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The effects of DEM resolution and neighborhood size on digital soil survey

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Abstract

Terrain characteristics, such as slope gradient, slope aspect, profile curvature, contour curvature computed from digital elevation model (DEM), are among the key inputs to digital soil surveys based on geographic information systems (GIS). These terrain attributes are computed over a neighborhood (spatial extent). The objective of this research was to investigate the combined effect of DEM resolution and neighborhood size on digital soil surveys using the *So*il–*L*andscape *I*nference *M*odel (SoLIM) approach. The effect of neighborhood size and DEM resolution on digital soil survey was examined through computing the required terrain attributes using different neighborhood sizes (from 3 to 54 m) for 3, 6, 9, 12, 18, and 27 m resolution DEM. These attributes were then compiled and used to digitally map soils using the SoLIM approach. Field work completed on a hillslope in Dane County, WI in the summer of 2003 was used to validate each of the SoLIM derived soil surveys for accuracy. The results of the soil survey validations suggest that there is a range of neighborhood sizes that produces the most accurate results for a given resolution DEM. This range of neighborhood sizes, however, varies from landscape to landscape. When the soils on a gently rolling landscape were mapped, the neighborhood sizes that produced the most accurate results ranged from about 33–48 m. When soils on short, steep backslope positions were mapped, the neighborhood size values that produced the most accurate results range from about 24–36 m. This paper also shows that it is not always the highest resolution DEM that produces the highest accuracy. Knowing which DEM resolution and neighborhood size combinations produce the most accurate digital soil surveys for a particular landscape will be extremely useful to users of GIS-based soil-mapping applications.

Keywords: GIS; Soil–landscape model; DEM resolution; Neighborhood size; Digital Soil Survey; SoLIM

1. Introduction

Creating detailed soil information is necessary to meet the demands of ecological and environmental management systems (Park et al., 2001; Zhu and Mackay, 2001). The scale at which traditional soil surveys are created and the polygon data model used is often incompatible with other environmental data layers derived from digital terrain analysis and remote sensing techniques (Zhu et al., 2001). In addition, the process of manually creating conventional soil surveys is often a subjective one because it relies on the visual identification of landscape conditions through airphoto interpretation for delineating soil–landscape units. The use of geographic information system (GIS) based soil-mapping applications can resolve these limitations associated with traditional soil surveys by producing digital soil information at very fine scales, and by using an objective quantification of the landscape to characterize the soil-formative environment (Zhu, 1997; McBratney et al., 2003).

In GIS-based soil-mapping applications, raster-based digital elevation models (DEM) are used to compute the terrain attributes, such as slope gradient, slope aspect, profile and contour curvature, which are required for characterizing a generalized soil-formative environment. Numerous authors have shown the need of terrain attributes derived from DEM for digital soil mapping (Moore et al., 1993; McSweeney et al., 1994; Zhu, 1997; McKenzie et al., 2000).

Many studies have shown the effect of DEM resolution on the spatial pattern of terrain attributes (Chang and Tsai, 1991;

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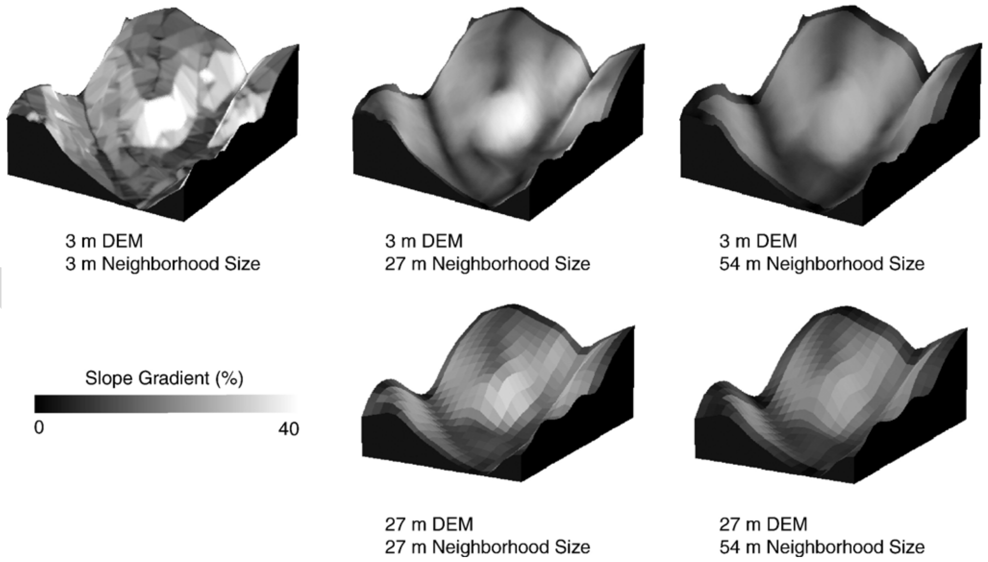
Wolock and Price, 1994; Zhang and Montgomery, 1994; Gao, 1997; Goyal et al., 1998; Chaplot et al., 2000; Schoorl et al., 2000; Wilson et al., 2000; Thompson et al., 2001; McMaster, 2002). Zhang and Montgomery (1994) used DEM of different resolutions in conjunction with the D8 flow algorithm to detect patterns in storm runoff and surface saturation. These authors found that the choice of resolution greatly affected the computation of slope gradient, specific catchment area and wetness index, and when used as inputs into a hydrologic model, produced varying results. Wilson et al. (2000) demonstrated how slope gradient tends to decrease and flow-path length and specific catchment area tend to increase as cell size increases. Steep slopes were shown to disappear as the cell size was increased from 30 m to 200 m. Larger cell sizes also produced shorter flow-length paths. These authors state that terrain attribute values derived from DEM with different resolution produced varying results when input into a Revised Universal Soil Loss Equation (RUSLE). Chang and Tsai (1991) used DEM of different resolutions (20 m, 40 m, 60 m and 80 m) in order to examine the effect of resolution on slope gradient and slope aspect characteristics. The authors concluded that the accuracy of slope gradient and slope aspect computations decreased with larger cell sizes.

Numerous authors have investigated the effect of DEM resolution on soil and geomorphological models. Thompson et al. (2001) examined how the vertical and horizontal accuracy of DEM as well as the DEM source affects the predicted distribution of A-horizon depth. The authors found that using larger cell sizes produces lower slope gradients on steeper slopes, steeper slope gradients on flatter slopes, narrower ranges in curvatures, larger specific catchment areas in upper landscape positions and lower specific catchment areas in lower landscape positions. The authors also discussed how finer resolution DEM may not be necessary for predicting the spatial distribution of A-horizon depth. Chaplot et al. (2000) investigated how DEM resolution affects the results of a soil hydromorphy prediction model. The results of this experiment show that 10 m and 30 m DEM were able to predict terrain characteristics (elevation above stream bank, downslope gradient and upslope contributing areas) in similar ways, however, the amount of error produced by these characteristics dramatically increased when using a 50-m DEM. With respect to the prediction of the hydromorphic soils, the results of the experiment showed that in each case the coarser resolution DEM deteriorated the prediction quality of the soils when compared to pedological investigations. Finally, Schoorl et al. (2000) used DEM of different resolutions to examine the effect of resolution on the results of geomorphological models. The authors input five different resolution DEM (1 m, 3 m, 9 m, 27 m and 81 m) into a model called LAPSUS (landscape process modeling at multi-dimensions and scales) that calculates erosion and sedimentation rates. In particular, this study examined the effect on Q (discharge) values derived as a result of applying either the steepest descent or multiple-flow direction algorithms to each DEM for the study area. The experiment found that soil loss predicated by both the path of steepest descent and the multiple flow routing techniques showed an increase of almost 97% from finest to coarsest resolution. This study also demonstrates that the calculated sedimentation rate and resultant sediment load of the catchment using the multiple-flow routing technique showed an exponential increase as scale input progressed from coarser to finer resolution DEM. The DEM resolution thus greatly affected values of computed terrain characteristics.

