

Representing and Negotiating Uncertain Geospatial Concepts

- Where are the exurban areas?¹

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Abstract

In urban landscape studies, there are geospatial concepts that have many different definitions and the spatial boundaries such as exurbanization concept. We identify and illustrate the uncertainty of the exurban concept using a fuzzy-set based conceptual space approach. Several definitions of exurbanization are investigated on how they conceptualize exurban areas, and we develop formal representations for our analysis and demonstration. To support this we suggest a software interface that would allow interactive exploration, analysis, negotiation, and visualization of uncertain geospatial concepts. With selected definitions applied to empirical spatial data we demonstrate some key features of the developed software. The case study of five different definitions of exurbanization in north central Ohio, U.S. shows varying degrees of agreement and illustrates the impact of different approaches to negotiate the multiple different definitions. The paper also provides the results from user evaluation of the developed software to better support the exchange of knowledge and communication between the users.

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1. Introduction

The urban landscape generally consists of urban, suburban, exurban, and rural areas from the core to the periphery in the landscape (Theobald 2001). Among these, the rapidly increasing size of the exurban areas has recently received attention (Irwin et al. 2007). There are many different terms related to exurbanization such as sprawl, exurbia, sub-/exurban, periurban, and rural area. Even in cases where terms are similar there are different definitions of exurbanization, each using various defining characteristics such as population density, distance, household lot-size, and so on. Berube et al. (2006) reviewed eighteen existing studies of exurbanization but found little consensus between these studies in their definition of exurbia. Since definitions are different, data and measurements of exurbanization are highly dependent on the researchers (Irwin and Bockstael 2004). A further complication is that it is difficult to determine exact boundaries between types of urban landscapes (Nelson 1992). This difficulty could depend on either definition issues or gradual changes in the landscape creating transition zones hard to define (Ahlqvist and Ban 2007).

Because of these issues, it is problematic to discuss exurban areas using a single, crisp boundary since the empirical spatial extent can vary between different definitions (Ban and Ahlqvist 2007). Instead of searching for a distinct boundary of urban sprawl, it can be useful to look at exurbanization as a fuzzy-set (Zadeh 1965) concept to have a vague boundary in space. A 'set' means a group that consists of one or more members in it. Fuzzy-set theory deals with vague concepts by allowing partial membership to a set (Zadeh 1965). In our case, a location with more exurbanization would have larger membership of the exurban fuzzy-set. Membership values of exurbanization can be represented for locations using empirical spatial data and geovisualization

techniques. Fuzzy approaches reveals greater detail in the representation of a boundary than the conventional crisp approach (Burrough 1989), and fuzzy-set theory offers various techniques for analyzing such imprecise data (Zadeh 1965; Zhang and Goodchild 2002). However, there are few existing studies that deal with the uncertainty of urban boundary issues using fuzzy-set approaches.

This paper has three main goals: 1) to identify and illustrate the semantic uncertainty of exurbanization from existing definitions, 2) to demonstrate the development of an interactive tool for working with uncertain geographic concepts, and 3) to demonstrate some implications of semantic uncertainty of exurban boundaries on empirical spatial data. We propose the use of fuzzy sets to represent the uncertain semantics in both conceptual and geographic spaces for modeling and representation of the exurban concept. Figure 1 illustrates a conceptual framework of this study.

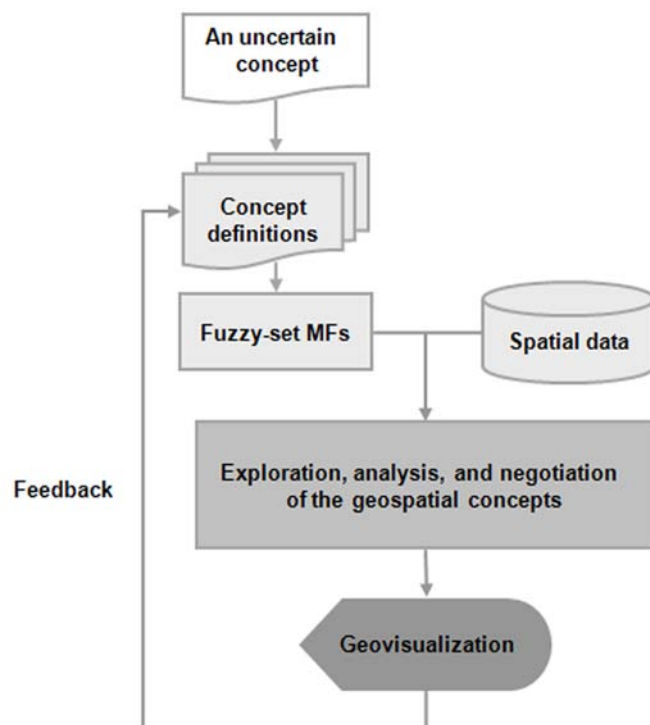


Figure 1. A conceptual framework of the study

2. Theoretical background

2.1 Existing definitions of exurbanization

Sprawl emerges from a rapid population growth that forms random clusters of development in low-density areas outside of urban areas (Sultana and Weber 2007; Spectorisky 1955; Davis et al. 1994). Sprawl is different from monocentric or polycentric urban forms (Ewing 1994) in that it is irregular. The “exurbs” are important since the proportion of area relative to other land uses is reported to be rapidly growing and having major implications for land use in the U.S. (Irwin et al. 2007; Nelson and Sanchez 2005). Land allocated or defined as exurbia grew faster than any other landscape type in the U.S. in the 1990s (Johnson and Beale 1998).

There have been efforts to measure exurbanization and describe its spatial patterns. Measures of sprawl often involve using attributes such as continuity, concentration, or proximity (Galster et al. 2001; Wolman et al. 2005). Population density and location (Daniels 1999; Brown and Robinson 2006; Martinuzzi et al. 2007), a process of population movement, one of the concepts of exurbanization (Long and Nucci 1997), and Landscape Sprawl (LS) metric (Theobald 2005) are examples that have frequently been used in defining exurban areas. In addition, the idea to determine geographic extent, patterns, and classes of urban growth over time using land cover data has been proposed (Hoffhine Wilson et al. 2003).

In this study we will focus on six different definitions of exurbanization chosen from the literature and in use today. These were selected because they provide multiple measurable criteria to identify exurbanization as follows.

According to Nelson (1992), exurban areas are defined by using the characterizing attributes of distance from a central metropolitan statistical area (MSA) and population such that “counties

within 50 miles of the boundary of the central city of a MSA with a population of between 500,000 and less than 2 million”, or “within 70 miles of the boundary of the central city of an MSA with a population of more than 2 million, but not otherwise classified as a central county or traditional suburban county”.

Similarly, Daniels (1999) defines exurban areas using slightly different attributes of distance and population: “10 to 50 miles away from a major urban center of at least 500,000 people” or “5 to 30 miles from a city of at least 50,000 people.” In addition, other characterizing attributes such as “the area is generally within a 25-minute commuting distance” and “the population density is generally less than 500 people per square mile” are used (Daniels 1999). There are several other typical characteristics mentioned that will not be used here. See details in Table 1.

