Multi-scale Landform Characterization for Land Use Evaluation Using Fuzzy Sets

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1. Introduction

In this paper we develop a method to evaluate spatial positioning of patches of conservation easement programs based on the underlying morphometric classification. We use a multi-scale approach to derive landform classes based on differential geometry and fuzzy set theory and examine the stability and scale-dependence of the analysis.

Fuzzy sets account for inherent uncertainty in defining semantic morphometric classes by assigning membership degrees on a continuous scale. Fuzzy overlay is used to combine different semantic fuzzy constructs of terrain attributes and create fuzzy semantic landform classes. We assess differences in areal and shape properties of extracted landforms underlying the considered land use patches between different scales and compare the results across spatial hierarchies of pixel, patch, and semantic class.

Such semantic models based in geomorphometry are potential tools to evaluate conservation programs with regard to current distributions of landforms, and the potential impact resulting from changes in the spatial extent and distribution of conservation areas. This method of exploring spatial patterns could become the basis for more advanced management of such programs.

We demonstrate this method using data from the Conservation Reserve Program(CRP), which is a voluntary land retirement program managed by the Farm Services Agency (FSA) of the United States Department of Conservation (U.S.D.A.). Since its inception in 1986, the program has grown to more than 34 million acres nation-wide, protecting and enhancing a variety of ecological services. Over the next five years, over 21 million acres are due to expire (Ducks Unlimited 2009).

2. Data and Study Area

The study area is Spring Creek Catchment, within the Upper Delaware Sub-basin in the Glacial Drift and Loess Hills Physiographic Province, Northeast Kansas, U.S.A. The area was part of the first national pesticide management area established (1987) due to elevated levels of the broad-spectrum herbicide Atrazine, and has numerous waterbodies listed as ‘impaired’ on the U.S. Environmental Protection Agency’s 303d list due to pollutant levels in excess of Total Maximum Daily Load requirements (NRCS 2006). 10-meter Digital Elevation Models were used for surface interpolation CRP parcels were available as digitized polygons at 1:24,000 scale.

3. Methods

The scales examined ranged from the data resolution (10 m) to the maximum window size (100 – 200 m) suggested for capturing in-hillslope variation (MacMillan and Shary 2009). To derive a system of simplified landform classes across scales from which basic mechanistic processes and physical soil properties could be inferred, a 6-class system was derived (Speight 1990, Qin 2009). To do so, we (1) calculated terrain attributes and converted them to fuzzy semantic constructs (Burrough et al. 1992) which describe the characteristics of semantic landforms, (2) carried out fuzzy overlay to develop semantic fuzzy representations of each landform class across multiple window sizes (Fisher et al., 2004), and (3) iteratively defuzzified landform regions to examine spatial stability across scales for the spatial hierarchies pixel, patch, and semantic-class.

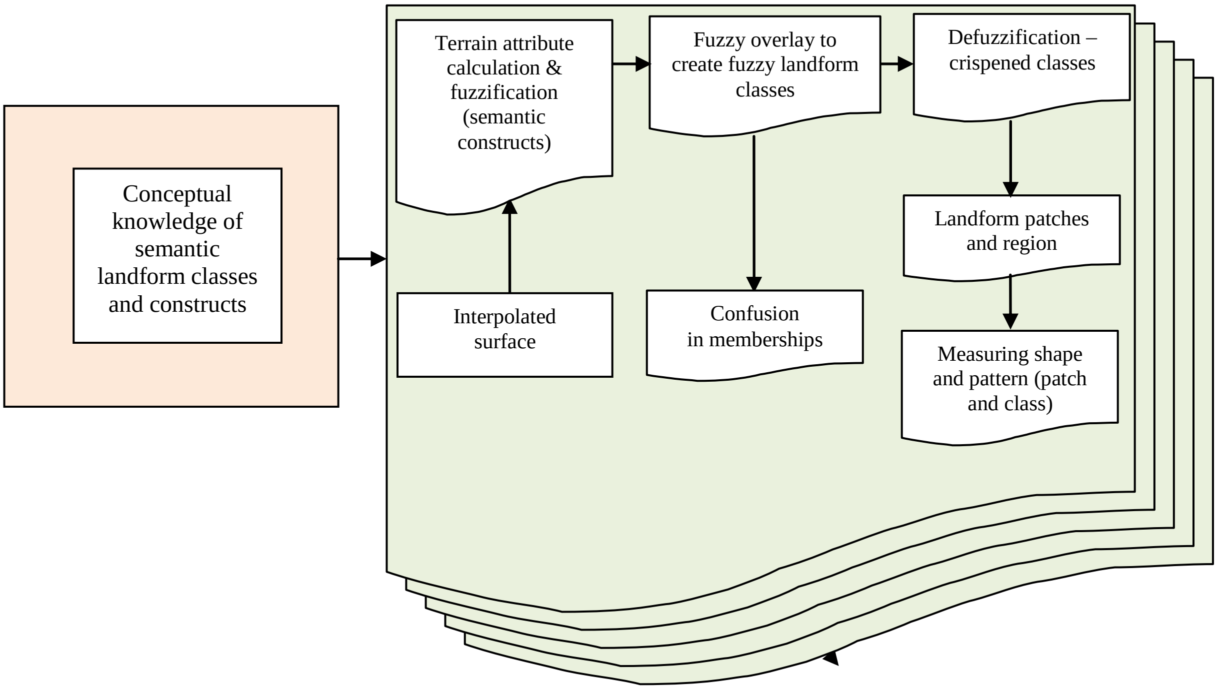

Figure 1. Methodological Steps.