This research addresses the effects of DEM resolution as well as “neighborhood size” on digital soil survey. We use “neighborhood” to mean the spatial extent over which terrain attributes are computed. Changing the neighborhood size obviously influences the effective smoothing (or generalizing) of the terrain surface, and like varying DEM resolution, it therefore alters the description of the soil-formative environment at a given


3 m DEM
3 m Neighborhood Size

3 m DEM
27 m Neighborhood Size

3 m DEM
54 m Neighborhood Size

27 m DEM
27 m Neighborhood Size

27 m DEM
54 m Neighborhood Size

Fig. 1. The effect of DEM resolution and neighborhood size on the computation of slope gradient.

location (Fig. 1). The goal of this research is thus to investigate how DEM resolution and neighborhood size affect the accuracy of the derived soil survey products.

2. Background

2.1. The SoLIM approach

The GIS-based soil-mapping application used in this research is the *So*il–*L*andscape *I*nference *M*odel (SoLIM) approach. Zhu and Band (1994), Zhu (1997), Zhu et al. (1996) and Zhu et al. (2001) have developed the SoLIM approach to overcome the limitations of conventional soil surveys. The SoLIM approach consists of three major components: 1) a similarity model for representing the spatial gradation of soils, 2) inference techniques for deriving similarity values for a given location and, 3) derivation of soil information products using the similarity values. The computation of similarity values at a given location under SoLIM is based on the soil-forming factor equation (Jenny, 1941) or the soil–landscape model (Hudson, 1992). With the SoLIM approach, GIS and remote sensing techniques are used to characterize soil-formative environments (terrain attributes are major part of soil-formative environment), a set of knowledge acquisition techniques is used to extract knowledge of soil-formative environment relationships from local soil experts and other sources, and an inference engine constructed under fuzzy logic is used to link the characterized soil-formative environmental conditions with the extracted knowledge to derive a similarity representation of soils over a landscape. This research focuses on the terrain related GIS inputs into the SoLIM approach.

2.2. Effect of DEM resolution and neighborhood size on terrain attribute calculation

Many studies have shown the effect of DEM resolution on the spatial pattern of terrain characteristics (Chang and Tsai, 1991; Wolock and Price, 1994; Zhang and Montgomery, 1994; Gao, 1997; Goyal et al., 1998; Chaplot et al., 2000; Schoorl et al., 2000; Wilson et al., 2000; Thompson et al., 2001; McMaster, 2002). These authors have generally concluded that as cell size increases, slope gradients tend to decrease, ranges in curvatures decrease, flow-path lengths tend to decrease and the accuracy of terrain attributes at particular locations tends to decrease.

The values of terrain attributes are not only affected by DEM resolution as these authors have shown, but also the neighborhood size at each DEM resolution over which they are computed. Perhaps the most popular method for computing terrain characteristics is the 3 × 3 roving window method used in such programs as TAPES (Moore, 1992) and ESRI Arc/INFO. These programs derive terrain attributes from a DEM by computing the value of certain terrain attributes (such as slope gradient) at the center cell based on the elevation values over a neighborhood centered around this center cell. Most important terrain attributes needed for GIS-based soil mapping approaches such as SoLIM are slope gradient (*S*) and the surface contour and profile curvatures. Mathematically, the slope gradient of a continuous surface is defined as the magnitude of the gradient vector at a point, which can be computed from the partial derivatives according to Hornbeck (1975):

$$\tan S = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2} \tag{1}$$

where $\frac{\mathrm{A}z}{\mathrm{A}x}$ and $\frac{\mathrm{A}z}{\mathrm{A}y}$ are the partial derivatives, that is the changes of elevation along the *x* axis and *y* axis direction, respectively. Typically, the partial derivatives are estimated using differences between grid point elevations (so-called finite difference methods). For example, a third-order method based on a 3 × 3 cell estimates the partial derivatives as:

$$\frac{\partial z}{\partial x} \approx \frac{[(z_{i+1,j+1} + 2z_{i+1,j} + z_{i+1,j-1}) - (z_{i-1,j+1} + 2z_{i-1,j} + z_{i-1,j-1})}{8\Delta x} \tag{2}$$

$$\frac{\partial z}{\partial y} \approx \frac{[(z_{i-1,j-1} + 2z_{i,j-1} + z_{i+1,j-1}) - (z_{i-1,j+1} + 2z_{i,j+1} + z_{i+1,j+1})}{8\Delta y} \tag{3}$$

Where *z* is altitude, *i* represents the pixel position along the *x*-axis, *j* represents the pixel position along the *y*-axis, Δx and Δy are the pixel size in the *x* and *y* directions (Horne, 1981).

When terrain attribute values are computed from a 3 × 3 roving window, the spatial extent over which the values are computed changes according to the resolution of the DEM. For example, if the cell size is 3 m, elevations of pixels 3 m away from the central cell are used. In other words, the neighborhood around the center pixel is consists of all cells lying one cell to north/south/east/west of the center, which we would describe as a 3-meter neighborhood. For a 3 × 3 cell window with a DEM of 5-meter resolution, the neighborhood is 5 m. (Of course the diagonal distance to the corner points is larger.) With these methods the neighborhood size is tied directly to the resolution of DEM and thus terrain attribute values derived using such methods will change when the DEM resolution changes.

There is one apparent problem with tying neighborhood size directly to DEM resolution, that is, there is no physical-process based significance behind using the 3 × 3 method for computing terrain attributes. For example, when the resolution of DEM is at 0.5 m, there is no reason for the slope gradient and aspect to be computed over a 1.5 by 1.5-meter area. In fact, the definition of slope gradient used by domain experts (soil scientists, geomorphologists, hydrologists, etc.) in the field is often very different from the mathematical definitions of slope gradient presented in the aforementioned equations ((1)–(3)). For example, when soil scientists are asked to define the slope gradient at a location for a particular soil-formative environment, the slope gradient is often captured over a distance, which the expert believes to be significant to the process under study, and in effect smoothing short-scale terrain complexity. Thus, it may be a mistake to compute terrain attributes according to such equations because the domain expert definition of slope gradient may be very different.

In addition noise or short-scale variations that are not easily explained by natural processes, may reflect real-world terrain variation, or may be artifacts of DEM generation (Burrough and McDonnell, 1998). If the result of the latter, this noise can greatly affect the accuracy of the terrain characterization if this information is not filtered out, particularly when the resolution of DEM is very high (such as at sub-meter level).

The SoLIM approach computes terrain characteristics using a much different method than the 3 × 3 roving window technique. The SoLIM approach uses the 3dMapper software (version 4, 2004) developed at the University of Wisconsin-Madison to compute terrain characteristics (Burt and Zhu, 2004). The method used by this program first creates a least-squares regression polynomial to produce a filtered (generalized) terrain surface over a user defined neighborhood (window) (see Shary et al., 2002; Schmidt et al., 2003; for a discussion on polynomial methods). This method uses the equation:

$$z = rx^2 + ty^2 + sxy + px + qy + u \qquad (4)$$

where one can estimate the values for r, t, s, p, and q by moving a window across the DEM and determining the elevation surface for a location by minimizing the squared difference between the polynomial calculated and the elevation values. This procedure is repeated for every elevation point, and is thus considered a local polynomial. This technique suppresses short-range variation at spatial scales smaller than the neighborhood size, regardless of DEM resolution (thus addressing the two issues associated with computing terrain characteristics identified above). The user specifies the neighborhood size, so one can control the amount of short-scale variation desired for analysis. Because slope gradient, slope aspect, profile and contour curvatures are computed by analyzing the polynomial, this method produces the most accurate terrain characterization when compared to other common methods (Florinsky, 1998).

