soil property and because soils within a map unit are assumed to have relatively homogeneous properties. However, soil maps are cartographic units representing abstract soil taxonomic constructs and inclusions. Unless within-map-unit variability could be delineated, the derived secondary interpretive maps will have smaller variability expressed. Consequently, simulation models incorporating multiple inputs including soil survey data would give less variable output maps than the original soil map. For example, Wösten et al. (1985) reported that the variability of calculated moisture supply capacities for soil series were considerably lower than the variability among the primary soil data sets as represented on the soil map. The soil map had 350 delineations, but the derived map showing areas with different classes of soil moisture supply capacity had only 100 units based on the outputs from a simulation model (Wösten et al., 1985). In other words, the functional properties of soils (either interpretive or model-simulated properties) would have less variability expressed than the original soil maps, unless within-map-unit variability could be delineated and quantified.

The fact that different soil series within a soil association map unit may share similar soil properties (e.g., soil hydrologic group class) suggests that the more generalized soil map (such as STATSGO) may not be less accurate than it may first appear. On the other hand, the use of soil association designations in the STATSGO map units may lead to the combination of two or more contrasting soil properties (e.g., soil

Table 2
Descriptive statistics of the composition and property purities (%) of the STATSGO soil map as compared to the Order II delineations for the entire Backswamp Watershed

Theme	Overall purity, P_m (%)	Individual map unit purity, P_i (%)				
		Mean (P_a)	S.D.	Minimum	Maximum	n[a]
Composition purity (%)						
Soil series (named in associations)	24.3	19.3	23.0	0.0	58.5	6
Similar series	45.2	35.8	23.8	4.7	63.4	6
Great group	38.8	30.2	24.4	0.0	63.3	6
Suborder	80.7	69.0	18.0	46.6	87.3	4
Order	80.7	64.0	19.9	47.1	86.0	3
Property purity (%)						
Surface texture	59.5	51.9	29.9	0.0	91.8	6
Surface thickness	86.8	79.3	12.8	67.4	92.8	3
Surface ped shape	82.1	58.1	37.4	5.7	93.7	4
Control section texture	75.9	63.1	35.0	9.3	94.2	5
Control section ped shape	76.6	56.3	36.1	5.6	90.9	5
Hydrologic group	89.8	80.6	15.9	63.3	95.0	4
Natural drainage	63.9	65.0	10.1	53.8	81.2	5

[a] n is the number of corresponding map units.

textural classes) into one map unit, which may not be desirable in modeling. The results in Tables 1 and 2 also show that soil map unit purities vary considerably among different map units within the same soil map and among different soil properties.

3. Case study II: soil variability at four scales using nested hierarchical sampling design

3.1. Materials and methods

3.1.1. Study area

The Minnesota River Basin, comprising approximately 3.9 million ha in southern Minnesota (Fig. 5), is located in the Central Iowa and Minnesota Till Prairies Major Land Resource Area (USDA-SCS, 1981). The majority of the soils in the Basin was formed in a calcareous glacial till deposited during the Wisconsin glaciation (Cummins, 1965; Lewis et al., 1967; Murray, 1985). Annual precipitation ranges from 550 mm in the west to 813 mm in the east. During pre-European settlement, much of the watershed was covered by prairie vegetation with hardwood forests in the river valleys. Currently over 90% of the area within the Basin is used for the production of various agricultural commodities, predominantly corn and soybean. The study area has similar parent material, vegetation, and time of soil formation, thus permitting the examination of the impacts of climate and topography (landscape positions) on soil variability.

Three locations in each of the three regions (Waseca, Lamberton, and Morris) within the Minnesota River Basin were chosen for studying soil spatial variability (Fig. 5). In each of the three regions, sampling locations were chosen within a single STATSGO map unit. The selected map units were dominated by the Clarion, Nicollet, and Webster soil series for the Waseca region; the Ves, Normania, and Webster soil series for the Lamberton region; and the Forman, Hamerly, and Parnell soil series for the Morris region (Table 3). Because of the climatic gradient present in the Basin (Fig. 5), these soils represent a climosequence in relation to spatial variability.

Several locations at each region were selected for sampling based on the presence of the above soil series, provided that they were mapped as adjacent polygons along a hillslope in the Order II soil survey. Of the locations meeting these criteria, three were chosen based on accessibility and minimal human impacts (except agriculture). Each of the sampling locations within the Waseca and Lamberton regions was under the most common crop rotation throughout the Basin, i.e., corn (*Zea mays* L.)–soybean [*Glycine max* (L.)