Martinuzzi et al. (2007) define urban sprawl by integrating the census data with patterns of development found in aerial photos. They start by identifying types of land-use into “urban, densely-populated rural, and sparsely-populated rural.” The “urban” and the “densely-populated rural” classes are then divided into five subclasses: (1) population of 50% above the mean population density or more, (2) population of 20 ~ 50% above the mean population density, (3) population of mean population density or up to 20% above the population density, (4) population below the mean population density, and (5) low-density development. The classes from (1) to (4) are considered “high-density development” classes, with the class (1) having the lowest tendency of urban sprawl.

Lang and Sanchez (2006) differentiate exurbs by commuting distance and population characteristics such as ethnicity, and define exurban counties to be within an MSA and share a functional relationship with neighboring counties via commuting. Also, they note that exurbs have a predominantly white population as opposed to more diverse metropolitan cores.

Nelson and Sanchez (1999) suggest that households with incomes higher than average are “likely to move into exurbia”. The difference between exurbanites and suburbanites is that the exurbanites are located far away from urban areas. However, it is hard to clearly differentiate exurbs and suburbs and the boundary between them is continuous (Nelson and Sanchez 1999). Theobald (2001) defines exurban areas using an “exurban density” attribute which is the housing density: “exurban density ranges from 0.025 to 0.1 units per acre, or 1 unit per 10–40 acres”. Very low-density development such as “ranchette” with “1 unit per 35–45 acres” also belongs to this class.

These existing definitions use different characterizing attributes and measurements to identify the exurbanization in empirical location. However, these works all utilize crisp definitions of the exurban boundaries. In contrast, there exist other approaches with more continuous views on the boundaries. For example, Pond and Yeates (1993) suggest the transition from exurban to suburban into five stages: agricultural stage, early urban influence, small town growth/exurbanization, and urban stage. Hence, the urban landscape could be treated as both “bona fide” and “fiat” (Smith 1995; Fonseca et al. 2000, Smith and Varzi 2000). In the following section we discuss important types of uncertainty found in the exurban concept and identify formal ways to represent it for analysis.

2.2 The uncertainty of exurbanization concepts

Uncertainty of information is a vitally important component when spatial data is used for decision support for allocating social and economic resources, and at least three types of

uncertainty can be identified: error, ambiguity, and vagueness (Fisher 1999). When classes of spatial objects and individuals are well-defined but poorly measured they generate errors. An example would be when an exurban area is defined as “areas with population density of 500people/mi² or less” (Daniels 1999) but population data to be used has some missing records or miscoded values. If classes are poorly defined with no unique allocation or membership of the individual objects to the classes, they generate vagueness and ambiguity (Fisher 1999; Leyk et al. 2005). Most of the example definitions above use quantitative characteristics to define exurbanization, and some of them also include qualitative expressions such as “generally within 25-minute commuting distance” (Daniels 1999). These are examples of vague exurban definitions.

Sometimes the two types of uncertainty combine: there could be ‘vagueness’ about how many people are required for a land to be classified as exurban, and ‘error’ in the data collection or measurement about the number of people residing in that location. As Ahlqvist and Gahegan (2005) mention, this “compound uncertainty” makes it difficult to determine if low accuracy is due to poor measurements, or if the concept itself generates problems due to its confusing definition. Since this paper is primarily interested in the representation and negotiation of definitions it will focus on uncertainty related to vagueness.

Vagueness in urban environment studies has been addressed by fuzzy-set approaches. For example, Hwang and Thill (2005a; 2005b; 2007) found uncertainty in the location of the urban environment between ontology, perception, and implementation levels that can be measured and represented using fuzzy-set theories.

There have been studies on uncertainty of the suburban concept due to its multiple definitions (Lineberry 1975), heterogeneous characteristics (Fisher and Pathirana 1990), and multiple

classifications between urban and suburban areas (Wilson 2001; Shackelford and Davis 2003). However, they specify the suburban concept using relationships between the other concepts such as urban and rural areas rather than explaining the suburban concept itself. This paper is distinguished from these studies by focusing on the uncertainty of the exurban concept and specifying the concept itself.

2.3 Definitions of exurbanization as conceptual spaces

The vague character of exurban definitions motivates us to make a transformation of the criteria into fuzzy-set membership functions. We argue that definitions of exurbanization should be treated in a way that explicitly represents their vagueness. Several approaches have been suggested to represent concept uncertainty in general (Fisher 1999; Pang 2001; Ahlqvist 2004; Leyk et al. 2005). In this work we adopt the methodology in Ahlqvist (2004) which is based on theories of conceptual spaces (Gärdenfors 2000) and fuzzy sets (Zadeh 1965). A conceptual space is formally represented as a collection of property definitions, for example the distance of “10 to 50 miles” (Daniels 1999).

Figure 2 shows the distance attribute from an urban core and the population attribute on the x and y axis respectively. As mentioned, Daniels (1999) defines exurban areas as “10 to 50 miles away from a major urban center of at least 500,000 people” or “5 to 30 miles from a city of at least 50,000 people”. These would correspond to all values within the zones A and B. Similarly, Nelson’s (1992) definition “counties within 50 miles of the boundary of the central city of a MSA with a population of between 500,000 and less than 2 million”, or “within 70 miles of the boundary of the central city of an MSA with a population of more than 2 million, but not

otherwise classified as a central county or traditional suburban county”, would correspond to zones C and D.

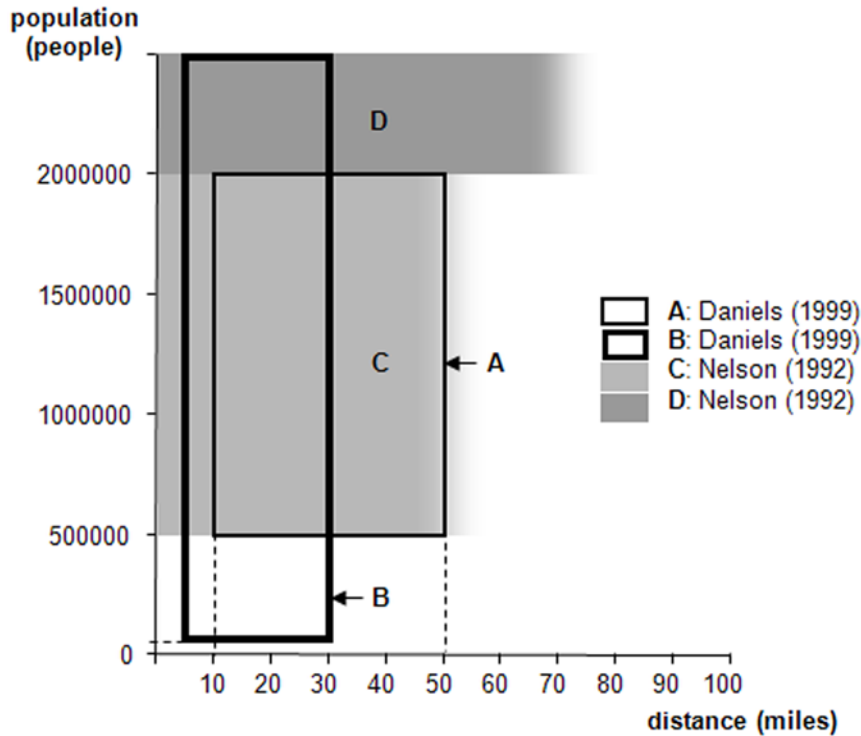


Figure 2. Illustration of existing definitions of exurbanization based on Daniels (1999) and Nelson (1992) using characteristics of distance from an urban core and population of the urban area.