3. Materials and methods

3.1. The study area

The study site is the 65-hectare Thompson Family Farm (NW 1/4, sec. 21, T5N, R6E), located approximately 3 km east of the town of Daleyville, in southwestern Dane County, WI (Fig. 2). This region of Dane County is located in the "Driftless Area" of Wisconsin. The Driftless Area did not experience direct glacial till depositions on the land surface during the Laurentide Ice Sheet advances, the last of which existed in this area until about 13,500 years before present. The landscape of the Driftless Area is characterized by plateaus or erosional remnants of dolostone (the Galena Formation) overlying sandstone scarps (the St. Peter Formation), which together form a branching network of valleys and ridges (Clayton and Attig, 1997). The Rountree Formation consists of clay units and overlies the Galena Formation. The Rountree Formation exists in varying thickness throughout the Driftless Area where loess overlies cherty dolomite, and is most prominent on broad ridges. Quaternary loess deposits occur at this site on the upland areas and as reworked loess in draws, footslopes and drainageways.

Elevations at the Farm range from 270 m in the bottomland drainageway to about 350 m on the upland ridgetop (Fig. 3). The majority of the Farm is underlain by the Galena Formation. Over the study area, the Galena Formation ranges in elevation from 320 m to approximately 350 m occupying the ridge and upslope areas. Slope gradient on the Galena Formation ranges from 0–1% at the summit to near 25% at the boundary of the Galena and St. Peter Formations. The St. Peter Formation is exposed below the Galena Formation for as much as 10 m and occupies the backslope, footslope and drainageway areas. The majority of the St. Peter Formation in this area has slope gradients ranging from 25 to 45%.

Two distinct vegetation communities exist at the Farm: the grassland of the Galena Formation uplands and the forest associated with the St. Peter Formation backslopes, footslopes

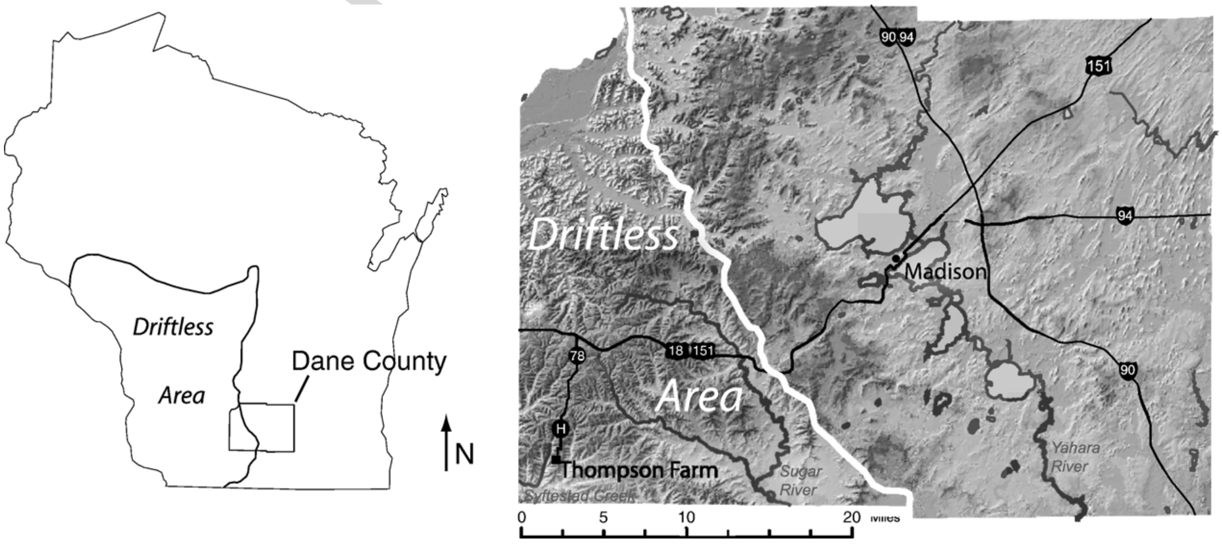


Fig. 2. The Thompson Family Farm is located in the Driftless Area of southwestern Dane County.

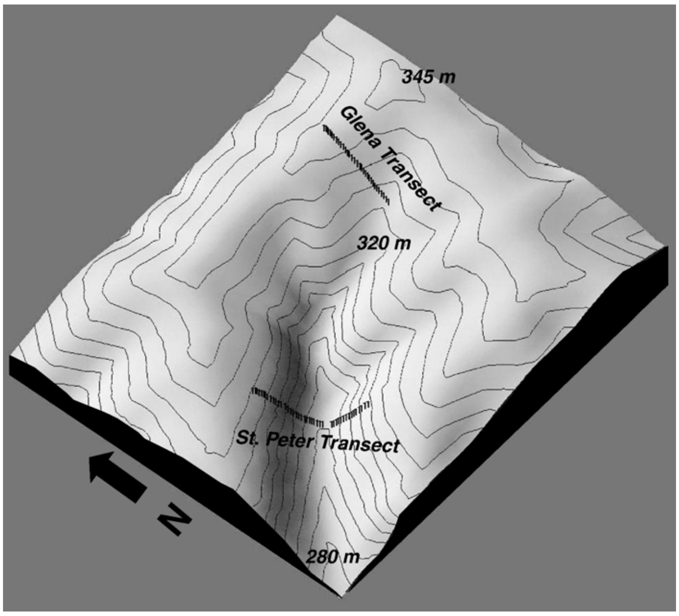


Fig. 3. Topography of Thompson Family Farm and locations of the transects. Contours placed at 5-m intervals (the vertical exaggeration of this view is 3).

and drainageways. The vegetation boundary delimits soils more suitable for agronomic crop production from those that are unsuitable and have been left to native vegetation growth. The dominant grassland species here is fescue (*Festuca* spp.). The forested areas of the site have not been recently cultivated. The species of the forested area include oak (*Quercus* spp.), alder (*Alnus* spp.) and other hardwood species.

There are nine different soil series located on the Farm (Table 1). Each series occupies a unique landscape position. Five of the series (Dodgeville, Edmund, Dubuque, Frankville and Brownbeth) are underlain by the Galena Formation. Three series (Galaville, Galerton and Galtown) occur on both the Galena and St. Peter Formations. The remaining series, Arenzville, occurs on drainageways and is relatively insensitive to bedrock type, occurring throughout the Driftless Area in this landscape position.

3.2. Terrain data preparation and knowledge on soil–environmental relationships

The elevation data source was a 3-meter (originally 10 ft) DEM produced by the Dane County Land Information Office (LIO). The LIO produced this DEM as part of its Fly Dane Project in the spring of 2000. Mass points and breaklines photogrammetrically collected from aerial photography were used to create a Triangulated Irregular Network (TIN) of elevation facets, and were then converted to a raster-based DEM (Fly Dane Partnership, 2005). The DEM has a horizontal accuracy of +/−1.8 m, a vertical accuracy of 0.6 m, and meets the National Standard for Spatial Data Accuracy for mapping at a 1: 2400 scale (Fly Dane Partnership, 2005). DEM at 6-, 9-, 12-, 18- and 27-m resolutions were created through averaging the elevation values of the corresponding pixels in a 3-meter DEM using ESRI Arc/INFO. We use averaging for creating the coarser resolution DEM because the elevation for a pixel represents the average height over the area covered by the pixel. Thus, it is more appropriate to use the averaging method than the nearest neighbor approach (picking the elevation of the pixel closest to the center of the coarser pixel). GIS databases for each resolution dataset containing terrain attributes computed across different neighborhood sizes were then created using 3dMapper (Table 2). GIS databases were created for all neighborhood sizes, up to 54 m, which produces a total of 42 GIS databases for this study.