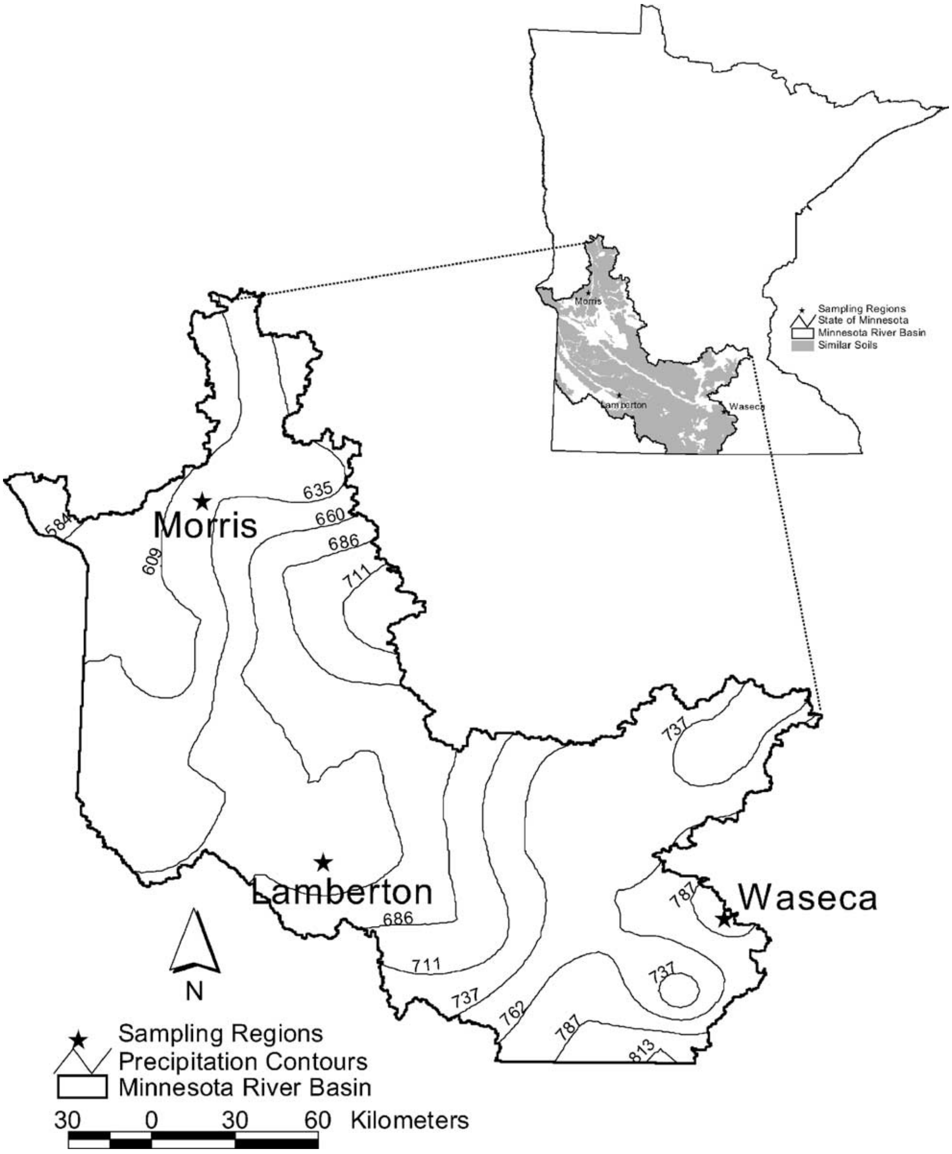


Fig. 5. The 30-year average annual precipitation contours (in mm) for the Minnesota River Basin, where annual rainfall increases from the west to the east. The three soil sampling regions are shown in the inset map, where the extent of the soils similar to the ones under this study within the Basin is indicated in shade (71% of the total area).

Merr.] rotation. Within the Morris sampling region, two locations sampled were under management by the US Fish and Wildlife Service's Waterfowl Production Area program. These sites have been converted from agricultural land to prairie grasses, and not artificially drained or have had tile lines disconnected to facilitate ponding of water. The third sampling location within the Morris region is under constant alfalfa (*Medicago sativa* L.).