Figure 2 clearly shows differences and overlaps between the definitions of Daniels (1999) and Nelson (1992). Each zone includes distance and population characteristics and allows for a graphic comparison between the two definitions. It is hard to determine exurbanization precisely since the boundaries between urban, suburban, exurban, and rural areas are uncertain (Nelson 1992). In the following sections we demonstrate representation multiple definitions of

exurbanization using fuzzy-sets (zones C and D in Figure 2) and logically combine them for a better understanding of discrepancies and spatial consequences.

3. Data and methods

3.1 Data and study area

Census data are frequently used to analyze exurbanization and define its location (Wolman et al. 2005). In our study the U. S. Census 2000 Summary File 3 (U. S. Census Bureau 2000) data including some attributes of exurbanization are used.

The study area includes Franklin, Delaware, and Morrow Counties in the Columbus MSA, Ohio, and Richland County in the Mansfield MSA, Ohio (Ohio Department of Job & Family Services 2007). Total population of the Columbus MSA was 1,527,948 in 2000 and that of the Mansfield MSA was 128,852 in 2000 (U. S. Census Bureau 2000). Recently, exurban areas in Ohio generally have experienced rapid population growth as compared to previous decades (Smith and Sharp 2005). Figure 3 provides a further orientation across the study area with population densities.

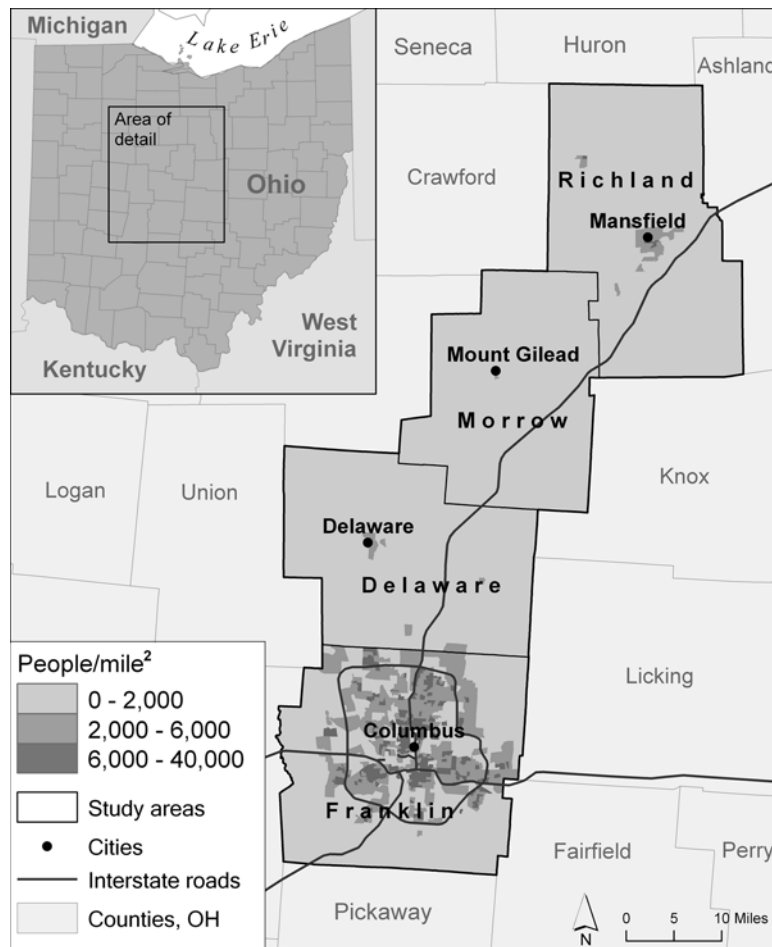


Figure 3. Study areas

3.2 Development of fuzzy-set membership functions (MFs)

In Nelson (1992)'s definition above, 50 miles from the boundary of a central city is an outer limit for exurban areas. Instead of seeing this as a crisp cut-off point we could think of it as a "crossover point" (Burrough and McDonnell 1998) that is used to decide whether a location is exurban or not, and give a membership value of 0.5 meaning the area could be either exurban or non-exurban. If the distance is 0 mile, the membership value would be 1 meaning the area is exurban. Using a simple linear fuzzy-set membership function we would then have membership

taper off to 0 at a distance of 100 miles away from the central city. The suggested membership function for distance in Nelson's (1992) definition, $MF_{(a)}$, is thus expressed by the formulas (1):

$$\begin{aligned}
 MF_{(a)} &: 1 - 0.01 \cdot X & \text{for} & \quad (X \leq 100) \text{ and} & & (1) \\
 MF_{(a)} &: 0 & \text{for} & \quad (X > 100)
 \end{aligned}$$

To define a membership function based on Daniels's (1999) definition, "10 to 50 miles away", a combination of simple linear functions was used following a similar logic as above.

Consequently a set of MF for distance, $MF_{(b)}$, is expressed as the formulas (2):

$$\begin{aligned}
 MF_{(b)} &: 0.05 \cdot X & \text{for} & \quad (X < 20), & & (2) \\
 MF_{(b)} &: 1 & \text{for} & \quad (X \geq 20 \text{ and } X < 40), \\
 MF_{(b)} &: 3 - 0.05 \cdot X & \text{for} & \quad (X \geq 40 \text{ and } X < 60), \text{ and} \\
 MF_{(b)} &: 0 & \text{for} & \quad (X > 60)
 \end{aligned}$$

Fuzzy-set MFs for commuting time (Daniels 1999), population density (Daniels 1999; Martinuzzi et al. 2007), population ethnicity (Lang and Sanchez 2006), household income (Nelson and Sanchez 1999), and housing density (Theobald 2001) were developed in the same manner and their specifications can be found in Table 1.