The following environmental data layers were used to characterize the soil-formative environments and were compiled for each of the 42 different GIS databases: elevation, slope gradient, contour curvature, profile curvature, fuzzy broad ridge and fuzzy narrow ridge. Elevation was used to separate soils located on the upper portions of the toposequence (summits, shoulders and headwater regions) from those located on the lower portions (backslopes, footslopes and drainage ways). Slope gradient, contour and profile curvatures were derived using the 3dMapper software. Slope gradient is especially important for characterizing the steep backslope positions. The profile and contour curvature data layers were used to map soil series that can be separated by concavity and/or convexity. Fuzzy broad ridge refers to a data layer contains the membership of locations being on a "broad ridge". Similarly, fuzzy narrow ridge is a data layer contains the membership of locations being on a "narrow ridge" (Shi et al., 2005). Based on the knowledge of local soil scientists the pedogenesis on the broad ridge area is quite different from the narrow ridge area. In addition as one moves away from these ridge tops (either broad or narrow) the pedogenesis transition into other forms. The fuzzy broad ridge and narrow ridge concepts are not only used to distinguish the different pedogenesis but also (more importantly) capture the nature of transition.

Table 1
The soil series and their *Soil Taxonomy* classification (Soil Survey Staff, 1999)

Series	Classification (subgroup)	Typical landscape position
Dodgeville	Typic Argiudoll	Broad summit
Edmund	Lithic Argiudoll	Narrow summit
Dubuque	Typic Hapludalf	Shoulder
Frankville	Mollic Hapludalf	Headwater area
Brownbeth	Lithic Hapludalf	Nose slope at shoulder
Galaville	Glossic Hapludalf	Backslope
Galerton	Typic Hapludalf	Nose slope at backslope
Galtown	Mollic Hapludalf	Footslope
Arenzville	Typic Udifluvent	Drainage way

Table 2
The 42 GIS databases with their respective combinations of DEM resolution and neighborhood size

DEM resolution (m)	Neighborhood size (m)
3	3, 6, 12, 15, 18, 21, 24, 27, 30, 33, 36, 39, 42, 45, 48, 51, 54
6	6, 12, 18, 21, 24, 30, 36, 42, 48, 54
9	9, 18, 27, 36, 45, 54
12	12, 24, 36, 48
18	18, 36, 54
27	27, 54

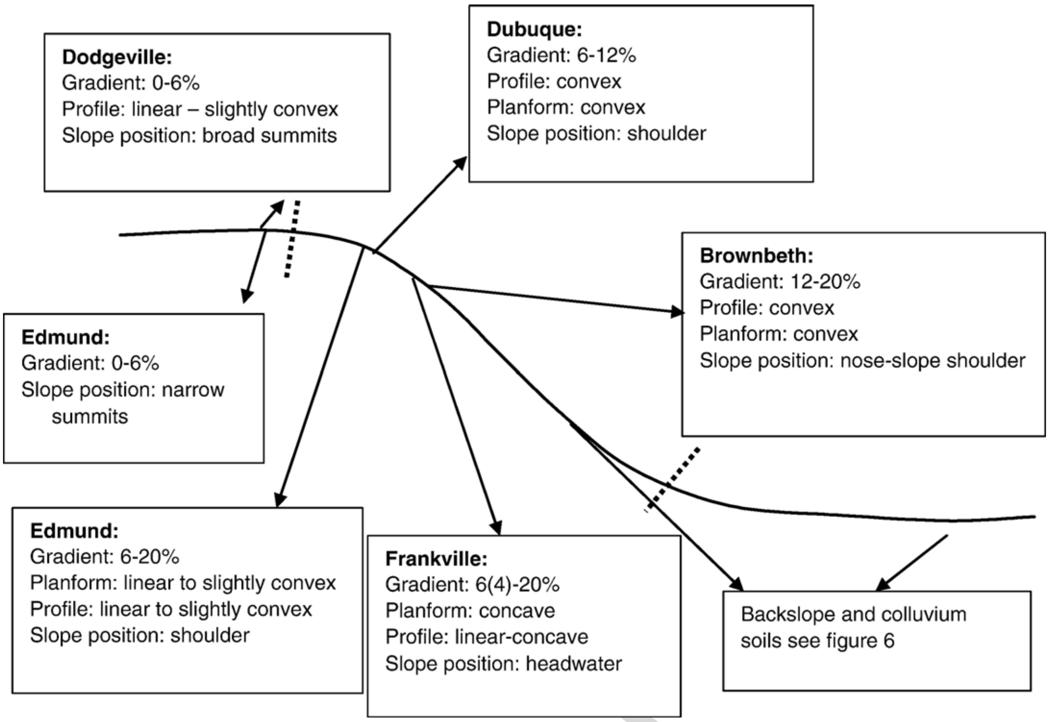


Fig. 4. Environment descriptions for the soil series occurring on upslope positions, as described by the local soil expert.

The ability of SoLIM to accurately predict the spatial distribution of soils relies heavily on the quality of the soil–landscape knowledge available for a given area. The soil–landscape knowledge for this site was acquired from a local expert, Duane Simonson, a USDA-NRCS soil survey project leader for this area, in September of 2001 and was modified in December of 2003. The original knowledge acquisition process was completed according to the procedures outlined by Zhu (1999). Two soil–environment descriptions, one for the summits, shoulders and headwater regions (Fig. 4) and one for the backslopes, footslopes and drainageways (Fig. 5), were created. The diagrams illustrate the relationship between soil series occurrence, landscape position, slope gradient and slope shape, and represent the knowledge of soil–environmental relationships implemented in digital soil survey of the area using the SoLIM approach.

Once the environmental data layers have been prepared and the knowledgebase is compiled, a typical process of fuzzy soil

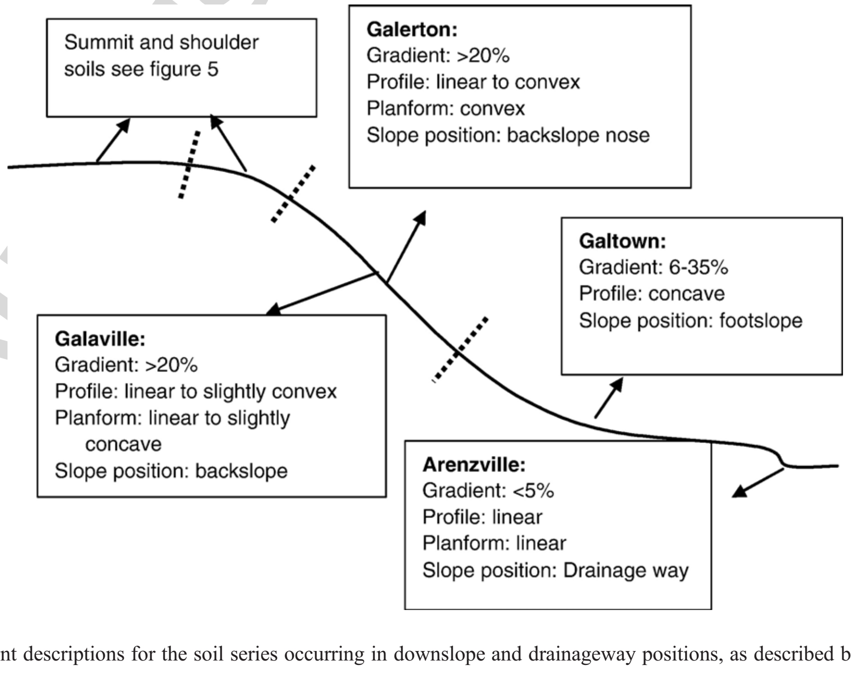


Fig. 5. Environment descriptions for the soil series occurring in downslope and drainageway positions, as described by the local expert.

