Geomorphic Objects and Scale in Digital Terrain Analysis for Digital Soil Mapping

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Abstract — **This paper presents our recent efforts on the two key issues in digital terrain analysis for digital soil mapping: quantification of spatial gradation of geomorphic objects and scale of digital terrain analysis. Geomorphic objects (such as slope positions, landform types) are rarely used as continuous variables in digital soil mapping. We developed a framework for characterizing and representing the spatial gradation of geomorphic objects. This framework consists of two major components: a fuzzy logic-based scheme for representing the spatial gradation and a prototype-based technique for quantifying the spatial gradation. Case studies in digital soil mapping have shown that the framework is effective in quantifying the spatial gradation of geomorphic objects. Our examination of scale in digital terrain analysis for digital soil mapping focuses on the following aspects: sensitivity analysis of computed terrain attributes and digital soil mapping to neighborhood size, and the relationship between neighborhood size and scale. Results show: 1) curvature measures are much more sensitive to neighborhood size than slope gradient and that terrain variables are more sensitive to neighborhood size at small neighborhood sizes than at large neighborhood sizes; 2) neighborhood size of digital terrain analysis has profound impact on the accuracy of digital soil mapping and the most accurate soil map is not obtained at the smallest neighborhood size; 3) There is no single spatial scale that can be unambiguously associated with a given neighborhood size and neighborhood size cannot be an adequate indicator of spatial scale.**

INTRODUCTION

Topographic condition is one of the most important soil-forming factors [1]. The wide availability of digital terrain data as well as the techniques for digitally deriving topographic attributes [2] greatly facilitates the use of digital terrain information in digital soil mapping. Among the studies in digital soil mapping examined by [3], about 80% of them employ topographic variables.

Two key issues in digital terrain analysis for digital soil mapping are the quantification of spatial gradation of geomorphic objects and scale of digital terrain analysis. Spatial gradation of geomorphic objects refers to the transition of one geomorphic object to another geomorphic object over space, such as the transition from shoulder slope to back slope. Information on this spatial gradation is rarely used because geomorphic objects (such as slope positions, landform types) are often considered as discrete, rather than continuous variables in digital soil mapping and other geographic modeling applications. Yet geographic processes over geomorphic objects are often continuous and gradual rather than abrupt. For example, soil erosion processes along a slope profile (from should slope to back slope to toe slope) are continuous. Furthermore, this spatial gradation of geographic processes often cannot be captured by topographic attributes (such as slope gradient) alone because topographic attributes contain only local topographic information and usually describe the geometric properties at a location on a terrain surface.

Examination of effect of spatial scale in digital analysis has primarily focused on the effects of spatial resolution of digital elevation model (DEM). Behrens et al.[4] and Smith et al.[5] recently examined effect window size in digital soil mapping. Their works show that the resolution of DEM is not as important as the window (neighborhood) size over which the terrain attributes are computed. Although these researches have led to the conclusion that the resolution effects really the manifestation of the effects of neighborhood sizes on terrain attributes, another question needs examination, namely how the effects of neighborhood size vary with the increase of neighborhood size and how this neighborhood size related to scale.

This paper presents our recent works on these two major issues through three case studies. The first examines the quantification of spatial gradation of geomorphic objects and its effects on digital soil mapping (Section 2). The second considers the effect of neighborhood size on digital soil mapping and the issues of relationship between neighborhood size and spatial scale (Section 3).

2. Spatial gradation of geomorphic objects

2.1 Quantification of spatial gradation

We believe that there are locations which capture (represent) the central concept of a geomorphic object type (such as should slope) better than other locations. These locations are treated as prototypes for that geomorphic object type and their membership in that geomorphic object type is 1. The membership of other locations in the object type is determined by comparing these locations with the prototypes of that geomorphic object type. The more similar the locations to any of the prototypes, the high the membership they have. In this way, spatial gradation of geomorphic objects is captured and quantified.

Based on the above idea, using slope positions as an example we developed a prototype-based approach to quantify the spatial gradation of geomorphic objects [6]. The approach employs a two-tier hierarchical system of slope positions as a basis for defining gradation among slope gradation. The first tier considers the spatial context down the slope profile and consists of five slope positions: ridge (summit), shoulder slope, back slope, foot slope, and valley. The second tier is a subdivision of three of the five first-tier slope positions (shoulder slope, back slope, and foot slope) based on surface curvature along the contour. They are further divided into convex (or divergent), planar, or concave (or convergent) in terms of contour curvature. Therefore, this slope position system contains a total of eleven slope positions: ridge, divergent shoulder slope, planar shoulder slope, convergent shoulder slope, divergent back slope, planar back slope, convergent back slope, divergent foot slope, planar foot slope, convergent foot slope, and valley.