Table 1. Definitions of exurbanization and their fuzzy-set MFs

Authors	Original description	Characteristic attributes	Graphic illustrations of memberships	Fuzzy-set MFs	Original description not used / omitted
Nelson (1992, 361)	“Counties within 50 miles of the boundary of the central city of a MSA with a population of between 500,000 and less than 2 million”	distance (mi)		$MF_{(a)}$: $MF=1-0.01 \cdot X$ (for $X \leq 100$) $MF=0$ (for $X > 100$)	“...counties neither central nor suburban” “...counties those have more than 10 percent of the work force commuting to a MSA”
Daniels (1999, 14)	“10 to 50 miles away from a major urban center of at least 500,000 people”, or “5 to 30 miles from a city of at least 50,000 people” “The area is generally within 25 minute commuting distance” and “the population density is generally less than 500 people per square mile”	distance (mi)		$MF_{(b)}$: $MF=0.05 \cdot X$ (for $X \leq 20$) $MF=1$ (for $X > 20$ and $X \leq 40$) $MF=3-0.05 \cdot X$ (for $X > 40$ and $X \leq 60$) $MF=0$ (for $X > 60$)	“...households have an on-site septic system and one’s own well. The community has both long-term residents and moved in within the last 10 years. The elected officials and neighbors are very interested in population growth, property taxes, and the rising cost of public services. The resident drives over 15,000 miles a year. The agriculture and forestry are declining in the community.”
		population density (people/mi ²)		$MF_{(c)}$: $MF=1-0.001 \cdot X$ (for $X \leq 1000$) $MF=0$ (for $X > 1000$)	
		commuting time (min)		$MF_{(d)}$: $MF=1-0.02 \cdot X$ (for $X \leq 50$) $MF=0$ (for $X > 50$)	

Table 1. Definitions of exurbanization and their fuzzy-set MFs (cont.)

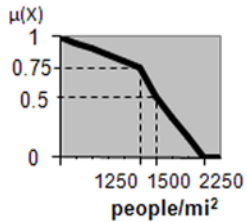
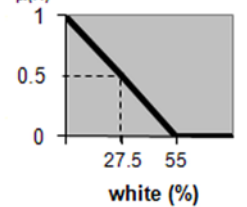
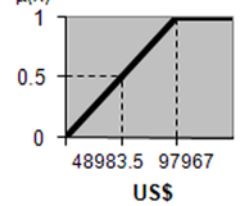
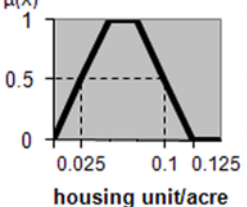
<p>Martinuzzi et al. (2007, 292)</p>	<p>(1) “population of 50% above the mean population density” (2) “population of 20 ~ 50% above the mean population density” (3) “population of 0~20% above the mean population density” (4) “population below the mean population density”</p>	<p>population density (people/ mi²)</p>		<p>MF_(e): MF=1-0.00005·X (for X≤5002) MF=2-0.00025·X (for X>5002 and X≤6002.4) MF=1.525-0.00017·X (for X>6002.4 and X≤7503) MF= 0.1-0.0001·X (for X>7503 and X≤10004) MF=0 (for X>10004)</p>	<p>“...regions where less than 20% of the pixels within a 300m x 300m area are developed.”</p>
<p>Lang and Sanchez (2006, 4-5)</p>	<p>“Exurbs are virtually all white with less diverse than suburbs that have 25 ~ 30% of minority”</p>	<p>population ethnicity</p>		<p>MF_(e): MF=1-0.018·X (for X≤55) MF=0 (for X>55)</p>	<p>“...they share a functional relationship with neighboring counties via commuting”</p>
<p>Nelson and Sanchez (1999, 697)</p>	<p>Households with average incomes or above average are likely to move into exurbia</p>	<p>household income (\$)</p>		<p>MF_(g): MF=0.0000102·X (for X≤97967) MF=1 (for X>97967)</p>	<p>“...families in the child-rearing stage and tend to move into exurbia more than other families”</p>
<p>Theobald (2001)</p>	<p>“Exurban density” ranges 0.025 ~ 0.1 housing units per acre</p>	<p>housing density (housing unit/acre)</p>		<p>MF_(h): MF=20·X (for X≤0.05) MF=1 (for X>0.05 and X≤0.075) MF=2.5-20·X (for X>0.075 and X≤0.125) MF=0 (for X>0.125)</p>	

Table 1 shows the selected definitions of exurbanization with their corresponding fuzzy-set MFs developed in this study. Some of their characteristics are not used in this study and these are also specified in Table 1. Using these fuzzy-set MFs, raster datasets of these variables were used to assign MF values to each location in empirical spatial data.

Regarding Daniels’s definition, we first generated three raster layers with membership values for each characteristic attribute—distance, population density, and commuting time—then calculated the mean value of these layers for each pixel. As a result, we made six raster datasets for the six definitions showing MF values.

MF values for definitions including multiple attributes can be generated by fuzzy-set combinatory approaches, some of which will be detailed in the next section. We follow Burrough (1989)’s “convex combination” approach because it most closely follows the conceptual spaces (Gärdenfors 2000; Ahlqvist 2004) theoretical framework in this study. The convex combination produces a “weighted sum” of ingoing fuzzy membership values as follows:

$$\mu(X) = \sum_{i=1}^n \omega_i \cdot \mu_{x_i} , \quad (3)$$

$$0 \leq \mu(X) \leq 1 ,$$

$$0 \leq \mu_{x_i} \leq 1 ,$$

$$\sum_{i=1}^n \omega_i = 1, \text{ and } 0 < \omega < 1$$

where μ_{x_i} is the value of a membership function i at a location and ω_i is non-negative weights for the membership function.

3.3 Combining different definitions of exurbanization

When there are multiple definitions for a term such as the exurbanization, it might be necessary to obtain a negotiated membership value for a location. Fuzzy sets can be operated to achieve this (Silvert 1997; Brown et al. 2003) using some logics such as algebraic product, convex combination, and conditioned fuzzy-sets (Zadeh 1965; Zimmermann 1987; Robinson 2003). In this paper, we explore five different combinatory-operations described below (formulas 4 - 8) to negotiate fuzzy sets of the exurban definitions.

Given three fuzzy-sets A, B, and C, the union is defined by $A \cup B \cup C$, and its MF is given by

$$\mu_{A \cup B \cup C} = \text{Max}[\mu_A, \mu_B, \mu_C] \quad (4)$$

which is a set of maximum values between the three sets (Zadeh 1965).

The intersection of A, B, and C is defined by $A \cap B \cap C$, and its MF is given by

$$\mu_{A \cap B \cap C} = \text{Min}[\mu_A, \mu_B, \mu_C] \quad (5)$$

which is a set of minimum values between the three sets (Zadeh 1965).

The algebraic product of A, B, and C is defined by ABC , and its MF is given by

$$\mu_{ABC} = \mu_A \mu_B \mu_C \quad (6)$$

which is a product of membership values between the three sets (Zadeh 1965).