3.1.2. Methodology

The soil sampling design used in this study was similar to that of Edmonds et al. (1985) with a few modifications. Three hillslopes (catenas), each composed of

Table 3
Soil series investigated in the three regions of the Minnesota River Basin

Soil series	Taxonomic classification (great group)	Composition (%) within each STATSGO unit	Hillslope position	Slope (%) range	Drainage class
Morris region					
Forman	Calcic Argiudoll	5	Summit	2–6	Well drained
Hamerly	Aeric Calciaquoll	10	Backslope	2–6	Somewhat poorly drained
Parnell	Vertic Agriaquoll	4	Depression	0–1	Very poorly drained
Lamberton region					
Ves	Calcic Hapludoll	26	Summit	2–6	Well drained
Normania	Aquic Hapludoll	10	Backslope	2–6	Somewhat poorly drained
Webster	Typic Endoaquoll	10	Depression	0–1	Poorly drained
Waseca region					
Clarion	Typic Hapludoll	30	Summit	2–6	Moderately well drained
Nicollet	Aquic Hapludoll	19	Backslope	2–6	Somewhat poorly drained
Webster	Typic Endoaquoll	16	Depression	0–1	Poorly drained

an upland, a backslope, and a depressional soil (Fig. 6), were selected within each of the three sampling regions (Fig. 7). At each hillslope, three clusters were located within each map unit (Fig. 7). The first cluster (A) was located randomly while the other two clusters (B and C) were at fixed distances from cluster A, so that cluster B was *x* distance from cluster A and cluster C was 2*x* distance from cluster B. The values used for *x* (20–60 m) varied as a function of map unit size and shape. Within each cluster four points were selected for sampling (Fig. 7). The points were arranged so that there was a center point, from which

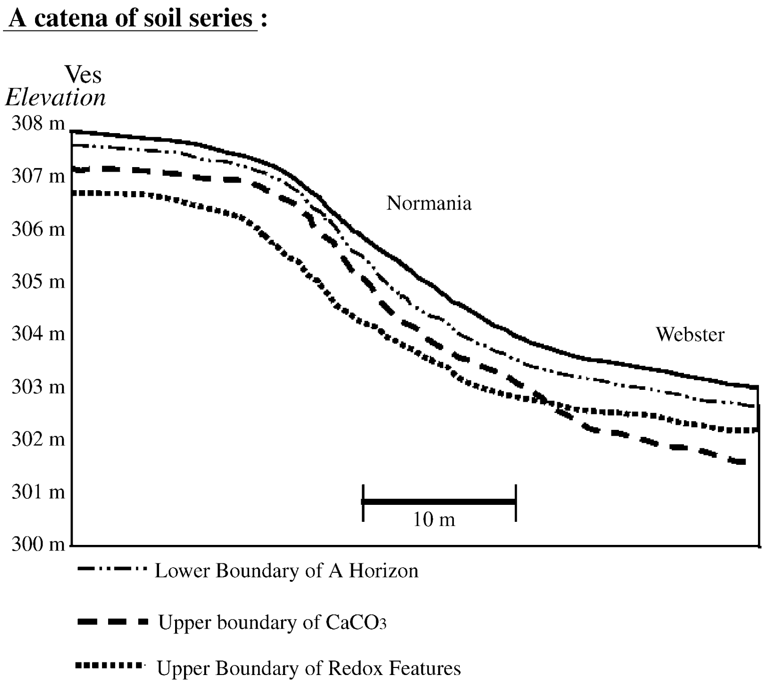


Fig. 6. Schematic cross-sectional view of a representative catena along a hillslope transect in the Lamberton region, depicting typical depth of A horizon thickness, depth to calcium carbonate, and depth to redoximorphic feature.