Table 3
Experiment one results (% accuracy (standard error)), Galena Transect (18 and 27 m resolutions)

Neighborhood size (m)	DEM resolution (m)	
	18	27
18	62.5 (8.6)	
27		31.3 (8.2)
36	37.5 (8.6)	
54	53.1 (8.8)	31.3 (8.2)

inference using the SoLIM approach is accomplished in three major steps as described below:

1) A fuzzy soil inference (similarity representation of a given soil series over a landscape) is created by locating tacit points (non-empirically implied locations, 1 to 2 tacit points per soil series) (Hudson, 1992) in the landscape for each soil series and defining membership functions. This process is referred to as the "implementation of knowledge" and is repeated for all soil series in the area. Once similarity representations for all soil series are created, a soil series map is produced by hardening the similarity vector at each point (assigning to each location the label of the soil class that has the highest membership value) (Zhu et al., 2001).
2) The hardened soil series map is then verified by a local soil expert (Chanc Vogel, USDA-NRCS, verified the maps produced in this research),
3) Changes, if necessary, are made by adjusting the location of tacit points and the membership functions for soil series that are identified by the local soil expert to be mapped in environments unsuitable for the formation of that soil. The final tacit point placement and membership functions are then considered the "verified implementation of knowledge".

The goal of this research is to investigate the effect of DEM resolution and spatial extents for computing terrain attributes on digital soil survey. To achieve this, it is important to keep the soil–landscape knowledge used in SoLIM unchanged. Keeping the soils knowledgebase unchanged during the fuzzy soil inference process was a great challenge when completing the experiments in this study, as the values of terrain characteristics vary at the same location when both the DEM resolution and neighborhood size are altered. As a result, the environmental conditions at the tacit point for each soil series may change. Thus, the actual implementation of knowledge on soil–environmental relationships may be different from one combination of resolution and neighborhood size to another. To avoid this problem, three different experiments were conducted to minimize the impact of the inconsistency in implementing the knowledge of soil–environmental relationships when performing soil inferences on the different GIS databases.

Table 4
Experiment one results (% accuracy (standard error)), St. Peter Transect (18 and 27 m resolutions)

Neighborhood size (m)	DEM resolution (m)	
	18	27
18	76.7 (6.4)	
27		60.5 (7.5)
36	67.4 (7.1)	
54	51.2 (7.6)	51.2 (7.6)

Table 5
Experiment two results (% accuracy (standard error)), Galena Transect (18 and 27 m resolutions)

Neighborhood size (m)	DEM resolution (m)	
	18	27
18	71.9 (7.9)	
36	68.8 (8.2)	
54	68.8 (8.2)	34.4 (8.4)

3.3. Experiment design

Experiment One was designed to investigate the effect of using both DEM of coarser resolutions and larger neighborhood sizes. The knowledgebase for each soil series was implemented using the SoLIM approach on the 3-m DEM with a 3-m neighborhood size, and a single soil inference was created. The resulting verified implementation of knowledge was then used to derive soil series maps for the 41 other GIS databases (different DEM resolutions with different neighborhood sizes).

Experiment Two was to investigate the effect of increasing the neighborhood size for a given resolution DEM. Only one verified soil inferences were created for each DEM resolution, that is, 3-m resolution with a 3-m neighborhood size (created in Experiment One), 6-m resolution with a 6-m neighborhood size, 9-m resolution with a 9-m neighborhood size, 12-m resolution with a 12-m neighborhood size, 18-m resolution with an 18-m neighborhood size, and the 27-m resolution with a 27-m neighborhood size. The resulting verified implementations of knowledge were then used to derive soil series maps for all other GIS databases of the same resolution but with different neighborhood sizes.

Experiment Three was to investigate the effect of using coarser DEM resolution alone. To achieve this goal, 12 verified soil inferences were created on the 3-m resolution DEM at 6-, 9-, 12-, 18-, 24-, 27-, 30-, 36-, 42-, 45-, 48- and 54-m neighborhood sizes. The verified implementations of knowledge created on these GIS databases were then used to derive soil series maps on the coarser resolution DEM having the same neighborhood size.

3.4. Validation data collection

In order to capture subtle variation in the landscape transect sampling was used to collect field data for assessing how well particular combinations of DEM resolution and neighborhood size

Table 6
Experiment two results (% accuracy (standard error)), St. Peter Transect (18 and 27 m resolutions)

Neighborhood size (m)	DEM resolution (m)	
	18	27
18	76.7 (6.4)	
36	69.8 (7.0)	
54	65.1 (7.3)	44.2 (7.6)

could infer the spatial variability of the soil series across the landscape. The transect trajectories were set to minimize the distance across major landforms while capturing the range of variability in the area. Coupled with a small sampling interval (sampling at every 5 m) we hope that the transect sampling allowed us to capture the range of variability occurring at different scales.

Two different transects were completed at the Farm, with point samples taken at 5-m intervals along the projected transecting line. Thirty-two samples of the soils underlain by the Galena Formation (hereafter referred to as the "*Galena Transect*") and 43 samples of the soils underlain by the St. Peter Formation (hereafter referred to as the "*St. Peter Transect*") were collected (Fig. 3). The transect samples were used to validate each of the digital soil surveys produced, and were not used to build the soil–landscape model of the study area.

Three types of sampling information were recorded at each of the visited locations. The first was the location of each sample site and the sampling method used (pit or auger hole). The second type of information recorded was about the observable landscape. Here, the geomorphic position, slope aspect, slope shape (profile and contour curvatures) and vegetation were recorded. The final type of information recorded was the soil profile descriptions. For each location, the name and depth of each horizon identified, and the soil color, texture, structure, clay films and any "other" information deemed important for classifying the sample location were recorded according to standard USDA-NRCS soil description procedures (Schoenenberger et al., 1998).

Each of the soils at the respective locations was classified to the series level after all the samples were collected. The landscape conditions, profile descriptions and a lab analysis of particle size distribution of the A and Bt horizons for each of the samples were used to aid in the classification. The correctness of the final soil classifications were verified by a local soil expert (Chanc Vogel, a local USDA-NRCS soil scientist in Wisconsin).

3.5. Accuracy assessment of inferred soil maps

To assess the accuracy of the inference predictions, a validation program containing the classified field samples was used on all inferred soil series maps. This program uses a georeferenced file of field observations, obtains the soil series label for each point on each of the soil series maps, and then constructs an error matrix from the two sets of labels. The output of the program is a file containing the overall accuracy measure — a percentage of the correctly matched pairs. This measure is computed by matching the number of correctly predicted soils (from the soil series map) with the observed soils (from the field samples).

Table 7
Experiment three results (% accuracy (standard error)), Galena Transect (18 and 27 m resolutions)

Neighborhood size (m)	DEM resolution (m)	
	18	27
18	71.9 (7.9)	
27		50.0 (8.8)
36	68.8 (8.2)	
54	68.8 (8.2)	34.4 (8.4)

Table 8
Experiment three results (% accuracy (standard error)), St. Peter Transect (18 and 27 m resolutions)

Neighborhood size (m)	DEM resolution (m)	
	18	27
18	76.7 (6.4)	
27		51.2 (7.6)
36	69.8 (7.0)	
54	65.1 (7.3)	44.2 (7.6)

All observations were used for each resolution/neighborhood combination. Using standard statistical methods (Burt and Barber, 1996, p. 273) the standard error of accuracy is estimated by $[p\ (1-p)/n]^{1/2}$ where p is the sample accuracy and n is the number of samples. In the worst case ($p=1/2$) the standard errors are 8.8% and 7.6% for the Galena and St. Peter samples, respectively. The actual standard errors encountered can be seen in Tables 3–8, which report accuracies and their associated standard errors as a way to illustrate the confidence in the accuracies. Caution is needed in using the standard errors to compare accuracies because the usual assumption of independent samples is not met. Ideally, truly independent samples would be collected for each resolution/neighborhood combination. Such an ambitious sampling scheme (requiring on the order of 800 samples) was well beyond the resources of this project.