The fuzzy-gamma operation of A, B, and C is defined by $A \theta B \theta C$, and its MF is given by

$$\mu_{A \theta B \theta C} = \mu_{A \oplus B \oplus C}^\gamma \mu_{ABC}^{1-\gamma}, \text{ where } 0 \leq \gamma \leq 1 \quad (7)$$

$$\text{and } \mu_{A \oplus B \oplus C} = 1 - (1 - \mu_A)(1 - \mu_B)(1 - \mu_C)$$

which is the product of the weighted membership values for the algebraic sum and the algebraic product (Zadeh 1965; Zimmermann and Zysno 1980; Champati ray et al. 2007).

The average of A, B, and C has a MF given by

$$\mu_{(A,B,C)} = \frac{\mu_A + \mu_B + \mu_C}{3} \quad (8)$$

which is a set of average membership values between the three sets.

Using these operations the MF values of different fuzzy-sets can be combined. We describe the results in the following sections.

In addition, we can measure difference or overall uncertainty between those memberships. One of the metrics is the “variance” index (Aerts et al. 2003) showing how a membership value is far from the mean membership-value. We followed Aerts et al. (2003) to generate uncertainty maps

between the definitions of exurbanization using variance of their membership values. This choice was motivated mainly because it provided the most well-known and intuitive interpretation compared to other metrics.

4. Software development – an interactive tool for working with uncertain geographic concepts

We developed a prototype software ‘pinu’—Program for Identification and Negotiation of Uncertain concepts—that aids comparison, construction, visualization, and negotiation of the uncertain concepts in an interactive graphical-interface online.

For software-development that could be used for Public Participation Geographic Information Systems (PPGIS) such as pinu, user friendliness should be considered, and one of the ways to achieve this is through user testing (Haklay and Tobon 2003). Consequently we developed a first-prototype for user testing to find limitations of the interface for concept comparison and creation activities. The subjects of this user-evaluation were graduate students in the Department of Geography, the Ohio State University. The survey included a combination of interviews and practical demonstrations to evaluate the readability, visual design, and usability of components. Based on the user responses, the software interface went through a substantive revision that resulted in the current prototype depicted in Figure 4.

The interface of pinu consists of components for ‘concept comparison activity’—to see difference between existing concepts, and ‘concept definition activity’—to create a user’s own concept. The user can select one or more concepts and spatial data located either online or on client machine. The concept(s) and data are represented in real-time graphical illustrations

including numbers, texts, graphic shapes, or maps. The user can measure difference between the concepts, combine them for negotiation, and create a new concept by manipulating the graphical interface. Each activity is described in detail in the following sections.

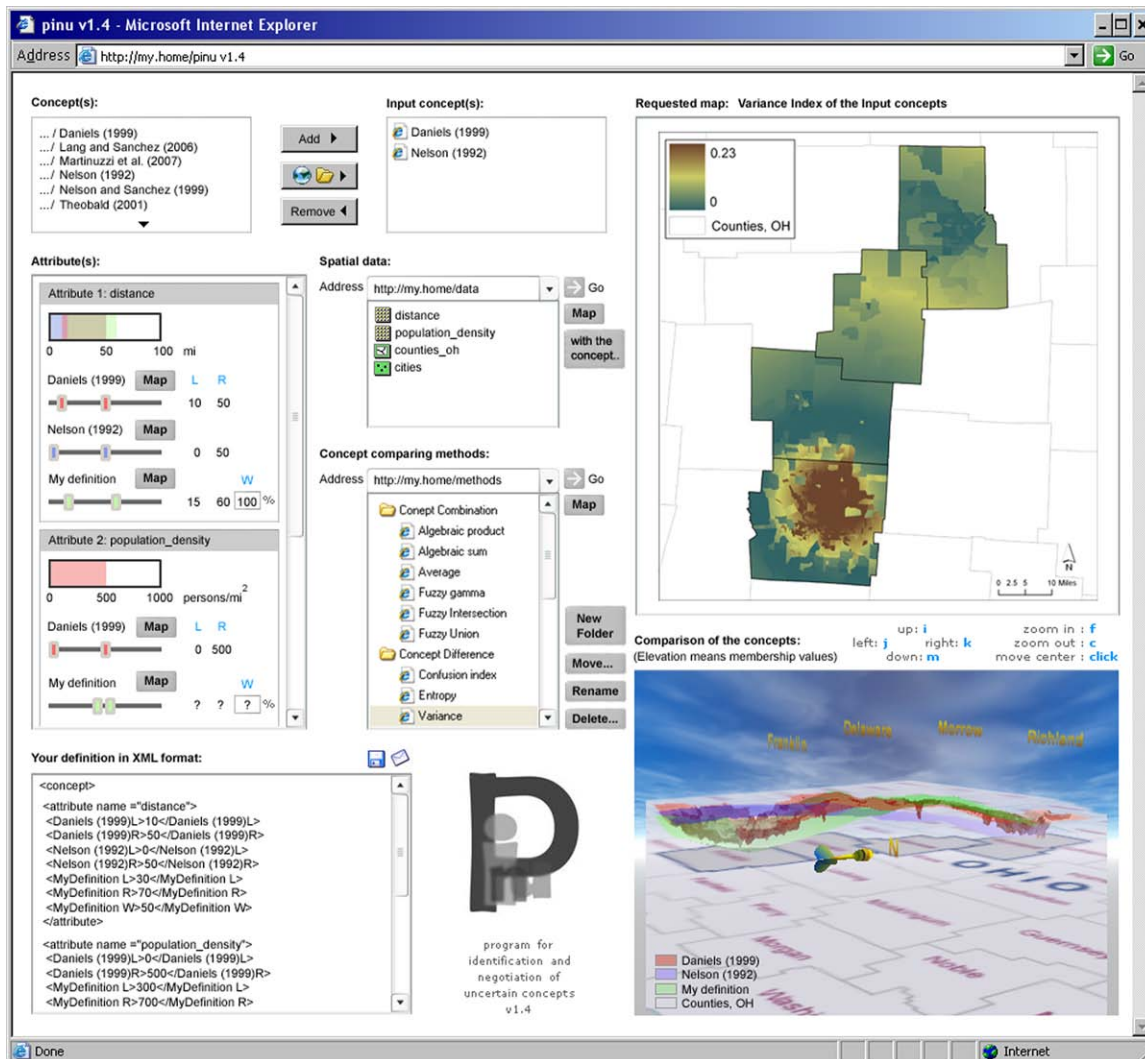


Figure 4. A prototype user-interface of the developed software 'pinu v1.4'

In this study, the full implementation of the prototype software is only partially completed but its components currently support interactive functionalities such as concept selection, attribute display, XML code generation, 2D and 3D geovisualization. The prototype is accessible online

but it is restricted to deal with concept documents and geospatial data in a local computing environment. In the future we anticipate substantial improvements, such as full interactive-functionalities.