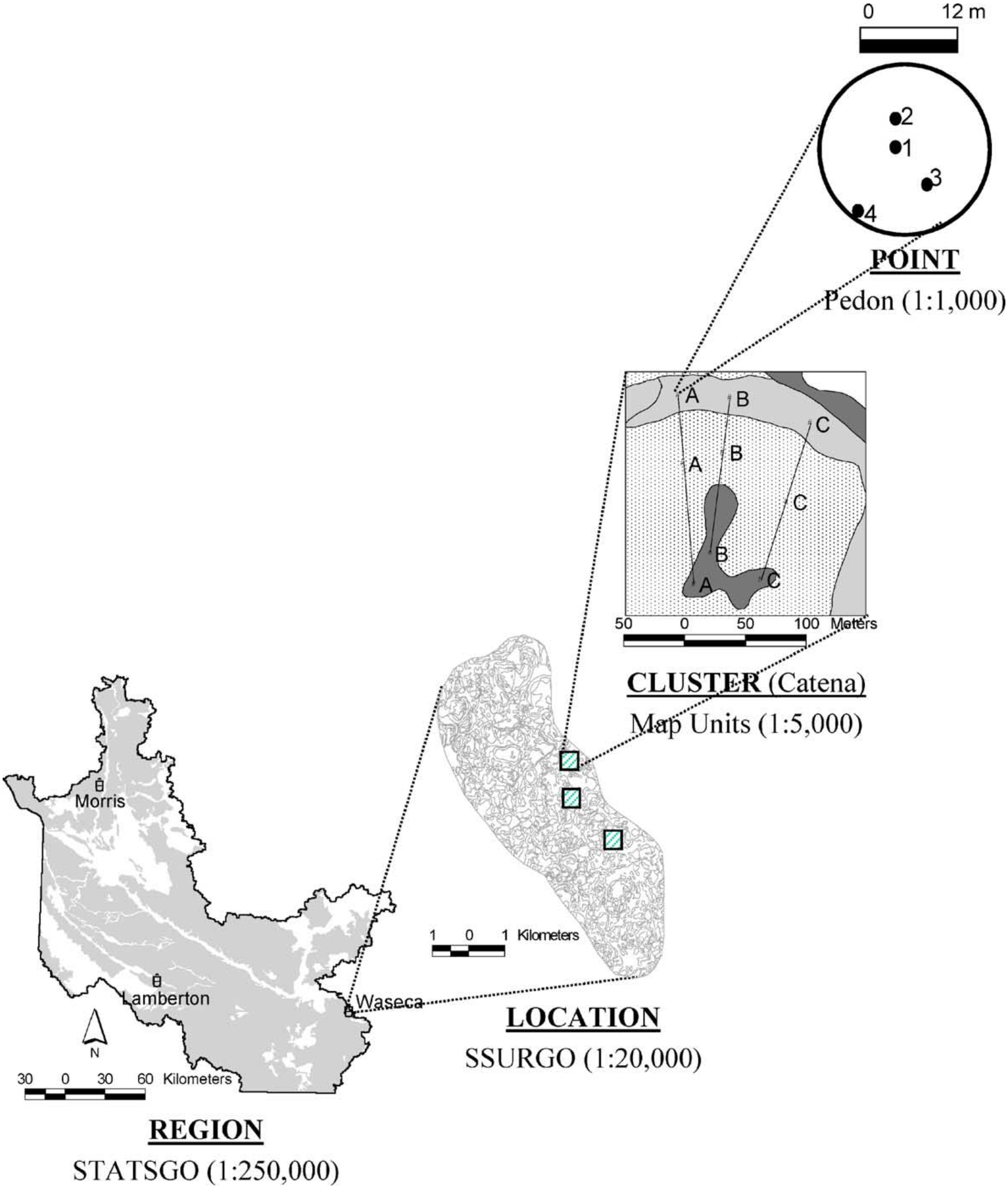


Fig. 7. Schematic representation of the hierarchical sampling design used in this study. Map scale is indicated for each of the four sampling levels. See the text for further details.

three other points were measured so that (i) point 2 is three meters downslope from the central point; (ii) point 3 is 6 m from the central point at an angle of 135° from the downslope direction; and (iii) point 4 is 12 m from the central point at an angle of 225° from the downslope direction.

At each point the soil was described following the standard procedures of soil surveys (Soil Survey Division Staff, 1993) to a depth of two meters or to calcium carbonate ($CaCO_3$) if it was shallower. Detailed soil morphological properties were examined for each point, including depth of A-horizon, depth to $CaCO_3$, texture, color, and horizon designation. Bulk samples were collected from the surface horizon at each point for laboratory analysis of pH (1:1 water dilution) (Soil Survey Laboratory Staff, 1996). Actual soil pH values are reported here, but H^+ concentrations were used for the laboratory analysis.

Each soil property was assumed to be explained by the nested linear model (Edmonds et al., 1985; Webster and Olive, 1990):

$$Y_{ijkl} = \mu + L_i + C_{ij} + P_{ijk} + \varepsilon_{ijkl}, \tag{2}$$

where μ represents the overall mean value of a soil property in a given region, L_i represents the effect of a given location, C_{ij} represents the effect of a given cluster; P_{ijk} represents the effect due to a particular point, and ε_{ijkl} represents the residual or unexplained variance. L_i, C_{ij}, P_{ijk}, and ε_{ijkl} were assumed to be independent random variables possessing means of zero and variance of σ_L^2, σ_C^2, σ_P^2 and σ_ε^2, respectively (Edmonds et al., 1985; Webster and Olive, 1990).