4. Results and discussion

4.1. Results of Experiment One

The goal of this experiment was to investigate the effect of using both coarser resolution DEM and larger neighborhood sizes on the accuracy of the inferred soil maps. The results of this experiment are presented in Figs. 6 and 7 and in Tables 3 and 4 (these two tables contains the accuracy information for DEM at 18 m resolution and 27 m resolution). The results show that the accuracy values of soil maps for DEM at a given resolution form a curve across the different neighborhood sizes. This result suggests that there is a range of neighborhood sizes at which digital soil surveys should be mapped: about 40 m over the Galena Formation and about 30 m for the St. Peter Formation. The 18- and 27-m resolution DEM are the exceptions to this trend. This exception is likely due to that fact that the minimum neighborhood size over which one can characterize terrain characteristics is very large for these coarse resolution DEM, thus suppressing any short-range variations necessary to examine the effect of neighborhood size.

In addition to an optimal range of neighborhood sizes for producing digital soil surveys, the range also varies from the landscape characterized by the Galena Transect to that characterized by the St. Peter Transect. The contrasting characteristics of the landscape ostensibly require different optimal ranges for each validation. First, the Galena Transect is a gently rolling

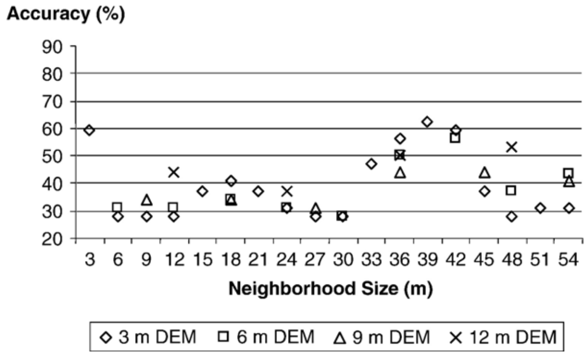


Fig. 6. Results from Experiment One over the Galena Transect.

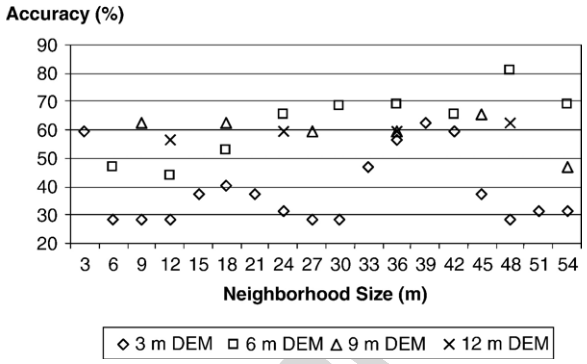


Fig. 8. Results from Experiment Two over the Galena Transect.

landscape where soil development is influenced by terrain characteristics over longer distances (about 30 m). Larger neighborhood sizes (about 40 m) must therefore be used on these locations in order to mimic these slight variations. Second, the St. Peter tends to occur on short, steep backslopes and footslopes. In this case, neighborhood sizes too small (such as 3–15 m) contain too many short-range terrain characteristic variations to which soil development is insensitive, while neighborhood sizes too large (such as over 40 m) may excessively remove the landscape variations important to soil formation — both instances lead to decreased accuracy. The results of this experiment thus suggest that it is very important to match the neighborhood size with the variations in the real-world landscape that affect soil development.

Further analysis of the accuracy curves for both validation sets reveals two additional pieces of information. First, when DEM of finer resolutions are used (3 and 6 m), a great amount variation in the accuracy values exist, indicating that these resolution DEM are very sensitive to the choice of neighborhood size. The range of accuracy value variation on the 3-m DEM is 35% on the Galena Transect and 28% on the St. Peter Transect; the range of variation for the 6-m DEM is 28% on the Galena Transect and 27% on the St. Peter Transect. Secondly, the DEM with coarser resolutions (9 and 12 m) do not appear to be as sensitive to the choice of neighborhood size. The range of accuracy values for the 9-m DEM is 13% on the Galena Transect and 21% St. Peter Transects; the range of accuracy variation for the 12-m DEM is 13% on the Galena Transect and 9% on the St. Peter Transect.

4.2. Results of Experiment Two

The goal of this experiment was to investigate the effect of increasing the neighborhood size for a given DEM resolution. Several of the data trends that were noted in Experiment One are also observed in this investigation in Figs. 8 and 9 and Tables 5 and 6. The first trend is that the accuracies for a given resolution DEM form a curve on the 3-, 6-, 9-, and 12-m resolutions. This trend verifies the notion that there is a range of optimal neighborhood size values at which digital soil surveys should be produced. More importantly, the results of this experiment again show that the range of neighborhood sizes at which digital soil surveys should be produced varies from landscape to landscape.

The results from Experiment Two can also be compared to the results from Experiment One in order to assess the impact of the knowledge implementation for a given resolution DEM (the results for Experiment One and Two are the same for the 3-m resolution DEM, so no assessment for this resolution can be made). When the highest accuracy values for each validation set from Experiment Two for the 6-m resolution DEM (81% at the 48-m neighborhood size for the Galena Transect and 67% both at the 18- and 24-m neighborhood size for the St. Peter Transect) are compared to the highest accuracy results from Experiment One for the 6-m resolution DEM (56% at the 42-m neighborhood size for the Galena Transect and 70% at the 30-m neighborhood size for the St. Peter Transect), it becomes apparent that the similar neighborhood sizes are producing the highest accuracy values for each validation set. However, much greater accuracies (as much as 25 percentage points more than

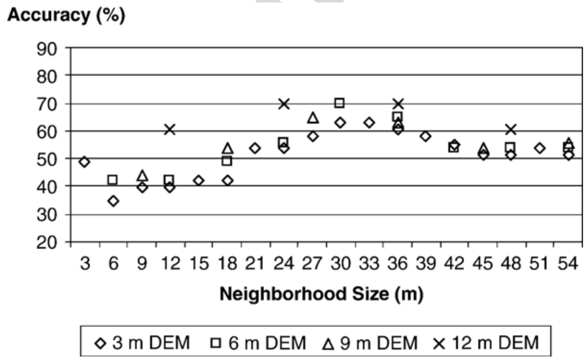


Fig. 7. Results from Experiment One over the St. Peter Transect.

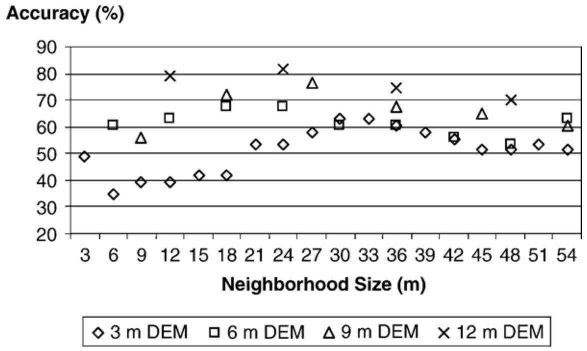


Fig. 9. Results from Experiment Two over the St. Peter Transect.

those in Experiment One) are attained in Experiment Two. The same is generally true for the 9-, 12-, 18- and 27-m resolution DEM, where the results from Experiment Two are as much as 22, 12, 12 and 31 percentage points higher, with a similar range of neighborhood sizes producing the highest accuracy values for both experiments. Again, the only difference between these experiments is the way in which the knowledge was implemented on the GIS databases — Experiment One implemented the knowledge only at the 3-m resolution DEM with the 3-m neighborhood size while Experiment Two implemented the knowledge at each resolution (with the smallest neighborhood size). As a result of this comparison, it appears that the implementation of knowledge does have a definite impact on the accuracy of the digital soil surveys produced. These results are not problematic to our finding on optimal neighborhood sizes because the differences between the experiments are in terms of the accuracy values attained rather than where the optimal ranges occur with respect to the neighborhood size and DEM resolution combinations.