4.1 Concept comparing activity

Within pinu's interface (Figure 4), the user can compare existing concepts by visualizing and analyzing their semantics as well as spatial implications. For example, the user can access online resources that contain concept definitions and add them to the 'Input concept(s)' list. Once concept definitions are chosen, their attributes are visualized in the 'Attribute(s)' list. In Figure 4, the attributes of Daniels (1999) and Nelson (1992) are represented as red (Daniels) and blue (Nelson) shapes, sliders, and numbers. Fuzzy membership functions are commonly represented using rectangular, triangular, quadratic, trapezoidal, Gaussian, or log-exponential shapes (Duch 2005). In our work, the fuzzy-set MFs developed for the attributes have the trapezoidal shapes (Table 1). The functions are portrayed by rectangular bars that cover semantic value ranges, distance, and overlap of the attributes following Ahlqvist (2004).

To see the spatial implication of the input concepts, the user can access spatial data that is either online or local in pinu, and match the data with the input attribute(s). Then the membership values of the concept or combinations of attributes are displayed as a 2D map (Figure 4).

Likewise, the 2D map interface helps the user dynamically explore membership values according to the definitions. The data is also visualized as a 3D map in a virtual environment of pinu (Figure 4) to compare the spatial implication of concept definitions. In each of the 3D surfaces, their MF values are represented as the elevation, and this makes it easier to compare the difference between them than in 2D. The user can also combine and compare the concept

definitions in several ways in local or online in pinu. In Figure 4 the variance of Daniels' (1999) and Nelson's (1992) definitions is measured and visualized. Figure 5 and Figure 6 show further examples of maps based on user requests.

4.2 Concept defining activity

In decision-making, some users may want to create their own definition and the pinu interface supports a dynamic tool for this activity. The user can create a new definition by manipulating 'My definition' area in pinu that support the convex combination process (Figure 4). The user can also define weight values for attributes to explore the spatial implication. There is no rule of thumb to decide the weights. For example, the user has several choices to assign an attribute more weights than the other, or assigning no weights at all. The new definition can be displayed in the map areas of pinu. In Figure 4, an example of the user's definition is represented as a 3D raster surface in green color.

An underlying requirement of pinu's prototype interface is to support a collaborative environment so that distant users can exchange information about the exurban concept. To support query and transfer of data on the web, information of attributes and concepts are encoded in Extensible Markup Language (XML) and displayed in the lower left area in pinu (Figure 4). The XML code is interactively updated whenever the user manipulates sliders or weight values, and any new definition can be saved as an XML text file that could be posted to the web as a reference for further dissemination.

In summary, using pinu, the users can 1) access existing concepts and spatial data located online or locally, 2) visualize the uncertainty between the attributes of the concepts and their spatial representation, 3) combine the multiple uncertain concepts, 4) compare and measure difference

between the concepts with the aid of interactive maps, 5) create a new concept by defining the attributes, and 6) disseminate concept information over the web.

5. Results

5.1 Spatial demonstration of uncertainty in exurban boundary

Figures 5(a-f) reveal that the different exurban definitions introduced in this paper generate different patterns of exurbanization throughout the study area. In Figure 5, the darker grey colors represent higher degree of being exurban area, whereas the lighter grey colors mean lower degree of exurbanization.

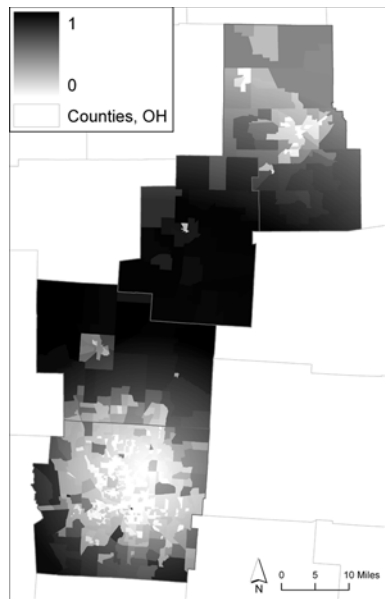
Figures 5(b-f) show similar spatial patterns of the membership values although the definitions used different attributes except Nelson's (1992) definition. Given that it is only based on distance from the boundary of the central city (Columbus) we disregard Nelson's (1992) definition in the remainder of the analyses. In addition to the graphic map-results presented in Figure 5, we provide summary statistics on areas above an example membership threshold value of 0.5 for each map.

5.2 Concept combination approaches for negotiation of the concepts

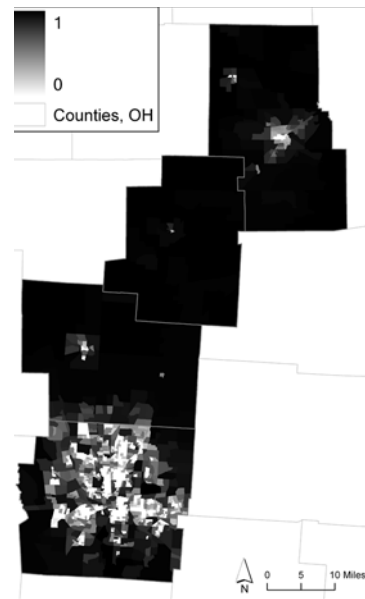
Figure 6 show the results of the union (Figure 6a), intersection (Figure 6b), algebraic product (Figure 6c), gamma: $\gamma = 0.9$ (Figure 6d), and average (Figure 6e) operations to negotiate the different exurban definitions.



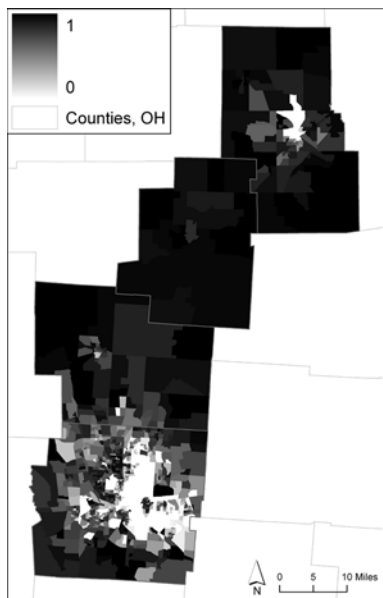
(a) using distance
(Nelson 1992;
Min: 0.41, Max:1,
Area: 1,808 mi²)



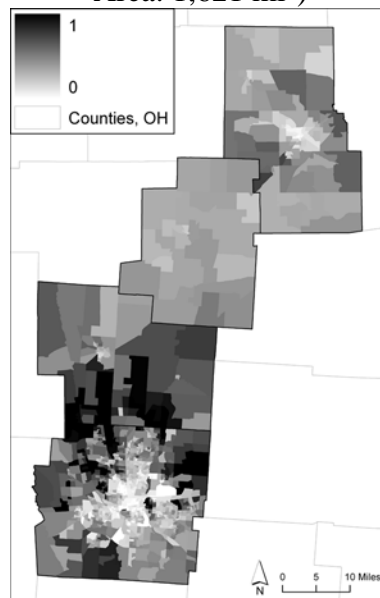
(b) using distance, population
density, and the commuting
time (Daniels 1999;
Min: 0.03, Max:0.98,
Area: 1,621 mi²)