Using the general linear model procedure, an analysis of variance (ANOVA) was performed at three levels: (i) among hillslope locations by sampling region, (ii) among clusters nested within map units at each hillslope, and (iii) among sampling points in each cluster. Significant differences ($\alpha = 0.05$) in mean soil property values were determined from the ANOVA output for each level of analysis. The ANOVA also calculates mean square (MS) values for each level in the analysis. The MS values were used in order to partition the amount of variability attributed to each level in the sampling design. The variance at each level of the sampling design was estimated as (Edmonds et al., 1985):

$$\sigma_L^2 = \frac{\mathrm{MS}_L - \mathrm{MS}_C}{rpc}, \tag{3a}$$

$$\sigma_C^2 = \frac{\mathrm{MS}_C - \mathrm{MS}_P}{rp}, \tag{3b}$$

$$\sigma_P^2 = \frac{\mathrm{MS}_P - \mathrm{MS}_\varepsilon}{r}, \tag{3c}$$

$$\sigma_T^2 = \sigma_L^2 + \sigma_C^2 + \sigma_P^2 + \sigma_\varepsilon^2, \tag{3d}$$

where Eq. (3a) is the calculation for the variance at the location level within a given region, Eq. (3b) is the calculation for the variance at the cluster level within a given location, Eq. (3c) is the calculation for the variance at the point level at a given cluster, and Eq. (3d) is the calculation for the total variance. The values r, p, and c represent the number of points per cluster (r), the number of clusters per location (p), and the number of locations per region (c). The percent of the total variance attributed to each level in the sampling design was calculated by taking the variance at a particular level divided by the total variance.

3.2. Results and discussion

3.2.1. Effects of soil regions on soil variability

There were significant differences ($P < 0.001$) in the mean depth to $CaCO_3$ among the three soil regions in an overall comparison and when the summit and backslope positions were compared (Table 4). The data show a general trend of increasing mean depth to $CaCO_3$ from west to east across the Basin. This result is consistent with the precipitation gradient presented in the Basin (Fig. 5), corresponding to leaching gradient. The mean depth to $CaCO_3$ was not significantly different at the depressional landscape positions among the three regions, indicating a change of primary influence from regional climate to a more local variability such as hydrology. These depressional soils were wetter than the upslope soils and were more strongly influenced by local or regional hydrologic patterns as compared to average annual precipitation.

Significant pH differences in surface soils were observed among the three soil regions (Table 4). The wetter regions (Lamberton and Waseca) had similar pH values, but the drier Morris region had significantly higher pH values (especially in summit and backslope hillslope positions). This suggests the drier climate leads to less leaching of $CaCO_3$ from the near-surface soils. A negative correlation between surface soil pH

Table 4
Descriptive statistics and significance tests (*P*-values) of the three soil properties by soil region and hillslope position (soil series) in the Minnesota River Basin

Soil region	Soil property	Hillslope position (soil series)											
		Summit						Backslope					
		Mean	*P*-value	S.D.	CV (%)	Minimum	Maximum	Mean	*P*-value	S.D.	CV (%)	Minimum	Maximum
		(Forman)						(Hamerly)					
Morris region	A horizon thickness (cm)	29	*0.060*	10	34.5	14	62	35	*0.045*	17	48.6	18	105
	Depth to $CaCO_3$ (cm)	26	*0.118*	14	53.8	0	62	20	*0.041*	17	85.0	0	63
	Surface soil pH	7.56	*0.740*	0.34	4.5	6.56	8.18	7.87	*0.247*	0.18	2.3	7.47	8.31
		(Ves)						(Normania)					
Lamberton region	A horizon thickness (cm)	25	*0.070*	9	36.0	5	53	49	*0.000*	23	46.9	24	103
	Depth to $CaCO_3$ (cm)	68	*0.001*	40	58.8	0	146	91	*0.094*	18	19.8	62	130
	Surface soil pH	5.78	*0.010*	0.97	16.8	5.35	8.25	5.63	*0.917*	0.38	6.7	5.13	6.60
		(Clarion)						(Nicollet)					
Waseca region	A horizon thickness (cm)	31	*0.334*	15	49.2	15	86	33	*0.042*	9	27.3	20	59
	Depth to $CaCO_3$ (cm)	126	*0.050*	36	28.6	72	199	103	*0.009*	42	40.8	20	199
	Surface soil pH	5.71	*0.000*	0.85	14.9	4.85	7.60	6.03	*0.004*	0.79	13.0	5.05	8.03
Hillslope position Overall	A horizon thickness (cm)	29	*0.105*	12	41.4	5	86	39	*0.000*	19	48.7	18	105
	Depth to $CaCO_3$ (cm)	74	*0.000*	52	70.3	0	199	71	*0.000*	46	64.8	0	199
	Surface soil pH	5.92	*0.000*	1.03	17.4	4.85	8.25	5.96	*0.000*	1.03	17.3	5.05	8.31