Further analysis of the accuracy curves for both validation sets again reveals how DEM with finer resolutions are much more sensitive to the choice of neighborhood size than those with coarse resolution, particularly on the Galena Transect. The range of accuracy value variation on the 3-m DEM is 35% on the Galena Transect and 28% on the St. Peter Transect; the range of variation for the 6 m DEM is 37% on the Galena Transect and 14% on the St. Peter Transect. The range of accuracy values for the 9-m DEM is 19% on the Galena Transect and 21% St. Peter Transects; the range of accuracy variation for the 12-m DEM is 6% on the Galena Transect and 12% on the St. Peter Transect.

4.3. Results of Experiment Three

The goal of this experiment was to investigate the effect of using coarser DEM resolution alone. The results from this experiment presented in Figs. 10 and 11 and Tables 7 and 8 support the findings of the previous two experiments. Fig. 11 shows that there is an optimal range of neighborhood sizes to use for conducting digital soil survey on the landscape characterized by the St. Peter Transect. Fig. 10 does not display this characteristic for the Galena Transect. However, higher accuracy is either achieved or maintained as the neighborhood size is increased for a given resolution DEM. This supports the finding that different optimal ranges of neighborhood sizes exist for a given landscape. Fig. 11 clearly exhibits that the landscape characterized by the St. Peter Transect is best represented by a neighborhood size of 24–33 m; neighborhood sizes of greater than 30 m are best representing the landscape characterized by the Galena Transect.

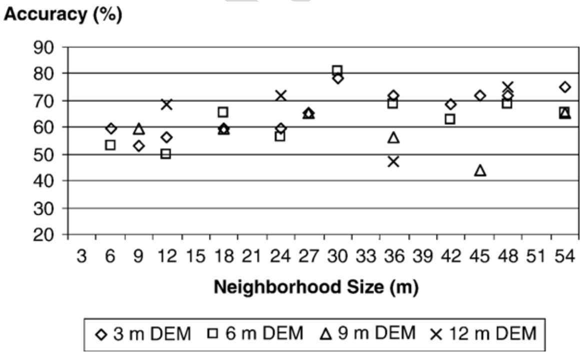


Fig. 10. Results from Experiment Three over the Galena Transect.

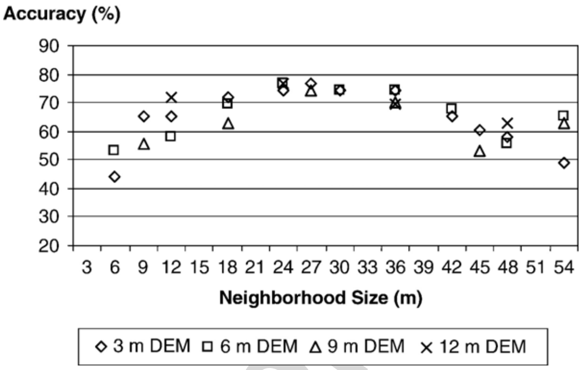


Fig. 11. Results from Experiment Three over the St. Peter Transect.

The results from Experiment Three can also be compared to the results from Experiment One in order to assess the impact of the knowledge implementation for a given neighborhood size. For example, when the highest accuracy values for the validation set from Experiment Three for the 36-m neighborhood size (72% at the 3-m DEM resolution for the Galena Transect and 74% at the 3- and 6-m DEM resolutions for the St. Peter Transect) are compared to the highest accuracy values from Experiment One for the same DEM resolution and neighborhood size combinations (56% at the DEM resolution for the 3-m DEM resolution on the Galena Transect and 67% at the 18-m DEM resolution for the St. Peter Transect), it becomes apparent that the similar DEM resolutions are producing the highest accuracy values for the validation set. However, much greater accuracy (as much as 16 percentage points higher) are attained in Experiment Three. The same is generally true for the 12-, 18 and 54-m neighborhood sizes, where the results from Experiment Three are as much as 25, 18, and 23 percentage points higher. However, similar resolutions are producing the highest results. Again, the only difference between these experiments is the way in which the knowledge was implemented on the GIS databases — Experiment One implemented the knowledge only at the 3-m resolution DEM with the 3-m neighborhood size while Experiment Three implemented the knowledge on the 3-m resolution DEM using various neighborhood sizes. As a result of this comparison, it appears that the implementation of knowledge does have a definite impact on the accuracy of the digital soil surveys produced. As noted before, these results are not problematic for our findings on general trend of optimal neighborhood size and DEM combinations.

The results of these three experiments suggest that there is a range of optimal neighborhood sizes at which digital soil surveys at the soil series level should be mapped. Neighborhood size exerts a considerable bearing on digital mapping accuracy for soil maps — too little information (large neighborhood) obscures important pedological differences which may strongly influence land use capabilities, and too much information (small neighborhood) overwhelms these significant variations with systematic high-frequency noise. This differs from the findings of Wilson et al. (2000) and Thompson et al. (2001) on slope gradient, of Chaplot et al. (2000) on prediction of hydromorphic soils occurrences, and of Thompson et al. (2001) on the predictability of spatial distribution of A-horizon depths (as reviewed in the Introduction section). The difference may be due to the fact that this study focuses on both the DEM resolution and neighborhood size on the accuracy of mapping soil series while the aforementioned studies examined the effect of DEM resolution on soil properties or terrain attributes. Nevertheless, the finding of this paper provided a different perspective.

The existence of optimal neighborhood sizes for mapping soil series in this case can be related to the fact that soil series is a scale-dependent concept, that is, soil series exists at certain spatial scale. When the scale is coarser than the coarse end of this optimal range the details in the terrain, which are needed to pick up the soil series, are averaged out. On the other hand, when the scale is finer than the fine end of this optimal range, the subtle details in the terrain spoil the relationship. The implication of this is that one needs to take neighborhood size into consideration in digital soil mapping. In addition, relief of landscape mapped is an essential constraint to neighborhood used in the mapping effort. High relief areas, where soil units are tightly related to topographic parameters, will necessarily have a different neighborhood size for mapping efforts than low-relief landscapes.

5. Conclusions

5.1. General findings

DEM resolution and neighborhood size play an important role in digital soil survey accuracy depending on landscape characteristics. The results of the three experiments suggests that there is an optimal range of a neighborhood size (between 24 and 48 m) for the study area over which the computed terrain attributes produce the more accurate results in mapping soil series using the SoLIM approach. The optimal neighborhood size varies between the two landscapes studied here, which suggests that this should be considered when generating soil maps based on DEM. When a gently rolling landscape (which was captured by the Galena Transect) was mapped, the neighborhood sizes that produced the most accurate results ranged from about 33–48 m. Using a neighborhood size outside of this range can produce a digital soil survey as much as 35 percentage points less accurate than the highest accuracy values. The soils that exist on this landscape are distinguished by only slight variations in their soil-forming factors, which attenuates soil variability. Using a large neighborhood size ensures that short-range variations that generally do not affect soil development do not influence the digital soil surveys produced. When a landscape with strong relief is mapped, such as short, steep backslopes as captured by the St. Peter Transect, the neighborhood sizes that produced the most accurate results ranged from about 24–36 m — using a neighborhood size outside of this range can produce a soil resource inventory as much as 28 percentage points less than the highest accuracy values.