3.1 Terrain attributes and fuzzy semantic import

To carry out the land surface parameterization we utilized a second-order polynomial (Evans 1972) to calculate terrain attributes using existing algorithms for multi-scale surface characterization (Wood 1996). Terrain attribute surfaces were created with a combination of customized algorithms in Python, MATLAB, and R.

Semantic Import Models based on first-order polynomials (Burrough et al. 1992, Robinson 2003) were utilized to convert terrain attributes to fuzzy membership values on a continuous scale [0,1], in order to develop the corresponding semantic constructs for landforms. For membership functions, central concepts were based on existing definitions; parameters and dispersion indices were taken from the statistical distribution of the terrain attributes over the study area to maintain a degree of generality of the approach. Thus, each location (pixel) was given a membership to each semantic construct of each terrain attribute for all window sizes.

3.2 Fuzzy overlay to develop multi-scale semantic representations

Semantic representations of landform classes were created for each window size by combining surfaces of semantic constructs in a fuzzy spatial overlay operation. We tested different fuzzy operators such as fuzzy intersection (MIN operator), fuzzy union (MAX operator), fuzzy gamma coefficients, and convex combinations of different operators (Robinson 2003) to produce 6 surfaces representing fuzzy semantic landform classes (crest, shoulder slope, back slope, foot slope, flat, drainage).

For each window size we measured the degree of confusion between classes by calculating confusion index and entropy. Low confusion and low values of entropy indicate that there is one dominating class; high confusion means there are at least two classes of similar high membership at the same location (Wood 1996, Burrough et al. 1997). We also tested the stability of memberships of each location by calculating their variety across scales. For various defuzzification thresholds (alpha cuts) we created final crisp morphometric landform classes, which were smoothed by a local majority filter and converted to raster regions.

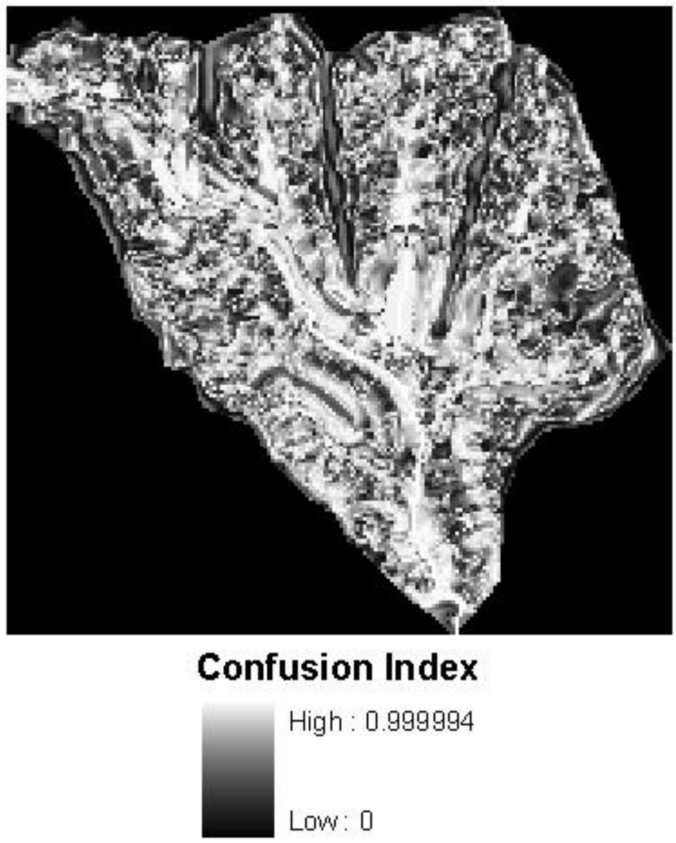

Figure 2. Confusion index map: Lower values (e.g., ridges) and higher values (e.g., valleys) exhibit lower and higher confusion, respectively.

3.3 Derivation and characterization of regions

We derived simple measures of area, shape (e.g. the circularity ratio) and adjacency for the regionized landforms (patches) using landscape metrics and repeated these calculations for all window sizes to produce a measure of landform-specific similarity across scales. Metrics were calculated for the patch and semantic-class levels.

4. Expected Results

We intend to investigate whether the areas of high confusion between classes represent areas of spatial instability in landform membership across scales using the derived shape descriptors. Previous authors (Arrell et al. 2007) have suggested that high confusion indices between morphometric classes could represent transitional areas of the landscape in. Thus, locations with a high degree of confusion, which indicates similar degrees of membership to multiple landform classes, can be understood as zones where multiple physical processes occur and thus as susceptible parts of the landscapes.

Changes in spatial properties of semantic landform classes (fuzzy and crisp) at the three spatial hierarchies will be examined across scales of analysis to examine the stability and scale-dependency of the final classification. From preliminary results, we expect the highest amount of stability and least amount of uncertainty within crests and highest areas in the landscape, but the degree of flux across scales is unknown. Additionally, we expect to find a higher diversity of edge adjacency between landforms at fine scales.

The ideas tested above will be applied to individual CRP patches to examine whether the areas with high confusion, high instability, and high variability in areal properties across scales are represented within CRP patches as a reasonable proportion.

5. Discussion and Conclusions

Since CRP enrollment occurs across physiographic regions, a generic model based on land-surface parameterization could be a promising tool for multi-scale assessment of landform proportions. This approach expands pixel-based classification based on terrain attributes by integrating spatial properties of derived landform classes represented at the different spatial hierarchies. Since many ecological processes are sensitive to area and edge characteristics of the considered patches, finer resolution data could be used to examine more process-specific local phenomena.

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