Soil region	Soil property	Hillslope position (soil series)											
		Depression						Soil region overall					
		Mean	*P*-value	S.D.	CV (%)	Minimum	Maximum	Mean	*P*-value	S.D.	CV (%)	Minimum	Maximum
		(Parnell)											
Morris region	A horizon thickness (cm)	68	*0.280*	23	33.8	30	114	44	*0.000*	24	54.7	14	114
	Depth to $CaCO_3$ (cm)	99	*0.137*	48	48.5	0	199	48	*0.000*	47	97.3	0	199
	Surface soil pH	6.97	*0.000*	0.58	8.3	6.08	8.10	7.47	*0.001*	0.45	6.0	6.08	8.31
		(Webster)											
Lamberton region	A horizon thickness (cm)	53	*0.013*	16	30.2	30	87	42	*0.000*	21	49.2	5	103
	Depth to $CaCO_3$ (cm)	93	*0.005*	58	62.4	27	199	84	*0.024*	43	51.4	0	199
	Surface soil pH	6.53	*0.006*	0.62	9.5	5.70	8.00	5.98	*0.000*	0.82	13.7	5.13	8.25
		(Webster)											
Waseca region	A horizon thickness (cm)	52	*0.099*	16	30.8	30	103	39	*0.000*	16	42.1	15	103
	Depth to $CaCO_3$ (cm)	90	*0.000*	57	63.3	0	199	106	*0.002*	48	45.6	0	199
	Surface soil pH	6.22	*0.231*	0.76	12.2	5.36	8.03	5.99	*0.017*	0.81	13.5	4.9	8.03
Hillslope position Overall	A horizon thickness (cm)	57	*0.000*	20	35.1	30	114	42	*0.129*	21	50.4	5	114
	Depth to $CaCO_3$ (cm)	93	*0.625*	54	58.1	0	199	79	*0.000*	52	65.5	0	199
	Surface soil pH	6.48	*0.003*	0.72	11.1	5.36	8.1	6.12	*0.000*	0.94	15.4	4.9	8.31

value and the depth to $CaCO_3$ was found among all the soil samples collected ($r = -0.535$, $P < 0.001$).

A significant difference in the mean thickness of A-horizon was found for the soils in the backslope and depressional landscape positions among the three regions, but not for the summit positions (Table 4). The overall difference among the three regions in the mean thickness of A-horizon was also not statistically significant ($P = 0.129$). No obvious trend in A-horizon thickness was observed from the west to the east in the Basin among the backslope and summit soils. But the depressional soils and the overall average of all soils in the three regions appeared to have a decreasing trend in A-horizon thickness from the west to the east, corresponding to increasing precipitation. In the Minnesota River Basin, where 90% of the soils have been disturbed by agricultural tillage, this trend may indicate increasing soil erosion by water with a corresponding increase in precipitation.

Although some variations of soil properties were observed for the Webster series (depressional hydric soil) within the Waseca and Lamberton regions, there was no significant difference between these two regions in terms of the Webster's A-horizon thickness, depth to $CaCO_3$, and surface soil pH ($P = 0.682$, 0.634, and 0.082, respectively). This suggests that the differences in the Webster soil properties were not affected as greatly by regional factors (such as climate) as by local processes (such as erosion/deposition and transformation/translocation along a hillslope, and recharge/discharge hydrology in depressional areas).

3.2.2. *Effects of hillslope positions within a region on soil variability*

Among the three hillslope positions in each of the three regions there were significant differences in all three soil properties investigated (Table 4). These differences were likely due to the differences in hillslope curvatures and their influence on water movement. However, not all soil properties showed similar trends in their differences. Among the three soil properties studied, A-horizon thickness had the most obvious trend with hillslope positions; that is, A-horizon thickness was greatest in the depressional soils and decreased from depression to backslope and from backslope to summit, presumably due to erosion and deposition.

Depth to $CaCO_3$ was greater in the depressions than in the backslope and summit positions in the Morris and Lamberton regions, while the opposite trend was observed in the Waseca region. Surface soil pH values tended to be the highest in the depressions in the wetter regions of Waseca and Lamderton, while the opposite was true in the drier Morris region. Such contrasting trends between the drier Morris region and the wetter Waseca region, with the Lamberton region intermediate, suggests that the impacts from the local topography and the associated flow and transport processes are important in determining local soil variability. In the drier Morris region, local accumulation of water and elevated leaching in depressional areas were significant; while in the wetter Waseca region, higher annual precipitation gave rise to higher leaching in the upslope positions (with sufficient permeability in the soil profiles), and excess water in the depressional areas lead to periods of near-surface saturation in the soil profiles and thus restricted $CaCO_3$ leaching because of poor drainage (Table 3). In some locations, soils received surface water inputs that carried dissolved $CaCO_3$ or had discharge hydrology where the ground water was supplying the $CaCO_3$, while soils in other areas had recharge hydrology where water percolated through the soil profile carrying the $CaCO_3$ to greater depths. Some of these soils are classified as hydric soils (e.g., Webster and Parnell series), which means saturated conditions most likely persist frequently or long enough so the redox chemistry tends to equilibrate soil pH values near neutral.