5.2. Implications

In addition to the above pedological and mapping accuracy implications, the findings also have economic implications for national soil survey programs such as the soil survey program of USDA. Very fine scale DEM are becoming increasingly available at a very high cost — the cost of the 3-m DEM used in this research is $600 per Public Land Survey System quad section (6.5 square km) (Fly Dane Partnership, 2005). While these datasets contain much more detailed terrain information, the results of this study show that finer resolution data (3- and 6-m resolutions) do not necessarily create more accurate soil resource inventories. Instead, it is much more important to match the terrain characteristics computed from the DEM using a specified neighborhood size with the characteristics of the real-world landscape.

We must also point out that the findings of this paper are based on a relatively small study area. Re-examination and validation of these findings and concepts over larger areas with more soil series and complex landscapes are necessarily before the concepts are taken into production.

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References

Burrough, P.A., McDonnell, R.A., 1998. Principles of Geographical Information Systems. Oxford University Press, Oxford, p. 333.

Burt, J., Barber, G., 1996. Elementary Statistics for Geographers. The Guilford Press, New York, p. 273.

Burt, J.E., Zhu, A.X., 2004. 3dMapper 4.02. Terrain analytics LLC, Madison, WI. [Online WWW]. Available URL: ”http://www.terrainanalytics.com” [Accessed 22 Jan 2005].

Chang, K., Tsai, B., 1991. The effect of DEM resolution on slope and aspect mapping. Cartography and Geographic Information Systems 18, 69–77.

Chaplot, V., Walter, C., Curmi, P., 2000. Improving soil hydromorphy prediction according to DEM resolution and available pedological data. Geoderma 97, 405–422.

Clayton, L., Attig, J.W., 1997. Pleistocene geology of Dane County, Wisconsin. Wisconsin Geologic and Natural History Survey Bulletin, vol. 95, p. 3.

Florinsky, I.V., 1998. Accuracy of local topographic variables derived from digital elevation models. International Journal of Geographical Information Science 12, 47–61.

Fly Dane Partnership, Dane County Land Information Office. [Online WWW]. Available URL: “http://www.co.dane.wi.us/lio/flydane.asp” [Accessed 22 Jan 2005].

Gao, J., 1997. Resolution and accuracy of terrain representation by grid DEMs at a micro-scale. International Journal of Geographical Information Science 11, 199–212.

Goyal, S.K., Seyfried, M.S., O’Neill, P.E., 1998. Effect of digital elevation model resolution on topographic correction of airborne SAR. International Journal of Remote Sensing 19, 3075–3096.

Horne, B.K.P., 1981. Hill shading and the reflectance map. Proceedings of IEEE 69 (1), 14–47.

Hornbeck, R.W., 1975. Numerical Methods. Quantum, New York.

Hudson, B.D., 1992. The soil survey as paradigm-based science. Soil Science Society of America Journal 56, 836–841.

Jenny, H., 1941. Factors of Soil Formation: a System of Quantitative Pedology. McGraw-Hill, New York, p. 281.

McBratney, A.B., Mendonca Santos, M.L., Minasny, B., 2003. On digital soil mapping. Geoderma 117, 3–52.

McKenzie, N.J., Gessler, P.E., Ryan, P.J., O'Connell, D.A., 2000. The role of terrain analysis in soil mapping. In: Wilson, J.P., Gallant, J.C. (Eds.), Terrain Analysis: Principles and Applications. John Wiley & Sons, New York, pp. 245–265.

McMaster, K.J., 2002. Effects of digital elevation model resolution on derived stream network positions. Water Resources Research 38, 1–9.

McSweeney, K., Gessler, P.E., Slater, B., Hammer, R.D., Bell, J., 1994. Towards a new framework for modeling the soil-landscape continuum. In: Amundson, R.G., Harden, J.W. (Eds.), Factors of Soil Formation: a Fiftieth Anniversary Retrospective. Soil Science Society of America, Madison, WI, pp. 1–13.

Moore, I.D., 1992. Terrain analysis program for environmental sciences (TAPES). Agricultural Systems and Information Technology Newsletter 4 (2), 37–39.

Moore, I.D., Gessler, P.E., Nielsen, G.A., Peterson, G.A., 1993. Soil attribute prediction using terrain analysis. Soil Science Society of America Journal 57, 443–452.

Park, S.J., McSweeney, K., Lowery, B., 2001. Identification of the spatial distribution of soils using a process based terrain characterization. Geoderma 103, 249–272.

Schmidt, J., Evans, I.S., Brinkmann, J., 2003. Comparison of polynomial models for land surface curvature calculation. International Journal of Geographical Information Science 17, 797–814.

Schoenenberger, P.J., Wysocki, D.A., Benham, E.C., Broderson, W.D., 1998. Field Guide for Describing and Sampling Soils. USDA, NRCS, NSSC, Lincoln, NE.

Schoorl, J.M., Sonneveld, M.P.W., Veldkamp, A., 2000. Three-dimensional landscape process modeling: the effect of DEM resolution. Earth Surface Processes and Landforms 25, 1025–1034.

Shary, P.A., Sharaya, L.S., Mitusov, A.V., 2002. Fundamental quantitative methods of land surface analysis. Geoderma 107, 1–32.

Shi, X., Zhu, A.X., Wang, R., 2005. Fuzzy representations special terrain feature using a similarity-based approach. In: Petry, Fred, Robinson, Vincent B., Cobb, Maria A. (Eds.), Fuzzy Modeling With Spatial Information for Geographic Problems. Springer, New York, pp. 233–251.

Soil Survey Staff. 1999. Soil Taxonomy: a Basic System of Soil Classification for Making and Interpreting Soil Surveys (2nd ed.). Agric. Handb. No. 436, USDA Natural Resources Conserv. Serv., Washington, D.C., U.S. Govt. Print.

Thompson, J.A., Bell, J.C., Butler, C.A., 2001. DEM resolution: effects on terrain attribute calculation and quantitative soil-landscape modeling. Geoderma 100, 67–89.

Wilson, J.P, Repetto, P.L., Snyder, R.D., 2000. Effect of data source, grid resolution, and flow routing method on computed topographic attributes. In: Wilson, J.P., Gallant, J.C. (Eds.), Terrain Analysis: Principles and Applications. John Wiley & Sons, New York, pp. 133–161.

Wolock, D.M., Price, C.V., 1994. Effects of digital elevation model map scale and data resolution on a topography based watershed model. Water Resources Research 30, 3041–3052.

Zhang, W.H., Montgomery, D.R., 1994. Digital elevation model grid size, landscape representation and hydrologic simulations. Water Resources Research 30, 1019–1028.

Zhu, A.X., 1997. A similarity model for representing soil spatial information. Geoderma 77, 217–242.

Zhu, A.X., 1999. A personal construct-based knowledge acquisition process for natural resource mapping. International Journal of Geographic Information Science 13, 119–141.

Zhu, A.X., Band, L.E., 1994. A knowledge-based approach to data integration for soil mapping. Canadian Journal of Remote Sensing 20, 408–418.

Zhu, A.X., Mackay, D.S., 2001. Effects of spatial detail of soil information on watershed modeling. Journal of Hydrology 248, 54–77.

Zhu, A.X., Band, L.E., Dutton, B., Nimlos, T.J., 1996. Automated soil inference under fuzzy logic. Ecological Modelling 90, 123–145.

Zhu, A.X., Hudson, B., Burt, J., Lubich, K., Simonson, D., 2001. Soil mapping using GIS, expert knowledge, and fuzzy logic. Soil Science Society of America Journal 65, 1463–1472.