In quantifying the spatial gradation of the slope positions, this approach consists of two parts. The first is to extract the prototypes for each slope position. The second is to compute the similarity between a given location and the prototypes of slope positions based on both the local topographic attributes and spatial context.

2.2 Effect on digital soil mapping

A case study was used to examine the usefulness of information on spatial gradation of slope positions for mapping soil organic matter content. The study area consists of two portions: One is about 4 km^2 used for model development; and the other is about 60 km^2 used for model extrapolation. The results of the evaluation show that the model based on the quantified spatial gradation predicts the SOM better than a multiple linear regression model (MLR) using topographic variables (Table 1). In addition, the information on spatial gradation of geomorphic objects can help us to identify where representative samples should be collected. Results in the model-development area show that the performance of the spatial gradation based model with 5 modelling points is comparable to that of the MLR developed with 48 points.

Table 1: Evaluation of predicted soil organic matter content in the top layer

Model	CC*	RMSE	Sample Used	Validation Points
Gradation	0.319	1.31	5	102
MLR	0.056	1.49	48	102

* CC: Correlation Coefficient

3. Scale of digital terrain analysis

3.1 Effects of neighborhood size

In this case study we examine effects of neighborhood size in two ways: 1) the sensitivity of terrain attributes to neighborhood size and 2) the impact of neighborhood size on accuracy of digital soil mapping.

We employed four basic terrain attributes (slope gradient, profile curvature, contour curvature) for examining the sensitivity of the terrain attribute values to the neighborhood size over which these attribute values were computed [7]. Fig. 1 shows the “relative change” across neighborhood. The “relative change” concept measures the difference in deviation from the mean between two consecutive neighborhood sizes at a point. It therefore provides a way to characterize the sensitivity across neighborhood size and it allows us to identify neighborhood sizes to which the terrain conditions are more or most sensitive. The results show that curvature measures are much more sensitive to neighborhood size than slope gradient and that terrain variables are more sensitive to neighborhood size at small neighborhood sizes than at large neighborhood sizes.

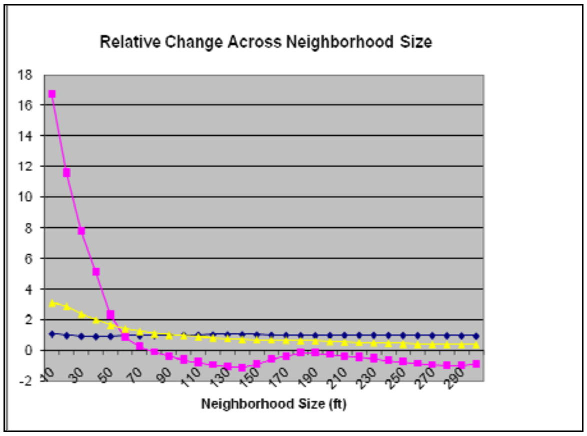

Figure 1: Relative change of deviation from the mean between two consecutive neighborhood sizes.

3.2 Effect on digital soil mapping

Effects of spatial processes on geographic patterns and vice versa manifest itself over a certain area. The interaction of geographic factors is a process of exchanging energy and matter and this exchange requires spatial extent (or a neighborhood) to be manifest. This neighborhood is referred to as the "effective neighborhood". Topography, as an important factor controlling the redistribution of energy and matter at local level, plays a key role in soil forming processes. The soil characteristics at a point are not purely dependent on the topographic conditions at this particular point but rather dependent on the topographic conditions over a certain area around this point because the redistribution of energy and matter needs an area of certain size to play out. We certainly expect that effective neighborhoods are different for different spatial processes.

Under the above notion, the assumption, that the accuracy of digital soil mapping will increase simply as the resolution of spatial data increases or the neighborhood size used decreases, may not always hold. Here we are trying to show how the impact of neighborhood size on digital soil mapping varies over a range of neighborhood sizes [5].