3.2.3. *Soil variability within the STATSGO and SSURGO map units*

Table 4 shows that significant variability exists within each of the three STATSGO map units (i.e., three regions). In the Morris region, for example, A-horizon thickness varied from 14 to 114 cm (with a CV of 54.7%), depth to $CaCO_3$ ranged from 0 to 119 cm (with a CV of 97.3%), and surface soil pH varied from 6.08 to 8.31 (with a CV of 6.0%). Similar variability of the three soil properties was also observed in the other two wetter regions, but with somewhat lower CV values for A-horizon thickness and depth to $CaCO_3$ and slightly higher CV values for surface soil pH values.

Within each of the STATSGO map unit, three SSURGO-level map units (i.e., consociations of soil

Table 5
Percentage (%) of total variability contributed by each of the hierarchical sampling levels for the three soil properties in the three regions of the Minnesota River Basin

Soil region (STATSGO unit)	Soil property	Hillslope position (SSURGO soil series)												Soil region overall			
		Summit				Backslope				Depression				Overall average			
		Location	Cluster	Point	Residual	Location	Cluster	Point	Residual	Location	Cluster	Point	Residual	Location	Cluster	Point	Residual
		(Forman)				(Hamerly)				(Parnell)							
Morris region	A horizon thickness	2	28	19	52	2	1	82	15	3	0	50	47	2	10	50	38
	Depth to $CaCO_3$	69	1	19	11	41	0	54	5	0	1	62	37	37	1	45	18
	Surface soil pH	99	0	0	1	100	0	0	0	11	32	49	8	70	11	16	3
		(Ves)				(Normania)				(Webster)							
Lamberton region	A horizon thickness	2	1	75	22	0	42	47	11	2	17	63	18	1	20	62	17
	Depth to $CaCO_3$	10	19	65	7	39	0	54	7	0	18	70	12	16	12	63	9
	Surface soil pH	4	11	76	10	11	0	22	67	4	25	51	20	6	12	50	32
		(Clarion)				(Nicollet)				(Webster)							
Waseca region	A horizon thickness	1	0	67	32	12	23	28	37	3	0	88	10	5	8	61	26
	Depth to $CaCO_3$	20	5	57	18	10	23	47	20	0	26	72	2	10	18	59	13
	Surface soil pH	0	47	35	18	5	34	36	25	1	0	58	41	2	27	43	28
Hillslope position Overall	A horizon thickness	2	10	54	35	5	22	52	21	3	6	67	25	3	12	58	27
	Depth to $CaCO_3$	33	8	47	12	30	8	52	11	0	15	68	17	21	10	56	13
	Surface soil pH	34	19	37	10	39	11	19	31	5	19	53	23	26	17	36	21

series differentiated by hillslope positions along transects) showed the lowest CV for the surface soil pH value (2.3–16.8%), the greatest CV for the depth to $CaCO_3$ (19.8–85.0%), with the CV of A-horizon thickness in between 27.3 and 49.2% (Table 4). Such variability difference among the three soil properties along hillslope positions is reflected in Fig. 6, where depth to $CaCO_3$ varied most significantly.

3.2.4. *Partition of total variability contributed by each of the hierarchical sampling levels*

The location-level variability within the STATSGO map unit in the Morris region accounted for 41–100% of the total variability for the summit and backslope soils in terms of the depth to $CaCO_3$ and surface soil pH value; while the corresponding variability was only 0–39% in the other two wetter regions (Table 5). For A-horizon thickness across the three regions and the three soil properties in all depressional soils, location-level variability within the STATSGO map unit accounted for almost none of the total variability (0–3%, except for the Nicollet A-horizon thickness that had 12% and the Parnell surface soil pH that had 11%). Instead, most of the variability among the four hierarchical sampling levels for each of the three soil properties was at the point sampling level within a 12 m distance (mostly over 50%, with a range from 19 to 88%, except for surface soil pH value in the Forman and Hamerly series) (Table 5). This suggests a great deal of local variability related to short-range variations in hydrology and hillslope curvature and an unknown degree of random variation. For instance, the depth to $CaCO_3$ is closely related to water movement through soils. Areas that are slightly concave are expected to focus water and have deeper infiltration, which dissolves and translocates $CaCO_3$ to greater depths. Burrough (1993) in his review of soil variability pointed out that considerable short-range differences in parent material, drainage, and biological activity (including human) can cause large differences in soil over short distances. Beckett and Webster (1971) also suggested that much of the total soil variation observed over longer distances may be present within the first few meters. Edmonds et al. (1985) reported that short-range variability ($\leq$7 m) dominated three soil map units at the Order II level for a number of soil properties. In terms of cluster sampling level, it accounted for 0–47% of the total variability, with an overall average of 12% for A-horizon thickness, 10% for depth to $CaCO_3$, and 17% for surface soil pH (Table 5). In terms of residual error, it accounted for 0–67% of the total variability, with an overall average of 27% for A-horizon thickness, 13% for depth to $CaCO_3$, and 21% for surface soil pH (Table 5). These results suggest that careful examination of short-range soil property variability should not be underestimated or overlooked in soil mapping, ecological modeling, and in applications such as precision agriculture.