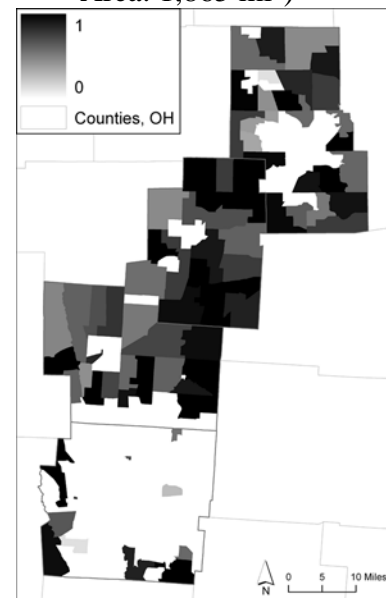
(c) using population
density
(Martinuzzi et al. 2007;
Min: 0, Max:1,
Area: 1,865 mi²)



(d) using population ethnicity
(Lang and Sanchez 2006;
Min: 0, Max:1,
Area: 1,812 mi²)

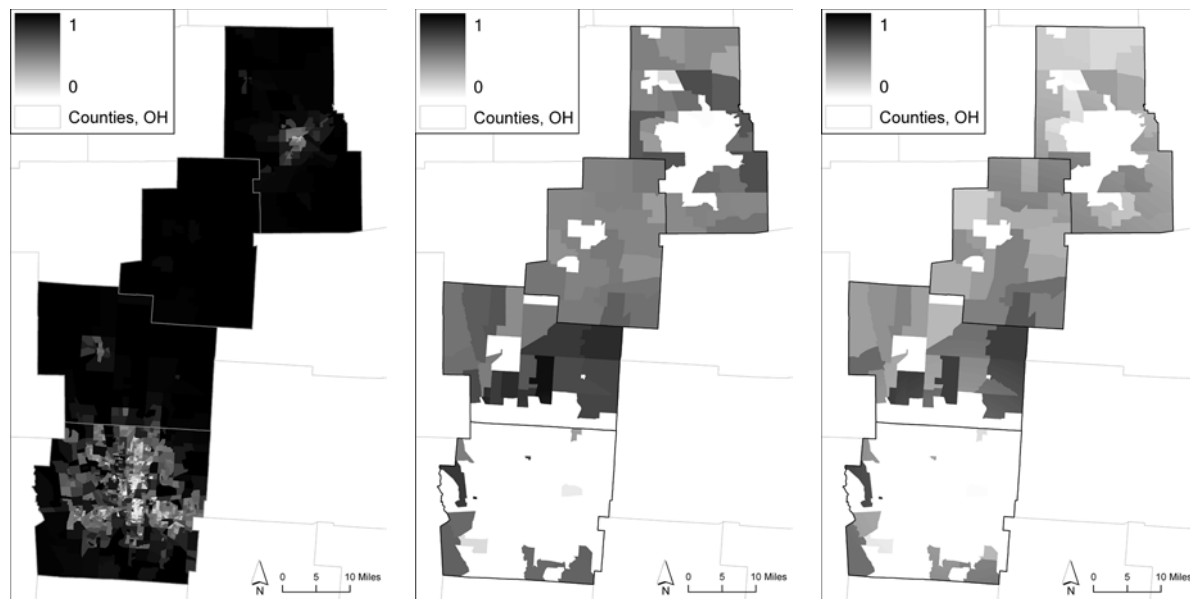


(e) using household income
(Nelson and Sanchez 1999;
Min: 0, Max:1,
Area: 845 mi²)



(f) using housing density
(Theobald 2001;
Min: 0, Max:1,
Area: 1,061 mi²)

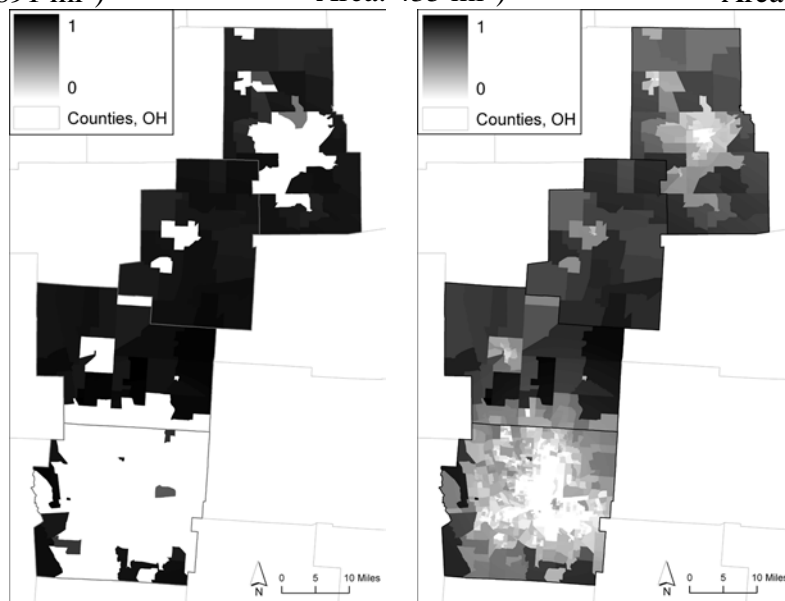
Figure 5. Maps showing different membership values of exurban area based on different attributes of different definitions (values of 1 mean high membership of being exurban area; values of 0 mean low membership). Area = exurban area calculated on areas above a membership threshold value of 0.5.



(a) union
(Zadeh 1965;
Min: 0.19, Max: 1,
Area: 1,891 mi²)

(b) intersection
(Zadeh 1965;
Min: 0, Max: 0.88,
Area: 435 mi²)

(c) algebraic product
(Zadeh 1965;
Min: 0, Max: 0.75,
Area: 126 mi²)



(d) gamma operation: $\gamma = 0.9$
(Champati ray et al. 2007;
Zimmermann and Zysno
1980; Min: 0, Max: 0.98,
Area: 1,213 mi²)

(e) average
(Ban and Ahlqvist 2007;
Min: 0.06, Max: 0.95,
Area: 1,730 mi²)

Figure 6. Maps showing examples of negotiated definitions of exurbanization based on different combinatory approaches of fuzzy-sets (values of 1 mean high membership of being exurban area; values of 0 mean low membership). Area = exurban area calculated on areas above a membership threshold value of 0.5.

Generally, the maps in Figure 6 show similar patterns of membership values; mostly low in Franklin County and Richland County, and high in Delaware County and Morrow County. However, they also show some differences. Similarly to the areas in Figure 5, the areas within the same membership threshold in Figure 6 vary between the maps since different combinatory approaches were used in each map.