In this illustration we use the SoLIM approach as means to examine the impact of neighborhood size on digital soil mapping [8]. Terrain attributes (slope gradient, profile curvature and contour curvature) were used together with other environmental variables (non-terrain data, such as geology) as inputs to SoLIM for soil mapping. To examine the impact of neighborhood size on digital soil mapping we held constant both the non-terrain data and the knowledge-base describing the relationships between soil and its environment. We changed only neighborhood size, which in turn gave varying terrain derivatives. Thus with each neighborhood size for each DEM resolution, we obtain a version of the soil map using the SoLIM approach based on terrain derivatives that have been generalized at that neighborhood size. The range of neighborhood sizes we employed in this study is from 10 ft to 180 ft for DEM resolutions of 10 ft, 15 ft, and 30 ft. Field soil samples were collected to assess the accuracy of predicted soil map at each neighborhood size.

Fig. 2 shows the variation in accuracy of predicted soil map and neighborhood size. It is clear that neighborhood size has profound impact on the accuracy of soil map. The difference in accuracy between different neighborhood sizes can be quite substantial, with the accuracy at one neighborhood size perhaps double of that at another neighborhood size. It is important to note that the most accurate soil map is not obtained at the smallest neighborhood size but at some particular neighborhood size (around 100 feet in this particularly case study). The finding here further suggests that removing certain fine scale variation in DEM is important for digital soil mapping because these fine scale details do not contribute to the differentiation of soil at the scale interested by the soil scientists.

The combination of what presented in 3.1 and what in this section makes a strong argument against the use of small neighborhood size in digital soil mapping because of the high sensitivity of terrain attributes to small neighborhood size and the effective neighborhood. This argument is of particular importance today when finer and finer DEM data are produced with the rapid deployment of Lidar for acquiring high resolution digital elevation data.

3.3Neighborhood size and spatial scale

Spatial scale is a fundamental issue in many geographic analyses [9][10][11][12][13]. Depending on the context, spatial scale could mean the followings: grain and extent [10][14][15][16]. Grain refers to the spatial detail or the minimum areal unit over which a particular process should be studied. Grain is not spatial resolution which refers to the spatial detail or the spatial unit over which spatial data are collected and/or represented. There is no necessary connection between grain size mentioned above and spatial resolution because the spatial detail at which spatial data are captured or represented may not be the spatial detail at which a given spatial process needs to be studied. Extent refers to the size of the study area.

In this paper spatial scale refers to "grain size". In other words, by 'spatial scale' we mean the size of a given feature or minimal area needed for a process to manifest itself. Note that in this paper 'scale' is defined as in earth sciences and physical sciences, e.g. the characteristic length scale in the turbulence theory, but not in cartography, where 'scale' is the ratio of map to earth distance. For example, the spatial scale of a rill might be 2m, while the spatial scale of a hill could be 200m or more.

Typical landscapes contain multiple scales, but for a particular application only some scales are relevant. Ideal terrain characterization (such as slope computation) would capture those and ignore the others.

"Neighborhood size" is often treated as the "spatial scale" of computation in digital terrain analysis, just as we have done above, but are they the same? If not, is 'neighborhood size' an adequate indicator of 'spatial scale'? Using rater-based slope estimation as example with amplitude response functions as the measure we analytically examine these questions.

As is well-known, a DEM can be represented using a discrete Fourier series, which decomposes the surface into a finite number of sinusoids of progressively shorter wavelength. Any particular slope calculation will treat information at various scales differently, suppressing some frequencies, amplifying others, and leaving the rest untouched. Therefore, a slope operator is like a digital filter of the input DEM and the 'spatial scale' of a slope calculation refers to the frequencies that pass through the filter and are reflected in the resulting slope matrix.

Table 2 compares the frequency of neighborhood size along the $f_x = f_y$ transects of the amplitude response surfaces of the slope estimators examined. As shown in Table 2, none of the analyzed slope estimators has the neighborhood size fall into a major passing band(s). Therefore, the neighborhood size and the spatial scale are not numerically the same. It is also important to note that neighborhood size corresponds to only one frequency/scale, while all the frequencies/scales that fall into the passing band(s) are part of the 'scale' of the slope estimator. Thus there is no single scale that can be associated with an estimator.

Through this case study, we hoped to shed some light on the effects of scale on digital terrain analysis and digital soil mapping. The effects of neighborhood size in digital terrain analysis and digital soil mapping are clear but neighborhood size is not space scale. The question remains as to what the neighborhood size is appropriate for a given scale of analysis.

Table 2: Comparison of neighborhood size and spatial scale

Method	*f* of neighborhood size	Peak passing *f*
Horn (1981)	0.333 for 3*3	0.168
Evans(1979)	0.033 for 3*3	0.149
Wood (1996)	0.2 for 5*5	0.085
Wood (1996)	0.14 for 7*7	0.06

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