At the hillslope scale, Milne's (1935) catena concept stated that soils along a hillslope are interconnected by the processes that occur along a hillslope (e.g., erosion, deposition, transformations, and translocations). As a result, soils may be quite different in various portions of a landscape, but these processes and relationships may be similar across a larger area. Numerous investigations of catenas have addressed this phenomenon (e.g., Veneman and Bodine, 1982; Evans and Franzmeier, 1986; Pennock and de Jong, 1990; Stolt et al., 1993; Khan and Fenton, 1994; Thompson et al., 1998). It follows that the greatest variability in certain soil properties within a physiographic region may occur along a hillslope rather than from one side of the region to the other (e.g., Pennock and de Jong, 1990; Wilding et al., 1994). This warrants a careful investigation and understanding of hillslope variability before making broad generalizations about the physiographic region in question. The soil-forming process that is considered to contribute the most to soil variability along a hillslope possessing similar parent material is hydrology (Hall and Olson, 1991; Moore et al., 1993; Thompson et al., 1997). Water movement affects transformations, translocations, additions, and losses to and from a soil profile. Differences in texture, porosity, bulk density, and structure of the soil result in differences in water movement through and across soils that result in varying soil properties, leading to considerable variability at the local scale.

4. Summary and conclusions

Enhanced understanding of soil variability across multiple scales is needed to improve the collections and utilizations of soils information for diverse applications. Generally speaking, soil variability is dictated by five space–time factors, i.e., spatial extent or area size, spatial resolution or map scale, spatial location and physiographic region, specific property or process, and time factor. Through the two case studies reported in this paper, it is clear that the mode and magnitude of soil variability as a function of scale are depended upon the soil location in the landscape and the soil property in question.

Proper use of soil survey maps requires a good understanding of soil component and property variability within a map unit at a given scale. Comparison of independent soil maps of different scales in a GIS provides an effective way to quantify soil map unit purity. The hierarchical sampling design is another useful approach for assessing soil property variability at multiple scales. The two case studies showed that considerable variability existed within the STATSGO and SSURGO soil map units. In the Backswamp Watershed in South Carolina, the area-weighted mean purity of soil taxonomic units and interpretive soil properties was in the range of 51.1–99.8% for the SSURGO-scale soil map and of 24.3–89.8% for the STATSGO-level map. In the Minnesota River Basin, the coefficient of variation within the STATSGO and SSURGO soil map units ranged from 2.3 to 85.0% for the three soil properties investigated, with the surface soil pH value being the least variable (2.3–16.8%), the depth to $CaCO_3$ being the most variable (19.8–85.0%), and the A-horizon thickness in between 27.3 and 49.2%. The varying degrees of composition and property purities of the SSURGO- and STATSGO-scale maps necessitate probabilistic approaches for assessing soil properties.

Causes of soil variability were shown to range from climate at the basin scale to localized effects of differential hydrology caused by the differences in landscape positions and soil characteristics. The majority of the variability for the soil A-horizon thickness, depth to $CaCO_3$, and surface pH in the Minnesota River Basin was at the point scale, accounting for over 50% of the total variability in most cases. The location-level variability within STATSGO map unit accounted for <5% of the total variability in most cases for the three soil properties studied, except for the summit and backslope soils in the Morris region where the location-level variability accounted for 41–100% of the total variability for the depth to $CaCO_3$ and surface soil pH value.

Despite the spatial variability at different scales, some regional and hillslope trends were observed in the Minnesota River Basin. The differences in the depth to $CaCO_3$ and surface soil pH follow a distinct pattern that corresponded to the increasing precipitation gradient from west to east in the Basin. Among the three hillslope positions in each of the three regions, significant differences in the three soil properties were observed. The A-horizon thickness had the most obvious trend with hillslope positions that showed an increase from summit to backslope and to depression. In terms of the depth to $CaCO_3$ and surface soil pH, contrasting trends were found between the drier Morris region and the wetter Waseca region, with the Lamberton region intermediate, indicating the impacts from the local topography and hydrology on short-range soil variability.

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