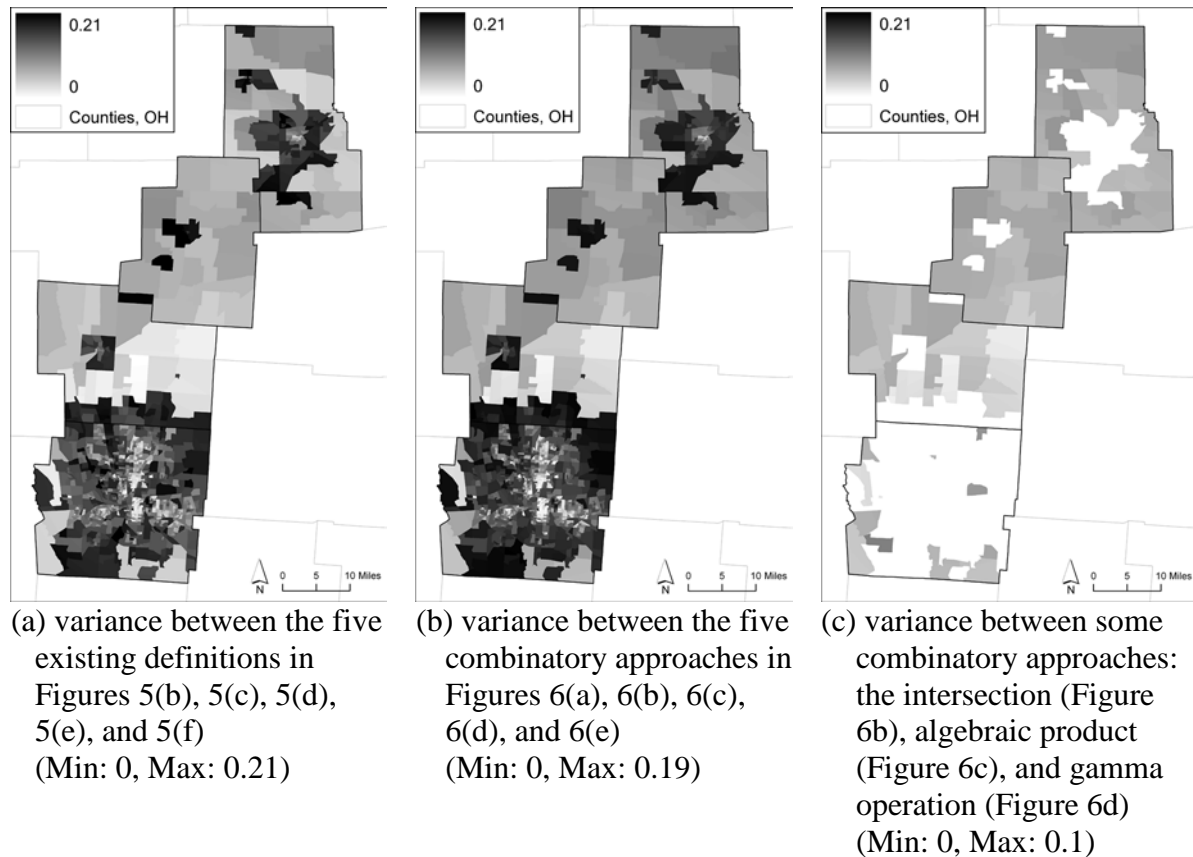


Figure 7. Examples of differences between the concept definitions and their combinatory approaches

5.3 Difference between the definitions and the combinatory approaches

In Figure 7(a), the spatial variance of the five definitions of exurbanization (see Figures 5 b-f) is illustrated. The darker grey color means that there is large variation in exurban membership

values in that location, which also is an indicator of high uncertainty or disagreement. In contrast, the lighter grey color represents areas where the five definitions agree.

Figure 7 (a) shows that the largest disagreement between the five exurban definitions is in and around the City of Columbus and the other urban centers of Delaware, Morrow, and Richland Counties. For most of the rural areas they have similarity with the largest agreement in Delaware County, just north of the southern part of the county where a big disagreement is also found. In Figure 7b, we present the difference between the five combinatory approaches. This map shows a very similar picture as we saw in Figure 7a. Furthermore, Figure 7(c) demonstrates how similar three of the combinatory approaches are.

5.4 Evaluation of the interactive tool for comparison and definition of uncertain geographic concepts

The current pinu interface (Figure 4) reflects feedback from a preliminary user-evaluation described in Section 4. Main points from that study centered on interface design and extensions of the software functionality. Additionally, the user feedback contributed to some improvements of pinu by identifying functional errors, difficulties in understanding how it works, design issues, and problems in visual displays. The current interface thus includes features to promote more interactivity, enhanced usability, and interoperability. In addition, the user can create a new concept definition and visualize that together with existing definitions and empirical spatial data in the revised interface.

6. Discussion and conclusions

Our first goal to identify and illustrate the semantic uncertainty of the exurban concept was addressed by the development of fuzzy-set based conceptual descriptions that could be analytically negotiated, visualized, and interactively explored in the developed software pinu. Six different definitions were investigated and the way they conceptualize exurban areas could in most cases be represented formally by fuzzy-set based conceptual space attributes (Table 1). When these definitions were applied to empirical spatial data they demonstrated surprisingly similar spatial patterns of exurbanization despite their differences in the defining attributes. The presented software, pinu, addressed the second goal; to seek an interactive tool for working with uncertain geographic concepts. Supported by a preliminary user-evaluation we developed and demonstrated functionality to aid both concept-comparing and concept-creation activities. We anticipate that the software interface can help communication and collaboration between a variety of stakeholders that seek to discuss hard to define concepts, and reach consensus. In our final goal to demonstrate some implications of semantic uncertainty we looked into the spatial outcomes of several exurban definitions, their variation, and various approaches for analytical combination of fuzzy-set definitions for concept negotiation. We demonstrated that the spatial outcome of six seemingly different definitions of exurban land-use turned out to produce similar spatial patterns of definition agreement (i.e. what constituted exurban land-use). Additionally, we also illustrated the effect of different combinatory approaches to numerically negotiate the definitions. A key point is that in the areas where definitions mostly agree, the choice of combinatory approach is of little importance, but in other places the choice of combinatory approach may create very different outcomes.

The illustrated approach and software could potentially be generalized to work with boundary negotiation for other types of contested spaces. Our preliminary experimentation with pinu's prototype indicates that the uncertainty specifications suggested in this paper supply sufficient flexibility for use in other application situations as well.

Although the approach and software design has been designed for a web-based architecture the current prototype interface provides limited support for web-based activities such as interactive distant-communication between the users. In our further development of pinu we will seek to address yet unsupported functionality, such as distant-communication.

Extending the approach further, we also see possibilities to investigate the temporal characteristics of geographic concepts, for example the spatio-temporal aspects of exurbanization as well as dealing with subjectivity issue in assignment of weights for concept attributes.

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